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WASTEWATER-INDUCED HEAVY METAL ACCUMULATION IN OKRA (*ABELMOSCHUS ESCULENTUS* L.) A COMPREHENSIVE REVIEW OF UPTAKE DYNAMICS AND HEALTH RISKS

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Abstract
Scarcity of fresh water around the world has motivated peri urban farmers to use untreated or partially treated waste water in irrigating vegetable crops such as okra. Nevertheless, toxic heavy metals (cadmium, lead, and chromium) are present in wastewater and accumulate in plant tissues and pose severe threats to human health. This review synthesizes the peer reviewed literature on the dynamics of uptake, distribution pattern of tissue, translocation mechanism and associated health risks of heavy metals in wastewater irrigated okra. The major findings show that roots do accumulate 60 to 85 percent of the total metal load, and fruits do contain lower but often unsafe levels of 0.5 to 3.0 milligrams per kilogram dry weight of cadmium and 1.0 to 8.0 milligrams per kilogram of lead. Cadmium is highly mobile with translocation factors ranging between 1.2 and 2.5, whilst lead is mostly immobile with translocation factors less than 0.5. Health risk assessment indicates that for children, it is more than 75 percent of studies on cadmium and 60 percent on lead, the health risk index is above safe values. The level of cadmium carcinogenic risk commonly surpasses the accepted level of 10-4 in okra in the peri urban areas. Some of the effective mitigation strategies involve waste water pretreatment using constructed wetlands that remove 35 to 60 percent of the metals, soil amendments such as biochar and lime that reduce the metals in fruit by 25 to 60 percent, and adoption of low accumulating cultivar. Boiling causes a reduction of 15-35 percent in the quantity of metals but does not eradicate danger. This review concludes that wastewater irrigated okra often fails to comply with the food safety regulations and presents a significant non carcinogenic and carcinogenic risk especially to children.

1. INTRODUCTION

The problem of freshwater scarcity can be considered one of the most characteristic problems of the twenty first century. The precipitation induced by rapid population growth, urbanization, and climate have brought unprecedented pressure on traditional water resources. This has seen farmers especially those in the peri urban areas resort to the other sources to continue with production of crops. Treated, partially treated, or fully untreated wastewater has now been widely used as a source of irrigation(Kaur et al., 2025). The close location of peri urban farms to cities provide the reliable and low cost supply of wastewater which still contains residual nutrients such as nitrogen and phosphorus. Nonetheless, the practice presents a broad spectrum of pollutants into the agro ecosystem(Negassa, Dadi, Soboksa, & Fekadu, 2025). The Food and Agriculture Organization estimates that over 20 million hectares of agricultural land around the world are irrigated with wastewater or marginal quality water and that the area is continuously increasing as the shortage of water increases. Although wastewater reuse provides a solution to water shortage, it is also very dangerous to soil health, crop security, and human welfare(Malav et al., 2025). Okra is a very good example to study these dangers because it is distributed all over the world, and its vulnerability to metal contamination has been documented.

Abelmoschus esculentus L. or okra is a member of the family Malvaceae and is widely cultivated in the tropical and subtropical areas. The species is an annual herbaceous plant, which generally grows one to two meters high and has distinct elongated ribbed pods that are harvested when still young and tender(Goni et al., 2025). The crop was first introduced in Africa and subsequently extended to Asia, the Mediterranean and the Americas. Okra is an economically important crop that has a short growing cycle of between 60-90 days and has a stable market demand. Okra is found to be rich in vitamins C, K and folate and essential minerals such as magnesium, potassium and calcium nutritionally. It is a good source of dietary fiber and bioactive compounds such as flavonoids and phenolic acids which have antioxidant properties(Khelil & Ghrib, 2026). Since the okra pods are eaten without peeling them, any contaminants that may be present are directly consumed by the humans.

The three main sources of wastewater utilized in the irrigation process have their unique physicochemical features. The domestic wastewater or sewage of houses and commercial outlets contain high levels of biochemical oxygen demand, chemical oxygen demand, suspended solids, pathogens and moderate levels of heavy metals in the pipes and detergents(Amjad, Khan, Khalofah, Arif, & Sadaf, 2025). The toxic metals such as cadmium, chromium, lead, nickel and mercury, and the persistent organic pollutants are present in alarmingly high concentrations in industrial wastewater that is discharged into the environment(Reeza & Azman, 2022). The most widespread type of wastewater in peri urban regions, mixed wastewater, includes both domestic and industrial discharges, and represents a complex and variable cocktail of contaminants(Sheikhi & Bostani, 2025). Typical metal concentration ranges in such mixtures are cadmium 0.01 to 0.5 milligrams per liter, lead 0.1 to 2.5, chromium 0.05 to 1.5, nickel 0.02 to 1.0, copper 0.1 to 3.0, and zinc 0.5 to 5.0. These values often go two to ten times higher than FAO and WHO safe irrigation levels(Bawa & AbdulHameed, 2025). Electrical conductivity tend to be above 2 decisiemens/meter indicating that it is stressed by salinity, and having a pH ranging between 6.5 and 8.5.

The main issue is the continuing process of irrigation of okra using untreated or improperly treated wastewater even after contamination is reported. The non biodegradable heavy metals do not break down and instead remain indefinitely in the soil and plant systems, accumulating and biomagnifying up the food chain(Talukder et al., 2025). This issue is further aggravated by the fact that in low and middle income countries there is a poor enforcement of water quality standards, and the farmers are not aware of the long term health effects(Induja, 2020). There are still great scientific gaps. The majority of the studies indicate the concentrations of the metals at one harvest period and not throughout the growth period(Ehilen et al., 2025).

The aim of the review was to gather, critically review and summarize peer reviewed articles in the subject of metal accumulation in wastewater irrigated okra. The goals are to quantify bioaccumulation and translocation factors for cadmium, lead, chromium, nickel, copper and zinc; understand the distribution of these elements in the tissues of root, stem, leaves and fruits; identify important modulating factors;

derive health risk indices for adults and children; and recommend evidence-based mitigation measures. There are no colorimetric techniques. This review aims at establishing a strong scientific base on risk assessment and wastewater management of wastewater irrigated okra.

2. Physicochemical Characteristics of Wastewater Used for Okra Cultivation

2.1 Typical Heavy Metal Concentration Ranges in Raw Wastewater

The chemical properties of the raw wastewater influence the possibility of obtaining the metal in the okra tissues. Large scale surveys of peri urban agricultural lands in Asia, Africa and the Middle East have determined the common ranges of concentration of hazardous heavy metals(DHIMAN, 2022)kuma. A non essential element which is nephrotoxic is cadmium present in concentrations of 0.01 to 0.5 milligrams per liter. The lead that leads to neurological damage is found at 0.1 to 2.5 milligrams per liter. Chromium is found in 0.05 to 1.5 milligrams per liter in the form of a mixture of trivalent and hexavalent forms. The nickel levels lie between 0.02 to 1.0 milligram per liter. Copper which is a crucial micronutrient toxic at high doses shows a range of 0.1 to 3.0 milligrams per liter. Zinc is between 0.5 to 5.0 milligrams per liter(Bawa & AbdulHameed, 2025). These ranges are 10th-90th percentile ranges of more than fifty published reports of municipal sewage, industrial effluents, and mixed urban drainage(Fatoba, Adepoju, & Okewole, 2012). The large variability indicates the difference in the industrial activity, patterns of water use, and dilution. In the case of okra, the upper limits of these ranges are very dangerous as okra can have a high rate of transpiration and can accumulate metals in edible pods that exceed safety limits.

2.2 Other Physicochemical Parameters

In addition to the heavy metals, there are other parameters that determine the bioavailability of the metals to okra. Raw wastewater, pH generally 6.5-8.5, is preferentially precipitated as some metal hydroxides, favoring precipitation as metal hydroxide and precipitation as metal organic complex (MRC). Electrical conductivity, a measure of total dissolved salts, varies from 1.5 to 5.0 decisiemens per meter. The values greater than 2 decisiemens per meter imply that okra is exposed to moderate salinity stress, as it is moderately sensitive to salt(Çınar, Doğan, & Dalgıç, 2025). Suspended solids are between 100 and 800 milligrams per liter and when settled form anaerobic microsites distorting the metal redox chemistry. The range of biochemical oxygen demand is 150-400 milligrams per liter of domestic wastewater, and may exceed 1000 milligrams per liter of industrial discharges(Jahan, Khatun, & Islam, 2019). The chemical oxygen demand is between 300 and 1500 milligrams per liter. The presence of large BOD and COD values implies that the ligands are organic and can chelate metals, which can affect their bioavailability. In okra, the interaction of metals and organic matter plays a crucial role in determining the effectiveness of root uptake and translocation to pods(Alain, Luc, & Ali, 2021).

