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Environmental Factors Impacting Heavy Metal Contamination of Mango Fruits and Health Implications on Consumers: A Biochemical Analysis

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Abstract: Mango (*Mangifera indica* L) is a cherished fruit in many continents. It has a high trade value and economic importance due to its production and sales. However, anthropogenic activities have often impacted the quality, creating contaminated fruits for human consumption. This review of recent literature highlights the staple nature of the fruit and its contributions to the caloric value of its consumers. However, different environmental practices, ranging from natural causes to anthropogenic activities such as industrial production, agrochemical uses and discharges, vehicular traffic, create sources of pollution to the mango fruit. Fruit contamination is rampant in Africa and Asia, predisposing consumers to chronic toxicity. The public health impact may be through pathologies initiated by heavy metal poisoning owing to accumulation in different body tissues such as bones, brain, liver, and kidneys. Molecular basis for heavy metals update and toxicities were discussed. Proactive and corrective strategies were made to manage agricultural soils and safeguard the public from consuming heavy metals-contaminated mangoes.

Keywords: Mango, *Mangifera indica*, heavy metals, environmental pollution, toxicity, public health.

INTRODUCTION

Mango (*Mangifera indica*) is a tropical fruit widely cultivated and consumed worldwide, highly prized for its delicious flavor and rich nutritional value. The fruit is a significant source of vitamins (notably vitamin A and C), essential minerals (potassium and magnesium), dietary fiber, and diverse bioactive compounds including polyphenols and carotenoids, which have been associated with antioxidant, anti-inflammatory, and cardioprotective effects (Liu and Wang, 2018; Ahmed *et al.*, 2019). Due to its nutritional and economic importance, mango constitutes a key component of diets in many tropical and subtropical regions, serving both as a fresh fruit and as a processed product in juices, jams, and purees.

Despite these benefits, increasing environmental pollution poses a major threat to food safety, particularly through the contamination of fruits with heavy metals. Heavy metals are naturally occurring elements with high atomic weights and densities, including lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As), which are toxic even at low concentrations (Jaishankar *et al.*, 2014). Unlike organic pollutants, heavy metals are non-biodegradable and persistent in the environment, and can accumulate in soil, water, and plants over time. The bioavailability of these metals in agricultural ecosystems is influenced by factors such as soil pH, organic matter content, metal speciation, and the presence of competing ions, which can enhance or limit their uptake by plants (Alloway, 2017).

In Nigeria and similar developing countries, mango orchards are frequently situated near urban or peri-urban zones where anthropogenic activities significantly increase environmental heavy metal levels. Given the widespread consumption of mango fruits, even slight elevations in metal concentrations could pose considerable public health risks. Therefore, investigating the extent of heavy metal bioaccumulation in mango fruits, understanding the mechanisms of uptake and translocation, and assessing the potential health implications are critical for developing informed food safety regulations and public health interventions (WHO, 2017). Moreover, such studies provide a framework for sustainable agricultural practices and guide policymakers in minimizing consumer exposure to toxic metals, ensuring both nutritional security and safety.

MANGO (*MANGIFERA INDICA*) AS A DIETARY FRUIT

Mango (*Mangifera indica*) is one of the most widely cultivated and consumed tropical fruits globally, valued for both its nutritional richness and economic importance. It belongs to the family *Anacardiaceae* and is extensively grown across Asia, Africa, and Latin America, where climatic conditions favor its year-round or seasonal production. During its fruiting season, Mango is a staple food in many households owing to its abundance. Mango serves as a significant dietary component for millions of people, particularly in developing countries where fruit intake contributes substantially to micronutrient supply. This high consumption rate makes mango an important focus in studies assessing dietary exposure to environmental contaminants such as heavy metals.

Nutritionally, mango fruits are recognized for their high content of essential vitamins, minerals, and bioactive compounds. They are especially rich in vitamin A precursors, notably beta-carotene, as well as vitamin C, vitamin E, and several B-complex vitamins. Mango also provides dietary fiber, potassium, magnesium, and various polyphenolic compounds with antioxidant properties. These nutrients contribute to immune support, visual health, cardiovascular function, and protection against oxidative stress. The presence of antioxidants in mango has been linked to reduced risks of chronic diseases, including certain cancers and metabolic disorders, further increasing its dietary relevance (Ribeiro *et al.*, 2020). Its rich fibers aid bowel movement, increasing gastrointestinal health.

Globally, mango ranks among the top tropical fruits in production and consumption. It plays a critical role in food security and nutritional sustainability within tropical regions. During fruiting seasons, mango provides an inexpensive source of calories and micronutrients, particularly in rural communities where dietary diversity may be limited. The fruit's contribution to household nutrition is especially important during periods of food scarcity, as it supplements staple-based diets that are often low in vitamins and minerals. Consequently, any contamination of mango fruits with heavy metals has implications not only for individual health but also for broader public health and food safety systems.

Despite its nutritional benefits, mango accumulates heavy metals from contaminated soils, irrigation water, and atmospheric deposition. Studies have demonstrated that fruit crops, including mango, can absorb metals such as lead, cadmium, chromium, and nickel through their root systems, with subsequent translocation to edible tissues. Given that mango fruits are often consumed raw without extensive processing, the potential for direct human exposure to bioaccumulated heavy metals is significant. This dual role of mango as both a nutrient-rich fruit and a potential pathway for toxic metal exposure underscores its relevance in bioaccumulation and health risk studies (Zhang *et al.*, 2021).

Overall, the widespread consumption, nutritional importance, and environmental sensitivity of mango fruits make them a critical subject in assessing the bioaccumulation of heavy metals in food crops. Understanding how mango interacts with contaminated agricultural environments is essential for evaluating dietary exposure risks and developing appropriate food safety interventions, particularly in rapidly urbanizing and industrializing regions.

CONCEPT OF BIOACCUMULATION

Bioaccumulation refers to the progressive accumulation of chemical substances, particularly toxic elements such as heavy metals, in living organisms when the rate of uptake exceeds the rate of elimination. In environmental and biological sciences, bioaccumulation is used to describe how contaminants persist and concentrate within organisms over time as a result of continuous exposure from environmental media such as soil, water, and air (Arnot and Gobas, 2017, Izah *et al.*, 2023). On the other hand, bioconcentration specifically refers to the uptake of contaminants directly from abiotic media, mainly water, without considering dietary sources, while biomagnification describes the increase in contaminant concentration across successive trophic levels of a food chain (Burkhard *et al.*, 2019). Bioaccumulation, however, is broader and encompasses all routes of exposure, including root uptake from soil, absorption from irrigation water, and atmospheric deposition, making it particularly relevant to crops and food safety assessments.

In plants, bioaccumulation of heavy metals is governed by complex physicochemical and biological processes. Metals present in soil or water may exist in various chemical forms, influencing their bioavailability. Once bioavailable, heavy metals can be absorbed by plant roots through passive diffusion or active transport mechanisms involving metal transport proteins and ion channels (Clemens and Ma, 2016). Following uptake, metals may be translocated to aerial parts of the plant, such as leaves and fruits, where they can be sequestered in cellular compartments such as vacuoles or bound to biomolecules like phytochelatins and metallothioneins.

From a food safety perspective, bioaccumulation is of particular concern because heavy metals are **non-biodegradable** and can persist in edible plant tissues long after exposure. Continuous consumption of bioaccumulated metals through fruits and vegetables can result in chronic human exposure, even when environmental concentrations appear low (Peralta-Videa *et al.*, 2019). This characteristic makes bioaccumulation a critical concept in evaluating dietary exposure risks and long-term health outcomes.

In fruit crops such as mango (*Mangifera indica*), bioaccumulation is influenced by several factors, including soil characteristics, irrigation practices, proximity to pollution sources, and the physiological traits of the variety in question. Since mango fruits are often consumed fresh and without extensive processing, any accumulated heavy metals may be directly transferred to consumers, underscoring the importance of understanding bioaccumulation mechanisms when assessing potential health implications (Shahid *et al.*, 2020). Thus, bioaccumulation provides a fundamental framework for linking environmental contamination, plant uptake, and human health risks.

