



# Integrated Risk Assessment of Food Contaminants and Implications for Human Health

Tryoga Ganjar<sup>1</sup>

<sup>1</sup> Sekolah Tinggi Ilmu Kesehatan Bina Putera Banjar, Banjar, Indonesia

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## Abstract

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### Article history:

Received: July 29, 2025

Revised: October 25, 2025

Accepted: November 14, 2025

Published: December 30, 2025

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### Keywords:

cumulative exposure,  
food safety,  
integrated risk assessment,  
mixture toxicity,  
risk assessment,  
toxicology.

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### Identifier:

Zera Open

Page: 145-161

<https://zeraopen.com/journal/fct>

Food safety in modern food systems is increasingly challenged by the simultaneous presence of multiple contaminants, including heavy metals, food additives, emerging contaminants, and natural bioactive compounds. This study develops an integrated perspective on food contaminant risk assessment by synthesizing evidence on contamination sources, exposure pathways, toxicological mechanisms, and regulatory frameworks. A qualitative Systematic Literature Review (SLR) approach was applied to analyze peer-reviewed studies published between 2020 and 2025. The findings indicate that human exposure is cumulative and influenced by dietary patterns, environmental conditions, and food production systems. Shared toxicological mechanisms, such as oxidative stress and metabolic disruption, suggest that combined exposure may amplify health risks. The study highlights limitations of traditional single-substance risk assessment models and emphasizes the need for integrative frameworks that account for mixture effects and exposure variability. These insights support the development of more adaptive and comprehensive food safety strategies.

## **1. Introduction**

Food safety has become an increasingly complex challenge in modern food systems due to the presence of diverse contaminants originating from environmental, industrial, and food processing activities. These contaminants include heavy metals, food additives, emerging substances such as microplastics and per- and polyfluoroalkyl substances (PFAS), as well as natural bioactive compounds that may exhibit toxic effects under certain conditions. Liu et al. (2025) emphasize that the evolving landscape of food contamination reflects the growing interaction between human activities and environmental systems. Traditional food safety concerns are therefore expanding to include both conventional and emerging risks that require more comprehensive evaluation. In addition, the globalization of food supply chains further increases the complexity of contamination pathways and exposure scenarios. These developments highlight the need for more integrative approaches to food safety assessment.

Human exposure to food contaminants occurs through multiple pathways, primarily via dietary intake, but also through indirect interactions with environmental media and food packaging materials. The diversity of contaminants means that individuals are rarely exposed to a single substance, but rather to mixtures of compounds with varying chemical properties and toxicological effects. Mititelu et al. (2025) note that dietary exposure to contaminants is continuous and influenced by food consumption patterns and environmental conditions. Similarly, Schoeters et al. (2025) identify food as a major route of exposure to persistent chemicals such as PFAS. These exposure patterns are further complicated by differences in geographic

location, lifestyle, and socioeconomic factors. As a result, assessing exposure requires consideration of multiple variables that interact within food systems. Understanding these pathways is essential for evaluating health risks.

The toxicological effects of food contaminants are diverse and depend on factors such as chemical structure, dose, exposure duration, and interactions with biological systems. Wu et al. (2022) highlight that contaminants can induce a range of biological responses, including oxidative stress, inflammation, and metabolic disruption. These mechanisms are not limited to specific contaminants but are often shared across different classes of substances. In addition, the potential for additive or synergistic effects among multiple contaminants introduces further complexity in understanding health outcomes. This is particularly relevant in modern diets, where exposure to multiple contaminants is common. The interaction between different toxicological pathways may amplify adverse effects. These considerations underscore the importance of evaluating contaminants within a broader biological context.

Current risk assessment frameworks for food safety are primarily based on evaluating individual contaminants using established thresholds and toxicological data. Regulatory guidelines, such as those provided by EFSA (2021), play a crucial role in setting safety standards and controlling exposure levels. However, these approaches may not fully capture the complexity of real-world exposure scenarios, particularly when multiple contaminants are present simultaneously. Cattaneo et al. (2023) emphasize that combined exposure to multiple chemicals represents a significant challenge for risk assessment. In addition, Gürtler (2021) notes that

traditional models may underestimate risks by failing to account for interactions between substances. These limitations highlight the need for more advanced and integrative assessment frameworks. Adapting risk assessment approaches is therefore essential for addressing modern food safety challenges.

