A review on heavy metal accumulation and toxicity in biotic and abiotic components

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Abstract: Pollutants in the environment remains to be a global issue and among the greatest challenges confronting mankind. Among the various kinds of pollutants, heavy metals have drawn a lot of attention owing to their toxicity. Heavy metals are recognized to be naturally existing, however they are introduced in considerable quantities in many environmental compartments due to anthropogenic activities. When added into the atmosphere eventually these find their way back to the ground, contaminating soils and water. These metals enter into the plant system through a variety of physiological mechanisms, affecting plant growth and development. The possible entry of these elements into the ecosystem has been attributed to the increased levels of heavy metals in the ecosystem through direct intake from polluted soils, vegetables grown on polluted soils, or drinking wastewater that has infiltrated through such soils. Heavy metal accumulation arises when vegetable crops are grown in an environment contaminated with heavy metal, further entering and magnifying in the food chain. Human health is jeopardised by the presence and consumption of potentially harmful heavy metals in biota and groundwater. Heavy metal exposure can cause a number of serious human health implications, including kidney disease, respiratory problems, neurological disorders, and cancer. These heavy metals have an impact not merely on plants and humans, but also on soil health, water sources, soil nutrient status, and other aquatic organisms. These are irreversibly introduced in the environment since they cannot be degraded and are typically present in trace amounts, yet even at low levels, many of them can be harmful. The increased levels of heavy metals in the environment are hence currently prompting increased concern and need improvised remedial measures.
Key words: Heavy Metals; Human Health; Soil; Water; Agriculture; Crops

1. Introduction

There is plethora of definitions for heavy metals which rely upon the specific circumstances and the goals of the present study. Heavy metals are naturally available elements with a high atomic weight and density that is at least five times that of water, posing a threat to the environment. The expression "metal trace elements" (MTEs) is frequently utilized somewhat that of "heavy metals," since the MTEs incorporate harmful hefty metals as well as other not so toxic, substantial components (metalloids). Even low amounts of nickel, copper, lead, chromium, zinc, mercury, and cadmium are hazardous above a certain threshold value (lower than about 0.01 mg L\(^{-1}\)) are exceptionally destructive to people. Mercury in drinking water is regulated at 2 parts per billion by the US Environmental Protection Agency. The world health organization recommends that Hg levels in wastewater and soils for agriculture be kept at 0.0019 and 0.05 parts per million, respectively. High levels of exposure to MTEs, most commonly by inhalation of toxins from the air, intake of polluted drinking water and food, and exposure to contaminated soils and industrial sites, can have serious consequences for human and animal health [1–3].

Heavy metals can originate from natural as well as anthropogenic sources and end up in several of environmental segments (soil, air, water and its interface). Multiple studies have identified a number of natural sources of heavy metal pollution. Natural weathering mechanisms can transfer metals from their endemic spheres into various environmental segments. Natural heavy metal emissions also occur under varied and specific environmental conditions. Rock weathering, sea-salt sprays, volcanic eruption, biogenic sources, and wind-borne soil particles are examples of such emissions [4–6]. As per numerous studies conducted on the estimation of heavy metals, anthropogenic sources are the primary causes of their pollution in the environment. Agriculture, mining, wastewater, industries, metallurgical processes, and runoffs are a few of the activities that result into the emission of pollutants to various environmental segments. Lead is emitted by automobiles; zinc, arsenic, and copper are emitted by smelting; arsenic is a waste product in insecticides; vanadium, selenium, mercury, nickel, and tin are released from fossil fuel burning. All these are the main anthropogenic sources of heavy metal pollution making a considerable contribution to heavy metal pollution in the environment [7–9].

