Exploration of Foods and Foodomics

Open Access Review

Persistence, toxicity, and risk assessment of toxic compounds in food: implications for food safety and public health

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Academic Editor: Gloria Sanchez Moragas, Spanish National Research Council (CSIC), Spain
Received: June 4, 2025 **Accepted:** July 24, 2025 **Published:** August 22, 2025

Cite this article: Khatri A, Kumar K, Meena R, Thakur IS. Persistence, toxicity, and risk assessment of toxic compounds in food: implications for food safety and public health. Explor Foods Foodomics. 2025;3:101097. https://doi.org/10.37349/eff.2025.101097

Abstract

The contamination of food by toxic chemical compounds is a significant global concern that threatens food safety and public health. These compounds originate from diverse sources, including naturally occurring toxins such as mycotoxins and plant alkaloids, environmental pollutants including heavy metals and persistent organic pollutants, substances formed during food processing and packaging such as acrylamide and bisphenol A, and newly emerging contaminants such as microplastics and nanoplastics. This review presents a comprehensive classification of toxic compounds in the food system, detailing their sources, persistence, and behavior within the environment. The objective of this study is to explore the toxicity, toxicokinetics, and toxicodynamics of foodborne contaminants by examining their absorption, distribution, metabolism, excretion, and mechanisms of biotransformation. The review also discusses how these toxicants interact with cellular and molecular targets, leading to adverse effects on various organs and biological systems. Furthermore, the manuscript highlights both conventional detection methods such as immunoassays, chromatographic and spectroscopic techniques, biochemical and microbiological assay, and recent innovations, including nanotechnology-based biosensors and computational tools driven by artificial intelligence. A novel contribution of this review is the inclusion of standardized chemical identifiers such as systematic names by the International Union of Pure and Applied Chemistry, the International Chemical Identifier, the Simplified Molecular Input Line Entry Specification, and the Chemical Abstracts Service Registry Number used in food-risk component databases. Additionally, the application of the One Health approach offers an integrated perspective on human, animal, and environmental health. This review identifies research gaps and promotes enhanced monitoring, regulation, and management strategies to ensure sustainable food safety.

Keywords

Chemical identifiers, emerging contaminants, food safety, One Health approach, toxicokinetics

Introduction

Food safety stands as a fundamental pillar in the architecture of public health. It plays a crucial role not only in preventing illness but also in promoting overall well-being and social stability. Every individual depends on food as a primary source of nourishment, and the expectation is that what is consumed supports health rather than undermines it [1]. Unfortunately, there may be serious and significant consequences when food safety is flouted. Each year, millions of people are impacted by contaminated food, which is a major source of sickness globally. These health conditions can vary from minor gastrointestinal distress and diarrhoea to serious disorders, including chronic illnesses and organ failure [2].

Food-risk components present serious threats on a global scale, creating substantial obstacles for international trade, compromising public health, and weakening the resilience of modern food systems. These hazardous elements are introduced into the food supply through a variety of pathways and can be broadly categorized into two main groups: anthropogenic chemicals and naturally occurring biogenic toxins. Anthropogenic chemical contaminants include pesticide residues, environmental pollutants originating from industrial and agricultural activities, illegal or unapproved food additives, and residues of pharmaceuticals administered to livestock [3].

Biogenic toxins, on the other hand, arise naturally within certain food matrices under specific environmental or storage conditions. According to the latest assessment by the World Health Organization published in the year two thousand and twenty-three, the consumption of food contaminated with these toxic substances results in illness in one out of every ten individuals globally and leads to approximately four hundred and twenty thousand fatalities each year. The ongoing industrial expansion and the accompanying environmental pollution have significantly exacerbated the accumulation of anthropogenic contaminants in the agricultural landscape. Industrial processes such as metal ore mining, smelting, and the release of untreated effluents from manufacturing units contribute extensively to the contamination of soil, groundwater, and surface water [4].

One of the most prominent sources of concern is the persistence of pesticide residues on consumable agricultural commodities, particularly fruits, vegetables, and cereal grains. These chemical substances are frequently applied in conventional agriculture to protect crops from various pathogens, insects, and weeds, thereby enhancing agricultural productivity and ensuring food availability. However, residues of these compounds often remain on the edible surfaces or within the tissues of food products even after standard washing, peeling, or cooking procedures. Scientific studies have consistently demonstrated that chronic ingestion of food containing pesticide residues can lead to a wide range of toxicological outcomes in humans, including endocrine disruption, neurodevelopmental impairment, immunosuppression, and an elevated risk of developing malignant tumors. The effects are especially pronounced in vulnerable populations such as newborns, toddlers, pregnant individuals, geriatric persons, and individuals with compromised immune function, all of whom exhibit reduced physiological capacity to detoxify and excrete these harmful compounds parallel to the pesticide issue is the contamination of the food supply with toxic heavy metals such as lead, cadmium, mercury, and arsenic [5].