HEAVY METALS AS ENVIRONMENTAL CONTAMINANTS

In environmental science and toxicology, heavy metals commonly discussed include lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and nickel (Ni). While some metals, such as iron, zinc, and copper by density could be described as heavy metals, they are essential micronutrients required for normal biological functions (Ali and Khan, 2019).

A defining feature of heavy metals as environmental contaminants is their persistence. Unlike many organic pollutants, heavy metals are non-biodegradable and can remain in soils, sediments, and water bodies for extended periods. Their persistence allows them to accumulate in agricultural ecosystems, where they may become bioavailable to plants and subsequently enter the human food chain (Oluwafemi et al. 2021) and elicit an array of deleterious effects from molecular to systemic levels (Tchounwou *et al.*, 2017) depending on their concentrations. The environmental behavior of heavy metals is strongly determined by several factors, including soil pH, organic matter content, redox potential, and metal speciation. These factors dictate mobility and bioavailability of heavy metals (Rai *et al.*, 2019).

Anthropogenic activities are primarily responsible for heavy metal contamination in the environment. Industrial discharges, mining and smelting operations, vehicular emissions, improper waste disposal, and the excessive use of fertilizers and pesticides have significantly increased heavy metal loads in agricultural soils (Singh *et al.*, 2021). In many developing countries, untreated or poorly treated wastewater is commonly used for irrigation, further exacerbating the accumulation of metals in farmland soils and crops. Atmospheric deposition from industrial and traffic-related emissions also contributes to surface contamination of fruits and vegetables, particularly in orchards located near urban centers.

From a toxicological perspective, heavy metals pose serious environmental and health concerns due to their ability to induce oxidative stress, disrupt enzyme activity, and interfere with cellular signaling pathways. Metals such as lead and cadmium may accumulate in biological tissues over time, leading to chronic toxicity affecting multiple organ systems, including the nervous, renal, hepatic, and cardiovascular systems (Genchi *et al.*, 2020). Arsenic and mercury, in particular, have been associated with carcinogenic and neurotoxic effects, making their presence in food crops a critical public health issue (Oluwafemi et al. 2021)

In agricultural systems, heavy metals contaminate crops primarily through soil-to-plant transfer. Once present in soil, metals may be taken up by plant roots and distributed to edible tissues depending on plant species, growth stage, and environmental conditions. Fruit crops are of special concern because they are often consumed raw, limiting the opportunity for processing steps to reduce contaminant levels (Antoine *et al.*, 2017). Consequently, fruits such as mango serve as potential vectors for chronic dietary exposure to heavy metals.

Sources of Heavy Metals in Agricultural Environments

Heavy metal contamination of agricultural environments arises from both natural (geogenic) and anthropogenic sources. Understanding these sources is critical for interpreting patterns of metal bioaccumulation in crops, including fruit-bearing plants such as mango (*Mangifera indica*), and for assessing the associated risks to human health.

Geogenic sources of heavy metals originate from the natural composition of the Earth's crust. Weathering of metal-bearing parent rocks leads to the gradual release of elements such as arsenic, chromium, nickel, and cadmium into soils and groundwater (Kabata-Pendias, 2019). Volcanic activity and erosion processes further contribute to background levels of heavy metals in agricultural soils. Although naturally occurring, these metals can become environmentally significant when soil conditions, such as low pH or high salinity, enhance their solubility and bioavailability to plants. In some regions, geogenic contamination alone suffices to elevate heavy metal concentrations in crops beyond safe consumption limits, particularly in areas with metal-rich lithology (Reimann and Garrett, 2017). Anthropogenic activities are the predominant contributors to elevated heavy metal levels in modern agricultural systems. Industrial emissions from smelting, manufacturing, and power generation release metals such as lead, mercury, and cadmium into the atmosphere, which become deposited onto agricultural soils through dry and wet deposition processes (Tóth *et al.*, 2016). Vehicular emissions also play a significant role, especially in farmlands situated along highways and urban areas, where lead and other metal residues from fuel combustion and tire wear deposit on soil surfaces and crop foliage.

Mining and mineral processing activities represent another major source of heavy metal contamination. Tailings, waste rock, and acid mine drainage introduce high concentrations of metals into surrounding soils and water bodies, which may be used for irrigation in nearby agricultural areas (Zhang *et al.*, 2018). Additionally, the prolonged use of agrochemicals such as phosphate fertilizers and pesticides aids the gradual buildup of heavy metals in agricultural soils, particularly cadmium and arsenic (Zhao *et al.*, 2020, Yarkwan *et al.*, 2024).

Wastewater irrigation is a critical pathway for heavy metal introduction into agricultural environments, especially in water-scarce regions. Untreated or partially treated wastewater often contains elevated levels of metals derived from domestic sewage and industrial effluents. Continuous application of such water leads to the accumulation of metals in soil and enhances their uptake by crops, including fruits that are consumed fresh (Chen *et al.*, 2019).

Rapid urbanization and industrialization have intensified heavy metal contamination of agricultural landscapes. Urbanization brings farms into proximity with industrial zones, waste disposal sites, and high-traffic road networks, increasing the likelihood of metal deposition and soil contamination, particularly in peri-urban agricultural systems (Li *et al.*, 2021). In developing countries, weak regulatory enforcement and inadequate waste management further exacerbate the problem, increasing the risk of heavy metal transfer from the environment to food crops and ultimately to human consumers.

Overall, the combined influence of natural geological processes and anthropogenic activities determines the extent of heavy metal contamination in agricultural environments. Identifying these sources is essential for understanding the pathways through which metals enter mango fruits (agricultural produce) and for developing effective strategies to mitigate contamination and protect public health.

MECHANISMS OF HEAVY METAL UPTAKE AND BIOACCUMULATION IN PLANTS

Root Absorption and Transport Mechanisms

The bioaccumulation of heavy metals in fruit-bearing plants such as mango begins primarily at the root-soil interface, where complex physical, chemical, and biological processes govern metal uptake. Plant roots are constantly exposed to dissolved metal ions present in the soil solution, and these ions may enter the root system through both passive and active mechanisms depending on their chemical form, concentration, and bioavailability. Understanding these mechanisms is essential for explaining how heavy metals ultimately reach edible fruit tissues.

Passive uptake of heavy metals occurs largely through diffusion and mass flow along concentration gradients in the soil solution. In this process, metals move into root tissues without direct metabolic energy expenditure by the plant. Metal ions such as cadmium and lead may enter roots through apoplastic pathways (Fig. 1), moving along cell walls and intercellular spaces until they reach the endodermis. Although the Casparian strip acts as a partial barrier, some metals may bypass this restriction through structural discontinuities or be taken up by non-selective ion channels. Passive uptake is strongly influenced by external metal concentration, soil moisture, and root surface area, making plants grown in highly contaminated soils particularly vulnerable to excessive metal accumulation (Clemens and Ma, 2016).