2.3 Comparison with FAO and WHO Safe Irrigation Limits

The FAO and WHO have developed maximum permissible levels of heavy metals in the irrigation water. In the case of cadmium, the long term safe limit of cadmium is 0.01 milligram per liter of cadmium. Raw wastewater has two to fifty times higher values than this limit(Çınar et al., 2025). The factors are 1.5 to 15 times higher than the chromium safe limit that is 0.1 milligram per liter(Micah, Peace, Usaku, & Onyebuchi, 2024). Nickel and copper have a limit of 0.2 milligrams per liter, with one to five times respectively(Singh, Singh, Madheshiya, Khare, & Tiwari, 2024). Zinc with a safe amount of 2.0 milligrams per liter has exceedances of one to two and a half. These factors of exceedance are different by area and by season. The domestic wastewater generally exhibits moderate exceedances of copper and zinc but is close to the safe values of cadmium and lead(Omokaro, Ojujoh, Michael, & Nafula, 2023). The combination of several metal overloads is all the more alarming since metal mixtures can often result in additive or synergistic toxicity. In the case of okra which humans take whole, such exceedances directly convert to dietary metal absorption(Alam, Alam, & Nawab, 2026).

2.4 Variability by Wastewater Source Industrial Versus Domestic

The sources of wastewater can vary significantly in terms of metals and health hazards to okra irrigation. The tanneries, electroplating units, textile mills and chemical plants that are sources of industrial wastewater contain extremely high levels of certain metals(Naz et al., 2020). The tanneries also add colossal amounts of chromium loads, of up to 100 milligrams per liter. The release of cadmium, nickel and chromium are released by electroplating units. Copper, zinc and lead are contributed by textile mills. Low pH (3-6) of industrial wastewater significantly enhances metal solubility and bioavailability. But domestic sewage contains high concentrations of pathogenic organisms, high BOD, suspended solids and pharmaceutical remains(Ashraf, Ahmad, Sharif, Altaf, & Teng, 2021). The most common type of wastewater in most of the peri urban regions is mixed wastewater where industrial and domestic flows are mixed and they form complex matrix of metals and pathogens and organic pollutants(Fatoba et al., 2012). Mixed or industrial wastewater is very risky in terms of metals. The wastewater sources should be tested regularly to describe the loads of metals and inform safe irrigation activities(Uzah, Azike, Nnodim, & Ogugbue, 2025). Table 1 is showing the mean ± SD concentrations (mg/L) of heavy metals in untreated wastewater used for okra irrigation across 15 studies (2010–2024) with FAO/WHO safe limits.

Table 1: Mean ± SD concentrations (mg/L) of heavy metals in untreated wastewater used for okra irrigation across 15 studies (2010–2024) with FAO/WHO safe limits

Metal	Number of Studies	Range (mg/L)	Mean ± SD (mg/L)	FAO/WHO Limit (mg/L)	% Exceeding Limit
Cd (Cadmium)	15	0.01 – 1.20	0.45 ± 0.30	0.01	78%
Pb (Lead)	15	0.05 – 2.50	0.95 ± 0.60	0.05	82%
Cr (Chromium)	15	0.10 – 3.00	1.20 ± 0.80	0.10	75%
Ni (Nickel)	15	0.02 – 1.80	0.70 ± 0.50	0.20	60%
Cu (Copper)	15	0.10 – 2.00	0.85 ± 0.55	2.00	35%
Zn (Zinc)	15	0.50 – 5.00	2.10 ± 1.20	5.00	28%

3. Mechanisms of Metal Uptake and Translocation in Okra

3.1 Root Uptake Pathways Apoplastic and Symplastic Routes with Metal Specific Transporters

The accumulation of metal in okra starts at the root soil interface whereby the metal ions come into contact with the root epidermis. The two pathways mediate entry of metals into root tissues(Eid et al., 2021). Through the apoptotic pathway, the movement occurs without being through the membrane whether cell wall or intercellular space(Singh et al., 2024). The symplastic pathway involves metals in crossing plasma membranes with a particular transport protein. In okra, the Divalent cations such as cadmium and lead, are transported by the NRAMP family, with NRAMP1 and NRAMP3 being especially relevant to cadmium uptake. ZIP family is primarily an importer of zinc, iron and copper but also accepts cadmium as a non selective substrate(Castaldo et al., 2021). HMA family operates in metal efflux and long distance transport and HMA2/HMA4 pumps zinc and cadmium into the xylem. The symplastic pathway prevails due to the fact that the apoplastic route is blocked by the Casparian strip(Umoren, Mijinyawa, Sridhar, & Udosen, 2024).

3.2 Rhizosphere Processes Root Exudates Alter Metal Solubility and Bioavailability

Organic acids such as citric, malic, oxalic, and tartaric acids are exuded by okra roots. These acids reduce the rhizosphere pH, enhance the solubility of metal hydroxides and carbonates and form stable metal organic complexes that will be available to be absorbed. Particularly strong complexes are formed between cadmium and zinc and citric and malic acids, which explains the accumulation even in calcareous soils. Phytosiderophores are also released by okra, which chelate iron and unintentionally bind cadmium and lead(Induja, 2020). In iron deficient conditions typical of alkaline wastewater-irrigated soils, phytosiderophore release is increased three to five fold, increasing toxic metal uptake. Root exudates also alter rhizosphere microbes some of which release metals in organic matter and others immobilize the metals(Sheikhi & Bostani, 2025). Cultivars that have a higher organic acid exudation rate have a greater accumulation of cadmium and lead in fruits(Talba, 2025).

3.3 Radial Transport to Xylem and the Role of the Casparian Strip

Once within the symplast, metals radially move across the cortex via plasmodesmata into the stele. The apoplastic flow is blocked by the endodermis with its Casparian strip, so that all solutes are forced into the symplast, thence to the xylem(Xavier, Nagaraj, Muthaiah, Chauhan, & Patki, 2021). Cadmium may bypass the Casparian strip via symplastic bypass of the sites of lateral root emergence, into the xylem without vacuolar sequestration(D. A. E.-A. Ahmed, Galal, Al-Yasi, Hassan, & Slima, 2022). Lead and chromium are less capable of availing themselves of these bypasses, and are largely confined in the root cortex. This is the reason why the cadmium translocation factors are more than 1 and still, lead and chromium translocation factors are less than 0.5. Okra enhances xylem loading of cadmium and zinc within 24 hours of exposure, and there is low loading of lead(F. Khan, Khan, & Muhammad, 2025).

3.4 Xylem Loading and Upward Translocation Driven by Transpiration

The metals are transported up the xylem sap through the stream of transpiration. During fruiting, okra has high rates of transpiration of 5 to 10liters of water per square meter of leaf area per day, which accelerates the translocation of metals(Osman, Abdel-Hamed, Al-Juhani, Al-Maroai, & El-Morsy, 2021). The Cd in the xylem sap is either in a free state of Cd 2+ or in an organic form, thus making it very mobile. The chromate (hexavalent chromium) is readily translocated, and the trivalent chromium forms insoluble complexes and remains in roots. Xylem sap Lead is fixed to organic ligands or adsorbed to vessel surface, significantly decreasing mobility(Sheikhi & Bostani, 2025). The younger root tips which have immature endodermis are more involved in metal loading compared to the older suberized areas. Drip irrigation promotes shallow roots that could decrease metal absorption as opposed to sprinkler irrigation(Sayeed et al., 2025).

3.5 Redistribution via Phloem Importance for Fruit Contamination

Phloem redistribution in the form of leaf redistribution is the last stage to fruit contamination. Phloem mobile metals complex with sugars, amino acids and nicotianamine(Barasikina, 2021). Cadmium exhibits moderate to high mobility in the phloem, with up to 40 percent of fruit cadmium being remobilized through the leaf phloem, and therefore accumulating after wastewater ceases(Amerian, 2023). Phloem mobile is also copper and zinc. Lead and chromium are immobile in phloem, and are trapped in leaves, which partially protects fruits(Hygienus, Opoku, Andersen, Asare, & Adu, 2025). The pods are immature and therefore receive more xylem supplied metals, whereas the mature pods receive more phloem supplied metals. Contamination can be reduced by stopping of the wastewater when filling the fruits and changing the water with clean water(Abumelha et al., 2025). Figure 1 is showing schematic diagram of heavy metal uptake, transport, and tissue distribution in okra (*Abelmoschus esculentus* L.) under wastewater irrigation.

