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Food Ethics and Biological Alignment : Rethinking Human Health In A Contaminated World

Sub-Theme: *Education for Sustainability*

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ABSTRACT

We are living in the Anthropocene, an era in which human activity profoundly shapes food systems and environmental conditions. While advances in agriculture and food technology have improved food availability, they have also intensified chronic exposure to chemical contaminants, including heavy metals, synthetic pesticides, and food contact chemicals. Conventional toxicological risk assessment emphasizes exposure avoidance and regulatory thresholds, effectively preventing acute toxicity but offering limited insight into health outcomes associated with chronic, low-dose, and cumulative exposure. This literature review synthesizes current evidence on chronic food-related chemical exposure through the framework of biological alignment. Cadmium, glyphosate, and bisphenol A were selected as representative toxicants reflecting cumulative accumulation, regulatory-permitted exposure, and dependence on individual detoxification capacity within modern food systems. The reviewed evidence indicates that risk under chronic exposure is shaped not only by external dose but also by internal biological mediation, including detoxification efficiency, oxidative stress regulation, endocrine sensitivity, nutritional status, and metabolic health. Biomonitoring studies consistently demonstrate measurable internal exposure across populations despite compliance with regulatory thresholds, highlighting substantial interindividual variability in biological response. Integrating biological alignment with conventional exposure-based assessment may strengthen public health protection by accounting for physiological variability and adaptive capacity while remaining consistent with regulatory frameworks and food system governance.

Keywords: *Anthropocene, Biological Alignment, Food Toxicology, Chronic Exposure, Detoxification*

INTRODUCTION

Human Health in the Anthropocene Era

Human health is increasingly shaped by environmental conditions created through modern industrial and agricultural activities. Large-scale food production, intensified farming, and widespread chemical use have improved food availability, but have also introduced persistent chemical contaminants into everyday diets. Bouida et al. (2022) reported that heavy metals and synthetic compounds, are now commonly detected across multiple food categories. This indicates dietary exposure has become continuous rather than incidental.

Unlike earlier toxicological concerns that focused mainly on acute poisoning events, current exposure patterns are predominantly chronic and low-dose. Suhani et al. (2021) highlighted that long-term dietary intake represents one of the most consistent exposure pathways for environmental toxicants. Particularly when contaminants are embedded within staple foods. As a result, food consumption has emerged as a primary route, through which chemical stressors enter the human body on a daily basis.

Cadmium provides a clear example of this shift. Genchi et al. (2020) demonstrated that although naturally occurring, cadmium becomes concentrated in food crops through fertilizer application, industrial emissions, and soil contamination. Qing et al. (2023) further showed that dietary intake alone can lead to cumulative cadmium exposure approaching regulatory limits in certain populations, even in the absence of occupational exposure. These findings suggest that chronic intake, instead of isolated exposure events, drives toxicological risk for many food-related contaminants.

Similar patterns are observed for anthropogenic compounds such as glyphosate and bisphenol A (BPA). Gillezeau et al. (2019) found that glyphosate residues are frequently detected in cereals and processed foods, resulting in repeated low-level exposure across the lifespan. EFSA (2023) also reported that food contact materials remain a significant source of exposure, particularly through canned and packaged products, despite regulatory restrictions and reformulation efforts.

This exposure landscape challenges the assumption that human health can be protected through avoidance of contaminants only. Complete avoidance seems unrealistic within modern food systems, especially for widely used agricultural chemicals and packaging materials. Instead of implying ethical acceptance of contamination, this reality underscores the need to understand how biological systems respond to unavoidable chemical exposure.

Recognizing exposure as an ongoing condition shifts the focus of toxicological interpretation. Health outcomes cannot be explained by external dose alone, but must also account for internal physiological processes that have impacts on absorption, detoxification, and tissue response. Understanding these biological factors is essential for interpreting toxicological risk under real-world dietary exposure conditions.

Current Paradigms in Toxicological Risk Management

Toxicological risk management in food safety is primarily based on exposure-centered assessment models. Regulatory agencies including EFSA (2015) establish safety thresholds such as Acceptable Daily Intake (ADI), Tolerable Weekly Intake (TWI) , and No Observed Adverse Effect Levels (NOAEL) to define limits that are considered protective for human health. These benchmarks play an essential role in guiding policy decisions, food monitoring programs, and consumer protection strategies.