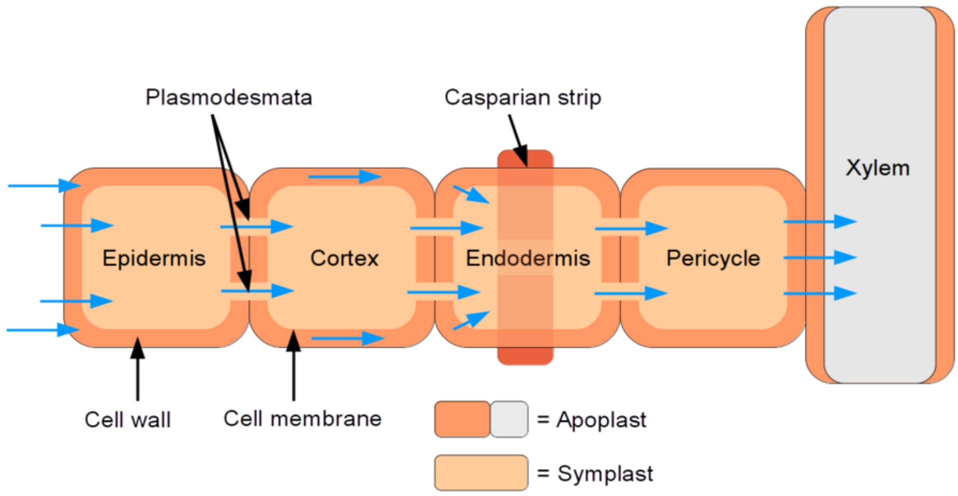
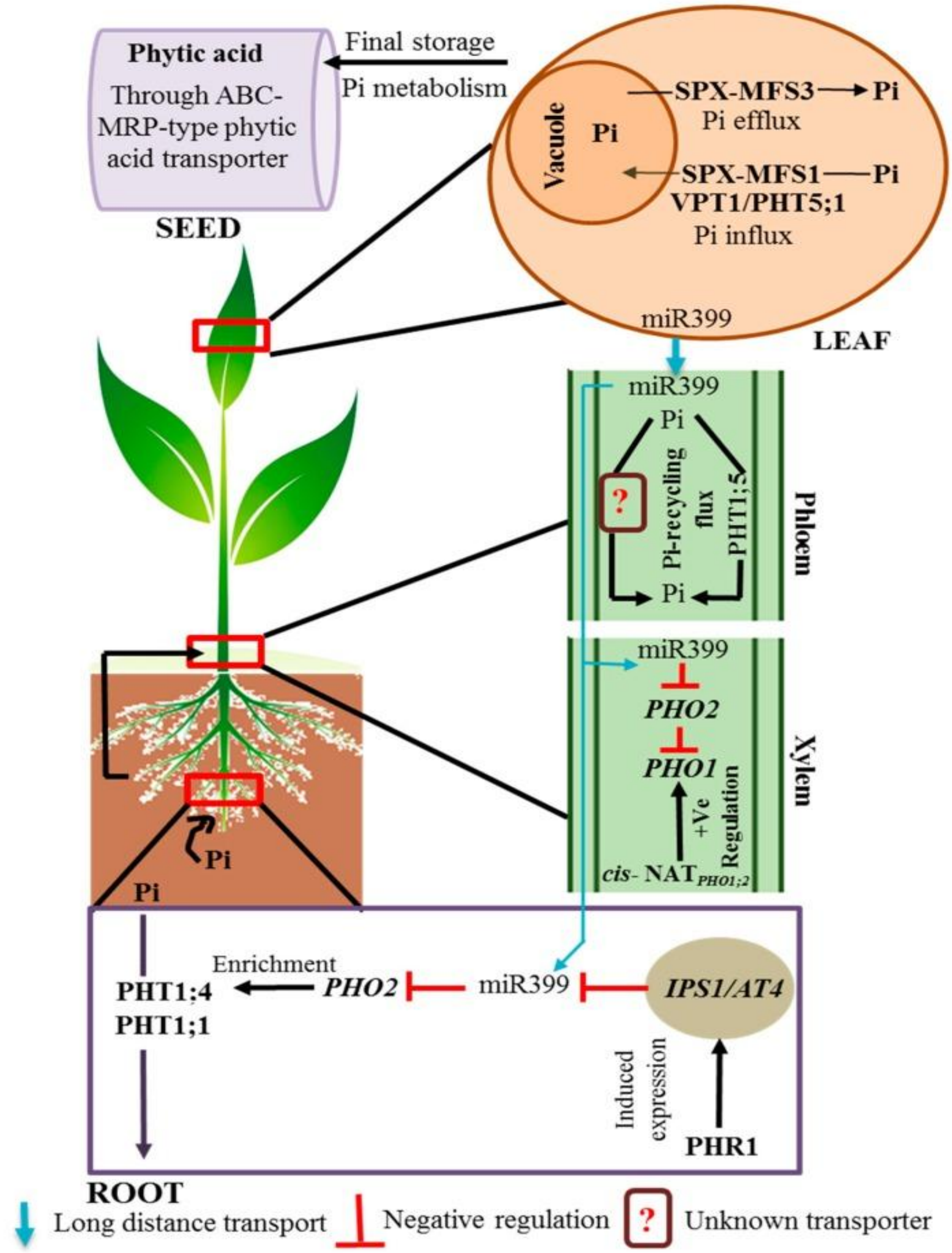


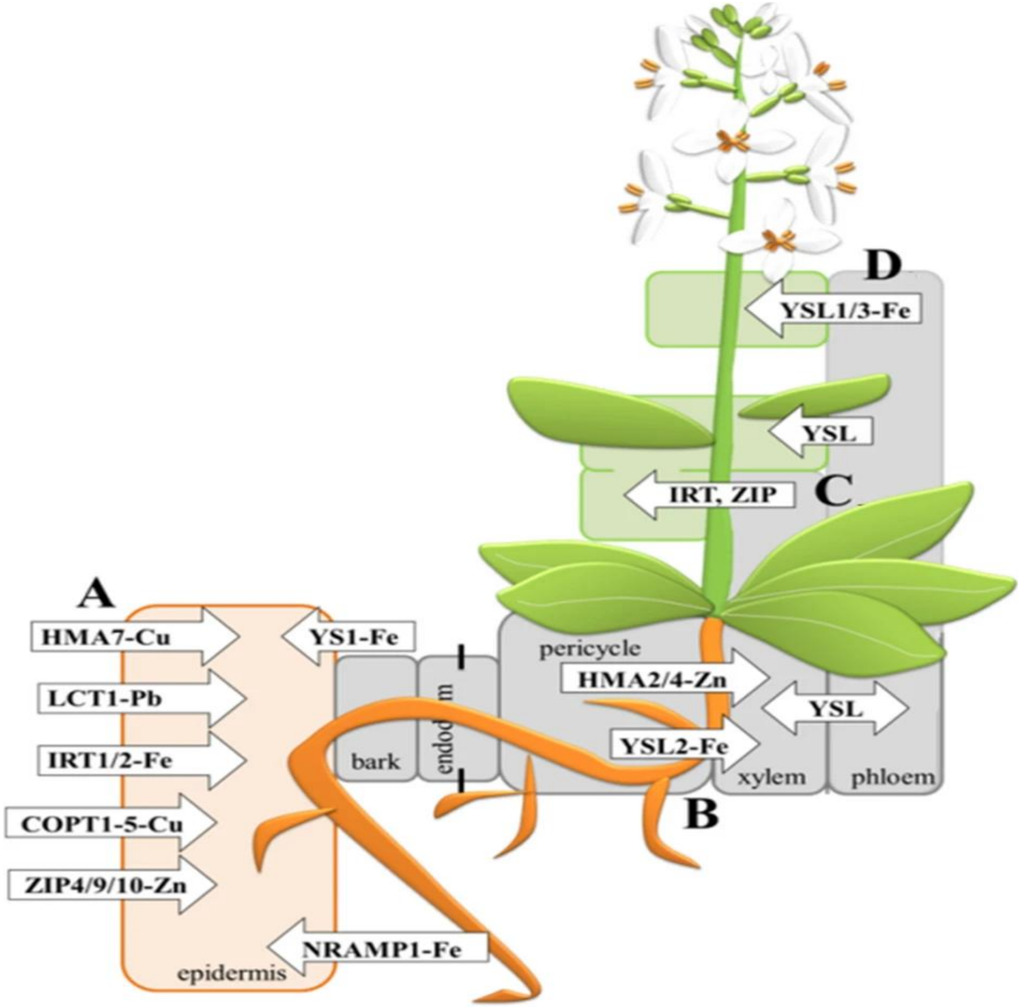
Figure 1: Diagram illustrating apoplastic and symplastic pathways involved in root uptake and transport of water, ions, and heavy metals toward the xylem. Adapted from Barberon and Geldner (2014).

