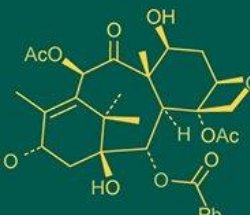
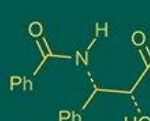


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(6): 142-148
www.biochemjournal.com
Received: 24-03-2026
Accepted: 28-04-2026

Shubham Bhatt
PG Student, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Mansi Nautiyal
PG Student, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Sharad Pandey
Professor, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Impact of agricultural and industrial waste on heavy metal accumulation in wheat (*Triticum aestivum* L.)

Shubham Bhatt, Mansi Nautiyal and Sharad Pandey

DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i6Sb.8579>

Abstract

Wheat (*Triticum aestivum* L.) is one of the world's most important cereal crops, but its productivity and grain quality are increasingly threatened by heavy metal contamination. This review summarizes the sources, pathways, accumulation mechanisms, and impacts of major heavy metals, including cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), copper (Cu), zinc (Zn), and nickel (Ni), in wheat production systems. Agricultural inputs such as fertilizers, sewage sludge, manures, and pesticides, along with industrial effluents used for irrigation, are major contributors to soil contamination. Wheat exhibits a relatively high capacity to accumulate certain toxic metals, depending on soil properties and plant genotype. Consumption of contaminated wheat grain may pose significant health risks, with reported levels in some regions approaching or exceeding WHO/FAO safety limits. Remediation strategies including biochar application, liming, phytoremediation, and improved wastewater management are discussed. The review emphasizes the need for integrated monitoring, sustainable management practices, and effective policy measures to ensure wheat safety and food security.

Keywords: Agricultural waste, arsenic, bioaccumulation, cadmium, food safety, industrial effluent, lead

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most widely cultivated cereal crops in the world, covering approximately 220 million hectares and providing nearly 20% of the global dietary intake of calories and protein (Saud *et al.*, 2022) ^[14]. Consequently, maintaining wheat quality and safety is essential for ensuring global food security and public health. However, increasing contamination of agricultural soils by heavy metals has become a major challenge for sustainable wheat production.

Heavy metals are metallic elements with densities greater than 5 g cm⁻³. Among them, cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), mercury (Hg), copper (Cu), zinc (Zn), and nickel (Ni) are of particular environmental concern because of their toxicity, persistence, and tendency to accumulate in biological systems (Rahman and Singh, 2019) ^[13]. Cadmium, lead, arsenic, mercury, and chromium are recognized as priority pollutants by international agencies such as the United States Environmental Protection Agency (USEPA) and the World Health Organization (WHO).

Heavy metal contamination in wheat-growing soils originates from both agricultural and industrial activities. Repeated application of phosphate fertilizers, sewage sludge, animal manure, and copper-based pesticides can gradually increase metal concentrations in soil (Li *et al.*, 2024) ^[9]. Industrial activities including paper manufacturing, textile processing, electroplating, metal fabrication, and chemical production also contribute substantially through the discharge of untreated or poorly treated effluents. In many developing countries, such effluents are frequently released into water bodies and irrigation channels, leading to contamination of agricultural lands (Singh *et al.*, 2025) ^[15].

Globally, more than five million contaminated sites covering approximately 20 million hectares have been reported, with extensive contamination occurring in several agricultural regions. China alone accounts for over 100 million hectares of contaminated farmland (as cited by Tauqeer *et al.*, 2024) ^[20]. The accumulation of heavy metals in wheat can adversely affect plant growth, reduce grain quality, and increase health risks associated with dietary exposure.

Corresponding Author:
Shubham Bhatt
PG Student, School of
Agriculture, Uttaranchal
University, Dehradun,
Uttarakhand, India

Therefore, understanding the sources, uptake mechanisms, phytotoxic effects, and associated risks of heavy metals in wheat production systems is essential. This review synthesizes recent findings on heavy metal contamination in wheat and discusses management strategies and future research needs.

2. Sources of Heavy Metals in Wheat-Growing Soils

2.1 Agricultural Waste and Agrochemical Inputs

Agricultural practices are among the major contributors to heavy metal accumulation in cropland soils. Phosphate fertilizers are widely recognized as an important anthropogenic source of cadmium contamination. Phosphate rocks used in fertilizer production often contain varying amounts of cadmium, lead, and uranium, which are gradually introduced into agricultural soils through repeated fertilizer application (Chen *et al.*, 2024) [25]. Previous studies have reported that calcium superphosphate generally contains higher concentrations of lead and chromium than monoammonium phosphate and diammonium phosphate fertilizers.

