Food and Chemical Toxicology
Volume 2, Number 1, 2023

Emerging Chemical Risks in Food Systems: Insights from Scientific Evidence and Safety Evaluations

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Abstract

Article history:
Received: January 7, 2023
Revised: February 20, 2023
Accepted: April 19, 2023
Published: June 30, 2023

Keywords:
Chemical Contaminants,
Food Safety,
Food Toxicology,
Health Risk,
Microplastics.

Identifier:
Zera Open
Page: 63-79
https://zeraopen.com/journal/fct

Chemical contamination in the food system is a growing global issue that poses serious risks to human health. Various types of chemicals, such as heavy metals, pesticide residues, food additives, and new contaminants, can enter the food chain through the environment, production, distribution, and storage processes. This study aims to systematically examine the types of chemical contaminants in food, their toxicity mechanisms, and their implications for food safety and public health. The method used was a Systematic Literature Review (SLR) of relevant, academically indexed scientific publications from 2017–2022. The results show that chemical contaminants are increasingly diverse and complex, with the main toxicity mechanisms including oxidative stress, DNA damage, enzyme system disruption, and vital organ dysfunction. Long-term exposure, even at low doses, has the potential to cause chronic effects such as cancer, neurological disorders, metabolic diseases, and reproductive disorders. Therefore, strengthening regulations, improving risk-based monitoring systems, and innovating food processing technologies are needed to sustainably minimize the risks of chemicals in food.

1. Introduction

Food safety is a fundamental aspect of maintaining global public health, especially amidst the increasing complexity of modern food production and distribution systems. One of the main challenges in today's food system is the increasing exposure to chemicals originating from various sources, such as polluted environments, the use of chemicals in production processes, and poorly controlled distribution and storage (Thompson & Darwish, 2019). This contamination can occur at various stages of the food chain, from raw materials to the final product consumed by the public. This situation requires serious attention because its impacts are not only short-term but also have the potential to cause long-term health effects.

Heavy metals such as lead, mercury, and cadmium are known to be highly toxic and can accumulate in human tissues through bioaccumulation. Long-term exposure to heavy metals can cause various serious health problems, such as nervous system damage, kidney disorders, and an increased risk of other chronic diseases (Rehman et al., 2018). Furthermore, pesticide residues in agricultural products are also a major concern in food safety. Uncontrolled pesticide use or exceeding safe thresholds can leave harmful residues in food. Long-term, continuous consumption of pesticide residues has the potential to cause chronic toxic effects, including hormonal and immune system disruption, and an increased risk of cancer (Upadhayay et al., 2020).

Therefore, increased oversight, strict regulatory implementation, and increased awareness among producers and consumers are crucial factors in minimizing the risk of chemical contamination in food. These efforts are essential to ensure sustainable food safety, maintain product quality, and protect public health from potential short- and long-term hazards.

The rapid development of the food industry has driven the increased use of chemicals, both as food additives and as components in packaging. This use aims to improve product quality, durability, and safety, but also poses its own risks. One major risk is the migration of chemicals from packaging into food, which constitutes a significant source of exposure for consumers (Hasibuan et al., 2020). Furthermore, the emergence of new contaminants such as microplastics further raises concerns, as these particles have been found in various food products, including drinking water and seafood (Budiarti, 2021), potentially impacting human health.

Chemical contamination in food does not originate from a single source but is the result of complex interactions between human activities and the environment. Various industrial, agricultural, and domestic waste activities contribute to the introduction of hazardous substances into the ecosystem. Persistent organic compounds and synthetic chemicals are known to be highly stable, allowing them to persist for long periods in the environment and accumulate in the food chain (Jones, 2021). This accumulation increases the potential for human exposure through daily food consumption. From a toxicological perspective, the impact of chemicals is highly dependent on the dose, duration of exposure, and the individual's physiological condition. Long-term exposure, even at low doses, can trigger various serious health problems such as cancer, nervous system disorders, hormonal disruption, and even decreased function of vital organs (Gupta, 2020). Based on this background, this study aims to identify various types of chemicals in food, analyze the mechanisms of their toxicity, and comprehensively evaluate their impact on human health. The research results are expected to provide a deeper understanding and serve as a basis for efforts to control food safety risks.