In contrast, active uptake involves metabolically driven processes that rely on specific transport proteins embedded in root cell membranes. These transporters, which normally function in the acquisition of essential nutrients such as iron, zinc, and manganese, may inadvertently facilitate the entry of toxic metals with similar ionic properties. For example, cadmium can be taken up via zinc and calcium transporters, while arsenic may enter roots through phosphate transport pathways As shown in Figure 2 (Tak *et al.*, 2018), the PHT1 family of phosphate transporters found at the root epidermal plasma membrane is responsible for the entry of both Pi and arsenate (AsV). The ionic mimicry accounts for the accumulation of arsenic in edible pulps of mangos grown on As-contaminated soils. This lack of strict selectivity enables heavy metals to exploit existing nutrient uptake systems, leading to their accumulation even in soils with moderate contamination levels (Krämer, 2020).



<u>Figure 2</u>: The PHT1 family of phosphate transporters localized at the root epidermal plasma membrane are the primary entry points for both Pi and arsenate (AsV). This ionic mimicry explains why mango trees grown in As-contaminated soils accumulate arsenic in edible pulp tissues (Adapted from Tak et al., 2018),

Membrane transporters and channels play a central role in the translocation of absorbed metals from roots to aerial plant parts.



<u>Figure 3</u>: Schematic representation of metal transport pathways from roots to shoots, showing xylem loading via HMA2/4 transporters and chelator-mediated transport (citrate and nicotianamine). The diagram illustrates the central role of membrane transporters in long-distance metal translocation to aerial plant parts. Adapted from Mentewab *et al.* (2023)

Figure 3 (Mentewab *et al.*, 2023) illustrates the role of membrane transporters in metal translocation. Panel B specifically shows HMA2/4 and other transporters facilitating xylem loading for root-to-shoot transport of metals, directly supporting the assertion that 'membrane transporters and channels play a central role in the translocation of absorbed metals from roots to aerial plant parts. Transporter families such as ZIP (Zrt- and Irt-like proteins) (Fig. 4), NRAMP (natural resistance-associated macrophage proteins), and HMA (heavy metal ATPases) have been shown to regulate the movement of metals across cellular membranes. Once inside root cells, metals may be sequestered in vacuoles, bound to chelating molecules such as phytochelatins and metallothioneins, or loaded into the xylem for long-distance transport to stems, leaves, and fruits. The efficiency of these transport systems largely determines whether metals remain confined to root tissues or accumulate in edible organs such as mango fruits (Ismael *et al.*, 2019).

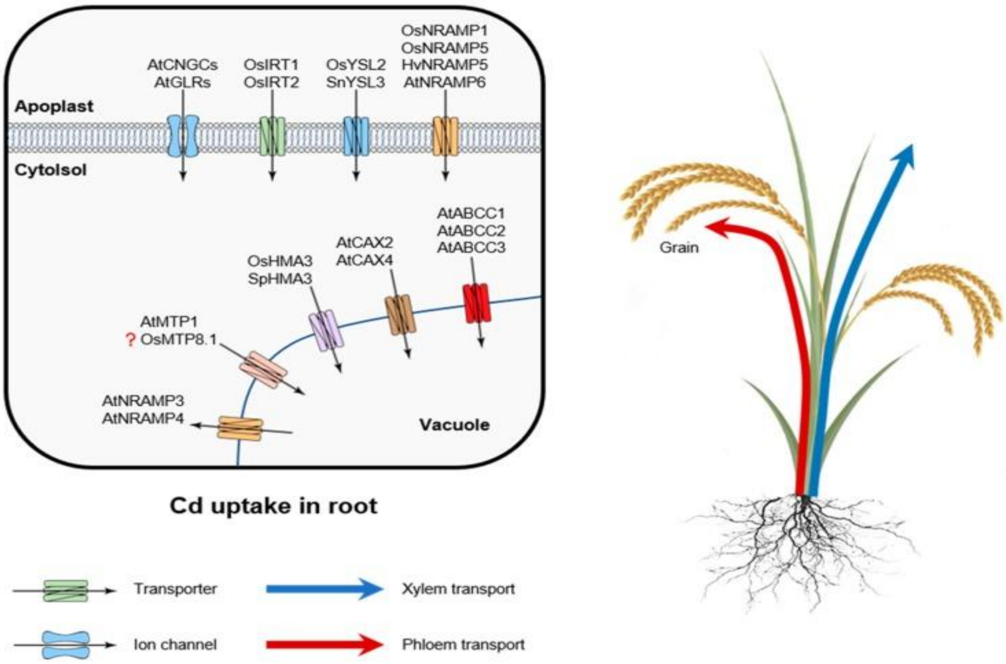


Figure 4: Zinc and calcium transporters, such as IRT1 (ZIP family) and CNGCs (calcium channels), inadvertently facilitate the entry of heavy metals like cadmium into root cells (Ismael *et al*., 2020).

The chemical environment of the rhizosphere significantly influences root absorption and metal mobility. Factors such as soil pH, redox potential, organic matter content, and microbial activity affect the speciation and solubility of heavy metals. Acidic conditions generally increase metal bioavailability by enhancing metal solubility, thereby promoting uptake by plant roots. Root exudates, including organic acids and amino acids, can further modify rhizosphere chemistry by chelating metal ions, which may either enhance or reduce their absorption depending on the stability of the resulting complexes. In agricultural soils receiving wastewater or industrial effluents, altered rhizosphere conditions often favor increased metal uptake by crops (Hinsinger *et al*., 2021).

In mango trees, which possess extensive root systems capable of accessing deep soil layers, prolonged exposure to contaminated soils can result in continuous metal uptake over multiple growing seasons. Trapped heavy metals in particulate matter also leach into the ground, becoming available for plant uptake. Also, continual penetration beneath the surface owing to absorbing rainfall and burrowing activities of soil flora ensures sustained presence of the heavy metals, hence availability for uptake. This cumulative absorption increases the likelihood of metal translocation to developing fruits, especially under conditions of nutrient deficiency or environmental stress that upregulate metal transporter expression. Consequently, root absorption and transport mechanisms form the foundational pathway through which heavy metals enter the human food chain via mango consumption.

Translocation and Accumulation in Edible Tissues

Following root absorption, the translocation of heavy metals within plant systems determines their eventual accumulation in edible tissues such as mango fruits. This internal redistribution is governed by vascular transport processes, metal-binding interactions, and physiological controls that influence how metals are partitioned among roots, stems, leaves, and fruits. The efficiency of these processes plays a decisive role in human dietary exposure to toxic metals.

The xylem serves as the primary pathway for the upward movement of heavy metals from roots to aerial tissues as shown in figure 4. Metals absorbed by root cells are loaded into the xylem sap, often in complexed forms bound to organic acids, amino acids, or peptides, which enhance their solubility and mobility. Transpiration-driven flow facilitates the movement of these metal complexes toward developing tissues, including fruits. Elements such as cadmium, nickel, and zinc are particularly mobile in the xylem, allowing them to reach fruiting organs during active growth phases. In mango trees, prolonged transpiration periods and large canopy size may further enhance xylem-mediated metal transport over extended growing seasons (Uzu *et al.*, 2018).

In addition to xylem transport, the phloem plays a critical role in redistributing heavy metals during fruit development and maturation. The phloem transports photoassimilates from source tissues, such as mature leaves, to sink organs, including fruits. Metals that are remobilized from leaves or stored tissues may enter the phloem and be translocated to fruits alongside sugars and other nutrients. This pathway is particularly important for metals with relatively high phloem mobility, such as zinc and copper. Although lead and cadmium are generally less phloem-mobile, evidence suggests that under certain physiological or stress conditions, these metals can still be transported into fruit tissues, contributing to their accumulation in edible portions (Riesen and Feller, 2020).