Organic amendments such as sewage sludge compost (SSC) and domestic waste compost (DWC) can also contribute to heavy metal accumulation in agricultural soils. Long-term application of SSC has been associated with increased concentrations of cadmium, lead, and zinc in wheat grains and straw. In addition, continuous use of these amendments may increase the proportion of bioavailable metal fractions, thereby posing potential risks to food safety and human health (Li *et al.*, 2025) [10].

Animal manure derived from intensive livestock production systems can introduce substantial quantities of copper and zinc into soils because these elements are commonly added to livestock feed as nutritional supplements. Continuous manure application may result in gradual enrichment of agricultural soils with these metals. Similarly, prolonged use of copper-based fungicides and certain pesticides may contribute additional metal residues, including copper and arsenic, to the soil profile (Singh *et al.*, 2025) [15].

Irrigation with contaminated water represents another important pathway for heavy metal entry into the wheat rhizosphere. Wastewater originating from industrial discharges, municipal sewage, and agricultural runoff often contains dissolved and particulate metals that accumulate in soils over time. This problem is particularly common in peri-urban regions of South and Southeast Asia where freshwater resources are limited. Studies conducted in India and Pakistan have shown that even irrigation water containing relatively low concentrations of heavy metals can cause gradual accumulation of metals in soil, leading to elevated pollution indices, particularly for cadmium (Hamoud *et al.*, 2024) [3].

2.2 Industrial Waste and Effluent Discharges

Industrial activities located near agricultural areas represent a major source of heavy metal contamination. Atmospheric deposition of metal-rich particulates and the discharge of untreated wastewater from tanneries, textile industries, chemical manufacturing units, and metal-processing facilities can substantially increase heavy metal concentrations in agricultural soils and irrigation systems (Singh *et al.*, 2025) [15].

A study conducted near the Star Paper Mill in Saharanpur, India, reported significantly higher concentrations of

cadmium and chromium in soils irrigated with industrial wastewater compared with soils receiving groundwater irrigation. Although metal concentrations decreased progressively from roots to shoots and grains, measurable quantities were still detected in wheat tissues, indicating limited but significant translocation to edible plant parts (Singh *et al.*, 2025) [15].

Similarly, research conducted in the industrial region of Pančevo, Serbia, demonstrated that the distance from industrial sources significantly influenced soil-to-wheat transfer of metals such as zinc, lead, chromium, copper, and cadmium. Differences in translocation factors among wheat genotypes further suggested that industrial emissions represent a distinct contamination pathway requiring targeted management strategies (Stefanovic *et al.*, 2023) [19].

Mining activities constitute another important source of heavy metal contamination in agricultural landscapes. Acid mine drainage (AMD) lowers soil pH and increases the mobility and bioavailability of metals including iron, manganese, arsenic, lead, and cadmium. Wheat cultivated in coal-mining regions of Punjab, Pakistan, showed elevated accumulation of several heavy metals, highlighting the influence of mining-related contamination on agricultural systems (Zainab *et al.*, 2023) [24].

Industrial wastewater generated by textile and carpet manufacturing industries often contains high concentrations of chromium, cadmium, lead, and nickel. Studies conducted in northern India have reported heavy metal concentrations in wheat grains exceeding WHO/FAO safety limits when crops were irrigated with untreated industrial effluents (Singh *et al.*, 2022) [16]. In addition to increasing metal accumulation, industrial wastewater can alter soil properties such as pH, salinity, and microbial activity, thereby influencing metal speciation and bioavailability (Soleimani *et al.*, 2023) [18].