Heavy metal contamination is a well-known environmental issue that presents a significant threat to human life. Some heavy metals have bio-importance and are vital for survival only in trace amounts but the bio toxic effects of many of them in physiology of biotic components are of great concern. With the increased usage of a vast range of metals in industries and our everyday lives, environmental issues resulting from hazardous metal pollution have grown significantly [10–12]. The toxicity of these compounds is determined by a variety of parameters, including chemical species, route of exposure, dose, as well as gender, age, genetics, and nutritional status of persons who are exposed.
Heavy metals are deposited into all environmental segments as a result of extensive usage of raw materials and processing, which affects human health. Heavy metal contamination has a negative impact on soil quality and, as a result of bioaccumulation, poses a health risk to humans. Several man-made sources of pollutants, including waste water from mines and storage of waste, pesticide runoff from agricultural activities, and air deposition, can impact the soil and water environment. Despite the critical role of fertilizers and amendments for enhanced crop productivity, they can contaminate in water and soil when applied in high quantities as they include undesirable contaminants such as heavy metals. Metal-containing sewage sludge applied to agricultural lands can cause contamination of water, crops, and soil since, soil acts as a dynamic entity through which metals flow during recycling from waste to hydrosphere, atmosphere and biosphere [13–15].

Furthermore, numerous investigations have reported the presence of heavy metal trades in marine waters as well as their implications on animal health and aquatic ecosystems. Humans, fish, and plants can be harmed by heavy metals like zinc, lead, copper, nickel, and cadmium if they are exposed to them for an extensive period. Harmful heavy metals including iron, mercury, and lead impair soil quality and agricultural yield. Research carried out in the water of Vasai Creek in Maharashtra found elevated amounts of heavy metals in treated sewage water, like Hg, Cd, Cu, Cr, Pb, Zn, and Ni, and further having the ability to ruin crops growing under this kind of irrigation [16].

Due to their widespread exposure, the impact of these materials on human health has become a matter of concern in the wake of increasing transportation and urbanisation. Zinc, copper, iron, molybdenum, and nickel are necessary for optimal biological function whereas Cadmium, Lead, Mercury are not biologically needed but play vital role in industrial processes. These disrupt ecosystems due to their ability to bioaccumulate in organisms and possessing harmful effects on biota and even premature death in most living organisms. Heavy metals build up in the kidneys, liver, brain, bone, heart, and other important organs, causing them to malfunction. Their accumulation also causes the important dietary nutritional minerals to be displaced from their original location, obstructing their biological activity [17–19].

So, the different approaches are required to be adopted for removal of these heavy metals from different components to have a safe environment. The ensuing segments of the paper glance through the various impacts of heavy metals on human health, through possible routes of contamination such as agricultural crops and water.

2. Impact of heavy metals on agricultural crops

The phenomenon of absorption, which happens inside the roots of a plant, is the principal way by which heavy metals enter the food chain. The activity of heavy metal absorption within plant tissues is dependent on temperature, moisture content, pH, availability of nutrients and organic matters. Moreover, it has been found that the activity of absorption is much more during the summer season as compared to winters. Accumulation of different heavy metals within the plants is dependent upon the type of plant species along with the efficiency of plants to absorb metals. Plants vary in their sensitivity towards various nutrients and concentration of heavy metals and show variable reactions. This load of changes in plant attributes bring about particular light absorption qualities in addition to reflectance qualities, which can be utilized as a pointer of soil pollution and the physiological status of the plant. Heavy metals and metalloids such as Cd, As, Pb, Cr, and Hg can accumulate toxically in underground and above ground plant components if their concentration in soil reaches the threshold level. Some of the physiological effects that have been observed because of metal toxicity within
plant species are inhibition of seed germination, declined growth rate, fluctuations in photosynthetic efficiency, alteration in respiration and transpiration rate.

A portion of many heavy metals like Pb, As, Hg, Cd, or Se are not essential for the overall growth of plants. The primary reason is that these heavy metals do not have any specific physiological capacity within the different plant species. On the other hand, heavy metals like Co, Cu, Fe, Mn, Mo, Ni and Zn are rudimentary metals which are required for the plant growth and digestion phenomenon within plants. But the availability of these metals above the prescribed permissible limits has a threatening impact on biotic and abiotic components. The utilization of manure to work on farming yield without taking into consideration the conceivable adverse consequences may be the point of concern as the waste fertilizers are used to develop soil for growing vegetables. The process of liming results in raising the heavy metals concentration in soil. Along with it, sewage sludge also responsible for degrading the soil quality. There are several parameters like moisture, pH, nutrient availability, temperature and organic matter, on which the absorption as well as accumulation of heavy metals within plant tissues is dependent.

