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Food Contaminants: A Scoping Review of Sources, Toxicity, Pathophysiological Insights, and Mitigation Strategies

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Review

Food Contaminants: A Scoping Review of Sources, Toxicity, Pathophysiological Insights, and Mitigation Strategies

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Abstract: Background: Food contamination is a major global issue that impacts public health, agriculture, and food security. The toxicological effects of contaminants can pose significant health risks, emphasizing the need for effective strategies to mitigate these dangers. **Objectives:** This narrative review explores the sources, toxicities, pathophysiological aspects and mitigation approaches related to food contaminants. **Methods:** A comprehensive review was conducted by analyzing relevant literature from PubMed, Scopus, Web of Science, and Google Scholar, with a focus on studies published in the last decade. Articles were chosen on the basis of their relevance, and a narrative approach was employed to summarize findings related to sources, toxicity, pathophysiology, and mitigation strategies for food contaminants. **Results:** This review highlights that food contaminants originate from diverse sources, including biological agents (bacteria, viruses), chemical substances (pesticides, heavy metals, mycotoxins), and physical materials (glass, plastics). Their toxicity varies, leading to acute and chronic health effects such as neurotoxicity, hepatotoxicity, endocrine disruption, and carcinogenicity. The underlying pathophysiological mechanisms include oxidative stress, deoxyribonucleic acid damage, inflammation, and metabolic dysfunction, which contribute to disorders such as cancer, metabolic syndrome, and neurological impairments. Effective mitigation strategies encompass good agricultural practices, advanced food processing and preservation techniques, regulatory enforcement, public education, and the incorporation of natural detoxifying agents, aiming to reduce contamination and ensure food safety. **Conclusions:** Food contaminants present significant health risks, so effective mitigation methods can reduce their impact. The development of new technologies and the enforcement of stricter food safety regulations are crucial in addressing emerging contaminants and safeguarding public health.

Keywords: Food contaminants; toxicity; mitigation strategies; pesticides; heavy metals; mycotoxins; sources; pathophysiological insights

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1. Introduction

Food contamination is a critical public health issue worldwide, as harmful substances in food can lead to serious health risks [1]. When present in food, contaminants can negatively affect human health and well-being [2]. These harmful substances can be introduced at various points throughout food production, processing, packaging, transportation, and even storage and consumption. Contaminants can be categorized into natural and synthetic types, including chemical, biological, and physical agents that compromise food safety [3].

Food contaminants originate from various sources, such as environmental pollution, food additives, microbial pathogens, and unintentional contamination during handling [4]. Chemical contaminants such as pesticides, heavy metals, mycotoxins, and industrial chemicals are of particular concern because of their widespread occurrence and persistence in the food supply [5]. Biological contaminants, such as bacteria, viruses, and parasites, can cause foodborne illnesses, whereas physical contaminants, such as glass, plastic, or metal fragments, may lead to injury [6].

The toxicity of food contaminants depends on the type, concentration, and duration of exposure. Chronic exposure to contaminants such as lead, cadmium, and pesticides has been linked to long-term health effects, including neurological disorders, developmental issues, and cancer [7]. Microbial contamination can cause foodborne diseases such as salmonellosis, listeriosis, and *E. coli* infections, significantly affecting public health [8]. Vulnerable populations, including children, pregnant women, and individuals with weakened immune systems, are particularly at risk from these contaminants.

Effective mitigation strategies are essential to reduce the risks posed by food contaminants. These strategies include both preventive measures and interventions aimed at lowering contamination levels in the food supply [9]. Prevention involves safe farming practices, proper food handling, and stringent quality control during food processing. Detection methods, such as advanced chemical analysis and microbiological testing, are also vital for the early identification of contaminants [10]. Regulatory measures, such as setting limits for contamination levels and enforcing food safety standards, play a significant role in minimizing exposure to harmful substances [11].

This review aims to provide a thorough overview of food contaminants, focusing on their sources, potential health risks, pathophysiological pathways, and various strategies to reduce their presence in the food supply. By understanding these factors, we can improve food safety and ensure that food remains safe and nutritious for consumption.

1. 1. What this study adds

The novelty of this review lies in its comprehensive approach, which involves examining food contaminants at the molecular level and integrating both the biological mechanisms of toxicity and practical mitigation strategies. This dual focus differentiates it from studies that focus on either aspect alone.

2. Methodology

2.1. Study Design

This narrative review aims to provide an in-depth summary and critical analysis of the literature on the sources, toxicity, pathophysiology, and mitigation strategies of food contaminants. A narrative review design is employed to offer a broad discussion by integrating key studies, identifying prominent trends, and delivering a coherent overview. Unlike a systematic review, this approach does not require statistical rigor but focuses on presenting a comprehensive perspective on the subject matter.

2.2. Research question

The central research question for this review is as follows: "What are the sources, toxicities, pathophysiological mechanisms, and current strategies for mitigating the impact of food contaminants on human health?" This question seeks to explore the various origins of food contamination, the health risks they pose, their pathophysiology, and the interventions designed to minimize their adverse effects.