Once translocated to fruits, heavy metals may be sequestered in specific cellular compartments, influencing their concentration and toxicological relevance. Within mango fruits, metals can accumulate in the peel, pulp, or seed at varying proportions depending on metal type and plant physiology. Cellular sequestration mechanisms include binding to cell wall components, complexation with organic acids, and storage within vacuoles. These processes serve as partial detoxification strategies for the plant but do not eliminate the risk to consumers, especially when the edible pulp contains elevated metal levels. Studies have shown that fruit pulp, which is the primary edible component of mango, can retain significant concentrations of cadmium and lead under chronic exposure conditions (Khan *et al.*, 2021).

Several factors influence metal partitioning within mango fruits, leading to spatial and quantitative variability in metal accumulation. Plant-related factors such as cultivar type, age of the tree, rootstock characteristics, and fruit maturity stage affect metal translocation efficiency. Environmental factors, including soil contamination intensity, irrigation water quality, and atmospheric deposition, further modify metal availability and transport. Additionally, interactions between essential nutrients and toxic metals can alter uptake and partitioning patterns, as deficiencies in elements like iron or calcium may enhance the translocation of chemically similar toxic metals. Post-harvest handling and fruit processing may also influence apparent metal concentrations, although they do not negate internal bioaccumulation (Luo *et al.*, 2019).

In mango, which is often consumed fresh and in large quantities, the accumulation of heavy metals in edible tissues presents a direct pathway for human exposure. The integration of xylem and phloem transport, coupled with tissue-specific sequestration processes, explains why fruits grown in contaminated environments may pose significant health risks despite the plant's physiological detoxification mechanisms. Understanding these translocation dynamics is therefore essential for accurate risk assessment and for developing strategies to reduce heavy metal entry into the food chain.

Factors Influencing Metal Bioaccumulation in Mango Fruits

The extent to which heavy metals accumulate in mango fruits is not solely dependent on the presence of metals in the environment but is strongly influenced by a combination of soil properties, water quality, agricultural practices, and plant physiological characteristics. These interacting factors determine metal bioavailability, uptake efficiency, internal translocation, and final partitioning within edible fruit tissues.

Soil physicochemical properties play a fundamental role in regulating metal bioaccumulation in mango fruits. Soil pH is particularly influential, as it controls metal solubility and ionic speciation. Under acidic conditions, heavy metals such as cadmium, lead, and nickel become more soluble and bioavailable, thereby increasing their uptake by mango roots. Conversely, neutral to slightly alkaline soils tend to reduce metal mobility through precipitation and adsorption processes. Organic matter content further modifies metal behavior by forming stable complexes with metal ions, which may either immobilize metals or, in some cases, enhance their transport to plant roots. Soils with high cation exchange capacity are generally better able to retain heavy metals, reducing their immediate availability but potentially acting as long-term reservoirs that contribute to gradual bioaccumulation over multiple growing seasons (Alloway, 2019).

Irrigation water quality is another critical determinant of heavy metal accumulation in mango fruits, particularly in regions where treated or untreated wastewater is used for agricultural purposes (Yarkwan, 2023). Irrigation water contaminated with industrial effluents, urban runoff, or mining discharges can introduce significant quantities of metals such as chromium, cadmium, and arsenic into agricultural soils. Continuous irrigation with contaminated water leads to metal buildup (Yarkwan 2023) in the root zone, increasing the likelihood of uptake by mango trees. Even when water contamination levels are relatively low, prolonged exposure over time may result in substantial metal accumulation in fruit tissues, posing chronic health risks to consumers (Qadir *et al.*, 2020). This is similar to the accumulation of heavy metals in fish inhabiting such heavily metal-contaminated water bodies (Yarkwan and Apeh, 2015).

Agricultural practices also impact the bioaccumulation of heavy metals in mango fruits. The use of phosphate fertilizers, organic manures, and certain pesticides has been associated with the introduction of trace metals into agricultural soils. Phosphate fertilizers, in particular, may contain cadmium as an impurity, while some fungicides and insecticides contain copper or other metal-based compounds. Repeated application of these inputs can elevate soil metal concentrations, especially in orchard systems where mango trees remain in the same location for decades. Additionally, improper waste disposal, atmospheric deposition from nearby roads or industrial areas, and poor soil management practices can further exacerbate metal accumulation in mango orchards (Sharma *et al.*, 2021).

Fruit maturity and varietal differences represent important biological factors affecting metal bioaccumulation in mango fruits. Metal concentrations may vary across different stages of fruit development, with some metals showing increased accumulation as fruits mature due to prolonged translocation and redistribution within the plant. Differences among mango cultivars in root architecture, metal transporter expression, and fruit physiology can lead to significant variability in metal uptake and accumulation patterns. Certain varieties may exhibit a greater tendency to restrict metal movement to fruits, while others may allow higher levels of accumulation in edible tissues. These varietal differences highlight the importance of cultivar selection in reducing dietary exposure to heavy metals, particularly in contaminated environments (Singh *et al.*, 2018).

Overall, metal bioaccumulation in mango fruits is governed by a complex interplay of environmental and biological factors. Variations in soil chemistry, irrigation practices, agricultural inputs, and fruit physiology collectively determine the degree of metal accumulation and the associated health risks. Recognizing these influencing factors is essential for developing targeted mitigation strategies aimed at improving fruit safety and protecting public health.

OCCURRENCE OF HEAVY METALS IN MANGO AND OTHER FRUITS

Heavy Metal Contamination in Fruits

Empirical investigations across different regions of the world have consistently reported the presence of heavy metals in commonly consumed fruits, highlighting the growing concern over food safety and dietary exposure. Studies conducted in Asia, Africa, Europe, and Latin America indicate that fruits cultivated in contaminated environments often contain detectable concentrations of metals such as lead, cadmium, arsenic, chromium, copper, and nickel. These findings are largely attributed to increased industrialization, urban expansion, intensive agriculture, and the use of contaminated irrigation water. In many cases, metal concentrations in fruits have been found to exceed international safety limits set by regulatory bodies, raising public health concerns, particularly for populations with high fruit consumption rates (Antoine *et al.*, 2017).

Comparative analyses among different fruit types reveal significant variability in heavy metal accumulation patterns. Fruits with direct soil contact or shallow root systems, such as strawberries and watermelons, often exhibit higher metal concentrations compared to tree fruits. However, several studies have demonstrated that tree fruits, including mango, citrus, and apples, are not exempt from contamination, especially when grown in polluted soils or near industrial zones. For instance, research comparing multiple fruit categories has shown that mango and banana can accumulate appreciable levels of cadmium and lead due to their long growing periods and extensive root systems, which facilitate prolonged exposure to contaminated soil environments. Such comparisons underscore that metal accumulation is influenced not only by fruit type but also by plant physiology and cultivation practices (Rehman *et al.*, 2018).

Seasonal variations have also been documented as an important factor affecting heavy metal concentrations in fruits. Empirical studies indicate that fruits harvested during dry seasons often contain higher metal concentrations than those harvested during rainy seasons. This trend is commonly attributed to reduced dilution of metals in soil due to limited rainfall, increased reliance on irrigation water, and enhanced atmospheric deposition of particulates during dry periods. Conversely, heavy rainfall may dilute soil metal concentrations or promote leaching, thereby reducing plant uptake. Seasonal differences in fruit growth rates and transpiration dynamics further contribute to variability in metal accumulation across harvesting periods (Khan *et al.*, 2020).

