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Pesticide Residues and Heavy Metals in Food: Sources, Occurrence, Health Risks, and Mitigation Strategies

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Abstract
Pesticide residues and heavy metals are among the major chemical contaminants affecting food quality and safety. Their presence in food has received increasing attention because these substances can persist in the environment, enter the food chain, and remain in edible plant and animal tissues. Pesticide residues mainly result from excessive or improper pesticide application, post-harvest treatments, and inadequate withdrawal periods. In contrast, heavy metals such as lead, cadmium, mercury, and arsenic may reach food through contaminated soil and irrigation water, industrial emissions, atmospheric deposition, and polluted processing environments.
These contaminants have been reported in a wide range of food commodities, including cereals, vegetables, fruits, fish, meat, milk, and processed foods, with concentrations influenced by production practices, environmental conditions, storage, and processing methods. Regular consumption of contaminated food may increase human exposure and, depending on the contaminant, dose, and duration of exposure, may contribute to oxidative stress, neurological effects, kidney and liver damage, endocrine disturbances, developmental problems, and other chronic health concerns.
This review examines the major sources and pathways of pesticide residues and heavy metals in the food chain, their occurrence in different food commodities, and their potential effects on human health. It also outlines commonly used analytical approaches, including chromatographic, spectrometric, and rapid screening methods, for their detection and monitoring. Finally, the review discusses practical mitigation measures, including responsible pesticide use, integrated pest management, soil and water management, bioremediation, improved processing practices, routine monitoring, and effective regulatory control. Strengthening these measures is essential for reducing dietary exposure and promoting safer and more sustainable food systems

Keywords:-Pesticideresidue, Heavy metals, Food processing, Bioaccumulation, Toxicity, Human health.

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Introduction

Food safety is an important public health issue because contamination can occur at almost any stage of the food chain, from cultivation and harvesting to processing, storage, transportation, and consumption. Chemical contaminants are especially concerning because they are often not visible and may not change the taste, colour, or smell of food. Among them, pesticide residues and heavy metals are widely recognized as important food-safety concerns because they can enter food through agricultural practices, environmental pollution, and contaminated production systems.
Pesticides play an important role in agriculture by controlling insects, weeds, fungi, and other pests

that affect crop production. However, excessive or improper application can result in residues remaining on crops and other agricultural products. Residue levels are influenced by the type and amount of pesticide applied, environmental conditions, crop characteristics, and the time between application and harvest. For this reason, food-safety authorities establish maximum residue limits (MRLs) based on toxicological information and estimated dietary exposure[1].

Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) present a different but equally serious concern. They may originate from natural geological sources as well as mining, industrial activities, contaminated soil and irrigation water, wastewater, fertilizers, and atmospheric deposition. Plants can absorb metals from soil and water, while fish and other animals may accumulate them through contaminated water, sediments, or feed. Unlike many organic pollutants, metals do not readily degrade, allowing them to persist and accumulate in the environment and food chain.

The health effects of these contaminants depend on their concentration, chemical form, exposure duration, and individual susceptibility. Long-term dietary exposure may affect the nervous system, kidneys, liver, endocrine system, and other biological functions. This chapter reviews the sources, occurrence, and pathways of pesticide residues and heavy metals in food, their potential health risks, methods of detection and risk assessment, and practical strategies for reducing contamination[2]. Emerging technologies for improved monitoring and food-safety management are also discussed.

2. Pesticide Residues in Food

2.1 Major Classes of Agricultural Pesticides

Pesticides are used to protect crops from insects, weeds, fungi, nematodes, rodents, and other pests. Major groups include insecticides, herbicides, fungicides, acaricides, nematicides, and rodenticides. They can also be classified according to their chemical structure, such as organophosphates, carbamates, pyrethroids, neonicotinoids, and triazoles. These groups differ in their toxicity, persistence, mobility, and behaviour in soil, water, plants, and food. Therefore, pesticide safety depends not only on residue concentration but also on the chemical properties and exposure pathway.

2.2 Sources and Pathways of Pesticide Contamination

Agricultural application is the main source of pesticide residues in food. Residues may remain on crop surfaces or enter plant tissues. Contamination can also occur through polluted soil and irrigation water, atmospheric deposition, post-harvest treatments, storage facilities, and food-processing environments[3]. Livestock may be exposed through contaminated feed and water, while fish and other aquatic organisms can accumulate pesticides entering water bodies through agricultural runoff.