2.3. Eligibility criteria

Studies were selected according to specific inclusion and exclusion criteria. The inclusion criteria included peer-reviewed articles, gray literature, and reviews published in English that focused on food contaminants, such as pesticides, heavy metals, mycotoxins, food additives, and environmental pollutants. Additionally, studies addressing the toxicity of food contaminants to human health and those discussing mitigation strategies will be included. The exclusion criteria included studies unrelated to food contaminants, non-English publications, studies that did not address human health, and studies with unclear methodologies or low-quality data.

2.4. Search strategy and keywords

A systematic search will be conducted across multiple electronic databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search will utilize a combination of relevant keywords such as "food contaminants," "toxicity of food contaminants," "food safety," "foodborne toxins," "mitigation of food contaminants," "heavy metals in food," "pesticides in food," "mycotoxins and food safety," and "foodborne diseases and prevention." To ensure that the findings are current, the search will be limited to studies published in the last 10 years.

2.5. Data extraction

Data extraction will be performed by collecting the following information from each eligible study: study characteristics (authors, publication year, country of study), the type of contaminants studied (e.g., pesticides, heavy metals, mycotoxins), sources of contamination (e.g., agricultural practices, environmental pollution, food processing), toxicity effects on human health (e.g., carcinogenicity, neurotoxicity, reproductive toxicity), and mitigation strategies (e.g., regulations, technological advances, public health interventions). The type of study will also be recorded, whether it is experimental, observational, or a review.

2.6. Data analysis and synthesis

The data extracted from the selected studies will be analyzed qualitatively to identify common patterns and trends related to the sources, toxicity, pathophysiological pathways, and mitigation strategies of food contaminants. The synthesis will be narrative in nature, offering a comprehensive summary of the findings and a critical discussion rather than relying on statistical analysis.

3. Results and discussion

3.1. Health impact of food contaminants

Food contaminants can harm human health through various chemical/physical, microbial or other agents, which may originate from environmental pollution, food additives, pesticides, or naturally occurring substances [12,13]. The toxicity of these contaminants depends on the type and level of exposure, and their effects can range from acute toxicity and digestive issues to chronic diseases such as cancer, neurodegenerative disorders, reproductive disorders, and developmental problems [7]. They may also impair immune system function, compromising immunity or causing dysfunction. Certain harmful substances in food can cause genetic damage, resulting in mutations or cancer [14]. Additionally, some chemicals, such as persistent organic pollutants (POPs), interfere with hormonal regulation, potentially causing reproductive and developmental issues [15]. Foodborne chemicals can also damage the nervous system, affecting cognitive function and behavior, and may contribute to conditions such as Parkinson's disease or Alzheimer's disease [16].

3.2. Foodstuff contaminants

Food contaminants come from various sources, including agricultural chemicals (pesticides, herbicides), heavy metals (lead, mercury, cadmium), mycotoxins (aflatoxins, ochratoxins), food additives, and environmental pollutants (dioxins, PCBs) [17,18]. These contaminants can enter the body when contaminated food is consumed in the form of pesticides, heavy metals (e.g., lead, mercury, cadmium), food additives, or microbial toxins (such as norovirus). Biological contaminants such as bacteria, viruses, parasites, fungi, and molds can be introduced through improper food handling, storage, or cooking. Bacteria and fungi thrive under unsuitable conditions, such as inadequate refrigeration or excessive moisture [19]. Chemical contaminants such as pesticides, heavy metals, mycotoxins, food additives, and residues from packaging materials can be absorbed during food production, processing, or packaging, often through contact with contaminated water, soil, or equipment [20]. Physical contaminants, such as foreign objects (glass, metal, plastic), typically occur during food

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handling, processing, or packaging due to equipment failure, human error, or environmental contamination [21].

3.2.1. Chemical contaminants

Pesticides and Herbicides: Pesticides, including organophosphates, carbamates, pyrethroids, and glyphosate, are used in agriculture to protect crops [22,23]. Prolonged exposure can lead to nerve damage, cognitive dysfunction, immune suppression, and hormonal disruption. They may also cause genotoxic effects such as DNA damage and chromosomal abnormalities while impairing immune function and promoting inflammation [24–26].

Food additives (e.g., monosodium glutamate – MSG): Certain artificial colors, preservatives, and flavor enhancers, such as MSG, can trigger genotoxicity and neuroinflammation [28,29]. Additives such as nitrates and nitrites can form carcinogenic nitrosamines in the body [30–33]. These substances may also lead to immune dysfunction, allergic reactions, and potential developmental issues, particularly in children. Excessive MSG consumption is linked to excitotoxicity, where overstimulation of neurons causes cell death [34].

Heavy metals: Metals such as lead, mercury, and cadmium can accumulate in food, triggering oxidative stress and cellular damage [35,36]. These metals disrupt thyroid and estrogen functions and may lead to immune suppression, cognitive deficits, developmental delays, and neurodegenerative diseases. Mercury and lead affect neurotransmission and brain development, particularly in children [37,38].