These metals are released into the environment through anthropogenic activities, including mining, fossil fuel combustion, discharge of industrial wastewaters, and the use of untreated or inadequately treated water for irrigation. Once these toxic metals enter the soil or aquatic systems, they tend to accumulate and persist due to their non-biodegradable nature. Plants cultivated in contaminated soils readily absorb these metals through their root systems, and animals feeding on such plants or drinking polluted water also accumulate these substances in their tissues. Consumption of these contaminated plant or animal-based food products introduces toxic heavy metals into the human body, where they can accumulate in vital organs such as the brain, liver, kidneys, and bones. Unlike many organic pollutants, heavy metals are not readily excreted and may cause irreversible physiological damage over prolonged exposure. Children and pregnant individuals are particularly susceptible, as exposure during critical developmental windows can result in cognitive deficits, motor dysfunction, and adverse pregnancy outcomes [6].

Moreover, the improper and excessive use of pharmacological agents in food-producing animals intended to prevent infections or promote growth has led to the presence of veterinary drug residues in products such as meat, milk, and eggs. Persistent exposure to these pharmaceutical residues can contribute to the emergence of antimicrobial-resistant pathogens, hepatotoxicity, nephrotoxicity, and even carcinogenesis in human consumers. Young children, due to their underdeveloped detoxification systems, may experience profound developmental and metabolic disturbances when exposed to such residues [7]. The summary of key toxic compounds in food and their health risks is shown in Table 1.

Table 1. Summary of key toxic compounds in food and their health risks

Toxic Compound	Common Sources	Associated Health Risks	Refrences
Mycotoxins	Mold contaminated grains, nuts	Liver damage, immune suppression, increased cancer risk	[8]
Pesticides	Residues on fruits and vegetables	Hormone disruption, neurotoxicity, cancer	[9]
Heavy Metals (Lead, Arsenic, Cadmium)	Contaminated water, soil, seafood	Neurological damage, kidney failure, developmental issues	[10]
Phthalates	Food packaging, processing materials	Hormonal imbalances, reproductive toxicity	[11]
Bisphenol A (BPA)	Plastic packaging, canned foods	Endocrine disruption, reproductive problems	[12]
Acrylamide	Fried, baked, and roasted starchy foods	Potential carcinogen, nervous system effects	[13]
Microplastics	Contaminated seafood and water	Unknown long-term effects, potential inflammation	[8]
Dioxins and PCBs	Environmental contaminants, fatty fish	Immune system suppression, developmental and reproductive toxicity	[3]
Advanced Glycation End-products (AGEs)	Processed and cooked foods	Increased oxidative stress, inflammation, chronic disease risk	[6]
Polycyclic Aromatic Hydrocarbons (PAHs)	Grilled and smoked meats, environmental pollution	Carcinogenic, respiratory problems	[6]

Mycotoxins are another big category of foodborne toxins. They are naturally occurring toxins produced by fungi like *Aspergillus* and *Fusarium* during the preservation and transport of crops. Mycotoxin contamination is prevalent in staple foods like maize, peanuts, and cereals, particularly in warm and humid climates where fungal growth thrives. These toxins have been linked to severe health outcomes, including liver cancer, immunosuppression, and stunted growth in children [14].

In addition to the well-characterized food-risk components that have been extensively documented in scientific literature and incorporated into regulatory frameworks and food safety databases, a growing body of evidence has highlighted the presence of emerging and previously overlooked toxic compounds in food systems. These lesser-known contaminants have come to light through advancements in high-throughput analytical platforms and multi-omics technologies, including genomics, transcriptomics, proteomics, and metabolomics. Among these emerging compounds, masked mycotoxins represent a particularly concerning group. These toxic derivatives are formed through enzymatic conjugation or chemical transformation of native mycotoxins during food processing, storage, or even plant metabolism. Due to their altered molecular structures, masked mycotoxins frequently escape detection in conventional analytical methods, leading to an underestimation of actual exposure levels in dietary risk assessments. Despite their structural modifications, these masked toxins often exhibit higher gastrointestinal absorption and bioavailability compared to their parent compounds. Moreover, under the influence of gut microbiota, they may undergo biotransformation into more toxic forms, exacerbating their potential health impacts [15].