3. Mechanisms of Heavy Metal Uptake and Translocation in Wheat

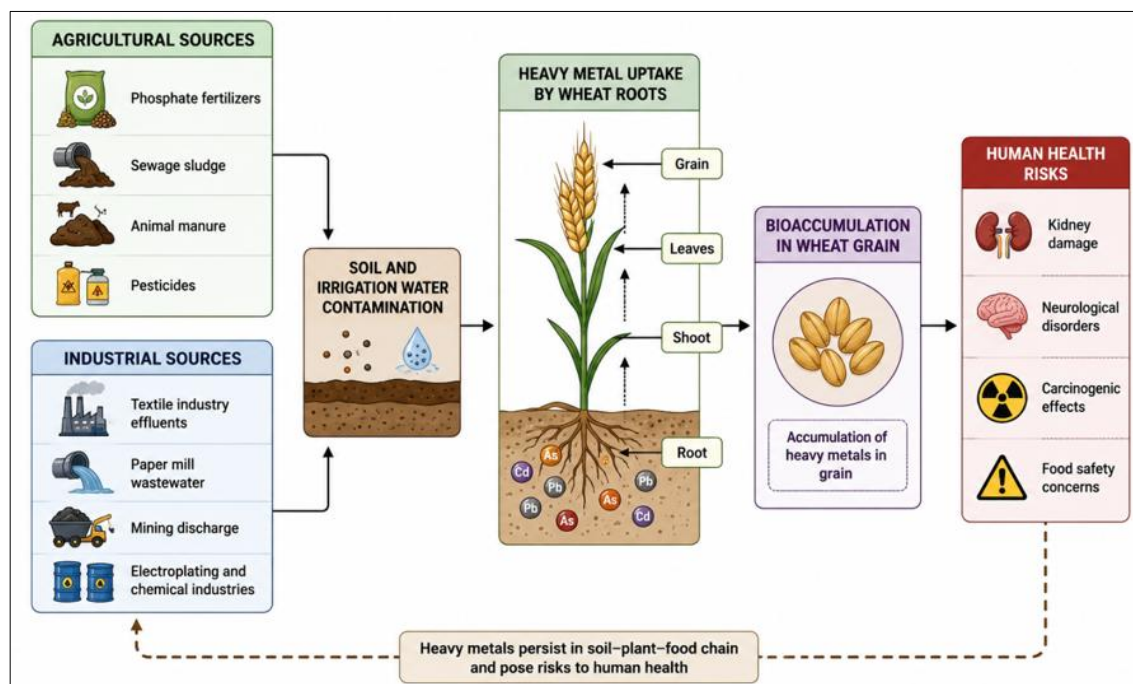
3.1 Root Uptake

Heavy metals enter wheat roots through both apoplastic and symplastic pathways. In the apoplastic pathway, dissolved metal ions move passively through cell walls and intercellular spaces along with water. In contrast, the symplastic pathway involves active transport across cell membranes through specific transporter proteins. Many of these transporters are not entirely selective and may facilitate the uptake of both essential and non-essential elements. For example, cadmium can enter root cells through zinc and iron transporters belonging to the ZIP transporter family (Tauqeer *et al.*, 2024) [20].

The availability of heavy metals for root uptake is strongly influenced by soil properties. Soil pH is one of the most important controlling factors because decreasing pH generally increases metal solubility and bioavailability. Other important factors include soil organic matter content, cation exchange capacity (CEC), soil texture, and redox conditions. Studies conducted in arid agricultural regions of Xinjiang, China, demonstrated strong relationships between metal accumulation in wheat and both soil chemical properties and irrigation water quality (Tudi *et al.*, 2021) [21]. Sandy soils with low organic matter and low CEC typically exhibit higher metal bioavailability than clay-rich soils with greater adsorption capacity. Figure 1 illustrates the major pathways of heavy metal contamination and accumulation in

wheat production systems. Agricultural activities such as the application of phosphate fertilizers, sewage sludge, animal manure, and pesticides, together with industrial sources including textile effluents, paper mill wastewater, mining discharge, and chemical industries, contribute significantly to heavy metal contamination of soil and irrigation water.

These contaminants are subsequently absorbed by wheat roots and translocated to aerial plant parts, including shoots, leaves, and grains. Accumulation of toxic metals in wheat grains may adversely affect crop growth and productivity and can ultimately pose serious human health risks through dietary exposure.



Source: Authors' compilation.

Fig 1: Mechanisms of Heavy Metal Uptake and Translocation in Wheat

3.2 Translocation and Grain Loading

Following root uptake, heavy metals are transported to aerial plant tissues through the xylem. Xylem-mediated transport facilitates the movement of metals from roots to shoots via the transpiration stream, resulting in their accumulation in leaves, stems, and reproductive organs (Kumari *et al.*, 2025) [6]. Several studies have reported higher translocation factors for the root-to-straw pathway than for the straw-to-grain pathway, indicating that a substantial proportion of absorbed metals remains in vegetative tissues.

Despite this restriction, wheat grains can accumulate considerable amounts of heavy metals under contaminated conditions. Compared with several other cereal crops, wheat exhibits relatively high grain-loading efficiency for certain toxic metals, particularly cadmium and mercury (Kumari *et al.*, 2025) [6]. A study evaluating heavy metal accumulation in soil-crop systems reported the following order of accumulation in wheat grain: $Zn < Pb < Cr < Cu < As < Cd < Hg$ (Wang *et al.*, 2017) [22]. These findings emphasize the importance of monitoring cadmium and mercury contamination in wheat-growing regions.