2.3 Factors Affecting Pesticide Residue Persistence

The persistence of pesticide residues is influenced by chemical structure, solubility, volatility, temperature, sunlight, rainfall, soil pH, organic matter, and microbial activity. Crop characteristics and application methods also affect residue levels. The time between the last application and harvest is particularly important. Failure to follow the recommended pre-harvest interval can increase residues in harvested food. Processing methods such as washing, peeling, cooking, and drying may reduce some residues, although their effectiveness varies with the pesticide and processing conditions.

2.4 Occurrence in Different Food Products

Pesticide residues have been detected in fruits, vegetables, cereals, pulses, fish, meat, milk, and other food products. Fruits and vegetables may show greater exposure because of intensive cultivation and repeated pesticide applications.

Cereals and pulses can acquire residues during cultivation or storage, while animal products may become contaminated through feed, water, or environmental exposure. Fish may accumulate pesticides from contaminated water and sediments. Residue levels vary with commodity, season, production practices, and geographical conditions, making regular monitoring across different food groups essential[4].

2.5 Bioaccumulation and Transfer Through the Food Chain

Persistent pesticides and their transformation products can remain in environmental compartments and become available to living organisms. Some compounds may accumulate in tissues and move through food webs, although the extent of bioaccumulation differs among chemicals and species. This transfer creates an important link between environmental contamination and human dietary exposure. Monitoring pesticide residues in food should therefore be supported by environmental monitoring, particularly in areas where pesticides are used intensively.

3. Heavy Metals in Food

3.1 Major Food-Associated Heavy Metals: Lead, Cadmium, Mercury, and Arsenic

Lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are among the major toxic elements of concern in food safety. Each has different sources, environmental behaviour, and effects on human health. Lead may enter food through contaminated soil and water, industrial emissions, dust, and some processing or packaging materials. Cadmium is commonly associated with contaminated agricultural soils, phosphate fertilizers, industrial activities, and wastewater and can be readily absorbed by certain crops. Mercury is especially important in aquatic foods because methylmercury can accumulate in fish and other aquatic organisms. Arsenic occurs naturally in some soils and groundwater but may also increase due to mining, industrial activities, and agricultural practices.

3.2 Natural and Anthropogenic Sources

Heavy metals may originate from natural processes such as weathering of rocks, volcanic activity, and mineral deposits. Human activities, however, can substantially increase their concentrations in the environment[5]. Mining, metal processing, industrial emissions, wastewater discharge, traffic, fertilizers, pesticides, and poorly managed wastes are important sources. Irrigation with contaminated or untreated wastewater can also introduce metals into agricultural soils. Repeated contamination may gradually increase metal levels in soil and increase their availability to crops.

3.3 Contamination Through Soil, Water, Air, and Food Processing

The soil–water–plant pathway is an important route by which heavy metals enter the food chain. Metals present in soil or irrigation water can be taken up by plant roots and transferred to edible parts such as leaves, grains, fruits, and roots. Their uptake depends on soil pH, organic matter, metal availability, plant species, and environmental conditions. Atmospheric particles can also settle on crops and agricultural land. During food processing, contamination may occur through water, equipment, packaging materials, or contaminated raw ingredients.

3.4 Occurrence in Plant- and Animal-Derived Foods

Heavy metals have been reported in cereals, vegetables, fruits, pulses, milk, meat, fish, and other food products. Some crops are more efficient at accumulating particular metals. Rice, for example, is an important food considered in relation to arsenic exposure, while fish and seafood can contribute substantially to dietary mercury exposure. Metal concentrations vary among regions according to soil properties, water quality, industrial activities, farming practices, and dietary habits[6].

3.5 Uptake, Accumulation, and Food-Chain Transfer

Plants mainly absorb metals through their roots, although deposition on leaves can also contribute to contamination. The amount accumulated depends on plant species, cultivar, soil characteristics, metal concentration, and environmental conditions. In aquatic ecosystems, metals may enter microorganisms and invertebrates and subsequently accumulate in fish. These processes allow contaminants to move through food webs and contribute to human dietary exposure.