This study aims to develop an integrated perspective on food safety risk assessment by synthesizing evidence on different types of food contaminants, exposure pathways, toxicological mechanisms, and existing regulatory approaches. Using a qualitative Systematic Literature Review (SLR) methodology, this study evaluates how multiple contaminants interact within food systems and influence human health outcomes. The analysis emphasizes the importance of cumulative exposure, mixture effects, and variability in real-world conditions. By integrating these dimensions, the study contributes to the development of more comprehensive and adaptive risk assessment frameworks. This approach supports improved decision-making in food safety management and public health protection.

## **2. Literature Review**

### **2.1. Types of Food Contaminants in Modern Food Systems**

Food contaminants in modern food systems encompass a diverse range of chemical substances originating from environmental, industrial, and biological sources. These include heavy metals, synthetic food additives, emerging contaminants such as microplastics and PFAS, and natural bioactive compounds that may exhibit toxic effects under certain conditions. Angon et al. (2024) highlight that heavy metals persist in environmental media and enter food systems through

soil and water contamination. Food additives, while intentionally used to improve food quality, have also been associated with potential health risks under certain exposure conditions (Cox et al., 2021). In addition, natural compounds are increasingly recognized for their dual nature, where beneficial effects may coexist with toxicological risks (Jitäreanu et al., 2022). The coexistence of these diverse contaminants reflects the complexity of modern food systems. Understanding these categories is essential for developing comprehensive risk assessment approaches.

## **2.2. Exposure Pathways and Dietary Intake**

Human exposure to food contaminants occurs through multiple pathways, with dietary intake representing the primary route. Sarker et al. (2022) emphasize that contaminants are transferred through food chains via processes such as bioaccumulation and trophic transfer. In addition, consumption patterns, particularly the intake of processed and ultra-processed foods, influence exposure to additives and other contaminants (Pagliai et al., 2021). Emerging contaminants such as microplastics further complicate exposure scenarios, as they are present in a wide range of food products (Lane et al., 2025). These pathways are influenced by environmental conditions, food production practices, and individual dietary habits. The variability in exposure across populations makes it difficult to establish uniform risk assessments. These findings highlight the importance of considering real-world consumption patterns in evaluating exposure.

## **2.3. Toxicological Mechanisms Across Contaminant Types**

The toxicological effects of food contaminants are mediated through multiple biological mechanisms that can affect human health. Campanale et al. (2020) note

that contaminants such as microplastics can induce oxidative stress and inflammation, leading to cellular damage. PFAS exposure has been associated with immune and metabolic disruptions due to their persistence and bioaccumulative properties (De Silva et al., 2021). Similarly, natural compounds may exert toxic effects through mechanisms such as oxidative stress and molecular interactions (Luo et al., 2021). These mechanisms are often shared across different contaminant types, suggesting common pathways of toxicity. The interaction between multiple contaminants may amplify these effects through additive or synergistic mechanisms. This highlights the need to consider cross-contaminant interactions in toxicological evaluation.

#### **2.4. Current Risk Assessment Approaches and Limitations**

Risk assessment frameworks for food safety are primarily based on evaluating individual contaminants using toxicological data and established safety thresholds. Gürtler (2021) explains that these approaches rely on determining acceptable exposure levels to minimize health risks. Regulatory bodies such as EFSA (2021) provide guidelines for assessing the safety of contaminants and ensuring compliance with safety standards. However, these frameworks often focus on single substances and may not adequately capture the complexity of real-world exposure scenarios. Wang et al. (2023) highlight the importance of quality control and monitoring systems in improving safety evaluation. Despite these efforts, limitations remain in addressing variability in exposure and interactions between contaminants. These challenges indicate the need for more comprehensive assessment models.

## 2.5. Integrated Risk Assessment and Future Directions

Recent research emphasizes the need for integrated risk assessment approaches that consider multiple contaminants and their interactions within food systems. Cattaneo et al. (2023) highlight that combined exposure to multiple chemicals requires new methodologies that account for additive and synergistic effects. Mukherjee et al. (2022) further note that mixed contaminants can influence toxicity in complex and unpredictable ways. Liu et al. (2025) suggest that advancing food safety requires integrating data from environmental, toxicological, and dietary studies. These approaches aim to provide a more realistic representation of exposure and risk in modern food systems. Developing integrated frameworks is essential for improving risk assessment and supporting effective regulatory decision-making. Such advancements will contribute to more robust and adaptive food safety strategies.