2. Literature Review

2.1. Types of Chemicals in Food

Chemicals in food can be classified into several main categories: heavy metals, pesticide residues, food additives, and emerging new contaminants. Heavy metals such as lead and mercury generally originate from environmental pollution and are bioaccumulative in the human body, potentially causing serious health problems (Ohiagu, 2022). Furthermore, pesticide residues widely used in the agricultural sector are frequently detected in various food products. Long-term exposure to these residues can cause toxic effects that are harmful to human health (Pusfitasari et al., 2021), thus requiring strict monitoring.

Furthermore, food additives such as preservatives, sweeteners, and colorings are often used to improve the quality, shelf life, and attractiveness of food products. Although beneficial, their use must be monitored and limited according to safety standards due to the potential health risks if consumed excessively. In addition to additives, the migration of chemicals from food packaging is also a significant source of contamination, especially when packaging does not meet safety standards or is used under inappropriate conditions (Hasibuan, 2020; Ong et al., 2022). On the other hand, microplastics as new contaminants have been found in various food products, such as drinking water and seafood, thus becoming a serious concern in global food security issues (Liu et al., 2021).

2.2. Mechanism of Chemical Toxicity

The mechanisms of chemical toxicity in the human body involve various complex and interconnected biological processes. One of the main mechanisms that often occurs is oxidative stress, a condition of imbalance between the production of free radicals and the body's ability to neutralize them. Excessive free radicals can damage cell structures, including lipids, proteins, and DNA, leading to cellular dysfunction and even cell death (Ahmadinejad et al., 2017). This damage can contribute to the development of various chronic diseases over the long term.

Furthermore, some chemicals have genotoxic properties, meaning they can damage genetic material (DNA) directly or indirectly. This DNA damage can cause mutations that can potentially develop into cancer if not repaired by the body's defense system. This process often occurs gradually and is not immediately apparent in the short term.

Pesticides, as a source of chemical contaminants, are known to disrupt the nervous system by inhibiting the activity of important enzymes such as acetylcholinesterase. This inhibition leads to the excessive accumulation of neurotransmitters, disrupting normal nervous system function and can cause symptoms such as seizures, respiratory distress, and even permanent nerve damage. On the other hand, heavy metals such as lead, mercury, and cadmium tend to accumulate in the body and cause damage to vital organs like the liver, kidneys, and brain (Lawal et al., 2021).

Furthermore, some chemicals also act as endocrine disruptors, substances that mimic or inhibit the action of natural hormones in the body. This disruption can affect the reproductive system, growth, and metabolism, potentially leading to long-term health impacts (Maggi & Della Torre, 2018).

2.2. Health Impacts of Exposure

Exposure to chemicals in food is a significant issue that can cause various health impacts, both short-term (acute) and long-term (chronic). Acute effects generally occur immediately after consuming contaminated food, such as food poisoning, nausea, vomiting, diarrhea, and digestive system disorders. These conditions are often caused by high levels of harmful substances entering the body over a short period of time. Meanwhile, chronic effects arise from exposure to chemicals in small doses but persisting over a long period of time. These chronic effects include the risk of cancer, nervous system disorders, organ damage, and metabolic diseases such as diabetes and hormone disorders (Hardianto, 2020).

In addition to conventional contaminants, the emergence of new contaminants such as microplastics is a global concern. Microplastics can enter the human body through the consumption of contaminated food and drinks, potentially disrupting the immune system, triggering inflammation, and affecting the body's metabolic balance (Kannan & Vimalkumar, 2021). Furthermore, chemicals from food packaging, such as plastics and coatings, can also migrate into food, especially if exposed to heat or stored for long periods. Continuous exposure to these substances can cause long-term health problems, including toxic effects and endocrine disruption. Therefore, monitoring and controlling chemicals in food is crucial.

3. Methods

This study used a Systematic Literature Review (SLR) approach to comprehensively assess the risks of chemicals in the food system. The SLR method was chosen because it provides a systematic, transparent, and structured synthesis of relevant research findings, resulting in a deeper understanding of the issue under study. This approach allows researchers to identify, evaluate, and integrate previous research findings objectively and based on scientific evidence (Paul et al., 2021 'vc). Therefore, SLR is an appropriate method for analyzing the complexity of chemical exposure in food, which involves multiple sources and mechanisms.