Effective management of these emerging and persistent contaminants demands an integrated understanding of their origin, environmental fate, metabolic pathways, toxicokinetics, and mechanisms of action. Comprehensive surveillance strategies that incorporate both experimental and computational methodologies are essential for early detection, risk assessment, and formulation of evidence-based policies. As food systems continue to evolve under the pressures of globalization, climate change, and

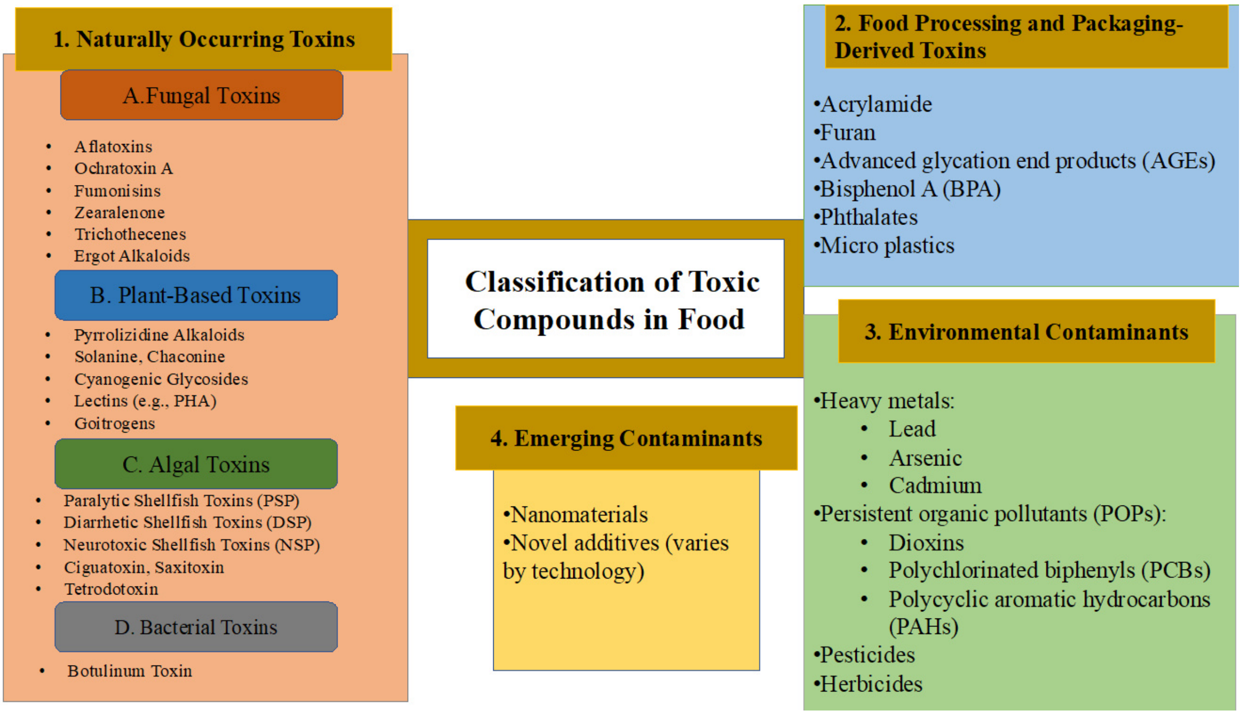

Figure 1. Types and sources of toxic compounds in food

technological transformation, proactive efforts to identify, monitor, and mitigate the risks posed by emerging food contaminants are imperative for safeguarding public health on a global scale [16].

The objective of this review is to systematically classify toxic compounds in food based on their sources naturally occurring toxins, environmental contaminants, processing- and packaging-derived chemicals, and emerging contaminants such as microplastics, and to examine their persistence, toxicokinetic behavior, and biological impacts. The study further aims to evaluate both conventional and advanced detection methods and assess their applicability in food safety monitoring. A key novelty of this work lies in its integration of diverse toxicants within a unified framework, the inclusion of underexplored emerging contaminants like nanoplastics, and the application of the One Health approach to connect human, animal, and environmental health. Additionally, the review uniquely emphasizes the role of standardized chemical identifier, including systematic names from the International Union of Pure and Applied Chemistry (IUPAC), the International Chemical Identifier (InChI), the Simplified Molecular Input Line Entry Specification (SMILES), and the Chemical Abstracts Service (CAS), in improving data harmonization across food-risk component databases. These elements together offer a comprehensive and forward-looking perspective on food safety and public health risk assessment [16].