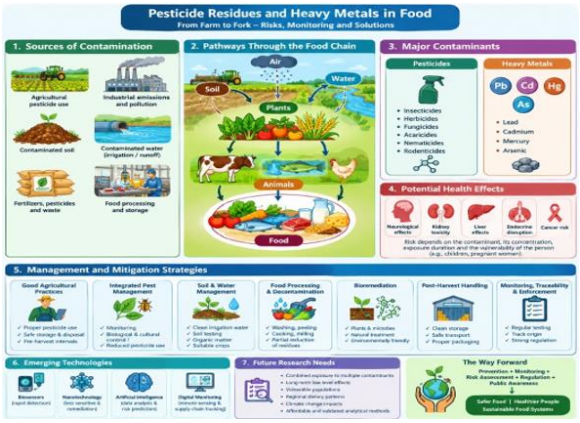
4. Human Exposure and Health Risks

4.1 Dietary Exposure and Major Exposure Pathways

Food is one of the main routes through which people are exposed to pesticide residues and toxic metals. The level of exposure depends on contaminant concentration, amount and frequency of food consumed, and body weight. Drinking water and environmental contact may provide additional exposure. People who regularly consume contaminated foods may therefore receive repeated low-level exposure. Children can be more vulnerable because of their lower body weight and developing organ[7]. Exposure assessment should consequently consider age, dietary habits, and consumption patterns rather than relying only on average population values.

4.2 Acute and Chronic Toxicity

Acute toxicity results from relatively high exposure over a short period, whereas chronic toxicity develops through repeated or long-term exposure. High pesticide exposure can cause acute poisoning, depending on the chemical and dose. Long-term exposure to certain pesticides has also been associated with possible neurological, reproductive, endocrine, and other health effects. Heavy metals are of particular concern because some can persist in the body and accumulate over time. Their effects depend on the specific metal, chemical form, dose, and duration of exposure.



4.3 Oxidative Stress and Cellular Damage

Oxidative stress is an important mechanism involved in the toxicity of several pesticides and heavy metals. These contaminants may disturb the normal balance between reactive oxygen species and antioxidant defences. Excess reactive oxygen species can damage lipids, proteins, DNA, and cell membranes. Changes in antioxidant enzymes, including superoxide dismutase, catalase, and glutathione-related enzymes, may indicate cellular stress.

4.4 Neurological, Renal, Hepatic, and Endocrine Effects

The effects of contaminants vary according to their chemical properties and target organs. Lead and mercury are particularly associated with neurological effects, while cadmium is an important cause of kidney toxicity[8]. Prolonged exposure to some contaminants may also affect liver function and endocrine regulation. However, detecting a contaminant in food does not necessarily mean that harmful effects will occur. Actual risk depends on the amount and duration of exposure, making both hazard and exposure important in risk assessment.

4.5 Reproductive and Developmental Toxicity

Pregnant women, infants, and children may be more sensitive to certain chemical contaminants. Exposure during pregnancy or early childhood can interfere with normal growth and

development for some toxicants. Food-safety programmes therefore give particular attention to foods consumed frequently by these vulnerable groups.

4.6 Carcinogenic and Genotoxic Potential

Some pesticides and heavy metals have been studied for carcinogenic or genotoxic effects. These may involve DNA damage, chromosomal alterations, or disruption of cellular repair processes. However, hazard and risk are different concepts. A chemical may possess a hazardous property, while the actual health risk depends on exposure level and duration. Food-safety assessments therefore combine toxicological evidence with dietary exposure estimates.

4.7 Combined Effects of Multiple Chemical Contaminants

People are often exposed to mixtures rather than a single contaminant. Food may contain several pesticide residues along with toxic metals, making health effects more difficult to predict. Chemicals may act through similar or different biological pathways, and their combined effects may not always be additive. Future risk assessment should therefore consider cumulative exposure using reliable toxicological and dietary data.

5. Detection and Analytical Approaches

5.1 Sample Collection and Preparation

Accurate contaminant analysis begins with representative sampling and careful handling to prevent contamination or residue loss. Sample preparation may involve homogenization, extraction, filtration, cleanup, concentration, and dilution. **QuEChERS (Quick, Easy, Cheap, Effective, Rugged, and Safe)** is widely used for pesticide analysis because it provides rapid extraction and cleanup of residues from complex food matrices. Proper preparation also minimizes interference from fats, proteins, pigments, and sugars

5.2 Chromatographic Techniques

Chromatographic methods are widely used for detecting pesticide residues. Gas chromatography (GC) is suitable for compounds that are volatile and thermally stable, whereas liquid chromatography (LC) is preferred for less volatile or heat-sensitive pesticides[9]. High-performance liquid chromatography (HPLC) and GC remain important laboratory techniques, while their combination with mass spectrometry has improved the sensitivity and reliability of multi-residue analysis.