The literature search was conducted through several reputable scientific databases, namely Scopus, PubMed, and Google Scholar. These databases were selected based on their broad publication coverage and the high credibility of the sources in providing quality scientific articles. Keywords used in the search process included "food contaminants," "chemical toxicity," and "food safety." Furthermore, keyword combinations with Boolean operators such as AND and OR were used to broaden and narrow search results to ensure greater relevance to the research focus.

The inclusion criteria applied in this study included scientific articles published between 2018 and 2022, directly relevant to the topic of chemical risks in food, and available in full-text form. Articles that did not meet these criteria, such as those not indexed, incompletely available, or not focused on the toxicity of chemicals in food, were eliminated from the analysis process. This was done to ensure the high quality and validity of the data used.

The research stages in this SLR included three main steps: identification, selection, and analysis of articles. In the identification stage, all articles obtained from the initial search results were collected. Next, the selection stage was carried out by filtering the articles based on predetermined inclusion and exclusion criteria. The final stage was data analysis, in which the selected articles were analyzed using a thematic approach. This approach aims to identify patterns, relationships, and trends in research related to chemicals in food, thereby providing a comprehensive picture of the risks and impacts on human health.

4. Results

4.1. Identification of Various Types of Chemicals in Food

Studies show that chemicals in food originate from various interrelated sources, including the environment, production processes, distribution, and packaging. One major group is heavy metals such as lead (Pb) and mercury (Hg), which enter the food chain through water, soil, and air pollution caused by industrial activities and waste. Seafood products such as fish and shellfish are the primary sources of accumulation due to their ability to absorb contaminants from the aquatic environment (Venugopal & Gopakumar, 2017). Furthermore, pesticide residues are also commonly found in agricultural products such as vegetables and fruits. Substandard pesticide use can leave residues that are harmful to human health. The level of these residues depends heavily on the type of pesticide, frequency of use, and the time interval between application and harvest.

New contaminants such as microplastics are also increasingly found in modern food systems. These particles have been detected in drinking water, salt, and seafood, indicating widespread and difficult-to-control contamination. Furthermore, chemicals from food packaging, such as per- and polyfluoroalkyl substances (PFAS), also have the potential to migrate into food, especially under certain conditions such as high temperatures and long-term storage (Laelasari, 2021). Thus, the types of chemicals in food are not limited to conventional contaminants but also include increasingly complex and diverse emerging contaminants.

4.1. Mechanisms of Chemical Toxicity in Food

Chemicals in food can cause toxic effects through various complex biological mechanisms. One key mechanism is oxidative stress, an imbalance between free radicals and the body's antioxidant system. This condition causes damage to cellular components such as lipids, proteins, and DNA, ultimately disrupting normal cell function (Venugopal & Gopakumar, 2017).

Furthermore, some chemicals have the ability to directly damage DNA, triggering genetic mutations that can potentially lead to cancer. Exposure to these hazardous substances is a serious environmental health concern. Heavy metals such as mercury and lead are also dangerous because they can damage neurons, disrupt brain function, and significantly inhibit nerve signal transmission.

Pesticide residues also have specific toxicity mechanisms, such as inhibiting important enzymes in the nervous system, such as acetylcholinesterase. This inhibition disrupts nerve impulse transmission, which can lead to neurological disorders. Furthermore, some pesticides and compounds like PFAS act as endocrine disruptors, substances that interfere with the body's hormone system. This disruption can affect various biological functions, including growth, metabolism, and reproduction.

Microplastics have unique toxicity mechanisms, acting not only as foreign particles in the body but also as carriers of various hazardous chemicals, such as heavy metals and toxic organic compounds. This property allows microplastics to bind and accumulate contaminants from the environment. Consequently, exposure to microplastics can significantly increase health risks, particularly when the body is exposed to a combination of various hazardous substances simultaneously and over a long period of time.

4.1. The Impact of Food Chemicals on Human Health

Exposure to chemicals in food, especially over the long term, has a significant impact on human health. One major impact is an increased risk of chronic diseases, such as cancer, which can be triggered by DNA damage and genetic mutations caused by exposure to hazardous chemicals (Venugopal & Gopakumar, 2017).

Furthermore, exposure to heavy metals such as mercury can cause serious neurological disorders, including decreased cognitive function, impaired motor coordination, and permanent damage to the central nervous system. Long-term accumulation of mercury in the body can also affect learning and memory. Meanwhile, lead exposure is known to be particularly dangerous for children, as it can inhibit brain development, reduce intelligence, and trigger behavioral disorders and learning difficulties.