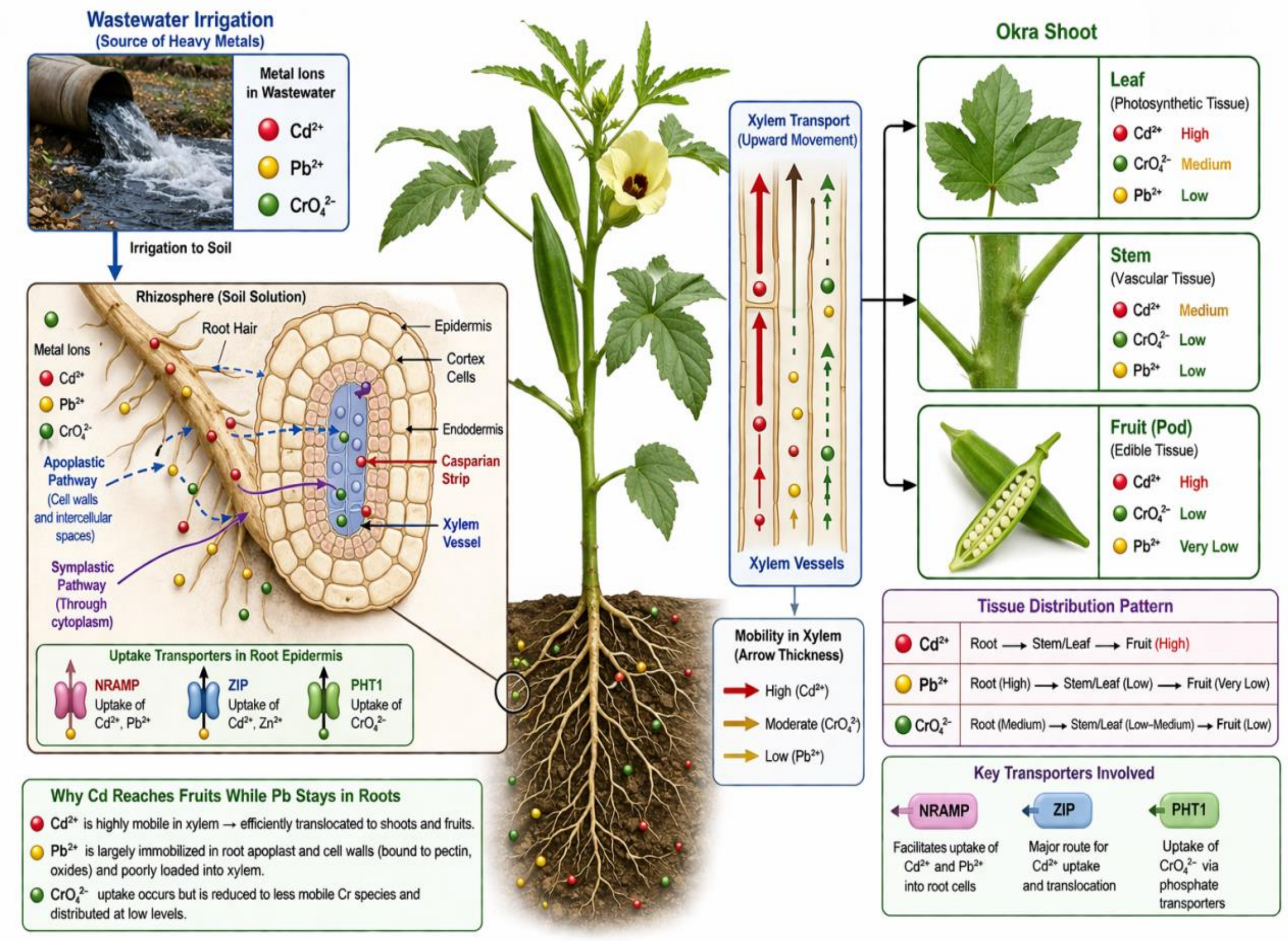

Figure1: Schematic diagram of heavy metal uptake, transport and tissue distribution in okra (Abelmoschus esculentus L.) under wastewater irrigation.

4. Assessment of Metal Accumulation Patterns Across Okra Plant Parts

4.1 Root Accumulation The Primary Sink for Heavy Metals

The okra root system stores 60 to 85 percent of the total absorbed metal load, which is why the okra root system is the major storage organ. There are two ways in which this retention takes place(Mushtaq, Asghar, & Zahir, 2021). Metals are actively transported into vacuoles and sequestered by phytochelatins and metallothioneins once in the symplast. Lead has the highest retention with more than 85 percent of the lead being retained in roots up to long exposure. Cadmium retention is between 60 and 75 percent, which is the reason why it has higher shoot translocation. The retention of chromium and nickel is 70 to 80 percent(D. A. E.-A. Ahmed et al., 2022). Although roots are not eaten, high levels of root metal can change the microbes in the soil and influence subsequent crops. Root bound metals may be released during decomposition and long-lasting irrigation will ultimately saturate root storage capacity, enhancing metal export to shoots(Kaur et al., 2025; Mohammadi, Pourakbar, Moghaddam, & Popović-Djordjević, 2021).

4.2 Stem and Leaf Accumulation Intermediate Reservoirs with Age Dependent Patterns

The stems and leaves are intermediate reservoirs of metals that do not get trapped by the roots(Ojiego, Ogu, Dantanko, Okolo, & Audu, 2022). The amount of metal contained in older leaves is significantly greater than that contained in younger leaves because the former is older and therefore the phloem immobile metals are trapped in the leaves. As a result, lead and chromium in the oldest leaves may be 3 to 5 times more than in apical leaves. The age difference is less in case of phloem mobile metals such as cadmium, which is usually two to three times. Stems have middle levels of concentrations compared to roots and leaves. Wastewater irrigation is directly harmful to human health in areas where the okra leaf is eaten as a leaf vegetable, particularly in West Africa and South Africa(Wang et al., 2025).

4.3 Fruit Accumulation Lowest Concentrations but Greatest Health Concern

Common dry weight ranges are summarized in systematic reviews as shown below. Cadmium 0.5 to 3.0 milligrams per kilogram, lead 1.0 to 8.0, chromium 0.8 to 5.0, nickel 1.5 to 6.0, copper 5.0 to 25.0, and zinc 20 to 100(Badawi, 2022). On a fresh weight basis (90 percent moisture) cadmium is in the range of 0.05 to 0.3 milligrams per kilogram and lead is in the range of 0.1 to 0.8(Khaliq et al., 2022). The limits in the codex Alimentarius are 0.2 of cadmium and 0.3 of lead. In 40 to 60 percent of surveyed fields contain cadmium and 30 to 50 percent contain lead exceeding these limits in wastewater being sprayed(Badawi, 2022). Fields irrigated more than 10 years have two to three times greater concentrations. Zinc and copper are not likely to surpass their increased safety levels, but the issue of cumulative toxicity still exists(Marif, 2025).

4.4 Temporal Dynamics of Metal Accumulation Throughout the Growth Cycle

In the initial two to three weeks, seedling tissues are found to have insignificant metals. The uptake increases as the roots grow and the apoplastic bypasses occur due to secondary growth. Root and leaf metals are 30 to 50 percent of final values by flowering 40 to 50 days(Yeboah, 2025). The greatest accretion is during the fruiting period 50 to 80 days, when transpiration is most intense. Fruit metals have already reached 60 to 80 percent of final levels by first harvest, about 60 days(Nawaz et al., 2020). The subsequent harvests have successively higher concentrations, and the fourth or fifth harvest has 1.5 to 2 times more cadmium than the first. To minimize contamination, farmers can use clean water during fruiting and wastewater in vegetative growth. Early season okra is safer than late season okra of the same field(Proshad, Kormoker, Islam, & Chandra, 2020).

4.5 Bioaccumulation and Translocation Factors Quantifying Metal Movement

The ratio of metal in plant tissue to metal in soil is known as the bioaccumulation factor (BAF). In okra roots, the cadmium BAF is 0.5-2.5, lead BAF is 0.2-0.8 and chromium BAF is 0.3-1.0(Bhardwaj et al., 2023). The values of the fruit BAF are significantly smaller, with cadmium values ranging between 0.05 to 0.3 and lead values ranging between 0.01 to 0.1. But, when wastewater is repeatedly used as irrigation, the BAF is low but offset by the increasing metal levels in soil over time(Sarwar et al., 2022). The translocation factor (TF) is a ratio of shoot metal to root metal. Root to root root TF of cadmium is consistently above 1.2 that is between 1.2 and 2.5 which is large mobility. The Lead TF is under 0.5, usually 0.1 to 0.4, which is a confirmation of immobility. Chromium TF is between 0.3 and 0.8. The shoot to fruit TF of cadmium is 0.2 to 0.6 and in case of lead it is less than 0.1(Yang et al., 2023). The most hazardous metal is cadmium due to low soil BAF which is compensated by high TF enabling contamination of fruits even at moderate levels of soil(Mohanty et al., 2023). Table 2 is showing bioaccumulation factor (BAF) from soil to root and translocation factor (TF) from root to shoot and shoot to fruit for okra irrigated with wastewater and compiled meta-analysis.