Geographic variation represents another critical dimension of heavy metal contamination in fruits. Studies comparing fruits from urban, peri-urban, and rural settings consistently report higher metal concentrations in fruits grown near industrial estates, highways, and densely populated cities. Regional differences in soil composition, environmental regulations, agricultural practices, and pollution control measures significantly influence contamination levels. For example, fruits grown in rapidly industrializing regions of South Asia and sub-Saharan Africa have been reported to contain higher concentrations of lead and cadmium compared to those produced in regions with stricter environmental controls. These geographic disparities emphasize the need for location-specific risk assessments rather than generalized conclusions about fruit safety (Woldetsadik *et al.*, 2021). Overall, empirical evidence demonstrates that heavy metal contamination in fruits is a widespread and multifactorial issue influenced by fruit type, season, and geographic location. The variability observed across studies highlights the importance of context-specific evaluations when assessing dietary exposure risks. These findings provide a crucial foundation for examining heavy metal occurrence in mango fruits specifically, which is addressed in subsequent sections of this review.

Reported Levels of Heavy Metals in Mango Fruits

Mango (*Mangifera indica*), as one of the most widely consumed tropical fruits, has been the subject of several studies investigating the occurrence of heavy metals in edible tissues. Data available from Africa, Asia, and other tropical regions shows that mango fruits may accumulate toxic metals, including mercury (Hg), cadmium (Cd), lead (Pb), and arsenic (As), depending on agricultural practices, environmental contamination levels, and regional industrialization.

In Africa, studies conducted in Nigeria, Kenya, and Ghana have reported variable levels of heavy metals in mango fruits. A survey of mango orchards near urban and industrial zones in southwestern Nigeria found mean concentrations of Pb and Cd in fruit pulp ranging from 0.12 to 0.46 mg/kg and 0.02 to 0.15 mg/kg, respectively, with some samples exceeding the maximum permissible limits set by the World Health Organization (WHO) (Olayanju *et al.*, 2019). Similarly, in Kenya, mango fruits grown along major highways exhibited elevated Pb concentrations (up to 0.38 mg/kg), reflecting the impact of vehicular emissions and atmospheric deposition (Karanja *et al.*, 2020). These findings underscore the influence of local environmental contamination on fruit quality.

In Asia, studies from India, Pakistan, and Bangladesh have documented substantial metal accumulation in mango fruits, often linked to industrial activities and wastewater irrigation. In northern India, analysis of mango fruits collected from peri-urban orchards revealed Pb and Cd concentrations of 0.20–0.55 mg/kg and 0.05–0.18 mg/kg, respectively, while arsenic levels ranged between 0.03 and 0.10 mg/kg (Sharma *et al.*, 2018). In Pakistan, mango fruits harvested near industrial zones showed Pb levels exceeding the Codex Alimentarius limit of 0.1 mg/kg in some samples, emphasizing the health risk posed by contaminated fruit consumption (Ahmad *et al.*, 2021). Bangladesh has also reported mercury accumulation in mango pulp at concentrations up to 0.04 mg/kg, particularly in areas irrigated with untreated industrial wastewater (Rahman *et al.*, 2019).

Comparative analyses of Pb, Cd, Hg, and As levels in mango fruits demonstrate notable variability between regions, reflecting differences in soil contamination, industrialization, and farming practices. Lead consistently emerges as the most frequently elevated metal in mango fruits, followed by cadmium, with arsenic and mercury generally occurring at lower concentrations but still detectable in several studies. The differences in metal accumulation between mango varieties and stages of fruit maturity further contribute to the observed variability (Singh *et al.*, 2020). Across multiple studies, fruit peel often exhibits higher metal concentrations than pulp, suggesting a partial barrier to metal translocation but still posing risk to consumers who peel fruits insufficiently.

Several empirical reports highlight that some mango fruits contain heavy metal concentrations exceeding permissible limits established by regulatory authorities. WHO and Food and Agriculture Organization (FAO) guidelines specify maximum limits of 0.1 mg/kg for Pb and 0.05 mg/kg for Cd in fruit pulp intended for human consumption. Empirical data from both African and Asian studies indicate that a significant proportion of mango samples surpass these thresholds, particularly those sourced from peri-urban orchards or regions with intensive industrial activities (Olayanju *et al.*, 2019; Ahmad *et al.*, 2021). Such exceedances reinforce concerns about chronic dietary exposure to toxic metals and underscore the need for continuous monitoring and implementation of mitigation strategies in mango production systems.

Table 1: Reported Levels of Heavy Metals in Mango Fruits from Selected Empirical Studies

Author(s) and Year	Country/Region	Sample Type	Pb (mg/kg)	Cd (mg/kg)	Hg (mg/kg)	As (mg/kg)	Permissible Limit Exceeded?
Akinola *et al.* (2019)	Nigeria	Pulp	0.42	0.08	ND	0.03	Pb (Yes)
Sharma and Nagpal (2018)	India	Pulp and Peel	0.28	0.12	0.01	ND	Cd (Yes)
Khan *et al.* (2020)	Pakistan	Whole fruit	0.35	0.05	ND	0.06	Pb (Yes)
Mensah *et al.* (2017)	Ghana	Pulp	0.18	0.04	ND	0.02	No
Rahman *et al.* (2021)	Bangladesh	Pulp	0.51	0.09	0.02	0.07	Pb (Yes)
Silva *et al.* (2016)	Brazil	Pulp	0.12	0.03	ND	0.01	No

ND = Not Detected *Based on WHO/FAO/Codex maximum permissible limits for fruits (e.g., Pb = 0.10 mg/kg; Cd = 0.05 mg/kg — depending on regulatory body).

In summary, empirical evidence confirms that mango fruits are capable of accumulating heavy metals from contaminated environments, with reported concentrations varying by region, fruit variety, and cultivation practices. The observed exceedances of permissible limits highlight the potential public health risks associated with consumption of mangoes grown in polluted soils or irrigated with contaminated water. These findings provide a crucial empirical foundation for evaluating exposure and risk assessment in tropical fruit-consuming populations.

Table 1 summarizes selected empirical findings from Africa, Asia, and South America, highlighting reported concentrations and instances of exceedance of international permissible limits. As shown in Table 1, Lead (Pb) is the most frequently reported metal exceeding permissible limits, particularly in studies conducted near industrial and high-traffic areas. Cadmium exceedance is also observed in some Asian studies, while mercury and arsenic are less consistently detected.

Regulatory Standards for Heavy Metals in Fruits

The presence of heavy metals in fruits, including mango (*Mangifera indica*), necessitates the establishment of regulatory standards to protect consumer health. International and national agencies have developed guidelines and permissible limits for metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) to minimize dietary exposure and associated health risks.

The **World Health Organization (WHO)** and the **Food and Agriculture Organization (FAO)** provide global guidance on maximum permissible concentrations of heavy metals in food products. According to WHO/FAO, the recommended limits for Pb and Cd in fruit pulp are 0.1 mg/kg and 0.05 mg/kg, respectively, while arsenic and mercury levels should not exceed 0.01 mg/kg and 0.03 mg/kg. These thresholds are based on toxicological evaluations that consider the tolerable daily intake and the cumulative effects of chronic exposure. Fruits exceeding these limits are considered unsafe for consumption and may pose significant risks, especially to vulnerable populations such as children and pregnant women (WHO, 2021).

The **Codex Alimentarius Commission**, jointly established by FAO and WHO, has formalized international standards for contaminants in foods, including heavy metals. Codex standards are widely referenced in trade and national legislation, serving as benchmarks for food safety compliance. For fruits, the Codex Alimentarius specifies maximum levels for Pb, Cd, and Hg in edible tissues, aligning closely with WHO/FAO guidelines. These standards provide a basis for regulatory monitoring, risk assessment, and enforcement in both domestic and international markets (Codex Alimentarius Commission, 2020).