Furthermore, pesticide residues in food can disrupt the endocrine system, affecting hormonal balance and impacting reproductive health. Long-term exposure is also associated with an increased risk of metabolic disorders such as obesity and diabetes. Furthermore, PFAS compounds are known to contribute to immune system disorders, hormonal imbalances, and an increased risk of various chronic diseases that are dangerous to human health.

The impact of microplastics on human health is still being researched, but several studies indicate potential disruptions to the digestive, immune, and metabolic systems. Furthermore, the presence of microplastics as carriers of toxic substances increases the potential for negative effects on the human body. Overall, the impact of chemicals in food is not only individual but also impacts public health at large. Therefore, integrated efforts in monitoring, regulation, and raising public awareness are needed to minimize chemical exposure and ensure sustainable food safety.

5. Discussion

The findings of this study confirm that chemical contamination in food is a multidimensional issue involving interactions between environmental factors, production practices, and distribution and consumption systems. The presence of heavy metals such as lead (Pb) and mercury (Hg) indicates that environmental pollution remains a major source of hazardous substances entering the food chain. The accumulation of contaminants in aquatic products, particularly fish and shellfish, indicates bioaccumulation and biomagnification processes that increase the risk of human exposure (Venugopal & Gopakumar, 2017). This reinforces the urgency of industrial waste management and aquatic ecosystem protection as part of a food safety strategy.

Furthermore, pesticide residues in agricultural products reflect ongoing gaps in the implementation of good agricultural practices. Variations in residue levels, influenced by pesticide type, dosage, and harvest interval, indicate that managerial aspects of agrochemical use significantly determine the level of risk to consumers. In this context, strengthening regulations and educating farmers are crucial steps to reduce exposure to hazardous residues in food.

Emerging contaminants such as microplastics and PFAS add to the complexity of modern food safety issues. Microplastics not only act as foreign particles but also as vectors for other toxic substances, thus synergistically increasing the potential for toxic effects. Meanwhile, PFAS originating from food packaging materials indicates that contamination sources originate not only from upstream production but also from downstream aspects such as packaging and storage (Laelasari, 2021). This phenomenon demands a more comprehensive approach to food safety monitoring, encompassing the entire supply chain.

In terms of toxicity mechanisms, studies indicate that chemicals in food can trigger oxidative stress, DNA damage, nervous system disorders, and endocrine disruption. This mechanism explains the link between chemical exposure and an increased risk of chronic diseases such as cancer, neurological disorders, and metabolic disorders. Long-term exposure, even at low doses, still has the potential to cause significant cumulative effects on human health (Venugopal & Gopakumar, 2017).

The implications of these findings demonstrate that food safety cannot be separated from public health policies and environmental protection. Therefore, an integrated approach is needed that involves strict regulation, ongoing monitoring, innovation in safe packaging technology, and increased public awareness. Thus, the risk of exposure to chemicals in food can be effectively minimized to support the creation of a safe and sustainable food system (Laelasari, 2021).

6. Conclusion

This research demonstrates that chemical contamination in the food system is increasingly diverse and complex, encompassing heavy metals, pesticide residues, food additives, and emerging contaminants like microplastics and PFAS. Key findings indicate that these chemicals have diverse toxicity mechanisms, including oxidative stress, DNA damage, enzyme disruption, and endocrine system dysfunction. Long-term exposure, even at low doses, has the potential to cause chronic impacts such as cancer, neurological disorders, metabolic diseases, and reproductive disorders. Furthermore, synergistic effects between contaminants exacerbate health risks, further complicating this issue from a food safety perspective.

However, this research has limitations, primarily due to its use of a Systematic Literature Review (SLR) approach, which relies on the availability and quality of previous studies within a limited timeframe (2018–2022). Variations in research methods, differences in study locations, and limited quantitative data on actual exposure levels also hinder broader generalizations.

The implications of this research emphasize the importance of strengthening regulations, improving risk-based monitoring systems, and implementing innovative technologies in food processing and packaging. Furthermore, it is necessary to increase awareness among producers and consumers regarding the dangers of chemicals in food.

For further research, it is recommended to conduct empirical studies based on primary data that directly measure exposure levels, as well as longitudinal studies to more comprehensively understand long-term impacts. Studies on interactions between contaminants (mixture effects) and the development of more sensitive detection methods are also important agenda items to support sustainable food safety.

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