[1] Analysed the status of various heavy metals using atomic absorption spectroscopy in seasonal vegetables namely cauliflower, spinach, cabbage and mustard sown in kakching-Wabagai. It was concluded that the Fe and Cu concentration was above permissible limits in the samples with nil concentration of lead in them. Some of the characteristic leaf symptoms have been observed among Raphanus and Phaseolus along with reduced root: shoot ratio and biomass ratio. [2] Discovered that the concentration of capsaicin and dihydrocapsaicin within pepper fruits that were grown in sludge-amended soil having heavy metals was extremely less which has resulted in reducing pungency levels. This has made the fruits unproductive in nature. [3] Investigated the different elemental concentrations for shoot, soil, root, and fruit samples in various vegetables. The concentration of Cu and Zn increases in plant shoots was found highest in pepper followed by collard, radish, lettuce and tomato. The Cu and Zn concentration accumulated fundamentally in the tomato plants contrasted with different sampled plants. The root exudates released organic acids due to the biogeochemical reactions. It adversely affects the growth of plant as the metal gets accumulated in roots during the development phases. Zn and Cu combine together to form the different organometallic complexes with the different organic acids from root exudates results in increasing uptake of contaminants among plants. The availability of Zn in abundance in growth media resulted in increased toxicity within the crops. [4] Concluded that the biomass of spinach has been diminished by the concentration of heavy metals fundamentally. The new weight and dry weights declined by 10.1 and 35.1 percent at the most noteworthy portion of Cd and in context to Pb the fresh and dry weights reduced by 8 and 28 percent. In reference to Zn the shoot and root lengths reduced by 3 and 13 percent separately, when contrasted with the control treatment. The total amount of protein, fibre, and moisture of spinach reduced by 31, 29, and 33 percent, respectively, at most elevated portion of Cd. The total amount of protein, fibre, and moisture declined by 23, 22, and 29 percent, individually, in case of Pb when contrasted with control. The high concentration of heavy metals brought about the decline of sodium, potassium, calcium, Fe, magnesium, Mn, and Cu in spinach.

3. Impact of heavy metals on water bodies

There are numerous anthropogenic sources of water pollution which may include mining, flue gases from vehicles, industrial exhaust gases, combustion, and incineration of solid waste. The water contamination hence, is toxic to biotic components as they generally enter food chain. The impact of heavy metals has been classified in two broad categories namely ground water and surface water.
4. Impact of heavy metals on surface water

Rivers have both biological and economical importance to society. Nonetheless, river water is easily prone to pollution since they are normally opened, accessible, and generously utilized not only in farming but also in industrial and municipal activities. The heavy metals have a great affinity to affect the environment by increasing toxicity, due to which they have emerged as a global concern in context to aquatic environment. The excessive exploitation of mines around the world has also aggravated numerous environmental issues like contamination of river water.

Due to the proliferating development of industries, effluents containing heavy metals either through surface run-off or direct discharge are posing imminent threat to water bodies. During transportation of heavy metals, a huge amount of these tend to accumulate in marine plants and estuaries. An elevated concentration of various heavy metals have been found among numerous estuaries around the world which are part of sediments, mangroves and many other species within the ecosystem. Estuaries are significant in terms of economic activities at coastal areas and therefore it becomes essential to examine the concentration of heavy metals and other pollutants in estuarine ecosystems. Heavy metals (e.g., Cadmium) can accumulate in the root and stems of the mangroves and also can replace the carbon and nitrogen ratio of the plants. This effect of heavy metal affects the carbon storage in estuarine plants and mangroves further impacting the global climate. It has been analysed that the contamination rate of heavy metals in estuaries increases at a proliferating rate and has been found to have huge negative impacts on Cochin estuary. Accumulation of arsenic in excessive amount can be toxic for various organisms living within an estuary ecosystem along with humans that consume fishes from such estuaries. Bioaccumulation of cadmium within marine organisms is dependent on different cadmium compound structures, temperature and salinity of marine system.