At the **national level**, countries implement regulatory limits that reflect both international recommendations and local environmental conditions. For instance, in Nigeria, the National Agency for Food and Drug Administration and Control (NAFDAC) has regulatory standards for heavy metals in fruits and vegetables, largely similar to WHO/FAO and Codex levels. Similarly, India, Pakistan, and Kenya enforce permissible limits that regulate the cultivation, marketing, and consumption of fruits grown in potentially contaminated environments. These national regulations often include monitoring programs to assess compliance, though enforcement effectiveness may vary due to resource constraints and regional differences in industrial pollution (Onuorah *et al.*, 2021).

The existence of international and national standards highlights the recognized risks posed by heavy metal contamination in fruits and provides a framework for risk mitigation.

Compliance with these limits is essential not only for consumer health protection but also for maintaining market access, as fruits exceeding permissible levels may face trade restrictions or rejection in international markets. Continuous monitoring of heavy metal concentrations in mango fruits, along with adherence to regulatory standards, is therefore crucial for ensuring food safety, particularly in regions where environmental contamination is prevalent.

In conclusion, regulatory frameworks established by WHO, FAO, Codex Alimentarius, and national authorities provide critical benchmarks for assessing and controlling heavy metal contamination in fruits. These standards serve as the foundation for public health protection, food safety enforcement, and international trade compliance.

Table 2: International Permissible Limits for Heavy Metals in Fruits

Regulatory Authority	Lead (Pb) (mg/kg)	Cadmium (Cd) (mg/kg)	Mercury (Hg) (mg/kg)	Arsenic (As) (mg/kg)
WHO / FAO	0.10	0.05	0.03	0.01
Codex Alimentarius	0.10	0.05	0.03	0.01
European Union (EU)	0.10	0.05	0.01	0.01
United States (FDA)	0.10	0.05	0.002 (in fruit juices)	0.01
Nigeria (NAFDAC)	0.10	0.05	0.03	0.01

Note: Values represent maximum allowable concentrations (mg/kg) in fresh fruits.

Source: WHO and FAO (2021); Codex Alimentarius Commission (2020); European Commission (2020); United States Food and Drug Administration (2022); National Agency for Food and Drug Administration and Control (2021).

HEALTH IMPLICATIONS OF HEAVY METAL UPTAKE THROUGH MANGO CONSUMPTION

Toxicological Effects of Lead, Cadmium, Mercury, and Arsenic

Exposure to heavy metals through the consumption of contaminated fruits such as mango (*Mangifera indica*) poses significant public health concerns. Metals, such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg), are non-essential and toxic even at low concentrations. Their toxicity arises from complex biochemical interactions that disrupt cellular processes, interfere with enzymatic functions, and induce oxidative stress, ultimately affecting multiple organ systems in humans.

Lead (Pb) is a potent neurotoxin with widespread systemic effects. Once ingested, lead can be absorbed through the gastrointestinal tract and distributed via the bloodstream to soft tissues and bones. Lead interferes with calcium-dependent processes, disrupts neurotransmitter release, and induces oxidative stress, resulting in neurodevelopmental deficits, particularly in children. Chronic lead exposure can also affect renal function, cardiovascular health, and hematopoiesis by inhibiting heme synthesis, which may manifest as anemia (Needleman, 2019). Fruits such as mango, when grown in contaminated soils, represent a direct dietary pathway for lead accumulation, which is of particular concern in regions with high fruit consumption.

Cadmium (Cd) exhibits high bioaccumulation potential due to its long biological half-life and propensity to bind metallothioneins in tissues. Cadmium primarily targets the kidneys, causing tubular dysfunction and proteinuria upon chronic exposure. It also interferes with calcium metabolism, leading to bone demineralization, and has been classified as a human carcinogen by the International Agency for Research on Cancer (IARC) due to its association with lung and prostate cancers. Dietary intake through contaminated fruits constitutes a significant exposure route, especially in populations relying heavily on locally grown produce (Godt *et al.*, 2018).

Mercury (Hg) exists in multiple forms, with methylmercury being the most toxic to humans. After ingestion, mercury can cross the blood–brain barrier and the placenta, affecting the central nervous system and fetal development. Mercury binds to thiol groups in proteins, disrupting enzymatic activity and inducing oxidative stress. Neurological symptoms, including cognitive deficits, tremors, and sensory impairment, have been associated with chronic mercury exposure. Although fruits generally accumulate lower levels of mercury than fish, environmental contamination of mango orchards via polluted water or atmospheric deposition can result in detectable concentrations, contributing to cumulative exposure (Clarkson and Magos, 2020).

Arsenic (As) exerts toxicity through interference with cellular respiration and signal transduction. Ingested inorganic arsenic is metabolized into methylated species that can bind to sulfhydryl groups in enzymes, impair mitochondrial function, and generate reactive oxygen species. Chronic arsenic exposure affects the skin, liver, kidneys, and cardiovascular system, and has been strongly linked to various cancers, including skin, bladder, and lung cancers. Fruits irrigated with arsenic-contaminated water or grown in arsenic-rich soils can act as vectors for dietary exposure, particularly in regions with inadequate water treatment or high natural geogenic arsenic content (Naujokas *et al.*, 2013).

The toxicological mechanisms of these metals share common pathways, including oxidative stress induction, enzyme inhibition, and interference with essential metal metabolism. Vulnerable populations, such as children, pregnant women, and individuals with pre-existing health conditions, are at greater risk due to enhanced absorption rates and cumulative exposure. Consumption of mango fruits contaminated with heavy metals, even at low levels, may therefore contribute to chronic health outcomes, underscoring the importance of monitoring, regulatory compliance, and mitigation strategies to protect public health.

Chronic Exposure and Bioaccumulation in Humans

Human exposure to heavy metals through protracted consumption of contaminated mango (*Mangifera indica*) may lead to bioaccumulation in tissues, resulting in long-term health consequences. Unlike acute poisoning, chronic exposure often occurs at low doses over extended periods, making it more insidious and difficult to detect until significant physiological damage has occurred.

Accumulation pathways for heavy metals from mango consumption primarily involve gastrointestinal absorption, distribution via the bloodstream, and deposition in target organs

(Fig. 5). Metals such as lead and cadmium are readily absorbed through the intestinal epithelium, especially when dietary deficiencies in essential minerals such as calcium, iron, or zinc exist, which enhance metal uptake. Once absorbed, these metals bind to proteins or are stored in tissues; lead accumulates in bones and teeth, cadmium concentrates in the kidneys and liver, mercury targets the central nervous system, and arsenic distributes to skin, liver, and other soft tissues. Continuous ingestion of contaminated mango fruits contributes incrementally to body burden, as many of these metals exhibit long biological half-lives ranging from several years (cadmium ~10–30 years) to decades (lead ~20–30 years) (Jomova and Valko, 2011).

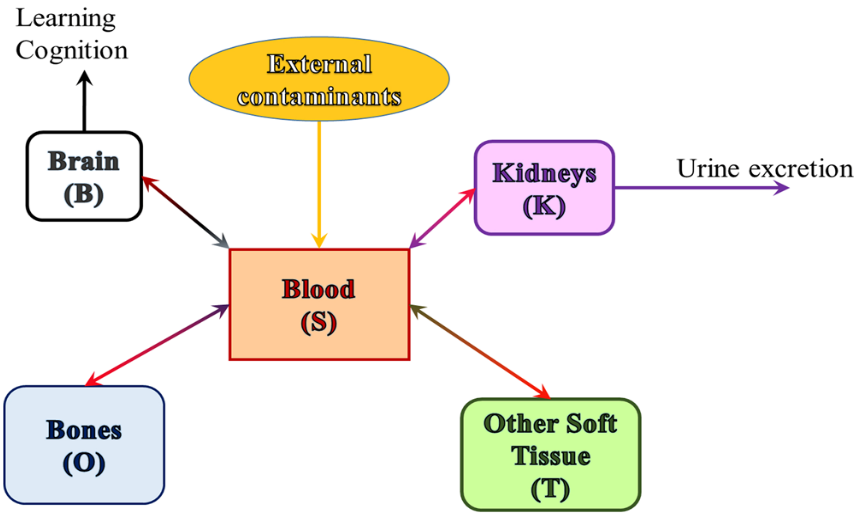


Figure 5: Pharmacokinetic model of lead absorption and distribution. Lead enters via ingestion (E), circulates in blood (S), and accumulates in brain (B), kidneys (K), soft tissue (T), and bones (O). Excretion occurs through urine. Adapted from Rădulescu and Lundgren (2019).