## 3. Methods

This study employs a qualitative Systematic Literature Review (SLR) approach to develop an integrated perspective on food contaminant risk assessment and its implications for human health. The SLR method enables a structured synthesis of existing scientific literature across multiple domains, including environmental toxicology, food safety, public health, and regulatory science, without generating new experimental data. Relevant studies were identified through academic databases to ensure comprehensive and reliable coverage. The search strategy utilized combinations of keywords such as “food contaminants,” “risk assessment,”

“cumulative exposure,” “mixture toxicity,” and “food safety frameworks” to capture studies addressing contamination types, exposure pathways, and assessment methodologies. The inclusion criteria were limited to peer-reviewed articles published between 2020 and 2025, ensuring the integration of recent developments in risk assessment approaches. Selected studies were analyzed using thematic synthesis to identify patterns, relationships, and gaps related to integrated risk assessment in modern food systems.

#### **4. Results**

This section presents the synthesized findings on integrated risk assessment of food contaminants, focusing on contaminant categories, exposure pathways, toxicological mechanisms, and the development of a comprehensive assessment framework. The results indicate that food safety risks in modern systems are shaped by the interaction of multiple contaminants rather than isolated substances. These contaminants originate from diverse sources and are introduced into food systems through environmental, industrial, and biological processes. The analysis also shows that exposure is continuous and influenced by dietary patterns, environmental conditions, and food production practices. Such complexity challenges traditional approaches that rely on single-contaminant evaluation. In addition, the findings emphasize the importance of considering cumulative exposure and interaction effects. Overall, the results support the need for an integrated framework to improve risk assessment and decision-making.

#### **4.1. Classification of Food Contaminants in Integrated Systems**

The findings show that food contaminants can be classified into multiple categories based on their origin and functional characteristics, including heavy metals, food additives, emerging contaminants, and natural bioactive compounds. Each category contributes differently to food safety risks, depending on its source, persistence, and exposure pathways. Angon et al. (2024) highlight that heavy metals originate primarily from environmental contamination, while food additives are intentionally introduced during food processing (Cox et al., 2021). Emerging contaminants such as microplastics and PFAS represent a growing concern due to their persistence and limited regulation. In addition, natural compounds exhibit dual effects, where beneficial properties may coexist with toxicological risks (Jitãreanu et al., 2022). The coexistence of these categories indicates that food systems are influenced by both intentional and unintentional contaminants. This classification provides a foundation for integrated risk assessment.

#### **4.2. Exposure Pathways and Cumulative Intake**

The results indicate that exposure to food contaminants occurs through multiple pathways, with dietary intake serving as the primary route. Sarker et al. (2022) emphasize that contaminants are transferred through food chains via processes such as bioaccumulation and trophic transfer. In addition, consumption patterns, particularly the intake of processed foods, influence exposure to additives and other substances (Pagliai et al., 2021). Lane et al. (2025) highlight that emerging contaminants such as microplastics are present in a wide range of food products, contributing to continuous exposure. These pathways are influenced by

environmental conditions, food production systems, and individual dietary habits. The cumulative nature of exposure means that individuals are exposed to multiple contaminants simultaneously. This complexity requires assessment approaches that consider total exposure rather than isolated intake.

#### **4.3. Shared Toxicological Mechanisms Across Contaminants**

The findings show that different categories of contaminants share common toxicological mechanisms that influence human health outcomes. Campanale et al. (2020) note that contaminants such as microplastics can induce oxidative stress and inflammation, leading to cellular damage. PFAS exposure has been associated with immune and metabolic disruption due to their persistence and bioaccumulation (De Silva et al., 2021). Similarly, natural compounds may exert toxic effects through molecular interactions and oxidative processes (Luo et al., 2021). These mechanisms are not unique to individual contaminants but are observed across multiple categories. The overlap of these biological pathways suggests that combined exposure may amplify toxic effects. This highlights the importance of considering shared mechanisms in risk assessment.

#### **4.4. Integrated Risk Assessment Framework**

The results support the development of an integrated risk assessment framework that incorporates multiple contaminants, exposure pathways, and biological mechanisms. Traditional models focus on individual substances and may not adequately capture real-world exposure scenarios. Gürtler (2021) emphasizes that risk assessment must evolve to include more comprehensive approaches. EFSA (2021) provides guidance for evaluating contaminants, but integration across

contaminant types remains limited. Cattaneo et al. (2023) highlight the importance of addressing combined exposure and mixture effects in modern risk assessment. The proposed framework integrates environmental sources, food chain transfer, exposure pathways, and toxicological mechanisms into a unified model. This approach provides a more realistic representation of risk in complex food systems.