Metal deposition in grains occurs predominantly through phloem transport during the grain-filling stage. Metals that are relatively mobile in the phloem, such as cadmium and zinc, are more readily transferred to developing grains than less mobile elements such as lead and chromium. Furthermore, metal concentrations are generally higher in the bran fraction than in the endosperm, which has important implications for consumer exposure because whole-grain products may contain higher levels of heavy metals than refined flour.

3.3 Bio concentration Factors

The bio concentration factor (BCF) and translocation factor (TF) are widely used indicators for assessing heavy metal accumulation and movement within plants. The BCF represents the capacity of a plant to accumulate metals from soil, whereas the TF describes the efficiency of metal transport from roots to shoots.

Field studies conducted in Italy demonstrated considerable variation in BCF and TF values depending on both the metal type and plant tissue examined. These parameters were strongly influenced by soil metal concentrations, with BCF values generally declining as soil contamination increased, suggesting saturation of metal uptake mechanisms at higher contamination levels (Berrettoni *et al.*, 2023) [1].

Cadmium frequently exhibits higher BCF values than lead and chromium, particularly in contaminated soils. In some cases, wheat grains may accumulate cadmium concentrations exceeding those present in the surrounding soil ($BCF > 1$), creating significant food safety concerns. Consequently, soils that comply with regulatory standards may still produce grains containing cadmium concentrations above permissible food safety limits (Li *et al.*, 2022) [8].

4. Phytotoxic Effects of Heavy Metals on Wheat

Heavy metals adversely affect numerous physiological and biochemical processes in wheat plants. Excessive accumulation can impair seed germination, inhibit root and shoot growth, reduce photosynthetic efficiency, disrupt nutrient uptake, and ultimately decrease grain yield and quality. At the cellular level, heavy metals interfere with enzyme activity, damage cellular membranes, and stimulate the production of reactive oxygen species (ROS), resulting

in oxidative stress, lipid peroxidation, and DNA damage (Tauqeer *et al.*, 2024) ^[20]. A study investigating the effects of industrial wastewater irrigation on wheat reported significant reductions in germination percentage, seedling vigor, root length, shoot length, and chlorophyll content as wastewater concentration increased. Simultaneously, lead accumulation in root and shoot tissues increased substantially (Hussain *et al.*, 2020) ^[4]. Lead toxicity disrupts calcium-dependent physiological processes and interferes with the function of several essential enzymes, thereby limiting plant growth and development. Chromium exposure has also been shown to negatively affect wheat growth by disturbing nutrient homeostasis and inducing oxidative stress (Saud *et al.*, 2022) ^[14]. Cadmium toxicity triggers the synthesis of phytochelatins and metallothioneins, which bind and detoxify metal ions within plant cells. However, the production of these protective compounds requires considerable metabolic energy, often resulting in reduced biomass accumulation and lower grain quality. Several mitigation strategies have been evaluated to reduce heavy metal toxicity in wheat. The combined application of silicon and zinc has shown promising results in alleviating cadmium stress. Silicon strengthens root barriers, particularly the Casparian strip, and enhances cadmium immobilization within root tissues, thereby reducing its translocation to shoots and grains (Liu *et al.*, 2023) ^[11].

5. Human Health Risks Associated with Heavy Metals in Wheat

Consumption of wheat contaminated with heavy metals represents a significant pathway of human exposure. Risk assessment commonly relies on indicators such as Estimated Daily Intake (EDI), Health Risk Index (HRI), Target Hazard Quotient (THQ), and Carcinogenic Risk (CR). These indices estimate exposure levels based on grain metal concentrations, dietary intake rates, and body weight and compare them with reference values established by organizations such as WHO, USEPA, and EFSA. Studies conducted near paper manufacturing industries in India revealed cadmium and chromium concentrations in wheat grain exceeding the permissible limits established by the FAO/WHO Codex Alimentarius Commission (Singh *et*