This approach has been effective in reducing acute toxicity and preventing high-dose exposure events. Regulatory evaluations focus on identifying critical toxicity endpoints and estimating exposure levels across populations to ensure that intake remains below established thresholds (EPA, 2020). As a result, exposure reduction has become the dominant strategy for managing chemical risks in food systems.

Cadmium shows how this regulatory framework is applied in practice. Exposure limits for cadmium are largely derived from renal toxicity endpoints, with benchmark dose modeling used to estimate intake levels associated with kidney damage (Nogawa et al., 2021). These limits are designed to prevent clinically apparent toxicity and irreversible organ injury under typical dietary conditions.

Glyphosate has undergone a similar regulatory process. Risk assessments have focused on toxicological data from animal studies, exposure modeling, and epidemiological evidence to determine acceptable intake levels for consumers (EFSA, 2023). These evaluations emphasize population-level protection and compliance with regulatory standards instead of individual biological variability.

While exposure-based regulation remains essential, it implicitly assumes that individuals respond similarly to equivalent exposure levels. Therefore, human biology is treated primarily as a passive recipient of chemical exposure, with risk defined largely by external dose instead of internal physiological response.

Limitations of Exposure-Centered Models

Growing evidence suggests that exposure-centered models are not enough for explaining health outcomes associated with chronic, low-dose chemical exposure. Individuals with comparable dietary intake often show markedly different biological responses, indicating that internal physiological factors play a significant role in toxicological risk (Satarug et al., 2022).

Cadmium is a clear example of this limitation. Epidemiological studies show that cumulative cadmium exposure is associated with renal dysfunction and metabolic disturbances even when estimated intake remains within regulatory limits (Qing et al., 2021). These findings indicate that long-term accumulation and biological retention are critical determinants of toxicity.

Glyphosate exposure presents a similar challenge. Chronic low-dose exposure has been linked to oxidative stress and alterations in gut microbiome composition, effects that are not fully captured by traditional toxicity endpoints (Mesnage & Antoniou, 2020). These biological changes may occur without exceeding established exposure thresholds.

In the case of BPA, toxicological concern arises from continuous re-exposure rather than persistence within the body. Although BPA is metabolized very fast, repeated dietary intake results in sustained internal exposure with documented endocrine-related effects at very low doses (EFSA, 2023). This pattern challenges the assumption that such rapid clearance necessarily equates to low biological risk.

Eventually, these findings demonstrate that regulatory compliance does not always correspond to biological neutrality. Exposure thresholds are necessary for population-level protection, but they may not fully reflect individual susceptibility under real-world conditions.

Biological Alignment Framework

The limitations of exposure-based toxicology emphasize the need for an interpretive framework that incorporates biological mediation of chemical risk. Internal factors such as detoxification efficiency, nutritional status, metabolic health, oxidative balance, and endocrine sensitivity influence how chemical exposure translates into human health outcomes (Genchi et al., 2020).

Biological alignment is introduced in this review as a framework that describes the capacity of physiological systems to maintain functional stability under conditions of unavoidable chemical exposure. Instead of replacing regulatory control, this perspective complements existing risk assessment approaches by accounting for biological variability.

By integrating evidence from toxicology, nutrition science, and physiology, biological alignment reframes toxicological risk as an interaction between exposure and biological response. This approach supports a shift away from avoidance-based narratives toward a more realistic understanding of health within contemporary food systems.

Understanding biological mediation does not imply ethical acceptance of contamination. Instead, it reinforces the responsibility of governance structures to minimize preventable exposure while

acknowledging the biological realities faced by populations living within contaminated environments.

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MATERIALS AND METHOD

Study Design

This study employed a **narrative literature review** design to synthesize scientific evidence on chronic food-related chemical exposure, biological mediation of toxicological risk, and ethical dimensions of food systems. A narrative approach was selected to enable integrative analysis across multiple disciplines, including environmental toxicology, nutritional biochemistry, endocrine physiology, microbiome science, and public health ethics, which are not readily addressed through quantitative meta-analysis.