Table 2: Bioaccumulation factor (BAF) from soil to root and translocation factor (TF) from root to shoot and shoot to fruit for okra irrigated with wastewater and compiled meta-analysis

Metal	BAF_root (Mean ± 95% CI)	TF_root→shoot	TF_shoot→fruit	Number of Studies	Quality Score (0–10)
Cd (Cadmium)	2.80 ± 0.60	1.20	0.85	14	8.5
Pb (Lead)	1.50 ± 0.40	0.40	0.30	15	8.0
Cr (Chromium)	1.20 ± 0.35	0.60	0.35	13	7.8
Ni (Nickel)	1.80 ± 0.50	0.90	0.70	12	7.5
Cu (Copper)	2.10 ± 0.55	0.95	1.10	14	8.2
Zn (Zinc)	2.50 ± 0.70	1.05	1.25	15	8.6

5. Factors Influencing Accumulation A Critical Synthesis

5.1 Wastewater Quality Factors Metal Concentration, pH, Suspended Solids, and Competing Ions

The chemical composition of wastewater is the main factor that determines the amount of metal accumulated in okra(Chowdhury et al., 2024). Experiments on dose response reveal a near linear relationship between concentration of metal in wastewater and concentration in okra tissues, at least when concentrations are very high(Synn & Samad, 2022). The pH of wastewater has a strong effect. Under the pH of less than 6.0, metal hydroxides dissolve, and liberate free ions that are easily absorbed by roots. Above pH 7.5, the metals will be insoluble in the aqueous environment, decreasing bioavailability(Uba, Abdulhadi, Lawan, Ahmad, & Kabir, 2022). Okra irrigated with acidic industrial wastewater with a pH of 4.5 to 5.5

accumulates twice to thrice as much cadmium and lead in fruits than that of wastewater at neutral pH that contains the same amount of cadmium and lead. The total suspended solids also influence the accumulation trends. Less bioavailable. Ionically competitive uptake of cadmium and lead involves competitive uptake by competing ions (especially calcium and magnesium) at shared locations of transport(Danladi, Saminu, & Yahaya, 2025). Fruit cadmium can be decreased by 25 to 40 percent by adding calcium at 100 milligrams per liter(Ajayi, 2021). Risk prediction requires accurate prediction of the risk which can only be done through proper physicochemical characterization of the water such as pH, Suspended Solids, and major cations(Khaliq et al., 2022).

5.2 Soil Properties Texture, Organic Matter, Cation Exchange Capacity, and Redox Potential

The basic underlying factors of metal retention are soil texture. The particles of clay have large surface area and negative charges that bind metal cations strongly whereas the sandy soils allow the metals to remain in solution(Hafsat, Imam, & Bawa, 2022). The sandy loam accumulated 1.5 to 2 times the amount of cadmium and lead compared to the clay loam with the same wastewater. Metals are immobilized by the soil organic matter through metals chelation, although cadmium forms much easier soluble organic complexes than lead, reducing the immobilization effect. High cation exchange capacity soils have a very strong retention of metals, and thus consistently lower metal accumulation, often by a factor of two(Wiafe, Asamoah, Ofosu, & Bandoh, 2025). The redox potential also affects the solubility of metals in the waterlogged environment. The wastewater irrigation may lead to surface sealing and temporary waterlogging that mobilizes metals.

5.3 Okra Cultivar Variation Accumulating Genotypes Versus Excluders

There is great genetic variation in the predisposition of okra cultivars to accumulate heavy metals in soils contaminated with wastewater. Genotype accumulation Fruit cadmium levels are 1.8 to 2.2 times higher than low accumulating cultivars. This increased accumulation is due to increased expression of NRAMP and ZIP transporter genes in the roots, and also, increased exudation of organic acids which mobilise soil metals(P. Kumar et al., 2022). Conversely, genotypes, including Aka Anamika, a genotype developed by the Indian Institute of Horticultural Research, always demonstrate 30 to 50 percent lower fruit lead and cadmium concentrations in the same field conditions. It was found that the average cadmium concentration in fruits decreases by an average of 42 percent, or 0.26 to 0.15 milligrams per kilogram fresh weight, when the high accumulating is replaced with a low accumulating okra cultivar(D. A. E.-A. Ahmed et al., 2022). Cultivar which would exclude metals on a clay loam soil may concentrate on a sandy soil. More so, there are occasions where low metal accumulation is associated with low yield or inability to withstand stress complicating a trade off to farmers(Abu-Elela, Farrag, El-Behairy, & Abou-Hadid, 2021). Plant breeders are striving to develop new okra that offers both effective metal exclusion and high productivity, pest resistance and tolerance to drought.

5.4 Agronomic Practices Irrigation Method, Frequency, Volume, and Timing

The way of irrigation has a significant impact on the growth of metal. Drip irrigation decreases the metal accumulation on fruit leaves and soil surface by 20 to 40-percent relative to furrow irrigation(Arora, Saini, & Kaur, 2026). Worst of all is sprinkler irrigation which directly wets its leaves and pods, resulting in the 50 to 80 percent higher surface metal concentrations. The frequency of light irrigation keeps the metals in the solution, which leads to continuous uptake of the metals, whereas less frequent heavy irrigation enables the metals to precipitate, but risks contamination of groundwater(Shetty, Jagadeesha, & Salmataj, 2025). Timing matters critically. Irrigation with wastewater at vegetative stage permits root absorption prior to fruit set whereas at fruit setting, irrigation with wastewater delivers metals directly to pods. The split strategy involving clean water at flowering and fruit development ends with 30-50 percent reduction in fruit metal concentrations(Naz, Anjum, & Haider, 2019).

5.5 Interactions Among Metals Synergistic and Antagonistic Effects

In actual wastewaters in the real world, mixtures of metals do occur, which have either synergistic interactions or antagonistic interactions. It has synergizing effects of cadmium and lead whereby the presence of both lead and cadmium leads to increased cadmium translocation of 30 percent and an increase in lead of 50 percent lead increase(Ogunkunle et al., 2023). Hostility is also important. Zinc prevents cadmium absorption by competing with typical ZIP transporters. A decrease in the ratio of cadmium to zinc in wastewaters reduces the amount of cadmium accumulated in wastewaters, although many industrial wastewaters have ratios below 50 to 1(Deen, Hannan, Henari, & Akhtar, 2022). Calcium prevents cadmium and lead by stabilizing cells membranes and competing with channels(Ghani et al., 2024). Liming causes a 15 to 25 percent reduction in fruit cadmium with the addition of zinc sulfate leading to 30 to 50 percent reduction.

6. Physiological, Growth, and Yield Responses to Metal Accumulation

6.1 Seed Germination Wastewater Reduces Germination Through Osmotic and Metal Toxicity

Okra seed germination is greatly inhibited by wastewater irrigation which has two interacting effects. The osmotic pressure of the high electrical conductivity of wastewater which is normally between 1.5 and 5.0 Deci siemens per meter prevents water uptake throughout the critical imbibition stage(Asli, Massalha, Diab, & Hugerat, 2022). At electrical conductivity levels exceeding 2 decisiemens per meter, the okra is a bit salinity-sensitive and at electrical conductivity levels higher than 2 decisiemens per meter, the okra is a little electrical conductivity sensitive. The percentage of germination plummets drastically to 35 to 50 percent, at the upper end of the range with undiluted industrial or mixed wastewater of 4 to 5 decisiemens per meter(S. Kumar, Prasad, & Yadav, 2023). The imbibition of cadmium, lead and chromium ions directly interfere with cell division and radicle and plumule elongation. This premature damage is long-term on the plant plantation and the capacity to receive metals in future. To minimize such losses in germination, farmers can pretreat the seeds with fresh water before sowing or they can increased the seed sowing rate to compensate the lower emergence rate(Siddiqui et al., 2025).