al., 2025) ^[15]. Although calculated THQ values for individual metals remained below one, concentrations above regulatory limits indicate potential health concerns, particularly when exposure from multiple dietary sources is considered. Research from South-western Guizhou, China, demonstrated that combined exposure to cadmium, lead, arsenic, chromium, and nickel through wheat consumption could exceed acceptable carcinogenic risk levels for both adults and children (Li *et al.*, 2022) ^[8]. Children are particularly vulnerable because they consume more food relative to body weight and generally absorb toxic metals more efficiently than adults. Long-term field experiments evaluating organic fertilization practices reported significantly higher HRI and EDI values for cadmium and lead in plots amended with sewage sludge compost compared with plots receiving chicken manure compost or domestic waste compost (Li *et al.*, 2025) ^[10]. These findings highlight the importance of monitoring and regulating the quality of organic amendments used in wheat production systems. Advanced risk prediction models based on deep learning approaches have also identified heavily industrialized and intensively farmed regions as high-risk areas for wheat contamination. Among the metals evaluated, cadmium, arsenic, and mercury were identified as the most critical contributors to food safety risks (Chen *et al.*, 2023) ^[2]. Table 1 presents the major heavy metals commonly detected in wheat production systems, along with their principal sources, effects on wheat growth and development, and associated human health risks. Cadmium (Cd), lead (Pb), arsenic (As), chromium (Cr), and mercury (Hg) are among the most hazardous metals because of their persistence, toxicity, and tendency to accumulate in plant tissues and the food chain. These metals originate mainly from agricultural inputs such as phosphate fertilizers, pesticides, sewage sludge, and wastewater irrigation, as well as industrial activities including mining, textile processing, and paper manufacturing. Excessive accumulation of these metals negatively affects wheat physiology by reducing growth, photosynthesis, nutrient uptake, and grain quality, while long-term dietary exposure may pose serious health risks to humans.

Table 1: Major Heavy Metals, Sources, Toxic Effects and Health Risks in Wheat

Heavy Metal	Major Source	Effect on Wheat	Human Health Risk
Cd	Phosphate fertilizers, wastewater	Reduced growth, oxidative stress	Kidney damage, carcinogenicity
Pb	Industrial effluents	Reduced chlorophyll, enzyme inhibition	Neurological disorders
As	Mining, pesticides	Growth inhibition	Cancer risk
Cr	Textile wastewater	Oxidative damage	Liver and kidney toxicity
Hg	Industrial discharge	Reduced biomass	Nervous system toxicity

Source: Authors' compilation.

6. Factors Modulating Heavy Metal Bioavailability in Wheat Systems

The bioavailability of heavy metals in soil is influenced by a range of physical, chemical, and biological factors. Soil pH is generally considered the most important determinant because decreasing pH increases the solubility and mobility of most divalent metal ions, including cadmium, lead, nickel, copper, and zinc. Consequently, acidic soils often exhibit higher metal bioavailability and greater plant uptake. Soil organic matter (SOM) can either reduce or enhance

metal mobility depending on environmental conditions. Humic and fulvic substances can bind metal ions and decrease their availability to plants. However, under acidic conditions, dissolved organic carbon may form soluble metal complexes that increase metal mobility and plant uptake. Soil texture and cation exchange capacity (CEC) also play important roles in regulating metal availability. Clay-rich soils with high CEC generally retain greater quantities of heavy metals, whereas sandy soils with low

CEC are more susceptible to metal leaching and plant uptake.

The bioavailability of arsenic and chromium is strongly influenced by soil redox conditions. Under reducing environments, arsenic may be released from iron oxides as arsenite, a more mobile and toxic form than arsenate. Similarly, hexavalent chromium [Cr(VI)] is considerably more mobile and toxic than trivalent chromium [Cr(III)], and its occurrence depends largely on soil oxidation-reduction processes.

Plant genotype is another important determinant of heavy metal accumulation. Studies involving multiple wheat genotypes grown near industrial areas in Serbia revealed substantial variation in BCF and TF values for zinc, lead, chromium, copper, and cadmium (Stefanovic *et al.*, 2023) [19]. These findings suggest considerable potential for breeding wheat cultivars with reduced heavy metal accumulation in grains.

7. Remediation and Management Strategies

Several approaches have been developed to reduce heavy metal accumulation in wheat cultivated on contaminated soils. These strategies include soil amendments, improved irrigation management, agronomic interventions, and regulatory measures aimed at limiting the entry and mobility of heavy metals within agricultural systems.

One of the most effective and economical methods for reducing the bioavailability of cadmium and lead, particularly in acidic soils, is liming. The application of calcium-based amendments such as calcium carbonate and quicklime increases soil pH, enhances metal adsorption, and reduces metal solubility. A study conducted in Pakistan demonstrated that in situ stabilization of cadmium using calcium carbonate, combined with optimized irrigation management, significantly reduced cadmium uptake in wheat-rice cropping systems cultivated on contaminated soils (Hamoud *et al.*, 2024) [3].

Biochar has received considerable attention as a multifunctional soil amendment for heavy metal remediation. Biochar produced from agricultural residues such as rice husk ash, sugarcane bagasse ash, and wheat straw possesses a large surface area and abundant functional groups capable of immobilizing toxic metals. Furthermore, phosphate-modified biochar enhances metal precipitation and adsorption, thereby reducing the availability of cadmium, lead, and chromium in soil. Studies have consistently reported reductions in grain metal concentrations and improvements in crop productivity following biochar application (Khan *et al.*, 2024) [5].