Literature Identification and Selection

The literature corpus focused on three representative food-related toxicants: cadmium, glyphosate, and bisphenol A (BPA). These toxicants were selected to reflect distinct exposure profiles, including cumulative bioaccumulation (cadmium), policy-mediated agricultural exposure (glyphosate), and detoxification-dependent consumer exposure (BPA).

Approximately 50 peer-reviewed publications published between 2005 and 2024 were reviewed, with emphasis on studies from the last decade. Literature sources included peer-reviewed journal articles, authoritative review papers, and regulatory assessments issued by recognized agencies. Inclusion criteria comprised studies addressing:

(1) chronic or low-dose dietary exposure,
(2) biological or physiological mechanisms of toxicity, and
(3) health outcomes relevant to renal, metabolic, endocrine, immune, or microbiome-related pathways.

Studies focused exclusively on acute poisoning, non-dietary exposure routes, or lacking biological relevance were excluded.

Analytical and Conceptual Synthesis

Rather than quantitative effect estimation, this review applied qualitative conceptual synthesis to integrate findings across toxicological mechanisms and physiological systems. Analytical dimensions included exposure characteristics, biological mediation processes, and contextual modifiers such as nutritional status, metabolic health, and regulatory environment.

From this synthesis, the framework of biological alignment was developed to describe the capacity of human physiological systems to maintain functional stability under chronic chemical exposure. Ethical considerations related to food systems, governance, and environmental responsibility were subsequently integrated to contextualize toxicological risk within broader public health and sustainability frameworks.

RESULTS AND DISCUSSION

Results

Evidence of Chronic Dietary Exposure to Food-Related Toxicants

Across the reviewed literature, consistent evidence indicates that human exposure to food-related chemical contaminants is widespread, measurable, and chronic. Biomonitoring and dietary assessment studies demonstrate detectable internal exposure to cadmium, glyphosate, and BPA across diverse populations and geographical regions.

For cadmium, dietary exposure through staple foods such as rice, cereals, and leafy vegetables frequently approaches or even exceeds established tolerable intake levels in high-consumption populations. Multiple studies report significant associations between urinary cadmium concentrations and renal biomarkers, including reduced glomerular filtration rate and evidence of tubular dysfunction, even when estimated intake remains within regulatory limits (Qing et al., 2021; Nogawa et al., 2021; Satarug et al., 2022). Food surveillance and exposure analyses further demonstrate heterogeneous cadmium burden linked to dietary patterns and agricultural context (Qing et al., 2023).

Glyphosate exposure is similarly characterized by high prevalence and repeated intake. Biomonitoring studies consistently report detectable urinary glyphosate in the majority of sampled individuals, often exceeding 70% detection frequency, indicating continuous dietary exposure through cereals, grains, and processed foods (Gillezeau et al., 2019; Zoller et al., 2020). These findings persist across regions despite differences in regulatory thresholds and agricultural practices (EFSA, 2023).

BPA shows a different pattern. Its dietary exposure is driven primarily by food contact materials. Analytical studies document continuous low-dose exposure through canned foods and packaged products, with BPA and its analogs detected in both animal- and plant-based food matrices (Chiu et al., 2024; Geueke et al., 2025). Although BPA is rapidly metabolized, frequent dietary contact results in sustained internal exposure, as reflected in biomonitoring data and regulatory reassessments (EFSA, 2023).

Together these findings confirm that exposure to major food-related toxicants occurs as chronic, low-dose intake rather than isolated events, supporting the characterization of contemporary toxicological risk as cumulative and persistent.

Association Between Chronic Exposure and Biological Outcomes

The reviewed studies consistently report associations between chronic dietary exposure and measurable biological outcomes, particularly involving renal, metabolic, oxidative, endocrine, and microbiome-related markers.

For cadmium, epidemiological and dose–response studies demonstrate significant associations between cumulative exposure and renal outcomes. Urinary cadmium concentrations correlate with biomarkers of kidney injury and reduced renal function, with effects observed even below conventional regulatory thresholds (Qing et al., 2021; Satarug et al., 2022). These associations are further supported by benchmark dose modeling and experimental findings indicating progressive tissue accumulation over time (Nogawa et al., 2021).