Toxic compounds in food: classification and sources

Toxic compounds in food come from several sources and can be grouped into four main types. Naturally occurring toxins include substances like mycotoxins and plant alkaloids found in some foods. Environmental contaminants such as heavy metals like lead, arsenic, and cadmium, as well as persistent organic pollutants like dioxins, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons, enter food through polluted soil, water, and crops. Food processing and packaging introduce compounds like acrylamide, furan, advanced glycation end products, and chemicals such as bisphenol A, phthalates, and microplastics from plastics. Emerging contaminants include nanomaterials, new additives, pharmaceuticals, and antibiotic-resistant bacteria that may affect health. Recognizing these sources helps improve food safety. Classification of toxic compounds in food is shown in Figure 1 [17].

Naturally occurring toxins

Some toxins in food come from natural sources like fungi, plants, algae, and bacteria. These toxins are not added on purpose but may enter food through contaminated crops, storage conditions, or certain types of seafood and vegetables. They can cause various health problems such as stomach upset, organ damage, and even long-term effects like cancer [18]. Fungi produce harmful compounds called mycotoxins. For example, aflatoxins, made by *Aspergillus flavus* and *A. parasiticus*, can be found in peanuts, maize, and spices. They can damage the liver and may cause cancer. Ochratoxin A, from *Aspergillus* and *Penicillium*, is often found in cereals and dried fruits and can harm the kidneys [19, 20].

Environmental contaminants

Environmental contaminants are among the most pressing concerns affecting food safety and human health worldwide. These contaminants, including heavy metals, persistent organic pollutant, and agricultural chemicals such as pesticides and herbicides, enter the environment through various natural and anthropogenic activities and eventually contaminate the food supply, posing significant risks. Heavy metals like lead, arsenic, and cadmium are naturally occurring elements found in the Earth's crust [21–23].

Food processing and packaging-derived toxins

Food processing and packaging can introduce a variety of harmful toxins into our food, raising concerns about their potential health impacts. Acrylamide, furan, and advanced glycation end products are compounds that often form during high-temperature cooking processes like frying, baking, or roasting [24, 25].

Emerging contaminants in modern food systems

Emerging contaminants in today's food systems are new or less understood substances that could affect food safety and health. These often come from new food technologies, changes in farming, or pollution. For example, nanomaterials are sometimes used in packaging to keep food fresh, and new additives are added to improve taste or shelf life. Sometimes, medicines and personal care products get into the environment and find their way into food through water or soil. Microplastics and antibiotic-resistant bacteria are also becoming common concerns as they appear more in food [26].

Chemical identifiers and representations used by food-risk component databases

Food-risk component databases often include chemical structure images; however, due to their size and complexity, they are not ideal for sharing or retrieving data efficiently. To overcome this, standardized chemical identifiers are used to ensure consistency and ease of access. These include systematic names given by the IUPAC, the InChI developed by the same organization, the CAS registry number, and the SMILES. These representations help streamline data organization, support data sharing, and improve the overall quality and standardization of food-risk component databases [27].

International Union of Pure and Applied Chemistry (IUPAC) names

In 1958, the IUPAC introduced a systematic and hierarchical nomenclature system for organic compounds. This system is primarily based on the naming of straight-chain alkanes and serves as a foundation for assigning names to more complex organic molecules. The nomenclature provides a direct correlation between the chemical name and the molecular structure, ensuring precision and standardization across scientific literature. However, due to the complexity and length of certain systematic names, for example, “2,6-dichloro-4-nitroaniline”, simplified or common names such as “dicloran” are often preferred for ease of use, memorization, and database management in food-risk component repositories [28].

Simplified Molecular Input Line Entry Specification (SMILES)

The SMILES is a linear notation system used to represent the molecular structure of chemical substances using concise ASCII text strings. Introduced by David Weininger in 1990, this system uses specific symbols to denote different types of chemical bonds: a single dash represents single bonds, an equals sign denotes double bonds, a hash symbol signifies triple bonds, and a colon is used for aromatic bonds. Atoms placed adjacently within the notation are assumed to be connected by either single or aromatic bonds. Owing to its brevity and simplicity, the SMILES is particularly advantageous for storing and managing large volumes of chemical data. Additionally, structural information of food-risk components can also be archived in file formats such as structure-data files and mol2 files, which provide detailed information on atomic connectivity, two-dimensional or three-dimensional coordinates, bond orders, and other relevant chemical attributes [29].

International Chemical Identifier (InChI)

The InChI is a non-proprietary, textual representation developed by the IUPAC to provide a standardized way of encoding molecular information. It enables consistent and unambiguous identification of chemical substances in electronic and printed resources. The identifier encompasses several layers of molecular data, including atomic composition, bonding patterns, tautomeric states, isotopic labeling, stereochemical configuration, and formal charge distribution. This comprehensive and structured format allows for the effective linking and integration of diverse chemical datasets and is frequently employed as a search tool within chemical and toxicological databases to retrieve precise molecular information [30].