Silicon and selenium supplementation have also shown potential in mitigating heavy metal stress. Silicon strengthens root tissues and improves the integrity of the Casparian strip, thereby restricting metal movement from roots to shoots. Selenium can reduce cadmium toxicity through the formation of less soluble Cd-Se complexes, which decrease metal mobility and plant uptake (Liu *et al.*, 2023) [11]. However, because selenium itself may become toxic at excessive concentrations, its application should be carefully managed and supported by appropriate risk assessments (Zhang *et al.*, 2024) [25].

In addition to field-based interventions, effective regulation remains essential for preventing heavy metal contamination at its source. Studies conducted in India, Pakistan, China, and Iran emphasize the importance of enforcing wastewater

treatment standards, restricting the use of untreated industrial effluents for irrigation, and ensuring quality control of fertilizers and organic amendments (Li *et al.*, 2024; Singh *et al.*, 2025) [9, 15]. Regular monitoring of heavy metal concentrations in wheat grain and agricultural soils, particularly near industrial areas, is necessary to protect food safety and public health.

8. Global Distribution and Hotspot Regions

Heavy metal contamination of wheat is a global concern, although certain regions have emerged as contamination hotspots because of intensive agricultural practices, rapid industrialization, and inadequate environmental regulation. These areas often experience elevated concentrations of heavy metals in soils, irrigation water, and agricultural produce.

South Asia represents one of the most extensively studied regions with respect to heavy metal contamination in wheat. Investigations conducted in peri-urban areas surrounding Lahore, Faisalabad, Multan, Saharanpur, and the Dhaka Export Processing Zone have frequently reported elevated concentrations of lead, cadmium, and arsenic in wheat grains, in some cases exceeding WHO/FAO permissible limits. Industrial wastewater irrigation and long-term application of contaminated agricultural inputs are considered the principal causes of contamination in these regions.

China also faces significant challenges related to heavy metal pollution of agricultural land. The Guizhou, Xinjiang, and Pearl River Delta regions have been identified as major hotspots because of intensive industrial activities and prolonged agricultural inputs. Approximately 80% of contaminated agricultural soils in certain areas contain elevated concentrations of heavy metals (Chen *et al.*, 2015, as cited by Li *et al.*, 2020). Continuous use of phosphate fertilizers has contributed to progressive cadmium accumulation in several wheat-growing regions, raising concerns regarding future food safety.

In Europe, historical industrial activities such as smelting and mining continue to influence agricultural soil quality. Countries including Serbia, Poland, and Romania have reported localized contamination associated with legacy industrial emissions. Studies conducted in Serbia demonstrated clear distance-dependent patterns of metal transfer from contaminated soils to wheat plants, highlighting the importance of establishing buffer zones around industrial facilities (Stefanovic *et al.*, 2023) [19].

In the Middle East and North Africa (MENA) region, increasing water scarcity has encouraged the use of treated and untreated wastewater for agricultural irrigation. Research from Iran showed that wastewater irrigation significantly increased concentrations of arsenic, lead, cadmium, nickel, and chromium in agricultural soils compared with conventional irrigation systems (Soleimani *et al.*, 2023) [18]. Similar challenges have been reported in several other arid and semi-arid regions where freshwater resources are limited.

9. Research Gaps and Future Directions

Despite substantial progress in understanding heavy metal dynamics in wheat production systems, several important research gaps remain.

First, many studies continue to focus primarily on total metal concentrations rather than the specific chemical

fractions that determine metal mobility and bioavailability. Sequential extraction procedures and isotopic techniques should be more widely adopted to improve understanding of metal behaviour under different soil management practices. Second, most risk assessments evaluate individual heavy metals separately, despite the fact that agricultural soils often contain complex mixtures of contaminants. Interactions among cadmium, lead, arsenic, chromium, and other metals may produce synergistic or antagonistic effects that significantly influence plant responses and human health risks. Therefore, future studies should incorporate multi-metal risk assessment frameworks that better reflect real-world exposure conditions.

Third, climate change may substantially alter heavy metal dynamics in agricultural ecosystems. Changes in temperature, precipitation patterns, soil moisture, flooding frequency, and microbial activity are likely to affect metal speciation, mobility, and plant uptake. Long-term studies integrating climate scenarios with heavy metal monitoring are needed to predict future risks and develop adaptive management strategies.