Mesnage and Antoniou (2020) reported that repeated low-dose glyphosate exposure is associated with oxidative stress responses and alterations in gut microbiome composition, even when systemic toxicity thresholds are not exceeded. Similar findings were reported by Walsh et al. (2023), who observed measurable changes in redox balance and microbial diversity across both experimental and observational settings. Biomonitoring evidence further supports these observations, with Zoller et al. (2020) reporting that such biological outcomes occur within exposure ranges commonly observed in the general population.

Evidence from experimental, analytical, and regulatory research indicates that BPA can produce endocrine-related effects even at low levels of exposure. Studies by Chiu et al. (2024) and EFSA (2023) report detectable BPA concentrations in food matrices alongside evidence of endocrine sensitivity and altered hormonal signaling, particularly under conditions of continuous dietary exposure. These findings align with earlier analytical investigations by Braunrath et al. (2005), Grumetto et al. (2008), and Cao et al. (2009), which documented the presence of BPA residues in canned and packaged foods.

Impact of Physiological Factors on Toxicological Outcomes

12 Multiple studies indicate that toxicological outcomes are shaped not only by external exposure levels but also by internal physiological factors. Cadmium provides a clear example of this pattern. Dietary exposure through commonly consumed staple foods, such as rice, cereals, and leafy vegetables, often approaches, and in some populations exceeds, established tolerable intake levels. Studies by Qing et al. (2021), Nogawa et al. (2021), and Satarug et al. (2022) report significant associations between urinary cadmium concentrations and indicators of renal impairment, including reduced glomerular filtration rate and evidence of tubular dysfunction, even when estimated intake falls within current regulatory limits. Food surveillance and exposure assessments further indicate that cadmium burden varies markedly across populations, reflecting differences in dietary practices and agricultural conditions (Qing et al., 2023).

Oxidative stress pathways and gut microbiome integrity play an important role in shaping biological responses to chronic glyphosate exposure (Mesnage and Antoniou, 2020). Peillex and Pelletier (2020) also observed disruptions in antioxidant defense systems under prolonged low-dose exposure, suggesting impaired redox regulation. Walsh et al. (2023) further identified changes in gut microbial composition associated with repeated dietary glyphosate intake, indicating that endogenous redox capacity and microbiome resilience may influence toxicological outcomes even when exposure remains within regulatory limits.

For BPA, regulatory and experimental evidence indicates that detoxification efficiency is a key determinant of internal exposure. EFSA (2023) documented that although BPA undergoes rapid Phase II metabolism, continuous dietary intake leads to repeated internal exposure. As also reported by Chiu et al. (2024), individual metabolic capacity and endocrine sensitivity influence biological responses under conditions of ongoing low-dose exposure.

Summary of Exposure Profiles and Biological Mediation

The combined reviewed results demonstrate that cadmium, glyphosate, and BPA represent distinct but converging exposure profiles within modern food systems. Cadmium exhibits cumulative bioaccumulation with long biological persistence, glyphosate demonstrates high-frequency dietary exposure with low environmental persistence, and BPA represents a detoxification-dependent exposure characterized by continuous re-intake. The summarized exposure characteristics, regulatory reference points, and associated biological findings are presented in Table 1.

Table 1.
Representative Exposure Characteristics of Key Food-related Toxicants

Toxicant	Primary Food / Exposure Source	Reported Exposure / Biomonitoring Data	Regulatory Reference Point	Key Sources
Cadmium	Rice, cereals, leafy vegetables	Dietary exposure frequently approaches or exceeds TWI in high-consumption populations; urinary Cd significantly associated with reduced GFR and rena tubular damage even below limits	TWI 2.5 µg/kg bw/week (EFSA)	Qing et al., 2021; Qing et al., 2023; Nogawa et al., 2021; Satarug et al., 2022
Glyphosate	Cereals, grains, processed foods	Detectable urinary glyphosate reported in majority (>70%) of samples across multiple biomonitoring studies	ADI 0.5 mg/kg bw/day (EFSA, EPA)	Gillezeau et al., 2019; Zoller et al., 2020; EFSA, 2023
Bisphenol A (BPA)	Canned foods, food contact materials	Continuous low-dose dietary exposure documented; BPA and analogs detected in packaged and plant-based foods	TDI 0.2 ng/kg bw/day (EFSA, 2023)	EFSA, 2023; Chiu et al., 2024; Geueke et al., 2025

Across these exposure profiles, measurable biological effects are consistently observed at exposure levels commonly encountered in the general population. Internal physiological factors, including nutritional status, detoxification capacity, antioxidant defenses, and microbiome integrity, repeatedly shape toxicological outcomes. The key physiological factors influencing toxicological risk under chronic exposure are summarized in Table 2.