Chemical Abstracts Service (CAS) Registry Number

The CAS assigns unique numerical identifiers to chemical substances mentioned in scientific literature. These registry numbers, such as 79-06-1 for acrylamide, consist of three parts separated by hyphens and do not contain structural information. However, a single compound may have multiple registry numbers due to differences in isomers, salts, hydrates, or historical naming. Therefore, careful consideration is required when using these identifiers for compound referencing [31].

Use of chemical identifiers in food-risk component databases

Analysis shows that CAS registry numbers are the most frequently used identifiers in food-risk component databases (46%), followed by SMILES (36%), InChI (22%), and IUPAC names (20%). About 35% of databases include detailed molecular structure data. Biogenic toxin databases provide the most comprehensive identifier coverage, while databases on pollutants and veterinary drugs focus more on regulations. Scientific research databases use chemical identifiers more extensively (over 80%) than regulation-focused databases (about 50%) [32].

Toxicity, toxicokinetics and toxicodynamics of foodborne contaminants

Absorption, distribution, metabolism, and excretion

The disposition of foodborne contaminants within the human body is governed by toxicokinetic processes: absorption, distribution, metabolism, and excretion. Upon exposure via ingestion, inhalation, or dermal contact, toxicants are initially absorbed into the systemic circulation. Once in the bloodstream, they are distributed throughout the body, reaching various tissues and organs. This distribution phase is often followed by metabolic transformation, primarily in the liver, where enzymatic activity converts lipophilic compounds into more hydrophilic metabolites [33].

Complementing toxicokinetics is the field of toxicodynamics, which examines the molecular and cellular interactions between the toxicant and biological targets. As depicted in the accompanying figure, toxicodynamics encompasses both pathological alterations and adaptive repair mechanisms initiated in response to toxicant-induced stress. The balance between damage and repair ultimately determines the manifestation of adverse health effects or the restoration of homeostasis [34]. Figure 2 clearly delineates the distinction between toxicokinetics and toxicodynamics [35].

Mechanisms of biotransformation

Biotransformation is the process by which the body chemically modifies xenobiotics, including foodborne contaminants, to facilitate their elimination. This transformation primarily takes place in the liver, though other organs such as the kidneys, lungs, and intestines may also contribute. The process is typically divided

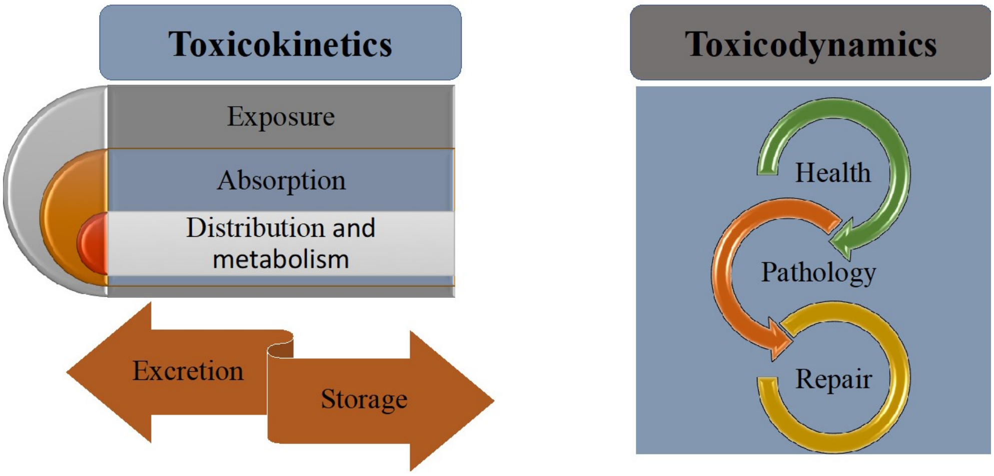

Figure 2. Toxic kinetics and toxicodynamics processes

into two main phases: Phase I (functionalization) and Phase II (conjugation). In Phase I, enzymes introduce or expose polar functional groups (e.g., $-OH$, $-NH_2$, or $-COOH$) on the parent compound. These reactions, which include oxidation, reduction, and hydrolysis, are chiefly mediated by the Cytochrome P450 enzyme family. While Phase I generally increases the compound's polarity, it may also result in reactive intermediates that are potentially more toxic than the original substance [36].