Fourth, emerging technologies such as remote sensing, geographic information systems (GIS), machine learning, and precision agriculture offer new opportunities for monitoring and managing soil contamination. These tools can facilitate the identification of contaminated areas, optimize remediation practices, and improve decision-making processes at both farm and regional scales.

Finally, breeding wheat cultivars with reduced heavy metal accumulation remains an important research priority. Advances in genomics, molecular breeding, and gene-editing technologies may help develop varieties capable of limiting metal uptake and translocation without compromising grain yield or nutritional quality.

10. Conclusion

Heavy metal contamination of wheat-growing soils has become a major environmental and food safety concern worldwide. Agricultural practices such as the use of phosphate fertilizers, sewage sludge, animal manure, and pesticides, together with industrial activities including mining, paper manufacturing, textile processing, metal smelting, and wastewater discharge, contribute significantly to the accumulation of toxic metals in agricultural ecosystems.

Wheat is particularly vulnerable to the accumulation of certain heavy metals, especially cadmium, arsenic, and mercury, because of their high mobility and potential for transfer into edible grains. Excessive metal accumulation adversely affects plant growth, physiological processes, grain quality, and overall crop productivity. More importantly, contaminated wheat represents a significant pathway of human exposure to toxic metals and may increase the risk of chronic diseases and other adverse health outcomes.

Several management practices, including liming, biochar application, silicon supplementation, improved irrigation management, and careful selection of organic amendments, have demonstrated considerable potential for reducing heavy metal bioavailability and plant uptake. Nevertheless, sustainable mitigation requires a combination of field-level interventions and effective regulatory measures aimed at controlling contamination at its source.

Future efforts should prioritize comprehensive monitoring programs, improved risk assessment methodologies, development of low-cost remediation technologies, and breeding of wheat cultivars with reduced metal accumulation. Strengthening environmental regulations, enforcing wastewater treatment standards, and promoting sustainable agricultural practices will be essential for ensuring food safety and maintaining wheat productivity in increasingly industrialized and urbanized landscapes. By integrating scientific innovation with effective policy implementation, it will be possible to minimize heavy metal contamination and safeguard both agricultural sustainability and public health.

11. Acknowledgement

The authors are thankful to the School of Agriculture, Uttaranchal University, Dehradun, Uttarakhand, for providing academic support and necessary facilities for the completion of this review work.

12. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

13. Author Contributions

S.B. conceptualized the study, collected the literature, and prepared the original manuscript draft. S.P. supervised the study and provided technical guidance and contributed to manuscript editing, language improvement, formatting, and final revision of the manuscript. All authors read and approved the final manuscript.

References

- Berrettoni M, Zamponi S, Conti P, Fattobene M, Liu F, Aborah M. Determination of heavy metals in root and shoot of durum wheat, plant soil: translocation and bioaccumulation factor. *Advanced Journal of Graduate Research*. 2023;14(1):38-50.
- Chen Y, Zhang X, Liu H, Wu F, Shi T. Prediction of food safety risk level of wheat in China based on Pyraformer neural network model for heavy metal contamination. *Food Control*. 2023;150:109728.
- Hamoud YA, Shaghaleh H, Zia-ur-Rehman M, Rizwan M, Umair M, Usman M, *et al.* Cadmium and lead accumulation in important food crops due to wastewater irrigation: pollution index and health risks assessment. *Heliyon*. 2024;10(3):e24712.
- Hussain S, Ahmad M, Khan ZH, Raza ST, Saddique M, Raza A, *et al.* Effect of industrial wastewater on wheat germination, growth, yield, nutrients and bioaccumulation of lead. *PLoS ONE*. 2020;15(6):e0235016.
- Khan A, Ali B, Azam M, Maqsood MA, Ashraf MY, Khalid R, *et al.* Heavy metal accumulation, yield and health risk assessment of wheat crop grown in contaminated soil amended with bioash for sustainable agriculture. *Food Chemistry*. 2024;465:142054.
- Kumari P, Rao A, Sharma V, Singh P. Heavy metal contamination and its impact on the food chain: exposure, bioaccumulation, and risk assessment. *International Journal of Food Science & Technology*. 2025;50(1):1-12.
- Li D, Liu H, Gao M, Zhou J, Zhou J. Effects of soil amendments, foliar sprayings of silicon and selenium