Phytotoxins: Phytotoxins are naturally occurring toxic substances produced by plants as secondary metabolites. These compounds function primarily as defense mechanisms to protect plants from herbivores, pathogens, and competing vegetation 11, 23]. Phytotoxins encompass a wide range of chemical classes, including alkaloids (e.g., strychnine), glycosides (e.g., cyanogenic glycosides found in cassava), terpenoids (e.g., abrin from Abrus precatorius), phenolic compounds (e.g., tannins), and lectins (e.g., ricin derived from castor beans). Owing to their concentration and chemical nature, these substances can pose risks to humans, animals, and other plants, leading to effects such as acute poisoning, neurotoxicity, liver damage, or even carcinogenesis [24]. However, some phytotoxins, when used in controlled doses, possess therapeutic properties, such as vincristine, which is utilized in cancer treatment. Additionally, certain phytotoxins act as allelochemicals, suppressing the growth of nearby plants through allelopathy. Notable examples of such toxic compounds include ricin, nicotine, cyanogenic glycosides, and saponins, which differ in their levels of toxicity and biological impact.

Mycotoxins: Mycotoxins are harmful secondary metabolites produced by fungi such as Aspergillus, Penicillium, Fusarium, and Claviceps [19]. These compounds frequently contaminate crops, food, and animal feed under warm, humid conditions. In resistance to heat, mycotoxins pose serious health risks to humans and animals, ranging from acute effects such as poisoning, nausea, and organ damage to chronic issues such as immune suppression, cancer, and hormonal imbalances. Commonly found in grains, nuts, spices, coffee, fruits, and dairy products, prominent examples include aflatoxins (potent carcinogens found in nuts and grains), ochratoxins (kidney toxins present in cereals and coffee), fumonisins (associated with esophageal cancer and detected in maize), deoxynivalenol (causing vomiting and immune dysfunction in wheat and maize), zearalenone (disrupting the hormonal balance in grains), and ergot alkaloids (linked to ergotism in rye) [31].

Why are mycotoxins not considered biological food contaminants? Mycotoxins do not multiply or develop within the host but cause harm when consumed, inhaled, or absorbed [9]. These toxins persist in food even after the fungi that produce them are destroyed (killed), as they are chemically stable and resistant to heat and food processing methods. Biological food contaminants refer specifically to living microorganisms, whereas mycotoxins fall into the category of chemical hazards in food safety because they are toxic metabolites that persist in food even after the mold has died or been removed [35].

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Processing aids: Processing aids are substances utilized during food production to achieve specific technical purposes, such as enhancing texture, flavor, or shelf life, without serving a functional role in the finished product [25]. Common examples include enzymes such as amylase in bread-making, solvents such as hexane for extracting oils, clarifying agents such as bentonite in wine production, catalysts used in processes such as oil hydrogenation, and antifoaming agents such as polydimethylsiloxane in frying oils. Although these substances may leave trace residues in food, they can pose health concerns if contaminant levels exceed regulatory limits. Potential hazards include toxic solvent residues (e.g., hexane), heavy metal contamination from catalysts (e.g., nickel or palladium), harmful byproducts (e.g., carcinogenic nitrosamines), and allergens from enzyme sources (e.g., gluten-derived enzymes) [5].

Veterinary drugs: Veterinary medications play crucial roles in animal farming by treating diseases, preventing infections, and increasing growth. However, improper usage or the absence of withdrawal periods can lead to the contamination of food products with drug residues [14]. These substances include antibiotics such as tetracyclines, sulfonamides, and penicillins; growth-promoting hormones such as estradiol; antiparasitics such as ivermectin and organophosphates; and coccidiostats commonly added to poultry feed. The presence of these residues in food poses significant health risks, including the development of antimicrobial resistance (AMR) from antibiotics, hormonal disruptions and potential cancer risks from growth hormones, and toxicity from antiparasitic agents.

Food contact materials: Food contact materials (FCMs) are substances found in items such as packaging, storage containers, and cooking tools that can leach chemicals into food [3,21]. Examples include bisphenol A (BPA) in plastics and resins, phthalates used to soften plastics, mineral oil hydrocarbons (MOHs) from recycled materials, per- and polyfluoroalkyl substances (PFASs) in grease-resistant products, and heavy metals such as lead and cadmium from inadequately regulated materials. Exposure to these chemicals poses significant health risks, including hormonal imbalances, cancer, neurotoxicity, and reproductive harm.

Phthalates, which are used as plasticizers to improve flexibility and durability, are commonly found in food packaging, cling wraps, and processing equipment [19]. These chemicals can migrate into food and disrupt endocrine functions, potentially leading to reproductive and developmental health risks. BPA, a compound used to make polycarbonate plastics and epoxy resins for containers such as water bottles and linings, can leach into food [12]. As an endocrine disruptor, BPA mimics estrogen and may interfere with hormone regulation, increasing the risk of chronic conditions such as cancer and heart disease. The health risks associated with these chemicals include hormonal disruption, carcinogenicity, neurotoxicity, and reproductive toxicity.

Process-related contaminants: Process-related contaminants are chemical substances formed during the processing of food as a result of heat, additives, or other treatments [23]. Examples include acrylamide, which develops in starchy foods exposed to high temperatures; polycyclic aromatic hydrocarbons (PAHs) generated during grilling or smoking; chloropropanoles such as 3-MCPD produced during oil refining; furan created through high-temperature methods such as canning; and nitrosamines, which arise in processed meats owing to interactions between nitrites and amines. These contaminants are associated with various health hazards, including carcinogenicity, mutagenicity, and toxicity to organs.