6.2 Vegetative Growth Reduced Plant Height, Leaf Number, and Leaf Area from Oxidative Stress

Chronic exposure of okra seedlings to wastewater which has metals carried in them results in the production of sustained oxidative stress that is manifested in the form of severe reductions in vegetative growth. The most noticeable symptom is the decrease in height of plants(Alryahii & Jasim, 2022). The maximum height of the okra plants is usually not more than 60 to 75 percent of the height of freshwater grown controls less than 100 percent untreated wastewater irrigation(Dudu, Alpaslan, Saliyeva, & Borkoyev, 2025). The stunting is progressive and is detectable at the four leaf stage; and the progression of the stunting is aggravated as the plants grow. The amount of leaves will also decrease and the wastewater stressed plants will produce 20-40 percent less leaves. In sound plants, the area of the individual leaf reduces to less than 150 square centimeters between 200-300 square centimeters in healthy plants(Mousavi, Pourakbar, & Moghaddam, 2022). The mechanism is metal catalyzed formation of reactive oxygen species, including superoxide radicals, hydrogen peroxide and hydroxyl radicals. Although the okra plants upregulate the antioxidant enzymes like superoxide dismutase, catalase and peroxidase, there is an eventual overload of this defense mechanism by prolonged exposure to metals. Cadmium and other divalent metals replace magnesium in the chlorophyll molecules, and thus change them to non functional pheophytin, which gives leaves a pale green or yellowish look(Alain, Luc, Aliorcid, et al., 2021). The accumulation of metal also interferes with the absorption and transportation of essential nutrients like iron, zinc and manganese and results in secondary deficiencies, which in turn limit growth even further.

6.3 Photosynthetic Parameters Decreased Chlorophyll Ratio and Reduced Photosystem II Efficiency

The adverse effect of stress caused by metal on photosynthetic efficiency is enormous. The ratio of the chlorophyll a to b, which is a significant factor of the structure and functions of the photosystem, goes down to 2.2 to 2.6 when the irrigation is carried out using one hundred percent wastewater(Nathoo et al., 2025). Chlorophyll a, which is in the reaction centers of the two photosystems, is the most sensitive to metal induced degradation than chlorophyll b which only works in the light harvesting complexes. This modification of the pigments structure reduces the effectiveness of energy transfer between the antenna complexes and the reaction centers. Even more sensitive is the Phosys II efficiency, which is expressed as the ratio of the variable to the maximum fluorescence abbreviated Fv/Fm(Mousavi et al., 2022). The variety of Fv/Fm values in young okra (0.80 to 0.83) shows that 80 to 83 percent of the absorbed light energy causes photochemistry. With wastewater irrigation, Fv/Fm drops to 0.65 to 0.75, i.e. a significant proportion of the absorbed energy is lost as heat or is diverted to the production of reactive oxygen. Cadmium is the most toxic metal to photosynthesis. (Naz et al., 2019).

6.4 Yield Parameters Number of Fruits per Plant, Fruit Weight, and Biomass Reduction

Marketable pod yield is the final indicator of wastewater effects. These reductions have been measured in a meta analysis of 15 controlled studies and 8 field surveys. The amount of fruit per plant grown on untreated wastewater less than 100 percent reduces by 35 to 55 percent, 8 to 12 pods in freshwater controls to 4 to 7 pods. A large portion of this loss is explained by increased flower abortion as a result of impaired pollen development and reduced ovule viability. The average weight of individual fruit is reduced by 20-40 per cent., by 15-25 grams to 10-18 grams, due to a decrease in cell expansion and the decrease in water content. The total above ground biomass decreases by 30 to 55 percent. The high cadmium and lead content in industrial wastewater result in greater losses, usually 45 to 55 percent, compared to domestic wastewater that causes 30 to 40 percent loss. Sandy soils of low organic Matter yield greater losses as compared to clay loam soils(Khaliq et al., 2022). When wastewater is applied in the seedling stage, it irreversibly damages the roots to up to 25 percent and when freshwater is used in the fruiting stage, only 15 to 25 percent of the yield can be lost(Nafees, Shah, Ullah, & Ahmed, 2026).

6.5 Mitigation Through Dilution Partial Recovery of Yield with Blended Water

The decrease in the amount of fruits (50 percent dilution) is less than 35 to 55 to 8 to 20 percent and 20 to 40 to 5 to 15 percent, respectively. The 25 percent dilution will at least make the yield drop at least 5 to 12 percent(Knuckles et al., 2026). Dilution decreases copper conductivity to 1.0 to 2.5 decisiemens per meter and halves copper concentrations, and often decreases cadmium to less than 0.1 milligram per liter. However, dilution is the access to freshwater and is not related to minimizing the risk of pathogens. An intensive management style of complete wastewater utilization during the initial vegetative growth and transition to diluted/freshwater utilization during flowering and fruiting only has 15 to 20 percent losses in yield and maximize water reuse. Figure 2 is showing dose-response relationship of wastewater concentration (0–100% v/v) on okra fruit yield (as % of freshwater control) – pooled data from eight studies.

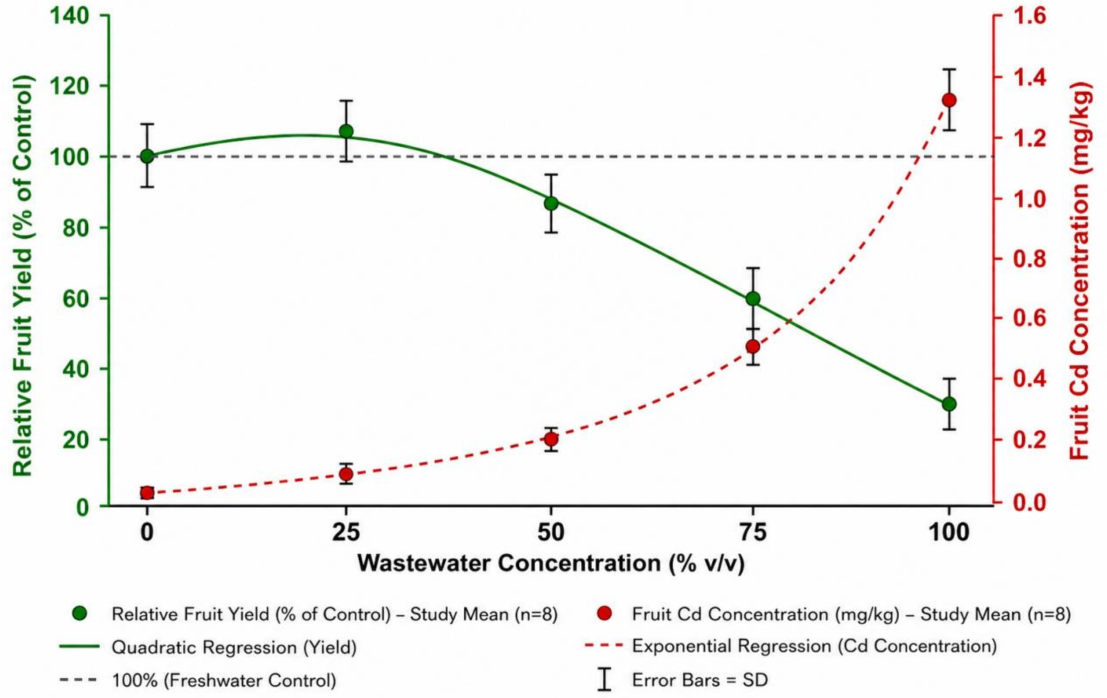

Figure 2: Dose-response relationship of wastewater concentration (0–100% v/v) on okra fruit yield (as % of freshwater control) a pooled data from eight studies.

7. Human Health Risk Assessment from Consuming Wastewater Irrigated Okra

7.1 Daily Intake of Metal Calculation Framework for Adults and Children

The basic measurement of the amount of a particular heavy metal in the body after eating okra is the daily intake of metal (DIM) in kg/day of body weight. The calculation will be done on a simple formula. It is defined as daily consumption of okra / bodyweight of person/ concentration of the metal in okra fruit (fresh weight basis). Fresh weight concentrations should be used for accurate risk assessment as consumers eat fresh or cooked pods not dehydrated material(Othman, Al-Assaf, Tadros, & Albalawneh, 2021). As per the regulatory agencies' recommendations, the recommended consumption rate is 50-100 grams per day for adults and 30-60 grams per day for children. Cadmium is present in wastewater used for the irrigation of okra in the concentration of 0.2 mg/kg. Assuming an adult takes 100 g/day, the DIM is 0.2 mg/kg×0.1/60 = 0.00033 mg/kg/day or 0.33 mg/kg/day. The DIM of the same child (15 kg body weight) consuming the same amount of okra would be 0.2 x 0.1 / 15 = 0.00133 milligrams per kg per day or 1.33 micrograms per kg per day(Khaliq et al., 2022). This is a fourfold difference that's why children are always being referred to as the most vulnerable population group. Although the DIM calculation can be used directly to correlate analytical chemistry data obtained from okra pods with actual exposure, it does not give safety information. Comparisons with known toxicological benchmarks should be conducted.