Phase II involves the conjugation of the compound or its Phase I metabolite with endogenous molecules such as glucuronic acid, sulfate, glutathione, or amino acids. These conjugation reactions are catalysed by specific transferases, including UDP-glucuronosyltransferases, sulfotransferases, glutathione S-transferases, and others. The resulting conjugates are typically more water-soluble, less biologically active, and are readily excreted through urine or bile. While biotransformation generally supports detoxification and clearance, it is not inherently protective [37].

Cellular and molecular targets of toxicity

The toxicological impact of foodborne contaminants is largely determined by their interactions with cellular and molecular components within the body. These interactions can impair vital physiological functions and initiate adverse biological responses. Key targets include cellular membranes, mitochondrial structures, nucleic acids, and regulatory proteins involved in signal transduction and gene expression. At the cellular level, one primary site of toxicant action is the plasma membrane. Exposure to certain contaminants can initiate lipid peroxidation, which alters membrane fluidity and disrupts the integrity of ion channels and transport systems [38, 39].

Impact on biological systems and organs

Foodborne contaminants, once absorbed and distributed in the body, can affect the structure and function of various organs and biological systems. The severity of these effects depends on the nature of the substance, the level and duration of exposure, and how the body processes the compound. These disturbances may trigger inflammation, reduce nutrient absorption, and compromise immune protection. Systemic effects of foodborne contaminants on human organs are shown in Figure 3 [40]. The liver, as the main organ responsible for detoxifying foreign substances, is highly exposed to foodborne chemicals. During the breakdown of these compounds, reactive by-products may be formed that damage liver cells. The kidneys, which help filter and remove waste from the blood, are also vulnerable [41]. The nervous system is another critical target. Certain contaminants can reach the brain and interfere with the normal activity of neurons. This may cause headaches, memory issues, reduced coordination, or, in more serious cases, long-term neurological damage, especially in developing children. Hormonal systems can also be affected. Some chemicals mimic or block natural hormones, disrupting how the body regulates growth, reproduction, and metabolism [42, 43].