Environmental pollutants: Environmental pollutants such as dioxins, polychlorinated biphenyls (PCBs), and persistent organic pollutants (POPs) are chemical food contaminants because they are toxic substances that chemically interact with the body, affecting immune responses and overall health [7,23]. POPs are hazardous chemicals that persist in the environment for long periods and bioaccumulate in the food chain, particularly in animal fats, posing serious risks to public health. These pollutants can contaminate food supplies through exposure to polluted water, soil, and air, as well as through various food production processes [7,19]. Examples of POPs include PCBs, dioxins, furans, hexachlorobenzene (HCB), and banned pesticides such as dichlorodiphenyltrichloroethane (DDT). POPs are associated with severe health concerns, including cancer, developmental disorders,

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immune system damage, and endocrine system disruption. Owing to their stability and ability to travel over great distances, these chemicals can impact areas far removed from their original sources.

3.2.2. Biological (microbial) contaminants

Biological food contaminants refer to living organisms or their byproducts that can cause food-borne illnesses. Bacteria are the most common biological contaminants in food and thrive under favorable conditions, such as warm, moist, and nutrient-containing conditions [3,4,39]. Pathogenic examples include Salmonella, which is found in raw poultry, eggs, and unpasteurized milk and causes diarrhea, fever, and abdominal cramps; *Escherichia coli* (*E. coli*), which are strains that contaminate raw meat and produce severe gastrointestinal infections; and *Listeria monocytogenes*, which is found in ready-to-eat foods such as soft cheeses and deli meats and can cause listeriosis, particularly in pregnant women, newborns, and immunocompromised individuals. Unlike bacteria, viruses do not grow on food but are transmitted via contaminated food or water, with common examples including norovirus, often called the "stomach flu," and hepatitis A, which spreads through poor hygiene and contaminated food or water, causing liver inflammation. Parasites, which are organisms that live and feed on hosts, also pose risks; examples include *Giardia lamblia*, which is found in contaminated water and causes giardiasis; *Toxoplasma gondii*, which is associated with undercooked meat and causes toxoplasmosis, which is particularly dangerous for pregnant women; and Trichinella spiralis, which is found in undercooked pork, leading to trichinosis. Finally, fungi, such as molds and yeasts, typically cause food spoilage, although certain molds produce harmful mycotoxins, and the consumption of contaminated products can sometimes result in allergic reactions or mild illnesses.

3.2.3. Physical contaminants

Physical food contaminants are foreign objects or materials that accidentally end up in food during production, processing, storage, or handling. These contaminants can cause physical harm, such as choking, injury to the mouth or teeth, or cuts, and may also indicate poor food safety practices [40–43]. Plastics are commonly used in food packaging, storage containers, and utensils. Although plastics themselves are not direct contaminants, they can degrade or leach harmful chemicals, including microplastics, into food. Plastics are categorized as physical food contaminants since they are foreign materials that may unintentionally enter food during production, processing, or packaging. However, if plastics release harmful substances such as bisphenol A (BPA) or phthalates into food, they can also be classified as chemical contaminants. Therefore, plastics can function as both physical and chemical contaminants depending on their interaction with food. Plastics are categorized as physical food contaminants because of their tangible and solid nature, although they may indirectly contribute to chemical contamination under specific conditions.

Broken glass from jars, bottles, or light fixtures poses risks of severe injuries, including cuts to the mouth, throat, or internal organs. Metal shards from machinery, utensils, or equipment used in food processing, such as loose screws, can cause cuts or punctures to the digestive tract. Damaged plastic packaging, utensils, or container fragments may result in choking or internal injuries if ingested. Stones or rocks, often from improperly cleaned grains, legumes, or vegetables, can damage teeth or cause choking. Wood splinters from crates, pallets, or utensils may injure the mouth or throat. Hair from humans or animals, though not physically harmful, is unappealing and signals poor hygiene. Bone fragments from improperly deboned meat or fish present risks of choking or injury. Finally, insects or insect parts, often due to poor storage or contamination, are unhygienic and can spread diseases if consumed.

3.2.4. Allergenic contamination

Allergenic contamination in food refers to the unintentional inclusion of allergenic substances in food products, which can trigger allergic reactions in sensitive individuals [11]. This type of contamination can occur at any point during the food production process, including during cultivation, processing, packaging, or preparation. It often results from cross-contact with allergens such as

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peanuts, milk, eggs, soy, wheat, fish, shellfish, tree nuts, or sesame seeds. Common factors contributing to this issue include cross-contact during manufacturing, improper storage practices, inadequate product labeling, shared equipment, and environmental factors such as airborne particles or spilled food. For example, a product may become contaminated with peanuts if processed in a facility handling peanut products or with milk proteins if made in a facility that processes dairy. Gluten contamination can also occur in gluten-free foods if the equipment used for gluten-containing products is not thoroughly cleaned.

3.2.5. Radiological contaminants

Radiological contaminants are radioactive materials present in food, water, or the environment that pose significant health risks when ingested or exposed [5,29]. These substances can result from nuclear disasters, improper disposal of radioactive waste, or environmental contamination. Notable examples include cesium-137 (Cs-137), which contaminates food and water following nuclear incidents such as Chernobyl and Fukushima; iodine-131 (I-131), which accumulates in food and impacts the thyroid gland; and radon, a naturally occurring radioactive gas that can affect crops growing in polluted soil [20]. Long-term exposure to such contaminants increases the likelihood of developing cancers, such as thyroid, lung, and liver cancers, and may lead to radiation sickness, genetic mutations, and a compromised immune system, increasing the vulnerability of individuals to infections [3].