Table 2.
Biological Mediation of Toxicological Risk Under Chronic Exposure

Toxicant	**Persistence Profile**	**Key Biological Modulators**	**Evidence From Literature**	**Key Sources**
	Highly bioaccumulative, long biological half-life	Iron and zinc status, renal detoxification capacity	Nutrient deficiencies increase cadmium absorption and nephrotoxicity; cumulative exposure linked to CKD	Genchi et al., 2020; Suhani et al., 2021; Satarug et al., 2022
	Low persistence, high exposure frequency	Gut microbiome integrity, oxidative stress pathways	Altered gut microbiota composition and increased oxidative stress observed under chronic low-dose exposure	Mesnage & Antoniou, 2020; Peillex & Pelletier, 2020; Walsh et al., 2023
	Rapid metabolism, continuous re-exposure	Phase II conjugation efficiency, endocrine sensitivity	Endocrine effects observed at extremely low doses; risk shaped by metabolic and life-stage vulnerability	EFSA, 2023; Chiu et al., 2024; Braunrath et al., 2005

DISCUSSION

Interpreting Chronic Foodborne Exposure Beyond Regulatory Thresholds

The findings of this review indicate that chronic dietary exposure to cadmium, glyphosate, and BPA occurs at levels commonly encountered in the general population and is consistently associated with measurable biological changes. These findings align with contemporary toxicological literature emphasizing that low-dose, cumulative exposure may produce health effects not fully captured by conventional exposure thresholds (Bereda, 2025; Khatri et al., 2025).

Traditional risk assessment frameworks have been effective in preventing acute toxicity. However, they are insufficient to address long-term biological responses arising from repeated exposure and internal accumulation. This limitation is particularly evident for foodborne contaminants with diverse persistence profiles and exposure frequencies, where biological response is shaped not only by dose, but by physiological mediation and cumulative burden.

Cadmium: Cumulative Toxicity and Renal Vulnerability

Cadmium provides one of the most robust examples of chronic toxicological risk arising from dietary exposure. Mechanistic studies demonstrate that cadmium accumulates primarily in renal tissue, where it induces oxidative stress, tubular dysfunction, and progressive loss of renal function (Bouida et al., 2022; Charkiewicz et al., 2023; Genchi et al., 2020).

Benchmark dose analyses and epidemiological studies shows that renal effects may occur at cumulative exposure levels near or below regulatory reference points, challenging the assumption that compliance with tolerable intake guarantees biological safety (Nogawa et al., 2021; Satarug et al., 2022). These findings support the interpretation that cadmium toxicity is driven by long biological half-life and accumulation dynamics rather than acute exposure magnitude alone.

Nutritional and physiological context plays a significant role in shaping cadmium toxicity. Deficiencies in essential minerals and reduced detoxification capacity can increase cadmium absorption and renal retention, therefore heightening susceptibility to chronic kidney disease. These factors highlight the importance of interpreting cadmium risk through both exposure control and biological vulnerability.

Glyphosate: Systemic Effects, Microbiome Interaction, and Scientific Controversy

Glyphosate presents a contrasting exposure profile characterized by low environmental persistence but high dietary frequency. Human exposure synthesis confirms widespread internal exposure through food consumption, as evidenced by biomonitoring data across populations (Gillezeau et al., 2019).

Beyond classical toxicological endpoints, mechanistic studies increasingly implicate glyphosate in oxidative stress, immune modulation, and disruption of gut microbiome composition (Mesnage & Antoniou, 2020; Peillex & Pelletier, 2020; Walsh et al., 2023). These biological effects provide plausible pathways linking chronic exposure to systemic health outcomes, including metabolic, immune, and inflammatory disturbances.