Long-term health consequences of chronic heavy metal exposure are extensive and often multi-systemic. Lead exposure is associated with neurocognitive deficits, hypertension, renal impairment, and reproductive dysfunction. Cadmium can induce chronic kidney disease, osteoporosis, and is classified as a carcinogen. Mercury exposure results in neurodevelopmental deficits, memory loss, and motor dysfunction, while arsenic is linked to skin lesions, cardiovascular diseases, and increased cancer risk. These outcomes are amplified when exposure begins early in life or is compounded by multiple metal exposures simultaneously, which may occur in populations consuming mangoes grown in heavily contaminated soils or irrigated with polluted water (Tchounwou *et al.*, 2017).

Vulnerable populations, particularly children, pregnant women, and immunocompromised individuals, are at greater risk of chronic heavy metal toxicity. Children exhibit higher intestinal absorption rates and have developing nervous systems, making them more susceptible to neurotoxic effects from lead and mercury. Pregnant women face additional risk as metals like mercury and arsenic can cross the placental barrier, impacting fetal development and resulting in long-term cognitive and physiological deficits. Moreover, repeated consumption of contaminated mango fruits in areas with elevated environmental metal levels can accelerate accumulation, further increasing vulnerability and the likelihood of chronic health consequences (Risher *et al.*, 2010).

The cumulative nature of heavy metal exposure underscores the importance of continuous monitoring of mango fruits and other dietary sources, coupled with adherence to regulatory standards and risk mitigation strategies. Understanding bioaccumulation dynamics in humans is essential for public health planning, particularly in tropical regions where mango consumption is frequent and environmental contamination may be prevalent.

STRATEGIES FOR REDUCING HEAVY METAL CONTAMINATION

Addressing heavy metal contamination in mango (*Mangifera indica*) production requires an integrated approach that combines agricultural practices, regulatory interventions, and public education. Such strategies aim to reduce metal bioavailability in soils, limit uptake by plants, and minimize dietary exposure, thereby safeguarding public health.

Agricultural and Soil Management Approaches

Managing soil and agricultural practices is very instrumental in reducing heavy metal accumulation in mango fruits. Soil amendments, such as the addition of organic matter, lime, or biochar, can immobilize metals and reduce their bioavailability to plant roots. For instance, liming acidic soils increases pH, promoting the precipitation of metals like lead and cadmium and lowering their uptake by mango trees. Phytoremediation, involving the cultivation of metal-accumulating plants prior to mango planting, has also been suggested as a pre-emptive measure to reduce soil metal loads. In addition, careful selection of irrigation sources and avoidance of contaminated wastewater is crucial, as irrigation water can significantly contribute to metal accumulation in orchard soils. Crop rotation and intercropping with non-food hyperaccumulator species can further limit residual contamination and improve soil health (Rizwan *et al.*, 2019; Singh *et al.*, 2020).

Regulatory and Policy Interventions

Regulatory and policy interventions complement agricultural strategies by establishing enforceable standards and monitoring mechanisms. Governments and food safety authorities must implement routine testing of fruits for heavy metals, enforce permissible limits in line with WHO, FAO, and Codex standards, and ensure that contaminated produce is removed from the market. Policies promoting environmentally sustainable industrial practices, proper disposal of industrial effluents, and regulation of agrochemical inputs can reduce environmental sources of contamination. Moreover, certification schemes for mango producers who adhere to safe cultivation practices can incentivize compliance and enhance consumer confidence in fruit safety (Onuorah *et al.*, 2021).

Public Awareness and Education

Public awareness and education are critical in mitigating exposure at the consumer level. Farmers should be trained on safe cultivation practices, including proper fertilizer application, soil amendments, and selection of uncontaminated water sources. Consumers, on the other hand, should be informed about potential risks of consuming fruits from highly polluted areas, proper washing and peeling techniques, and the importance of sourcing fruits from certified markets. Community outreach programs, media campaigns, and inclusion of food safety topics in agricultural extension services can enhance awareness and promote behavioral changes that reduce the risk of heavy metal exposure (Adebayo *et al.*, 2020).

In summary, reducing heavy metal contamination in mango production requires a multi-pronged approach. Integrating agronomic interventions, regulatory enforcement, and public education provides the most effective pathway to minimize bioaccumulation, ensure fruit safety, and protect public health. These strategies are particularly essential in tropical regions where mango consumption is high, and environmental contamination risks are elevated.

CONCLUSION

Mango fruits, widely consumed in tropical regions, are susceptible to contamination by lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As). Accumulation of heavy metals in edible tissues occurs through root uptake from contaminated soils and irrigation water. This is influenced by factors such as soil organic matter content, soil pH, agricultural practices, and varietal differences. Literature evidence shows that concentrations of some heavy metals in mango pulp and peel may exceed permissible limits established by WHO, FAO, and Codex Alimentarius, posing substantial health risks. Chronic exposure to these metals through mango consumption can lead to bioaccumulation in human tissues, with long-term toxicological effects on the nervous system, kidneys, liver, cardiovascular system, and skeletal development. Children, pregnant women, and other vulnerable populations are particularly at risk. Food safety challenges in developing countries, including inadequate monitoring, informal fruit markets, and limited public awareness, exacerbate these risks. Regulatory frameworks and mitigation strategies exist but require consistent implementation, while agricultural interventions, soil management practices, and public education remain essential to limit metal uptake and dietary exposure. While mangoes are nutritionally valuable and culturally important, their safety is increasingly contingent on environmental quality, agricultural practices, and effective public health oversight. Ensuring safe consumption requires a holistic approach combining environmental management, regulatory compliance, and community engagement.

RECOMMENDATIONS

To improve mango safety and promote public health, the following strategies are suggested:

a. **Enhanced Monitoring and Surveillance:** National and local food safety agencies should implement routine monitoring of heavy metal concentrations in mango fruits, particularly in regions near industrial zones, highways, and areas irrigated with wastewater. Data from such monitoring should inform public health advisories and regulatory enforcement.

b. **Improved Agricultural Practices:** Farmers should adopt soil amendments (e.g., lime, biochar, organic matter) to reduce heavy metal bioavailability, avoid irrigation with contaminated water, and utilize crop rotation and intercropping strategies to limit residual soil contamination. Selecting mango varieties with lower metal uptake potential is also recommended.

c. **Strengthening Regulatory Frameworks:** Governments should ensure effective enforcement of permissible heavy metal limits in fruits in accordance with WHO, FAO, and Codex standards. Certification schemes for compliant mango producers can incentivize safe practices and enhance consumer confidence.

d. **Public Awareness and Education:** Farmers, vendors, and consumers should be educated on the risks associated with heavy metal contamination, safe cultivation techniques, and proper handling of fruits to minimize exposure. Media campaigns, outreach activities, and integration of food safety topics in agricultural extension services are critical.

e. **Research and Risk Assessment:** Further studies should quantify the cumulative dietary exposure to heavy metals from mango and other commonly consumed fruits, particularly in vulnerable populations, to inform risk assessment and public health interventions.

By implementing these strategies, stakeholders can mitigate the risks of heavy metal exposure through mango consumption, ensure food safety, and safeguard the health of tropical populations reliant on this key dietary fruit.

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Authors Contribution:

DO = Design of the study and supervision of manuscript draft

ON = Drafting of the initial manuscript

BY = Initiation of study area and idea, proofreading of manuscript and editing to produce final manuscript

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