Table 1. Types, examples and health effects of food contaminants.

Types	Examples	Health risks
Chemical contaminants		
Pesticides and Herbicides	organophosphates, carbamates, pyrethroids, and glyphosate.	Neurological damage, cognitive impairments, immune suppression, hormonal disruptions, genetic mutations, inflammation, and DNA damage.
Food Additives	MSG, nitrates, and nitrites	Genotoxic effects, brain inflammation, neuronal overstimulation, immune dysfunction, allergic reactions, and developmental issues, especially in children, are notable concerns.
Heavy Metals	Lead, mercury, chromium, nickel, and cadmium	Oxidative stress contributes to brain dysfunction, neurodegenerative diseases, hormonal imbalances affecting thyroid and estrogen

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		activity, immune suppression, and developmental delays.
Phytotoxins	Cyanogenic glycosides, ricin, saponins, and tannins.	Toxicity causing liver damage and possible cancer development.
Mycotoxins	Aflatoxins, ochratoxins, fumonisins, deoxynivalenol, zearalenone, and ergot alkaloids	Toxicity, malignancies, immune dysfunction, hormonal disruption, and organ damage.
Processing Aids	Amylase, solvents like hexane, catalysts such as nickel, and antifoaming agents	Toxic residues, heavy metal contamination, allergens, and carcinogenic byproducts.
Veterinary Drugs	Antibiotics like tetracyclines, hormones like estradiol, and antiparasitics like ivermectin	Antimicrobial resistance, endocrine disruption, carcinogenesis, and overall toxicity.
Food Contact Materials	BPA, phthalates, mineral oil hydrocarbons, and PFAS	Hormonal imbalance, cancer, nerve damage, and reproductive issues.
Process-Related Contaminants	Acrylamide, PAHs, chloropropanols, furan, and nitrosamines	Carcinogenic, mutagenic, and toxic to organs.
Environmental Pollutants	Dioxins, PCBs, and POPs like DDT and HCB	Cancer, birth defects, immune dysfunction, and hormonal imbalance.
Biological contaminants		
Bacteria	Salmonella, *E. coli*, and *Listeria monocytogenes*	Diarrhea, fever, gastrointestinal infections, and listeriosis.
Virus	Norovirus and Hepatitis	Stomach flu, liver inflammation, and other foodborne diseases
Paasites	*Giardia lamblia*, *Toxoplasma gondii*, and Trichinella spiralis	Giardiasis, toxoplasmosis, and trichinosis.

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Fungi	Molds and yeasts	Health problems and allergic reactions caused by mycotoxin exposure.
Physical contaminants		
	Plastic, shattered glass, metal bits, stones, wood splinters, hair, bone fragments, and pests.	Physical harm like cuts or choking, along with possible chemical exposure from plastics.
Allergenic contamination		
	Peanuts, dairy, eggs, soybeans, wheat, seafood, shellfish, tree nuts, and sesame.	Allergic reactions and in some cases, severe anaphylaxis
Radiological contaminants		
	Cesium-137, Iodine-131, and radon	Cancer, genetic alterations, radiation poisoning, and immune deficiency.

BPA: bisphenol A; DNA: deoxyribonucleic acid; DDT: dichlorodiphenyltrichloroethane; HCB: hexachlorobenzene; MSG: monosodium glutamate; PAHs: polycyclic aromatic hydrocarbons; PCBs: polychlorinated biphenyls; PFAS: per- and polyfluoroalkyl substances; POPs: persistent organic pollutants.

4. Molecular Mechanisms of Toxicity

Food contaminants such as pesticides, heavy metals, food additives, and microorganisms can trigger oxidative stress in the body. Oxidative stress arises when there is an imbalance between reactive oxygen species (ROS) production and the body's ability to neutralize or repair the damage caused by these species. These contaminants often induce ROS production, which can harm cellular components such as lipids, proteins, and nucleic acids, contributing to diseases such as cancer, inflammation, and neurodegeneration. Additionally, contaminants can affect immune responses by altering immune cell function, leading to immune suppression or autoimmune disorders [44].

4. 1. Genotoxicity: Contaminants in food can cause significant genetic damage through various mechanisms, increasing the risk of cancer and other genetic disorders [45–48]. Direct DNA damage occurs when these contaminants interact with DNA molecules, leading to mutations, chromosomal breaks, or disruptions in cell function. Additionally, many contaminants generate reactive oxygen species (ROS) or free radicals, which induce oxidative stress. This oxidative stress can alter DNA bases, cause strand breaks, and lead to mutations that may promote cancer if not properly repaired. Some contaminants further exacerbate this problem by inhibiting DNA repair mechanisms, allowing genetic mutations to accumulate over time. Chromosomal aberrations, such as deletions, duplications, or translocations, may also result from exposure to these harmful substances, contributing to cancer and other genetic diseases. Moreover, certain contaminants can influence gene expression through epigenetic modifications, such as changes in DNA methylation or histone modifications. These alterations can activate oncogenes or silence tumor suppressor genes, further increasing the risk of cancer.