Interpretation of glyphosate-related risk remains contested within the scientific literature. Zhang et al. (2019) reported associations between glyphosate exposure and increased risk of non-Hodgkin lymphoma in their meta-analysis, raising concerns about potential carcinogenic effects. Mazuryk et al. (2024) further identified evidence of broader systemic toxicity, extending the discussion beyond cancer-related outcomes. In parallel, Glenna and Bruce (2021) examined regulatory decision-making processes and highlighted ongoing tensions between commercial interests, regulatory conclusions, and findings from independent scientific research.

This divergence underscores the importance of integrating mechanistic biology, exposure evidence, and governance transparency when interpreting glyphosate-related health risks.

Biological Modulation and Endogenous Defense Mechanisms

The literature consistently indicates that internal biological systems significantly affect toxicological outcomes among many toxicants. Antioxidant capacity, redox balance, detoxification efficiency, and immune regulation emerge as central determinants of resilience under chronic exposure conditions.

Evidence supporting antioxidant modulation demonstrates that oxidative stress is a shared pathway across cadmium, glyphosate, and BPA exposure. Interventions that support endogenous antioxidant systems have been shown to reduce tissue damage and inflammatory responses in experimental and clinical contexts as mentioned by Kalogerakou & Antoniadou (2024). Hepatoprotective and nephroprotective phytochemicals also illustrate the capacity of biological systems to modulate toxicant-induced injury when physiological defense mechanisms are supported (Shawon et al., 2024; Bhatti et al., 2023).

Emerging literature highlights the importance of gut microbiome as a mediator of toxicant effects. Alterations in microbial composition can influence immune signaling and systemic inflammation, therefore modifying susceptibility to chemical stressors. Probiotic-based approaches have been explored as complementary strategies to support detoxification and reduce internal toxicant burden (Kiousi et al., 2022). In the study by Takahata et al. (2023), botanical interventions were shown to modulate biological responses to chemical stressors, suggesting potential protective effects in high-risk populations, although these findings require cautious interpretation. These studies do not suggest replacing exposure mitigation with supplementation but reinforce the concept that biological response capacity shapes toxicological risk.

Integrating Toxicology, Food Systems, and Public Health

At the food system level, recent syntheses emphasize that chronic chemical exposure arises from interconnected agricultural practices, processing technologies, and regulatory frameworks (Duan et al., 2025; Oliveira et al., 2025). Persistence, mixture effects, and cumulative exposure complicate traditional single-chemical risk assessment approaches, necessitating broader interpretive frameworks (Khatri et al., 2025). The interaction between regulatory exposure control and internal biological response capacity is conceptually illustrated in Figure 1.

Figure 1. Parallel Strategies in Exposure Mitigation

From a public health perspective, these findings support a dual strategy approach. Regulatory control remains essential to reduce contamination and prevent high-dose exposure, particularly for pesticides and heavy metals (Adjei, 2025). Public health strategies must simultaneously recognize biological variability and support physiological resilience, especially in vulnerable populations exposed to unavoidable dietary contaminants.

The concept of biological alignment offers a framework for integrating these dimensions, positioning toxicological risk as an emergent property of exposure, biology, and governance rather than as a function of exposure alone. A conceptual synthesis integrating governance mechanisms, food system practices, and biological response capacity is summarized in Table 3.

Table 3. Conceptual Synthesis Integrating Governance, Food Systems, and Biological Response Capacity

Governance & Policy	Food System & Industry	Biological Response Capacity
Regulatory threshold setting and periodic revision	Sustainable, low-migration packaging innovation	Nutritional adequacy supporting detoxification pathways
Chemical approval and reassessment frameworks	Agricultural input management and residue reduction	Physical activity as a modulator of metabolic clearance
Environmental monitoring and compliance mechanism	Food processing and formulation decisions	Clinical interventions in high-risk or occupational contexts
Incentives for sustainable materials and practices	Transparency in sourcing and material disclosure	Biomarker monitoring of oxidative stress and biotransformation

Acknowledging that some level of exposure is unavoidable within modern food systems does not remove responsibility for contamination. It actually shifts accountability across governance structures, industry practices, and public health institutions. Effective food system governance should aim to reduce preventable exposure while also acknowledging the biological realities faced by populations living in contaminated environments. Public health strategies based only on avoidance narratives risk widening inequities, particularly for groups with limited access to alternative food sources or protective resources, as highlighted in recent food policy and public health analyses (Adjei, 2025).