- and their combinations on the reduction of cadmium accumulation in rice. *Pedosphere*. 2022;32(4):649-659.
8. Li D, Zhang C, Li X, Li F, Liao S, Zhao Y, *et al.* Co-exposure of potentially toxic elements in wheat grains reveals a probabilistic health risk in Southwestern Guizhou, China. *Frontiers in Nutrition*. 2022;9:934919.
 9. Li W, He Z, Xu Q, Li M, Wang Y, Yang X, *et al.* Heavy metals in agricultural soils: sources, influencing factors, and remediation strategies. *Agronomy*. 2024;14(1):193.
 10. Li Y, Gao L, Zheng R, Wang Y, Chen H, Zhang M, *et al.* Heavy metal(loid)s accumulation and human health risk assessment in wheat after long-term application of various urban and rural organic fertilizers. *Science of the Total Environment*. 2025;967:178590.
 11. Liu Y, Feng X, Zhong Y, Zhang H, Li X, Zhao H. Interactive effect of silicon and zinc on cadmium toxicity alleviation in wheat plants. *Journal of Hazardous Materials*. 2023;458:131933.
 12. Manzoor MZ, Sarwar G, Ibrahim M, Luqman M, Gul S, Shehzad I. Heavy metals toxicity assessment in different textured soils having wastewater irrigation. *SABRAO Journal of Breeding and Genetics*. 2024;56(2):488-501.
 13. Rahman Z, Singh VP. The relative impact of toxic heavy metals (THMs) (arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. *Environmental Monitoring and Assessment*. 2019;191(7):419.
 14. Saud S, Wang D, Fahad S, Javed T, Jaremko M, Abdelsalam NR, *et al.* The impact of chromium ion stress on plant growth, developmental physiology, and molecular regulation. *Frontiers in Plant Science*. 2022;13:994785.
 15. Singh P, Chauhan N, Tiwari KN, Gupta A, Rani R. Risk assessment of potentially toxic heavy metals in wheat (*Triticum aestivum* L.) grown in soils irrigated with paper mill effluent. *PLoS ONE*. 2025;20(6):e0324991.
 16. Singh PK, Yadav JS, Kumar I, Kumar U, Sharma RK. Carpet industry irrigational sources risk assessment: heavy metal contaminated vegetables and cereal crops in northern India. *Toxicology Reports*. 2022;9:1906-1919.
 17. Singh R, Kumar A, Mishra P, Sharma N, Gupta P, Jaiswal S. Heavy metal accumulation in agricultural soils: environmental risk assessment and remediation strategies. *International Journal of Environmental Sciences*. 2025;11(19):1-15.
 18. Soleimani H, Mansouri B, Mehrpour O, Ranaei A. Ecological risk assessment and heavy metals accumulation in agriculture soils irrigated with treated wastewater effluent, river water, and well water combined with chemical fertilizers. *Heliyon*. 2023;9(3):e14580.
 19. Stefanovic VM, Roljević Nikolić S, Matković Stojšin M, Majstorović H, Petreš M, Cvikić D, *et al.* Soil-to-wheat transfer of heavy metals depending on the distance from the industrial zone. *Journal of Agricultural Sciences*. 2023;68(2):145-158.
 20. Tauqeer HM, Ahmad S, Ali MA, Gardezi SSA, Siddiqui MH, Abbas Z. Heavy metals toxicity in plants: understanding mechanisms and developing coping strategies for remediation: a review. *Environmental Science and Pollution Research*. 2024;31(36):54000-54035.
 21. Tudi M, Ruan HD, Yu Y, Wang L, Wei B, Tong S, *et al.* Bioaccumulation and translocation of trace elements in soil-irrigation water-wheat in arid agricultural areas of Xinjiang, China. *Ecotoxicology*. 2021;30(7):1290-1302.
 22. Wang S, Wu W, Liu F, Liao R, Hu Y. Accumulation of heavy metals in soil-crop systems: a review for wheat and corn. *Environmental Monitoring and Assessment*. 2017;189(5):1-14.
 23. Yu X, Wang X, Sun M, Liu H, Liu D, Dai J. Cadmium immobilization in soil using phosphate-modified biochar derived from wheat straw. *Science of the Total Environment*. 2024;926:171614.
 24. Zainab N, Mehmood S, Amna, Shafiq-Ur-Rehman, Munir A, Tanveer ZI, *et al.* Health risk assessment and bioaccumulation of potentially toxic metals from water, soil, and forages near coal mines of district Chakwal, Punjab, Pakistan. *Environmental Geochemistry and Health*. 2023;45(7):5441-5466.
 25. Zhang Y, Fang L, Zhang Z, Chen S. Risk assessment of selenium-enriched agricultural products in relation to heavy metal contamination: a whole agri-food-chain perspective. *Comprehensive Reviews in Food Science and Food Safety*. 2024;23(1):e13298.