4. 2. Oxidative stress: Contaminants, such as heavy metals, can trigger the production of reactive oxygen species (ROS) and reactive nitrogen species (RNS), which play a significant role in cellular damage. Heavy metals interfere with the electron transport chain in cells, resulting in the overproduction of harmful reactive species such as superoxide radicals (O_2^-), hydrogen peroxide (H_2O_2), and hydroxyl radicals (OH). These reactive species are highly unstable and can cause extensive damage to cellular structures [49–56], including lipid membranes, proteins, and DNA. This damage manifests as lipid peroxidation, alterations in protein function (which may lead to enzyme dysfunction or aggregation), and DNA mutations, all of which impair cellular processes and can eventually lead to cell death. The presence of ROS and RNS also triggers an inflammatory response by activating signaling pathways, such as nuclear factor-kappa B (NF-κB), which increases the release of proinflammatory cytokines. Chronic oxidative stress and inflammation are strongly associated with the development and progression of various diseases, including cardiovascular diseases, cancer, and neurodegenerative disorders.

4. 3. Endocrine Disruption: Certain environmental contaminants, such as pesticides, plastics (e.g., bisphenol A or BPA), and industrial chemicals (e.g., phthalates), have the potential to disrupt normal hormonal processes by mimicking natural hormones such as estrogen [57–64]. These chemicals can bind to hormone receptors, leading to altered signaling that affects vital biological functions such as growth, reproduction, and metabolism. In some cases, these contaminants may block hormone receptors, preventing natural hormones from binding and impeding normal actions. For example, some pesticides can interfere with thyroid hormone receptors, disturbing metabolic and developmental processes. Furthermore, certain contaminants can affect hormone production by influencing the function of endocrine glands, such as the thyroid, adrenal glands, and ovaries. Heavy metals such as lead and cadmium, for example, are known to disrupt the synthesis and secretion of thyroid hormones. Contaminants may also alter hormone metabolism, particularly hormones such as estrogen and thyroid hormones, leading to imbalances that contribute to conditions such as obesity, insulin resistance, and diabetes. Moreover, some chemicals, including organochlorine pesticides, can impact the metabolism of these hormones. Finally, prolonged exposure to persistent organic pollutants (POPs) can affect the expression of genes related to hormone regulation, resulting in long-term changes that influence tissue development, growth, and reproductive health. This alteration of gene expression increases the risk of developing hormone-related diseases, including certain types of cancer.

4. 4. Immunotoxicity: Consuming food contaminants such as pesticides, heavy metals, mycotoxins, and food additives can negatively impact the immune system by either suppressing its response or triggering harmful immune reactions. Contaminants in food can significantly impact immune function in various ways, leading to a compromised immune system [65–71]. These contaminants can interfere with the development, activation, and survival of immune cells, such as T cells, B cells, dendritic cells, and macrophages. For example, organophosphate pesticides are known to impair T-cell function, thus weakening the immune system's ability to respond to infections. Additionally, contaminants can disrupt cytokine production, which plays a crucial role in regulating immune responses. Heavy metals such as lead and mercury are especially harmful in this regard, as they can alter cytokine release, potentially resulting in chronic inflammation or immune suppression. Furthermore, many food contaminants, such as mycotoxins such as aflatoxins, generate reactive oxygen species (ROS) that induce oxidative stress. This oxidative damage can harm immune cells and tissues, reducing the body’s ability to fight infections effectively. Certain contaminants, such as aflatoxins, can also cause direct DNA damage in immune cells, leading to mutations that impair immune function and may even contribute to immune-related diseases or cancers.

4. 5. Neurotoxicity: Food contaminants can also cause neurotoxic effects, damaging both the central and peripheral nervous systems [72–78]. Contaminants, including heavy metals and pesticides, can significantly impact brain health by inducing various pathological processes. One of the primary mechanisms is oxidative stress, where these toxins generate reactive oxygen species (ROS) that cause neuronal damage, leading to dysfunction and eventual cell death. In addition, exposure to

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these substances triggers inflammation by activating microglia, which contributes to chronic brain inflammation and is closely linked to neurodegenerative diseases such as Alzheimer's disease and Parkinson's disease. Some contaminants, such as organophosphate pesticides, disrupt neurotransmission by inhibiting acetylcholinesterase, resulting in the overstimulation of cholinergic pathways and neurotoxicity. Another consequence of exposure is calcium dysregulation, with heavy metals such as lead interfering with the calcium balance in neurons, causing excitotoxicity and further neuronal injury. Mitochondrial dysfunction is another critical issue, as pesticides and heavy metals impair mitochondrial activity, leading to energy deficits and increasing susceptibility to neurodegenerative processes. Finally, exposure to toxic food contaminants can also alter gene expression, influencing cellular processes such as survival, apoptosis, and neuroplasticity, increasing the vulnerability of neurons to damage and contributing to the development of neurological disorders.

Table 2. Molecular mechanisms of food contaminant toxicity.