By integrating exposure mitigation with support for biological response capacity, public health policy can better align regulatory goals with human physiological limits. This dual approach emphasizes precaution, transparency, and resilience, positioning food ethics not as an abstract principle but as a practical framework guiding decision-making in the Anthropocene.

Implications for Risk Interpretation and Future Research

The evidence discussed in this chapter suggests that future toxicological assessment should move beyond static exposure thresholds toward dynamic models that incorporate cumulative burden, biological mediation, and population heterogeneity. These advances in analytical chemistry and biomonitoring provide opportunities to better characterize real-world exposure, while mechanistic studies continue to elucidate pathways linking chronic exposure to disease outcomes (Oliveira et al., 2025; Singh et al., 2024).

By integrating toxicological mechanisms, endogenous defense capacity, and ethical governance, biological alignment offers a coherent interpretive lens for understanding health in contaminated environments. This approach does not diminish the importance of regulation but complements it by acknowledging the biological realities of the Anthropocene.

Further progress will depend on longitudinal and systems-based approaches that can capture dynamic interactions among chronic exposure, biological mediation, and health outcomes. Developments in exposomics, high-resolution biomonitoring, and analytical chemistry continue to expand the ability to characterize cumulative and mixture exposures within food systems, where multiple contaminants frequently co-occur (Duan et al., 2025; Oliveira et al., 2025; Khatri et al., 2025). Integrating these exposure data with biomarkers of oxidative stress, endocrine disruption, renal function, and metabolic health will support more comprehensive toxicological risk interpretation beyond static regulatory thresholds.

Vulnerable and high-risk populations, including nutritionally compromised groups, pregnant women, and individuals with pre-existing renal or metabolic conditions require additional attention. Evidence indicates that biological susceptibility varies substantially across life stages and physiological states, suggesting that population-averaged exposure limits may not adequately protect all individuals (Satarug et al., 2022; EFSA, 2023). Future studies should also explore stratified risk assessment models that incorporate physiological variability, cumulative burden, and adaptive capacity.

From a governance perspective, interdisciplinary research linking toxicological evidence with policy analysis remains important. Evaluations of regulatory decision-making processes, industry influence, and transparency mechanisms will help clarify persistent discrepancies between regulatory classifications and independent scientific assessments, particularly for controversial compounds such as glyphosate (Glenna and Bruce, 2021; Zhang et al., 2019; Mazuryk et al., 2024). These analyses are critical for maintaining public trust and ensuring that food safety policies evolve alongside emerging scientific evidence.

Limitations of the Review and Methodological Considerations

Although this narrative review provides an integrative synthesis of chronic food-related chemical exposure and biological mediation of toxicological risk, several limitations should be acknowledged.

1. Narrative review design and inferential scope

   The narrative review design prioritizes conceptual integration across disciplines rather than quantitative effect estimation. As a result, causal inferences regarding exposure–outcome relationships cannot be established, and effect sizes cannot be directly compared across studies as well. This reflects the complexity of integrative reviews that span environmental toxicology, nutritional biochemistry, physiology, and governance, which limits the precision of risk quantification.

2. Diversity in the reviewed evidence

   The reviewed literature shows substantial heterogeneity in study design, exposure assessment methods, and biological endpoints. Biomonitoring studies differ in analytical techniques, biological matrices, and population characteristics, which may influence reported exposure levels and associated health outcomes. Variability in dietary patterns, agricultural practices, and regulatory frameworks further complicates cross-study comparison, particularly for globally distributed toxicants such as cadmium and glyphosate, as highlighted by exposure syntheses and biomonitoring analyses (Qing et al., 2023; Gillezeau et al., 2019; Zoller et al., 2020).

3. Limitations of human epidemiological evidence

   The available human evidence is derived from cross-sectional or observational studies. Although biomonitoring data consistently demonstrate widespread internal exposure, longitudinal studies linking cumulative exposure trajectories to long-term clinical outcomes remain limited. This constraint is particularly relevant for toxicants with long biological half-lives or delayed disease manifestation, such as cadmium, where renal effects may develop over decades of accumulation (Nogawa et al., 2021; Satarug et al., 2022; IARC, 2017).