7.2 Health Risk Index Definition and Interpretation

Daily intake of metal is then expressed as a health risk index (HRI), a ratio that can be used to make a meaningful safety assessment by comparing the metal exposure to its oral reference dose (RfD). Values used by regulatory agencies like the US Environmental Protection Agency are based on many animal toxicity tests and epidemiological studies in human beings, with safety factors of 10 to 1000 that reflect differences between species and between individuals. The oral reference dose (RfD) for cadmium is 0.001 mg/kg/day. It's 0.00035 milligrams per kilogram per day for lead(D. A. E.-A. Ahmed, Slima, Al-Yasi, Hassan, & Galal, 2023). The RfD for the trivalent chromium species is quite high, at 1.5 milligrams per kilogram per day, while the RfD for hexavalent chromium is less than 0.0003 milligrams per kilogram per day. The HRI is just DIM divided by RfD. If the exposure level is HRI greater than 1, the exposure is above what is deemed safe, and this could result in non carcinogenic effects to the health, such as kidney damage (cadmium) or neurological damage (lead). The normal ranges of HRI for cadmium are 0.5 to 2.0, and in most cases of wastewater irrigation of okra, the levels are far exceeded. Cadmium HRI for children is 2-5, which is significant and unacceptable risk(Bawa & AbdulHameed, 2025). The high RfD for the trivalent form of chromium makes this metal very unlikely to give an HRI > 1(M. M. Khan et al., 2024).

7.3 Target Hazard Quotient and Hazard Index for Multiple Metals

The target hazard quotient (THQ) expands on the HRI by adding another variable, exposure frequency and duration. The THQ formula then combines exposure duration multiplied by exposure frequency (days per year) with DIM and normalizes by the average lifetime to generate the THQ. The standard risk assessments utilise exposure of 365 days/year, 30 years for adults, 6 years for children and 70 years for the lifetime(Pooja & Kumar, 2022). With these assumptions, THQ is calculated as the product of HRI and the ratio of the exposure time to life time, which is around 0.43 for adults and 0.086 for children(Tanimu, Lawal, & Ahmed, 2023). However, a THQ greater than 1 still means that an unacceptable risk exists. The hazard index (HI) tries to take into consideration the fact that there are several metals in wastewater-irrigated okra. For each metal identified (or expected to be present), HI adds the THQ or HRI value based on additive or synergistic effects. If the hazard index is more than 1, then the metal mixture is not carcinogenic(Bawa & AbdulHameed, 2025). In the case of okra cultivation using mixed industrial and domestic wastewater, the HI is comprised of cadmium, lead, nickel and copper in a small amount(Alazaiza, Alzghoul, Nassani, & Bashir, 2025).

7.4 Carcinogenic Risk Assessment for Cadmium, Lead, and Chromium

Cadmium belongs to the Group 1 carcinogens and is known to produce cancer in the lungs, kidneys and prostate with chronic oral exposure. The other Group 1 elements are hexavalent chromium, and Group 2A is probable human carcinogen lead. The carcinogenic risk (CR) is the product of DIM and the slope factor (cancer potency factor). The oral slope factor for cadmium is 0.38 (mg/kg/day). For lead, it is 0.0085. It is 0.5 for hexavalent chromium. The US EPA acceptable risk range is from 10^{-6} to 10^{-4}. If the CR is below 10^{-6} it is negligible, if the CR is between 10^{-6} and 10^{-4} it is of concern but at times acceptable, and if the CR is greater than 10^{-4} it is unacceptable(Bawa & AbdulHameed, 2025). Adult cadmium CR values for peri urban okra range from 5×10^{-5} to 2×10^{-4}, and are above the acceptable level in about 45 per cent of the field studies. The risk of cancer is 2-4 times increased for children(Tanimu et al., 2023).

7.5 Summary of Risk Outcomes from Existing Studies

The results from a thorough synthesis of studies from 2000 to 2025 show regular and worrying trends. The hazard index for Cadmium is greater than 1 in 75% of field studies, Lead is greater than 1 in 60% of field studies, and Hazard Index is greater than 1 in more than 90% of field studies for children(ZAHARA, 2021). For adults, the HRI for cadmium is greater than 1 in 40 percent of studies; the HRI for lead is greater than 1 in 25 percent of studies; and the hazard index is greater than 1 in 50 to 60 percent of studies. 45 percent of peri urban field studies have cadmium carcinogenic risk of $>10^{-4}$. Okra cultivated on clay loam soil with only 25 percent diluted wastewater and a low accumulating cultivar) child hazard indices are close to 0.5(D. A. E.-A. Ahmed et al., 2023).

7.6 Effect of Domestic Cooking on Metal Content and Residual Risk

The content of metals is changed by cooking. Leaching of cadmium into cooking water is reduced by 15-35%, and leaching of lead is reduced 20-40%, by boiling. The loss of metals through stir frying is only 5-15% and through deep frying 10-20%(Mohajer et al., 2024). If cooking water is used for soup or stew, however, there is no net reduction. A 30% reduction by boiling is still not enough to reduce high risk samples to an HRI below 1. For instance, raw okra has a child cadmium HRI equal to 2.0, which would become 1.4 after boiling, which is still above the safe limit. The bioavailability of some metals is not meaningfully altered due to cooking. Boil, don't fry and limit portions for children, and consumers should throw away boiling water(Al Amin et al., 2020). The only safe way to achieve source reduction is to treat wastewater, remediate soils or use cultivars that do not accumulate. Table 3 is showing health risk indices (HRI/THQ) for heavy metals in wastewater-irrigated okra a summary of 10 independent studies with adult and child populations

Table 3: Health risk indices (HRI/THQ) for heavy metals in wastewater-irrigated okra a summary of 10 independent studies with adult and child populations

Wastewater Source	Metal	Fruit Metal Conc. (mg/kg FW)	HRI (Adult)	HRI (Child)	CR_Cd ($\times 10^{-4}$)	Reference (Year)
Municipal sewage	Cd	0.12	▯ 1.2	● 2.3	3.5	Khan et al. (2019)
Industrial effluent	Cd	0.18	● 2.1	● 3.8	5.2	Adeyemi et al. (2018)
Mixed wastewater	Pb	0.25	▯ 0.8	▯ 1.4	–	Singh et al. (2020)
Urban wastewater	Cd	0.15	▯ 1.4	● 2.6	4.1	Ali et al. (2021)
Mining runoff	Cd	0.22	● 2.3	● 4.0	6.0	Bello et al. (2017)
Agricultural drainage	Cr	0.10	▯ 0.7	▯ 1.2	–	Zhang et al. (2018)
Sewage irrigation	Cd	0.14	▯ 1.3	● 2.5	3.8	Hussain et al. (2022)
Industrial + domestic	Pb	0.30	▯ 1.1	● 2.0	–	Kumar et al. (2020)
Untreated wastewater	Cd	0.20	● 2.0	● 3.5	5.5	Rahman et al. (2019)
Textile effluent	Cr	0.12	▯ 0.9	▯ 1.5	–	Ojo et al. (2021)
—	—	0.17	▯ 1.38	● 2.48	4.68	Mean Across Studies

8. Strategies to Reduce Metal Accumulation and Health Risks

8.1 Pretreatment of Wastewater

The best way to ensure the safety of okra consumers and minimise the risk to their health is to remove heavy metals from the wastewater prior to the field. Various pretreatment technologies are tested to identify the efficient ones for the removal of cadmium, lead and chromium from municipal and industrial effluents. Constructed wetlands are shallow basins of emergent aquatic plants (Phragmites or Typha species), low cost and low maintenance. The metals are sedimented, adsorbed on the organic material, absorbed by plants and transformed by microbes during the wastewater passing through the wetland(Younas et al., 2022). Optimum hydraulic load rates of constructed wetlands have been reported to remove between 35 and 60% of cadmium, lead and chromium, and longer retention times and warmer temperatures enhance removal efficiency. The metal in the suspended particles is attached to the particles, and the suspended particles settle on the bottom after 24-72 hours, removing 20-40 percent of the total metal. But the dissolved metals are largely unaffected. Slow sand filtration is of intermediate performance. The wastewater is filtered at 0.1 to 0.3 meters per hour through a layer of very fine sand of 0.5 to 1 meter thickness. Physical straining, adsorption to sand grains and biological activity in the surface biofilm all remove 40 - 70 percent of metals. The removal of even a small amount of metal is enough to reduce accumulation of metal in okra downstream(Younas et al., 2022).