Mechanism	Description	Examples	Health implications
Genetic Damage (Genotoxicity)	Can damage DNA by causing mutations, chromosomal breaks, and producing ROS, leading to oxidative stress. They can also impair DNA repair and trigger epigenetic changes that alter gene expression.	Toxic metals, fungal toxins, agricultural chemicals, industrial pollutants	Increased risk of cancer, genetic disorders, chromosomal abnormalities, activation of cancer-promoting genes, and suppression of tumor-suppressing genes.
Cellular Damage through Oxidative Stress	Contaminants produce ROS and RNS that harm lipids, proteins, and DNA, impairing cell function and triggering inflammation. This can result in tissue damage, cellular dysfunction, and death.	Toxic metals, agricultural chemicals, synthetic food additives	Increased likelihood of cancer, heart disease, neurodegenerative conditions, chronic inflammation, and cellular death.
Hormonal Disruption (Endocrine Disruption)	Some pollutants mimic or obstruct natural hormones, disrupting receptor function and endocrine gland	Agricultural chemicals, A BPA, plasticizers like phthalates,	Hormonal imbalances, weight gain, insulin resistance, diabetes, Reproductive issues,

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	activity. They can disturb hormone balance, causing lasting gene expression changes and affecting regulation.	persistent environmental pollutants, toxic metals	and cancers associated with hormone disruptions.
Impact on the Immune System (Immunotoxicity)	Contaminants can hinder immune cell function, disrupt cytokine production, and trigger oxidative stress, compromising immune responses or causing harmful reactions.	Agricultural chemicals, heavy metals (e.g., lead, mercury), mold toxins (e.g., aflatoxins), food additives	Weakened immunity, increased vulnerability to infections, persistent inflammation, immune-related conditions, and genetic mutations in immune cells.
Damage to the Nervous System (Neurotoxicity)	Contaminants can harm the nervous system by inducing oxidative stress, inflammation, altering neurotransmitter activity, disturbing calcium regulation, damaging mitochondria, and altering gene expression.	Toxic metals (e.g., lead, mercury), nerve agent pesticides	Development of neurodegenerative diseases such as Alzheimer's and Parkinson's, neuronal damage, excitotoxicity, mitochondrial damage, and altered brain plasticity.

BPA: bisphenol A; ROS: reactive oxygen species; RNS: reactive nitrogen species.

5. Mitigation strategies

Mitigation strategies for food contaminants rely on a comprehensive approach to safeguard food quality and protect human health. Key measures include adopting best practices in agriculture and manufacturing, such as good agricultural practices (GAPs) and good manufacturing practices (GMPs), to reduce contamination risk across production, processing, and distribution stages [3,28]. The use of robust cleaning methods, maintaining optimal storage conditions, and employing modern processing techniques such as pasteurization and irradiation are effective in minimizing contaminants. Establishing strict regulations, such as maximum allowable limits for pesticides, heavy metals, and additives, along with rigorous monitoring systems, is critical. Raising public awareness, educating consumers, and encouraging sustainable methods in food production and supply chains are

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equally important in addressing food safety challenges [56]. The mitigation strategies outlined below provide a concise overview.

5. 1. Regulation and surveillance: Governments and health organizations establish maximum residue limits (MRLs) for contaminants and enforce strict food safety monitoring. This includes regulatory frameworks and standards set by national and international bodies such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), which set acceptable contaminant levels for substances such as pesticides, heavy metals, toxins, and pathogens. Food safety authorities monitor food products through inspections, sampling, and laboratory tests to detect harmful contaminants [79–81]. Surveillance includes random marketplace testing, monitoring of food production environments, and analysis of imported foods. When contaminants are found, mitigation strategies are implemented, such as regulating agricultural practices, promoting organic farming, enforcing safe pesticide use, and ensuring proper food handling and storage to minimize contamination [82,83]. Public education on food safety and advances in food safety technologies, such as improved packaging and preservatives, also help reduce contamination risks. Enforcement is carried out through inspections and penalties, whereas international collaboration ensures that the global food supply remains safe [84–87].

5. 2. Food processing techniques: Various methods, including washing, peeling, fermentation, and cooking, can reduce or eliminate contaminants such as pathogens, chemicals, and toxins. Heat processing, such as pasteurization and sterilization, kills harmful microorganisms, whereas cold processing, such as freezing, slows microbial growth. Fermentation helps control pathogens and extends shelf-life, and drying removes moisture to inhibit microorganism growth. High-pressure processing (HPP) and irradiation destroy pathogens while preserving the sensory qualities of food. Ultraviolet (UV) light treatment is also effective for surface disinfection. Hygiene and sanitation practices are critical, alongside GAP and GMP, to reduce contamination during farming, harvesting, and processing. Food safety certifications such as hazard analysis and critical control points (HACCPs) help identify and control contamination risks. Natural preservatives and proper packaging materials also prolong shelf-life and reduce contamination [88–93].

5. 3. The use of biocontrol agents (BCAs), such as beneficial microorganisms and biopesticides, helps reduce the reliance on harmful chemicals in food production. BCAs work by competing for resources, producing antimicrobial substances, degrading toxins, inducing resistance in plants, forming biofilms to prevent pathogens, and even breaking down environmental contaminants such as pesticides and heavy metals, thereby reducing health risks [94–97].

5. 4. Consumer education: Educating the public on food safety practices, such as proper storage, handling, and consumption, is crucial for minimizing contamination risk. Key practices include washing hands, cooking food to appropriate temperatures, and preventing cross-contamination. Regulations set by agencies such as the FDA or EFSA establish safety limits for contaminants, and consumer awareness campaigns encourage the reading of food labels, the understanding of safety standards, and the recognition of contamination signs. Promoting the choice of organic or locally produced foods, which tend to contain fewer contaminants, is also part of consumer education efforts. Digital platforms, such as apps or websites, can provide real-time food safety information [98–100].