In context to lead it has been analyzed that the presence of lead is acceptable in aquatic systems as lead is slightly soluble in saline water bodies. This provides protection against lead to accumulate within marine organisms. Presence of lead is toxic for different organs but it has affinity to damage the lungs specifically which may result in development of lung cancer. Mercury is one of the highly toxic heavy metals that have been found in marine ecosystem. Methyl mercury is a common compound of mercury found in the sea foods and especially at Indian Ocean.

5. Impact of heavy metals on Ground water

The groundwater extracted through wells is directly been used for different domestic activities. The availability of toxic heavy metals in various water sources as aquifers pose a great threat on environment and society across the world. The heavy metals pose a problem to human health by consuming contaminated heavy metal enriched water. This results in deteriorating the overall quality of various water sources as heavy metals are added into minute quantities in ground water from the various industries that manufacture batteries, leather, pharmaceutical products, paints, agrochemicals and many other products. Such industries dispose off the wastewater/effluent into the water bodies without any specific treatment in coastal areas. The most common type of contamination because of heavy metals is observed around landfill sites. Along with landfill sites, agrochemicals are also considered as a cause of contamination as they are retained in the different unsaturated zones. From these zones the contaminated effluent containing heavy metals enter the groundwater sources. Thus, the pollution created by deposition of heavy metals has emerged as one of the major areas of concern in context to water bodies and human health.

6. Impact of heavy metals on human health

Excessive levels of heavy metals (Ni, Cr, Cd, etc.) in human body have been linked to severe chronic effects such as developmental/reproductive toxicity, immunotoxicity, and neurotoxicity. Exhaustive
analyses have revealed that heavy metals (Hg, Pb, and As) may induce prechronic toxicity and carcinogenesis in humans. Based upon the epidemiological studies, chromium, arsenic, and nickel are designated as human carcinogens whereas berillium, lead, and cadmium, are possibly carcinogenic in humans. Because of its potency, cadmium, arsenic, nickel, and chromium have been categorised as group 1 carcinogens by the International Agency for Research on Cancer and they have multiple commercial application. To explore the toxicity and carcinogenic effects of these metals, performed molecular pathway analysis. The research revealed that the metallic substances described above cause DNA damage, cell death, and oxidative stress increasing the risk of cancer and related disorders.

Heavy metals are both necessary components for basic biological activities and toxic agents that cause harm when present in excessive amounts. Due to their numerous medical, domestic, industrial, and agricultural applications, they are widely distributed in the environment, prompting a reason to worry about their probable impact on the human health and environment. The environmental risks of heavy metal contamination increase the possibility of negative consequences from exposure to them, whether through direct or indirect intake. These are extremely harmful to the terrestrial as well as aquatic life forms and to the various segments of environment. Not only can these heavy metals deposit but can also increase in concentration owing to their retention capability in living organisms via food chain.

Bioaccumulation is the net assimilation of a pollutant from any source through all potential channels such as respiration, ingestion, and direct contact. Bioaccumulation and further transfer of heavy metals into the food chain can lead to biomagnification at upper trophic levels, resulting in an elevated concentration of a contaminant in an organism than in its prey. Additionally, heavy metals have been found to have an impact on cellular organelles and components like the mitochondria, endoplasmic reticulum, lysosomes, nuclei, cell membrane, and some enzymes engaged in detoxification, metabolism, and damage repair. Metal ions have been reported to interact with cell components like nuclear proteins and DNA, triggering DNA damage and conformational changes that can lead to cell cycle modulation, cancer, or apoptosis. Toxic metals can disrupt a variety of physiological processes, including those of the central nervous system, hepatic, haematopoietic, and renal systems. Metals can cause a variety of toxic consequences, which can be systemic or local, chronic or acute, due to their unique interactions with organ, tissues, and cells. As lead has a high tendency to accumulate in erythrocytes and bone, acute intoxications are uncommon; instead, chronic intoxications are more common. Heavy metal poisoning by mercury and lead, can cause autoimmunity, a condition in which the patient's immune system attacks his own cells. This can result in joint diseases like rheumatoid arthritis, as well as kidney, and neurological system issues.