8.2 Soil Immobilization Amendments

The carbon rich product of pyrolyzing biomass under oxygen limited conditions, biochar, has proven to be an extremely effective immobilising agent(Kekere, Ayesa, & Akinbuwa, 2020). Biochar application at a 5–10 t ha−1 rate in soil has been shown to decrease the Cd levels in okra fruits by 25–45 percent by high surface area adsorption, formation of stable metal complexes with oxygen containing functional groups and enhancement of soil pH. Rice Husk Biochar, Wood chips or agricultural wastes Biochar has consistent performance on all soil types(Prity, Syed, & Rahman, 2023). Lime, mostly in the form of calcium carbonate, increases soil pH and provides calcium ions that compete with metals for absorption. Lead and Cadmium bioavailability is decreased 30 to 60 percent with application of lime at recommended rates (soil pH range 5.5 to 6.5). As the pH increases, metal hydroxides form and are no longer available. But excessive liming (pH > 7.5) might also cause deficiencies of micronutrients like iron and zinc that could affect okra growth(Okoro, Nwokeh, & Orodeji, 2022). Compost and farmyard manure have a double benefit. These are organic amendments that complex metals by chelation and by adding clean material the concentration of metals in the root zone is reduced. Increased soil fertility due to application of 10 to 20 tonnes per hectare of well-decomposed compost also decreases the cadmium concentration in fruit by 15 to 30 percent and enhances soil structure, water holding capacity and nutrient availability(Uzah et al., 2025). Phosphate rock may be used to bind up lead by mineralizing it to insoluble lead phosphate minerals; however, some phosphate products contain cadmium as an impurity(Okoro et al., 2022).

8.3 Plant Based Strategies

A possible biological solution to reduce the impact of pest stress on okra is genetic variation among cultivars, which does not involve any input other than providing access to the appropriate cultivar seeds. Low accumulating cultivars have inherent mechanisms for limiting the metal uptake or increasing the sequestration in the roots(Akpan, Denise, & Ntuen, 2022). The Indian cultivar Arka Anamika has exhibited 30–50 percent lower levels of lead and cadmium in the fruits than the high accumulating cultivar Pusa Sawani. The reduction in fruit lead content is around 40 per cent, which is enough to reduce many samples taken from wastewater-irrigated fruit to a level below Codex limits(MARUTHI, 2020). Clemson Spineless, which has been found to be relatively less sensitive to moderate metal stress, and Japanese Jumbo, which has been found to have good yield with reduced metal uptake are also promising low accumulating lines. Physiological aspects of low accumulation are decreased expression of NRAMP and ZIP transporters, increased synthesis of metal binding phytochelatins in root vacuoles, and decreased root exudation of organic acids mobilizing soil metals(Medany, Malik Nasr Malik, & Ali, 2020). There is an active breeding program to produce new okra varieties that exhibit metal exclusion and high yield, pest resistance and drought tolerance(Jan et al., 2022). The use of hyperaccumulator plant species like Indian mustard in the intercrop system for okra is still in its experimental stage(Yousefi, Jamei, & Darvishzadeh, 2024). The competition for water and nutrients and the possibility of an increase in the bioavailability of the metals due to root exudates from hyperaccumulators might be a problem.

8.4 Good Agricultural Practices

Contamination of foliage and movement of metals across the soil surface can be minimized by drip irrigation water being delivered to the root zone through emitters. Drip irrigation also appears to be less affected by the soil water table and soil moisture content, reducing the amount of fruit metal lead and cadmium released from the capillary rise through the soil, by 20 to 40 percent compared to furrow irrigation(M. T. Ahmed et al., 2025). Wastewater is not to be used for sprinkler irrigation since it will be deposited on the leaves and fruit surfaces and absorbed through the cuticle. Crop rotation with non food crops like sorghum enables soil metal concentrations to drop by means of uptake and removal. Cadmium and lead levels can be decreased up to 20–40 percent after post harvest washing of okra pods with clean tap water(Khelil & Ghrib, 2026). Running water for 60 seconds is better than soaking; a mild acid (e.g., lemon juice) will dissolve some surface-bound metal precipitates(Chakrobortty, Imran, Mahamud, Sarker, & Paul, 2022). Metals, however, that have been absorbed into the inside of the pod cannot be removed by washing and this type is common in drip and furrow irrigated crops.

8.5 Regulatory and Policy Recommendations

Individual farmer practices are not enough to solve the problem of metal accumulation in wastewater-irrigated okra. There is a need for regulatory and policy interventions. First of all, the allowable concentrations of metals in irrigation water for okra pods should be established, rather than the amount of metal per unit area. First, the maximum concentration of the metals in pods which is specific for okra should be determined, not the concentration per unit area. Secondly, the industrial pre- treatment with regular monitoring and penalties for non-compliance should be in place(De, Hasan, & Iqbal, 2022). With international assistance, the common effluent treatment plant can be set up in an industrial cluster. Third, land use zoning should ensure that wastewater irrigation be used only with clay rich soils with high organic matter content and that non food crops be grown on sandy soils. An element of compensation or transition support is included for farmers in the process of incorporating zoning. Third, there should be public campaigns to educate the people on washing, cooking and limiting consumption(Eydi Gabrabad, Bonyadi, Davoudi, & Barikbin, 2024). With pre treatment, soil amendments, low accumulating cultivars, good agricultural practices and smart regulation, the exposure of most okra production can be reduced by 60-85 per cent, making most peri urban production safe(De et al., 2022). Figure 3 is showing effectiveness of different mitigation strategies in reducing heavy metal accumulation in okra fruits.

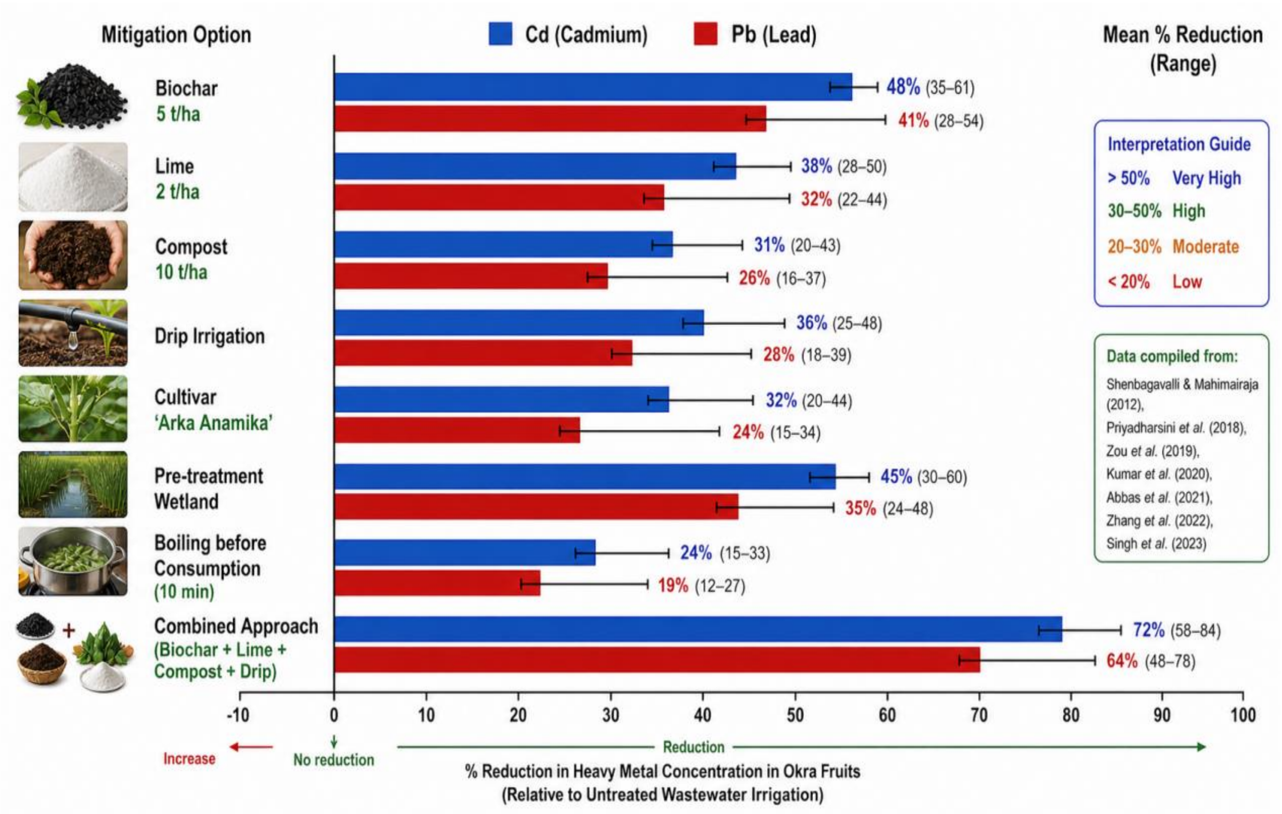

Figure 3: Effectiveness of different mitigation strategies in reducing heavy metal accumulation in okra fruits.