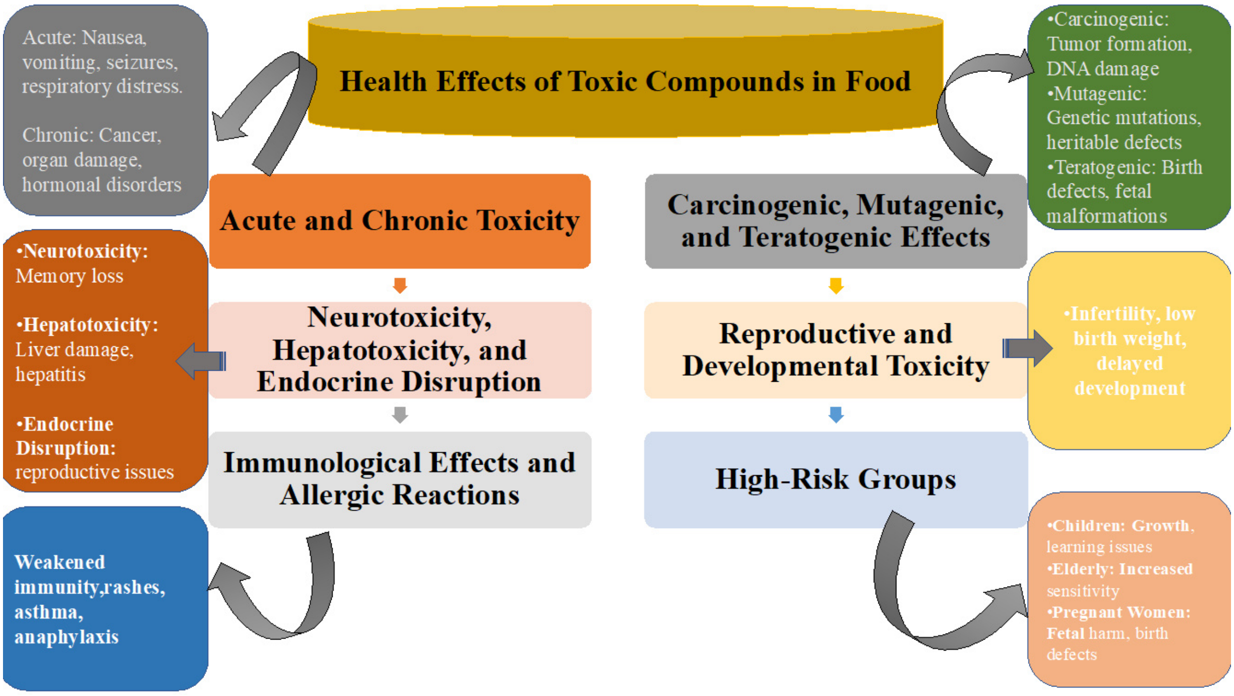

Figure 3. Systemic effects of foodborne contaminants on human organs

Detection and monitoring of food toxins

Conventional analytical methods

Food safety is continually monitored and regulated using a number of specialised and proven traditional methods. While the sensitivity, rapidity, and capacity to identify a broad variety of poisons may be limited, these techniques are frequently specific. Schematic representation of various conventional methods used for the detection of food toxins shown in Figure S1. Below is a list of some of the most often used traditional techniques for identifying dietary toxins [44].

Immunoassays

In the realm of food toxin detection, lateral flow immunoassays and enzyme-linked immunosorbent assays are the most often utilised immunoassay techniques. These techniques provide simple detection and are incredibly quick. In order to aid in detection, samples are permitted to interact with either labelled enzymes or antibodies. False positive findings, however, can be produced by substances with comparable core structures or harmless analogues. Mycotoxins such as Aflatoxin B1, Deoxynivalenol, Fumonisin B1 Zearalenone, and T-2, phycotoxins such as Okadaic acid, Yessotoxin, Pectenotoxin, Azaspiracid, Cyclic imines, Palytoxin, Domoic acid, Saxitoxin, Microcystin, and Cylindrospermospsin; and bacterial toxins such as *Clostridium perfringens* α, β, and ε toxin, Staphylococcal enterotoxins A, B, C, and E, botulinum toxins, and *Escherichia coli* enterotoxins are identified through immunoassay techniques [45].

Chromatographic techniques

Food toxins can frequently be identified and measured using gas chromatography, high-performance liquid chromatography, and thin-layer chromatography. Aflatoxin B1, paralytic shellfish toxins, and domoic acid are among the several toxins originating from seafood that are readily identified by high-performance liquid chromatography and thin-layer chromatography. Thin-layer chromatography is a straightforward method that helps separate and visualise dietary toxins by chromatographing them using several mobile phase solvents on a plate covered with a thin layer of stationary phase. However, high-performance liquid chromatography and gas chromatography are advanced methods of toxin separation based on different principles, which allow us to differentiate and measure distinct dietary toxins. One of the main disadvantages of using high-performance liquid chromatography and thin-layer chromatography methods is that they frequently need a complicated sample preparation methodology [46].

Spectroscopic-based techniques: UV-visible and fluorescence spectroscopy

Every toxin has a distinct core structure with unique patterns, which allows it to absorb light at a certain wavelength and to be detected if monitored at that wavelength. With the use of UV-fluorescence spectroscopy, this approach is used to test food contaminants such as aflatoxins.

A sample is considered to be contaminated with aflatoxins if it exhibits a response at 400 and 550 nm in comparison with 365 and 730 nm excitation wavelengths. Both fluorescence and UV-visible spectroscopy methods are affordable and easy to use. Furthermore, dietary poisons may be detected with great sensitivity using fluorescence spectroscopy. Despite these benefits, one of the primary drawbacks of employing this method for toxin detection is that certain toxic substances may have wavelengths of absorption and emission that are not highly selective and specific. The complex structure of dietary poisons can also be understood by other spectroscopic techniques, such as nuclear magnetic resonance spectroscopy. The identification of poisons in food can also be assisted by near infrared spectroscopy, which utilises NIR (14000–4000 cm^{-1}) wavelengths that produce vibration of C−H, O−H, N−H, and C=O bonds in biomolecules. This method was recently applied to find the toxins in the mussels that cause diarrhoea [47].

Biological assays

The most common technique involves injecting poisonous substances directly into organisms and monitoring their behaviour, mortality, and physiological reaction. This assay is frequently utilised for identifying marine toxins in seafood, such as toxins from diarrhoeal shellfish. However, these tests present serious ethical issues and are expensive and time-consuming [48].

Biochemical assays

Biochemical tests analyse enzymes and other toxin-induced biochemical changes rather than directly measuring dietary poisons. Toxins from diarrhoeal shellfish, for example, can be found by inhibiting phosphatase activity. This method is less suitable for the detection of diverse dietary toxins since it is relatively limited in its application, uses separate tools and reagents, and cannot be used for different kinds of toxins [49].

Microbiological assays

Specific microorganisms create specific dietary poisons. As a result, tests that include the microbe's presence are occasionally employed as a stand-in to find them. For example, *Bacillus cereus* found in food samples may indicate the presence of enterotoxins. These assays are cheap and simple to use, but their sensitivity and specificity are low [50].