5. 5. Development of safer alternatives: Advances in biotechnology and chemistry are driving the development of safer food additives, preservatives, and pesticides. Strategies for controlling foodstuff contamination include improving agricultural practices, using safer pesticides, and reducing industrial pollutants. Other preventive measures involve implementing GAP, GMP, and HACCPs in food production. Safer alternatives in food processing include the use of nontoxic preservatives and natural additives. Biological control methods, such as probiotics or beneficial microorganisms, help reduce harmful pathogens. Advanced detection methods, such as sensors and molecular technologies, allow for early identification of contaminants. Nanotechnology and smart packaging materials also offer innovative ways to prevent contamination and monitor food quality in real time [101–108].

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Table 3. Mitigation strategies for food contaminants.

Mitigation strategy	Description	Examples	Key stakeholders
Regulatory Oversight and Monitoring	Set limits for harmful substances in food and implement thorough safety checks, including inspections, tests, and samples. Create strong legal frameworks through bodies like WHO and FAO, monitor production sites, and assess imported food. Promote food safety awareness and incorporate cutting-edge technology into safety procedures.	Promoting organic agriculture, ensuring proper storage and handling, safe pesticide practices, and using enhanced packaging solutions.	Government agencies, health organizations, and regulatory bodies.
Advanced Food Processing Practices	Use techniques like washing, peeling, cooking, and fermentation to remove contaminants. Heat methods like sterilization and pasteurization, along with freezing, reduce microbial growth. Advanced methods like irradiation, high-pressure processing, and UV treatment effectively eliminate pathogens. Ensure strict sanitation and hygiene during production.	Certifications like HACCP, use of natural preservatives, and innovative packaging solutions.	Food processors, manufacturers, and agricultural producers.
Integration of Biological Control Measures	Utilize beneficial microbes and sustainable biopesticides to replace harmful chemicals in agriculture. These agents fight contaminants by producing antimicrobial substances, neutralizing toxins, creating protective barriers, and	Use of environmentally safe biopesticides and growth-promoting microorganisms.	Farmers, researchers, and food producers.

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	breaking down harmful residues such as heavy metals and pesticides.		
Public Awareness and Education	Educate consumers on safe food handling, storage, and preparation to minimize contamination. Promote hygiene practices such as hand washing, thorough cooking, and preventing cross-contamination. Support the consumption of locally sourced or organic foods and share food safety tips through digital platforms and campaigns.	Consumer education initiatives, mobile apps for food safety, and promoting awareness of food labeling.	Health organizations, nonprofits, consumers, and government agencies.
Development of Innovative Alternatives	Develop safer food additives, preservatives, and pesticides using biotechnology and chemistry innovations. Improve farming methods by following standards such as GAP, GMP, and HACCP. Create advanced solutions like nontoxic preservatives, probiotics, molecular detection tools, and nanotech for contamination control and quality assurance.	Smart packaging, natural preservatives, and probiotic solutions.	Biotech firms, researchers, and the food production industry.

FAO: Food and Agriculture Organization; GAP: Good Agricultural Practices; GMP: Good Manufacturing Practices; HACCP: Hazard Analysis and Critical Control Points; UV: Ultraviolet (radiation); WHO: World Health Organization.

6. Strengths and limitations

This study offers a comprehensive overview of food contaminants, detailing their molecular toxicity and various strategies to mitigate their harmful effects. It synthesizes existing scientific literature, delivering evidence-based insights into the molecular mechanisms behind toxicity, thus enhancing our understanding of food safety. By including a variety of mitigation strategies, this review presents practical solutions that can be applied in food safety management and public health initiatives. Its limitations include that the study may lack the rigor of a systematic review, which could lead to biases in article selection or interpretation. The study may depend heavily on secondary data, which might not offer the same level of experimental validation as primary research does. The absence of quantitative data, such as risk assessments or epidemiological models, may limit the ability to accurately estimate the health impacts of food contaminants.

7. Future directions

Further research is needed to explore the molecular mechanisms behind food contaminant toxicity, with particular attention given to their long-term effects. Studies should focus on developing new technologies or interventions to reduce food contamination at the molecular level, prioritizing sustainability and cost-effectiveness. Research aimed at creating universal standards for acceptable food contamination levels and improving global food safety regulations is needed. Investigating the toxicity of lesser-known contaminants, such as endocrine-disrupting chemicals or emerging pollutants in food, is crucial to understanding future risks.

8. Conclusion

Food contaminants present serious threats to public health and originate from various sources, such as environmental pollution, farming activities, food production processes, and packaging materials. These contaminants include biological entities (e.g., microbes such as bacteria, viruses, and molds), chemical compounds (e.g., fertilizers, toxic metals, and synthetic additives), and physical impurities (e.g., fragments of plastic and glass). Their harmful effects are driven by distinct pathophysiological mechanisms, such as triggering oxidative damage, hormonal interference, nerve toxicity, and cancer development, potentially resulting in both short- and long-term health issues. Gaining insight into these mechanisms is crucial for formulating robust prevention strategies. Key measures include adopting best practices in agriculture and manufacturing (GAPs and GMPs), leveraging innovative food processing methods, implementing stringent regulatory policies, and enhancing public education to reduce the risk of exposure.

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