5.3 Mass Spectrometry-Based Methods

LC-MS/MS and GC-MS/MS are widely used for sensitive and selective pesticide determination. These techniques can identify and quantify multiple compounds in a single analysis and are particularly useful when residues occur at very low concentrations. High-resolution mass spectrometry also supports suspect and non-target screening, allowing laboratories to investigate compounds beyond a fixed target list.

5.4 Atomic Absorption and ICP-Based Techniques

Heavy metals are commonly determined using atomic absorption spectroscopy (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS). ICP-MS provides high sensitivity and allows several elements to be measured simultaneously at low concentrations.Method selection depends on the sample type, detection limit, number of elements, and available laboratory facilities.

5.5 Immunoassays and Rapid Screening Methods

Rapid screening methods can help analyse large numbers of samples in less time. Immunoassays use specific antibodies or recognition molecules to detect selected contaminants. They are useful for preliminary screening, although positive results generally require confirmation by validated instrumental methods.

5.6 Emerging Biosensors and Nanotechnology-Based Detection

Biosensors and nanotechnology-based methods are being developed for faster and more portable contaminant detection. Materials such as graphene, carbon nanotubes, metal nanoparticles, and metal-organic frameworks can improve sensor sensitivity and signal response. These technologies show potential for on-site monitoring, but issues such as matrix interference, stability, reproducibility, validation, and regulatory acceptance still need to be addressed before wider routine use.

6. Risk Assessment and Food Safety Standards

6.1 Hazard Identification and Exposure Assessment

Food-safety risk assessment begins by identifying the harmful properties of a contaminant and then estimating the level to which people are exposed. For food contaminants, exposure is commonly assessed using residue concentration, amount of food consumed, body weight, frequency of consumption, and exposure duration. This approach helps distinguish between the simple detection of a contaminant and exposure levels that may pose a health concern.

6.2 Acceptable Daily Intake and Reference Dose

The acceptable daily intake (ADI) is commonly used for pesticides to indicate the estimated amount that can be consumed daily over a lifetime without appreciable health risk, based on available toxicological evidence. When short-term exposure is important, an acute reference dose (ARfD) may also be established.

6.3 Maximum Residue Limits and Maximum Permissible Levels

Maximum residue limits (MRLs) specify the highest permitted concentration of a pesticide residue in or on a food or feed commodity when the pesticide is used according to approved agricultural practices[10]. International MRLs are established through the Codex Alimentarius system for many pesticide–commodity combinations. For heavy metals, maximum or permissible levels are set for specific contaminants and food categories under applicable national or international standards.

6.4 Dietary Risk Assessment

Dietary risk assessment compares estimated contaminant intake with relevant health-based guidance values. Measures such as estimated daily or weekly intake, hazard quotient, and hazard index may be used. Assessment should also consider children and other vulnerable groups, as well as foods that contribute substantially to overall exposure. Frequent consumption of a moderately contaminated food may contribute more to long-term exposure than occasional consumption of a highly contaminated product.

6.5 National and International Regulatory Frameworks

Food safety depends on coordinated efforts involving international organizations, national authorities, laboratories, farmers, processors, and food businesses. The Codex Alimentarius Commission provides internationally recognized standards, while individual countries establish and enforce their own requirements. Continuous monitoring is important because pesticide use, environmental contamination, analytical methods, and dietary patterns change over time.

7. Mitigation and Management Strategies

7.1 Good Agricultural Practices

Contamination can often be reduced at the farm level through good agricultural practices. Farmers should use only approved pesticides, follow recommended doses and pre-harvest intervals, properly calibrate spraying equipment, and avoid unnecessary applications. Safe storage, handling, and disposal of pesticides are also necessary to prevent contamination of crops, soil, and water.

7.2 Integrated Pest Management

Integrated Pest Management (IPM) combines pest monitoring with cultural practices, resistant varieties, biological control, mechanical methods, and selective pesticide use when required. By relying on several control measures rather than routine spraying, IPM can reduce pesticide use and help lower residue levels.

7.3 Soil and Water Management

For heavy metals, preventing contamination at its source is generally more effective than trying to remove metals from food after harvest[11]. Regular testing of agricultural soil and irrigation water can identify contaminated areas. Using clean irrigation water, maintaining suitable soil conditions, managing organic matter, and selecting appropriate crops can help reduce metal availability and uptake.

7.4 Reducing Heavy Metal Uptake by Crops

Crop uptake of heavy metals can be reduced through suitable soil amendments, biochar, organic materials, and other immobilizing agents. Selecting crop varieties that accumulate lower amounts of metals is another useful approach. Phytoremediation may also help manage contaminated soils.