The threat of developing cancer has been linked to prolonged exposure to various heavy metals and chemicals. Long-term exposure to lead, arsenic, vanadium, chromium, mercury, cadmium, copper, zinc, and nickel can have negative health consequences in humans, including chronic inflammation and an elevated risk of cancer.[6] reported an elevated death risk from lung cancer throughout the life through workplace exposure to dusts containing hexavalent chromium. Consumption of cadmium-contaminated rice and other foods has been linked to elevated risk of postmenopausal breast cancer. Chronic and acute arsenic exposure can result in various human health issues like neurological, respiratory, hepatic, cardiovascular, genotoxic, dermal, haematological, renal, gastrointestinal, mutagenetic, developmental, immunological, reproductive, and carcinogenic effects.

Heavy metal contamination has also been linked to a variety of chronic diseases around the world, including Minamata disease that was caused due to methylmercury poisoning, itai-itai disease caused due to cadmium poisoning, and blackfoot disease due to arsenic poisoning. Minamata disease was
caused by methylmercury, which had neurological symptoms, and was driven by daily intake of enormous quantities of contaminated fish and shellfish heavily contaminated with toxic chemicals released by chemical factories. The Minamata disease not only claimed many lives among locals, but it also sparked tension in the community and left plenty of political and social concerns in its wake. Numbness in the feet and hands, generalized muscle weakness, narrowing of the range of vision, and hearing and speech impairment are the symptoms. In the worst-case scenario, paralysis, insanity, coma, and death occur within weeks of the appearance of symptoms. A congenital form of the disease can even harm the foetus in the womb.

Itai-itai disease, which is caused by continuous oral intake of Cd, is the most severe form of chronic Cd poisoning. It developed in a large number of people of the Jinzu River basin in Toyama Prefecture, Japan, a region heavily contaminated by Cd from a zinc mine upstream. After prolonged cadmium exposure, the kidney is the organ most severely affected due to which population of the Jinzu River basin have a high rate of occurrence of proximal tubular dysfunction. One of the principal effects of cadmium poisoning is weak and brittle bones, leg and spinal discomfort, and a waddling gait associated with bone deformities triggered by cadmium. As the bone weakens, the pain becomes debilitating, and fractures become more likely. Coughing, anaemia, and kidney failure are further problems that can lead to death.

Blackfoot disease was reported in southwestern Taiwan as a consequence of consuming well water with excessive arsenic levels. In the southwestern coastal region of Taiwan, this is a unique peripheral vascular ailment that leads to dry gangrene and spontaneous amputation of the affected extremities. Ever since early twentieth century, infrequent occurrences of a peculiar disease affecting the lower extremities have been observed, which is characterized by a progressive blackish darkening of the skin that extends from the toes to the ankles. Prior to the emergence of gangrene, the patients experienced numbness or coldness of their extremities, as well as intermittent claudication. The lesions might progress to spontaneous amputation in some cases and in rare cases, the fingers might also be involved.

7. Conclusion

Heavy metal pollution is a global issue owing to the persistence and accumulation of metals in the environment. These are natural elements present in the earth, but indiscriminate anthropogenic activities have drastically altered their biochemical balance and geochemical cycles. Heavy metal fate and mobility in soil and groundwater can take a variety of forms. Heavy metals are harmful to living organisms due to their inability to be removed by biological degradation and their potential to accumulate in the organs of living organisms. Heavy metals have an impact on all types of organisms as well as ecological functions, including microbial activity. Excessive amounts of essential and non-essential metals disrupt normal biological activities and trigger cellular stress responses. Heavy metal exposure can cause a number of major health problems in humans, including respiratory problems, kidney problems, neurological disorders, and cancer. This study focuses on the effects of heavy metals accumulation on the biotic and abiotic components. The study herein unequivocally concluded that heavy metals pose a serious impact on the agricultural crops, water, and human health. But further study is needed to assess the level of risk through the exposure to individual heavy metals.
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