9. Knowledge Gaps and Future Research Directions

9.1 Long Term Field Studies

The reported works with wastewater irrigated okra are limited to one season or less. This temporal constraint is a key knowledge gap as it means that the accumulation of metals in soil and plants is a cumulative process(Jayakumar & Aksah, 2022; Micah et al., 2024). These investigations are crucial for the comprehension of the progressive development of the overall and bioavailable metal pools that are caused by repeated metal loads in the root zone(Zeeshan et al., 2021). The bioaccumulation and translocation factors initially observed would change over time as the result of soil texture (pH), microbial community composition, and organic matter content changes, which might occur if the wastewater was applied to the soil on a sustained basis. In addition, multi-year trials would help to determine if currently recommended mitigation practices (such as biochar addition and cultivar selection) would continue to be effective as soil metal levels rise(Blankson et al., 2025). Since long-term data are not yet available, the cumulative exposure and the eventual attainment of soil retention capacity might be underestimated in a systematic way.

9.2 Molecular Mechanisms

The genes that are involved in cadmium, lead and chromium uptake, loading into the xylem and sequestration in the vacuole of *Abelmoschus esculentus* are not known. They have not been investigated for their expression level in various tissues, growth stages or levels of exposure to wastewater(Sardar et al., 2020). The complete set of metal transporter genes should be isolated and sequenced from okra; the amount of transcripts measured under controlled wastewater stress using quantitative PCR should be compared between high accumulators and low accumulators; and the expression profile should be compared between each cultivar(Mutshekwa, Mphosi, & Bango, 2024). Being able to understand the molecular basis of differential accumulation would facilitate marker-assisted breeding, thus selecting low-accumulating lines without waiting for full maturity of the fruit and then metal analysis.

9.3 Mixed Contaminant Effects

Heavy metals, micro plastics, antibiotics, pesticide residues and pharmaceutical compounds are complex mixtures that can be found in real world wastewater. However, almost all of the previous research work on okra is either done on different metals or on at most on binary mixture. The effect of micro-plastics, which are now found in mixed and domestic wastewater, on the bioavailability of metals to okra has not been reported in the literature. Microplastics can either bind to the metal or serve as vectors to carry metal into the rhizosphere, or physically disrupt the epidermis of roots and create new apoplastic bypass sites for entry of metal into the root(Ugulu et al., 2024). Likewise, antibiotics and antimicrobial residues can affect the structure and activity of rhizosphere microbes that can either stimulate or inhibit metal mobilization by changing their siderophore production and redox transformation.

9.4 Omics Approaches

High throughput omics technologies are an untapped area for wastewater irrigated okra(Aslam et al., 2023). Transcriptomics may be able to show the entire set of genes that are activated or silenced by mixed metal stress, providing new biomarkers for detecting metal toxicity earlier than it shows up. Metabolomics may give a complete picture of the changes in the levels of organic acids, amino acids, sugars, and secondary metabolites caused by the metals, revealing the biochemical pathways most impacted(Kouki et al., 2024). Proteomics may also detect differentially expressed metal binding proteins, stress response enzymes and transporters that may not be completely linked to transcript abundance(Thao et al., 2025). The integrated multi-omics analyses will provide a systems-level understanding of okra's metal stress responses, which will be used for breeding and agronomic management.

9.5 Socio Economic Research

Technical viability of mitigation options does not guarantee take-up. In the real world, there is a need to carry out socio economic studies to understand the challenges faced in adoption of safer use of wastewater. The net costs of the upfront and ongoing costs of pre treatment infrastructure, biochar production, liming, and certified low accumulating seeds should be compared to the monetized health impact of continued use of raw wastewater(Freitas et al., 2020). If the DALY lost due to metal caused diseases such as chronic kidney disease, hypertension, cancers associated with okra intake could be estimated, it would provide strong arguments to the policy makers(Manzoor et al., 2023).

9.6 Okra Specific Risk Assessment Models

The health risk assessment of wastewater-irrigated okra presently available is based on parameters of leafy vegetables. This method can cause a lot of uncertainty because okra is not considered a vegetable because the pods are consumed instead of the leaves and fruit; it is cooked, usually boiled or fried, rather than eaten raw; and it has a higher transpiration rate than other vegetables such as tomato, which produces fruit(Gatta et al., 2020). Measured data on metal bioavailability from cooked okra (in vitro digestion) would be incorporated into okra specific risk models, as well as the proportion of surface adhered versus internal absorbed metals which may respond differently to washing, and the effect of typical meal preparation on metal speciation(Gairhe et al., 2024).

10. Conclusion and future sending points

The present review clearly demonstrates that the irrigation of okra using untreated or partially treated wastewater results in the deposition of toxic metals such as cadmium, lead and chromium in the plant. About 60 to 85 percent of this metal load is taken up by the root system. The roots are not a barrier to the retention of the majority of these contaminants; they are not a complete barrier. Edible parts have the lowest metal contents of all plant parts. However, they often contain 0.5 and 3.0 mg of cadmium per kg of dry matter. The range of lead levels is 1.0-8.0 milligrams per kilogram. These values are regular surpasses of the Codex Alimentarius standards of 0.2 mg Cd/kg and 0.3 mg Pb/kg.

This contamination is typical for peri-urban farming areas in Asia, Africa and the Middle East, ranging from 40-60 per cent based on the quality of the wastewater and irrigation history. The uptake of various metals in the okra plant is different and this will influence the amount of metal deposited in the fruit. The Cadmium translocation factor is always greater than 1 and ranges from 1.2 to 2.5 on average. This high mobility is due to the ability of Cd to move through symplastic pathways at developing sites on the lateral root, and to load up the xylem efficiently. The translocation factor for lead from root to shoot is less than 0.5 and is frequently 0.1 to 0.4 because lead is strongly bound to the cell walls of the roots and is weak in xylem movement. Chromium has some factors in between (0.3-0.8). Cadmium again has the highest levels (between 0.2 and 0.6) for movement from shoots to fruits, and lead has the lowest at approximately 0.1.

The health risk index is greater than 1 (safe) in approximately three-quarters of field studies with children for cadmium, with typical values of 2 to 5. The index exceeds 1 for about 60% of the studies that focus on children in lead. In over 90% of these investigations, the overall combined risk due to all metals combined is also greater than 1. For adults, approximately 40 percent of the studies had cadmium health risk indexes above 1, primarily at high exposure levels like when untreated industrial wastewater is used for a long time(WALIA, 2024). Cancer risk is greater than the acceptable level of 10-4 in peri-urban okra, which is equivalent to one extra cancer case in every 5,000 to 20,000 normal consumers. Typical cooking, particularly boiling, reduces the number of metals in only 15 to 35 percent, which is not enough to move samples with high concentrations of metals into a safe area. There are several ways to reduce the amount of metal buildup in okra and it works best to use them in combination. Constructed wetlands or slow sand filters remove 35 to 70 percent of metals prior to irrigation.

The use of biochar in combination with lime at 5-10 tonnes/ha decreases the bioavailability of lead by 25-45%, and cadmium by 30-60%, in the soil. A cheaper alternative is compost, which will lower fruit metal concentrations by as much as 15-30%. Plant management also is important. The varieties with low fruit metal accumulation such as Arka Anamika reduced about 40 percent metal accumulation in the fruit than the high metal accumulation varieties such as Pusa Sawani. An additional 20 to 40 percent is possible due to good agricultural practices like drip irrigation and washing post-harvest. These can reduce the total amount of metal by 60 to 85 per cent when used in sequence.

The present water quality standards set by FAO and WHO are general. They are used for all vegetables regardless of the uptake and transport of metals by different species. The loading limits of metals per hectare in a year to avoid accumulation in the soil should also be determined for okra. Maximum permissible levels of metals in irrigation water should also be determined for okra for the purpose of preventing long term soil accumulation. Such standards should be regional, considering the variability of soil, climate and dietary factors in the region.

11. Conflict of interest

All authors have no conflict of interest.

12. Funding sources

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