Rapid and modern detection techniques

Nanoparticle-based sensor technologies have become increasingly important due to their high sensitivity, selectivity, and adaptability across various fields, including environmental monitoring, healthcare, and food safety [51].

A transducer element and a recognition element are the two characteristics that sensors must have. Sensor devices cannot operate without these characteristics. To offer high specificity and selectivity for the target analytes, the recognition element frequently employs DNA, peptides, aptamers, antibodies, and other compounds, as seen in Figure S2 [52, 53]. Biosensors can be classified according to a number of factors, but two popular methods are the kind of transduction system used (e.g., thermal, piezoelectric, optical, or electrochemical biosensors) and the type of bio recognition element (bio interceptor or bio component). The primary biosensors used in the food business to identify food pollutants are shown in Figure S3 [54, 55].

Mass-based sensors, including quartz crystal microbalances, measure changes in the resonant frequency caused by added mass on the sensor surface, making them useful for detecting microorganisms or residues on food packaging. Optical biosensors rely on variations in light properties like fluorescence, absorbance, or refractive index to detect analytes [56]. The potential of these AI models for food contamination identification to advance our procedures and guidelines for safer eating makes them invaluable. While neural networks of the same sort may predict pollutant concentrations based on labelled training data, supervised learning models like Support Vector Machine and Random Forests are employed for contaminant classification, as their names imply [57]. Figure S4 illustrates the Workflow of AI models used for the detection of food contaminants [57].

Conclusion

This review has brought to light the multifactorial nature of food contamination and the pressing need for integrated solutions to safeguard food safety and public health. A key takeaway is the widespread occurrence of diverse contaminants, biological, chemical, and physical, across all stages of the food supply chain. These include pathogenic microorganisms, pesticide residues, heavy metals, microplastics, and processing-related byproducts, which pose significant risks to consumers. The complexity of these hazards is compounded by environmental changes, industrial activities, and globalized food networks. Although significant progress has been made in developing advanced detection tools such as biosensors, molecular diagnostics, and AI-supported analytics. These innovations are not yet accessible or fully integrated into routine monitoring in many regions, particularly in developing countries. A critical issue that emerged is the persistent disconnect between scientific research, regulatory enforcement, and practical application. Despite the abundance of scientific evidence on emerging contaminants and available mitigation technologies, this knowledge often fails to inform timely policy action or reach stakeholders on the ground. Regulatory frameworks are frequently outdated or inconsistently implemented due to bureaucratic delays, insufficient technical capacity, and limited stakeholder engagement. Bridging this gap will require stronger collaboration between academia, government bodies, industry actors, and civil society. It is vital to foster knowledge exchange, support capacity-building, and develop mechanisms that translate scientific insights into practical, context-specific solutions. Looking ahead, the development of a resilient and safe global food system must be grounded in systems thinking and sustainability. Climate change, resource scarcity, and evolving consumer demands are reshaping the landscape of food production and safety. Resilience in this context means not only the ability to respond to contamination events but also the capacity to adapt to long-term systemic challenges. This includes strengthening surveillance infrastructure, promoting climate-resilient agricultural practices, and embedding food safety into broader health, environmental, and economic policies. Ultimately, securing the future of food safety demands sustained global cooperation, evidence-based policymaking, and inclusive stakeholder participation. A resilient food system will depend on our collective ability to align scientific innovation with regulatory frameworks and real-world practice. By embracing a holistic, forward-thinking approach, we can ensure that food systems remain safe, sustainable, and equitable for future generations.

Abbreviations

CAS: Chemical Abstracts Service

InChI: International Chemical Identifier

IUPAC: International Union of Pure and Applied Chemistry

SMILES: Simplified Molecular Input Line Entry Specification

Supplementary materials

The supplementary figures for this article are available at: https://www.explorationpub.com/uploads/Article/file/101097_sup_1.pdf.

Declarations

Acknowledgements

The authors are grateful to Prof. Pritam Babu Sharma, Vice Chancellor, Amity University Haryana, Gurugram, for the necessary help and support related to the completion of work.

Author contributions

AK: Writing—original draft, Conceptualization, Investigation. KK: Formal analysis, Visualization, Data curation. RM: Formal analysis, Visualization, Data curation. IST: Conceptualization, Supervision, Visualization, Writing—review & editing.

Conflicts of interest

The authors declare that they have no competing interests.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publication

Not applicable.

Availability of data and materials

Not applicable.

Funding

Not applicable.

Copyright

Publisher's note

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