**Table 1.** Integrated Framework for Food Contaminant Risk Assessment

Component	Description	Role in Risk Assessment
Contaminant Types	Heavy metals, additives, emerging, natural	Identify sources of risk
Exposure Pathways	Dietary, environmental, indirect	Determine intake routes
Biological Mechanisms	Oxidative stress, inflammation, disruption	Explain health effects
Interaction Effects	Additive, synergistic	Capture combined impact
Risk Outcome	Health impact	Final risk evaluation

#### 4.5. Implications of Combined Exposure and Risk Variability

The findings indicate that combined exposure to multiple contaminants significantly influences risk variability across populations. Mukherjee et al. (2022) highlight that mixed contaminants can interact in complex ways, affecting toxicity and health outcomes. Liu et al. (2025) further emphasize that modern food systems create diverse exposure scenarios that vary across geographic and demographic contexts. In addition, Schoeters et al. (2025) identify dietary intake as a key pathway for persistent contaminants such as PFAS. These variations make it difficult to apply uniform risk assessment models across populations. The interaction between exposure variability and contaminant mixtures introduces uncertainty in risk evaluation. These findings highlight the need for adaptive and context-specific assessment approaches.

**Table 2.** Factors Influencing Variability in Food Contaminant Risk

<b>Factor</b>	<b>Description</b>	<b>Impact on Risk</b>
Dietary habits	Variation in food consumption	Alters exposure level
Environmental conditions	Pollution and contamination	Affects contaminant presence
Contaminant mixtures	Multiple substances	Increases complexity
Biological variability	Individual differences	Influences susceptibility
Food systems	Production and processing	Modifies contamination pathways

## 5. Discussion

The findings demonstrate that food safety risks in modern food systems cannot be adequately understood through isolated evaluation of individual contaminants. Instead, risk emerges from the interaction of multiple contaminant types, exposure pathways, and shared toxicological mechanisms. This interconnected structure highlights the limitations of traditional assessment models that rely on single-substance analysis and fixed exposure thresholds. The integration of different contaminant categories, including heavy metals, additives, emerging substances, and natural compounds, reveals that real-world exposure is inherently cumulative and multidimensional. In addition, variability in environmental conditions and dietary patterns further complicates the assessment of risk. These factors indicate that food safety should be approached as a system-level issue rather than a series of independent concerns. A shift toward integrated frameworks is therefore essential for capturing the complexity of modern exposure scenarios.

Another important implication is that the effectiveness of risk assessment depends on its ability to incorporate variability and interaction effects into decision-making processes. Traditional models often underestimate risk by failing to account

for combined exposure and shared biological pathways. The presence of common mechanisms such as oxidative stress and metabolic disruption suggests that different contaminants may contribute to similar health outcomes, potentially amplifying overall risk. Furthermore, differences in individual susceptibility and consumption patterns introduce additional uncertainty that must be addressed. These challenges highlight the need for adaptive and flexible assessment models that can respond to evolving food systems. Improving regulatory strategies will require integrating scientific evidence from multiple disciplines and adopting a more holistic perspective. Such advancements are critical for ensuring effective protection of public health in increasingly complex food environments.

## **6. Conclusion**

This study demonstrates that food safety in modern food systems is shaped by the interaction of multiple contaminants rather than isolated exposure to individual substances. The findings show that heavy metals, food additives, emerging contaminants, and natural bioactive compounds collectively contribute to complex exposure scenarios that influence human health. These contaminants enter food systems through diverse pathways and are affected by environmental conditions, production practices, and consumption patterns. Their combined presence leads to cumulative exposure, which increases the difficulty of accurately assessing risk. This highlights the limitation of traditional approaches that evaluate contaminants independently. A comprehensive and integrated perspective is therefore essential for understanding food safety risks.

From a toxicological standpoint, the study emphasizes that different contaminants often share common biological mechanisms, including oxidative stress, inflammation, and metabolic disruption. These shared mechanisms suggest that combined exposure may amplify health effects through additive or synergistic interactions. In addition, variability in exposure levels and individual susceptibility further complicates the evaluation of risk. These factors indicate that risk assessment must account for both the diversity of contaminants and the complexity of biological responses. Understanding these interactions is critical for improving the accuracy of health risk evaluations. An integrated approach provides a more realistic representation of how contaminants affect human health in real-world conditions.

In practical terms, the findings highlight the need to advance current food safety frameworks toward more adaptive and integrative models. Traditional risk assessment methods based on single-substance evaluation and fixed thresholds may not adequately reflect the complexity of modern food systems. Future research should focus on developing methodologies that incorporate cumulative exposure, mixture effects, and variability across populations. Strengthening monitoring systems and improving data integration are also essential for supporting more accurate assessments. In addition, collaboration across scientific, regulatory, and industrial sectors will be necessary to implement effective risk management strategies. These efforts are critical for ensuring that food safety policies remain effective in addressing evolving challenges in global food systems.

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