7.5 Food Processing and Decontamination

Simple processing steps such as washing, peeling, trimming, blanching, cooking, and milling can reduce some pesticide residues, although their effectiveness varies with the pesticide and food type. Processing may also reduce or redistribute certain metals, but it cannot be relied upon to remove them completely.

7.6 Bioremediation and Biological Approaches

Plants, microorganisms, fungi, algae, and other biological materials have potential for managing contaminated environments. Phytoremediation can remove or immobilize metals in polluted soils, while selected microorganisms can degrade some pesticide compounds[12].

7.7 Post-Harvest Handling and Storage

Proper post-harvest management prevents additional contamination and helps maintain food quality. Storage areas should be clean and dry, and treated commodities should be kept separate from untreated products.

7.8 Monitoring, Traceability, and Regulatory Enforcement

Regular testing helps identify contamination trends, high-risk foods, and problem areas. Traceability systems can help track contaminated products back to their source and support timely corrective action. Effective food-safety standards also require reliable laboratories, trained personnel, accurate reporting, and proper enforcement.

8. Emerging Technologies and Future Perspectives

8.1 Artificial Intelligence and Digital Food Safety Monitoring

Artificial intelligence (AI) is becoming useful in food-safety monitoring because it can analyse large amounts of data collected from farms, laboratories, sensors, processing units, and supply chains[13]. Machine-learning models can help identify contamination patterns, recognize high-risk conditions, and support decisions about where laboratory testing is most needed.

8.2 Biosensors and Smart Detection Systems

Portable biosensors offer the possibility of rapid contaminant screening at farms, markets, storage facilities, and processing sites. When linked with smartphones or digital platforms, they can provide quick results and facilitate data recording. Before routine use, these systems require proper validation, reproducibility, sensitivity, and reliable performance in complex food matrices.

8.3 Nanotechnology-Based Detection and Remediation

Nanotechnology is being explored for both contaminant detection and environmental treatment. Nanomaterials can improve sensor sensitivity and may be applied in adsorption, filtration, and catalytic treatment systems. Although early studies show considerable

potential, wider application will depend on addressing issues such as cost, stability, environmental safety, large-scale production, and regulatory approval.

8.4 Sustainable Approaches to Contamination Control

Future food-safety programmes should place greater emphasis on preventing contamination at its source. Integrated pest management, responsible pesticide use, clean irrigation water, soil-health management, efficient fertilizer use, safer alternatives, and proper waste disposal can reduce contamination before it enters the food chain. A farm-to-fork approach is particularly important for heavy metals because contamination may begin in soil or water long before food reaches consumers.

8.5 Research Gaps and Future Directions

Important research gaps remain in understanding combined exposure to pesticides and heavy metals and the effects of long-term, low-level exposure. Affordable and reliable analytical methods are also needed, particularly where laboratory facilities are limited. Future work should strengthen rapid detection, AI-based monitoring, biosensors, nanotechnology, and non-target screening through standardized validation[14]. Greater attention is also needed for vulnerable populations, regional diets, climate-related changes, and differences in farming practices. Combining prevention, monitoring, risk assessment, regulation, and public awareness will be essential for safer food systems.

Conclusion

Pesticide residues and heavy metals continue to be important challenges for food safety and public health. These contaminants can enter the food chain through pesticide application, contaminated soil and water, industrial activities, environmental pollution, and food-processing practices. Their detection in a wide range of foods, including cereals, vegetables, fruits, fish, meat, and dairy products, shows the need for regular monitoring across the entire food chain. The health concern depends not only on the presence of a contaminant but also on its concentration, chemical form, frequency of exposure, and the characteristics of the exposed population.

Reducing contamination should begin at the source. Good agricultural practices, appropriate pesticide use, integrated pest management, clean irrigation water, proper soil management, and safe post-harvest handling can reduce the entry of contaminants into food. Reliable analytical methods and routine surveillance are also necessary to identify contamination early and support effective food-safety decisions.

New technologies, including biosensors, nanomaterials, artificial intelligence, and digital monitoring systems, offer promising tools for rapid detection and improved surveillance. However, their wider application requires proper validation, reproducibility, and comparison with established analytical methods. Future research should focus more on combined exposure to pesticides and heavy metals, long-term low-level exposure, vulnerable populations, and environmental changes that may influence contaminant behaviour**.**

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