Finally, while this review integrates emerging evidence on biological modulation and adaptive capacity, translating these findings into population-level public health strategies remains challenging. Biological resilience is shaped by socioeconomic conditions, nutritional access, healthcare availability, and baseline health status, which vary widely across populations. These contextual factors limit the generalizability of biological mitigation strategies and underscore the need for cautious interpretation of intervention-oriented findings.

CONCLUSION

This review synthesizes evidence demonstrating that modern food systems are characterized by pervasive, chronic exposure to chemical contaminants, including heavy metals, pesticides, and food contact chemicals. Biomonitoring and dietary studies consistently confirm that such exposures are widespread and unavoidable for large segments of the population, positioning food as a primary pathway of long-term chemical intake rather than an occasional source of risk (Geueke et al., 2025; Pekmezci, 2025).

Current toxicological and regulatory frameworks have played a critical role in reducing acute toxicity and guiding population-level risk management. Authoritative assessments by international and national agencies continue to provide essential benchmarks for regulatory decision-making (ATSDR, 2020; EFSA, 2023; EPA, 2020). However, the evidence summarized in this review indicates that exposure thresholds alone are insufficient to fully explain health outcomes under chronic, low-dose, and cumulative exposure conditions. This limitation becomes very relevant for toxicants exhibiting long biological half-lives, detoxification-related re-exposure mechanisms, or high-frequency intake through dietary sources, because these characteristics complicate accurate exposure assessment and risk characterization.

From a global toxicology perspective, emerging literature emphasizes that toxicological risk in the Anthropocene must be interpreted as a dynamic interaction between environmental burden, biological systems, and governance structures rather than as a static function of external dose (Bereda, 2025). Discrepancies between regulatory classifications and independent hazard evaluations, including carcinogenic risk assessments, further underscore the need for continuous reassessment, transparency, and precaution in chemical governance (IARC, 2017; EFSA, 2023).

Overall, this review highlights that biological systems actively mediate toxicological outcomes. Internal factors such as detoxification capacity, nutritional status, antioxidant defense, and microbiome integrity shape individual susceptibility to chronic exposure. Evidence that supports biological mitigation strategies, including microbiome-supportive interventions as well as functional nutritional approaches, suggests that physiological resilience can influence health outcomes without substituting for exposure reduction policies (Kiousi et al., 2022; Kalogerakou & Antoniadou, 2024).

These insights have direct implications for public health and food policy. Effective prevention in contaminated environments requires parallel strategies :

1. Continued regulatory control to minimize environmental contamination
2. Population exposure, alongside measures that support biological response capacity, especially in vulnerable or high-risk groups.

This approach aligns exposure governance with human physiological limits instead of relying solely on avoidance narratives that may be unrealistic under current food system conditions.

Recent developments in food contaminant research and analytical chemistry have enhanced the ability to characterize real-world exposure patterns and mixture effects. Therefore, it is able to support more adaptive risk assessment models (Duan et al., 2025; Oliveira et al., 2025). Continued work, however, is still needed to establish integrative frameworks that link exposure science, biological mediation, and ethical governance, enabling policies that reflect environmental complexity alongside human resilience.

In conclusion, safeguarding human health in the Anthropocene era requires moving beyond exposure purity as the sole benchmark of safety. By integrating toxicological evidence, regulatory oversight, and biological response capacity, the concept of biological alignment provides a coherent foundation for resilient and ethically grounded food systems and public health strategies in an increasingly contaminated world.

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1 **CONFLICT OF INTEREST**

The author declares that there is no conflict of interest regarding the publication of this article.

AUTHORS’ CONTRIBUTIONS

5 AAM: Conceptualization ; Writing – original draft preparation.
DW: Conceptualization ; Writing – review and editing.
CR: Conceptualization ; Writing – review and editing.

4 **ETHICAL STATEMENT**

This study was conducted in accordance with established ethical standards for
2 scientific research. As this research is based on a narrative review of previously published literature and does not involve direct interaction with human participants or the use of animals,
3 ethical approval from an institutional review board or ethics committee was not required. No
10 personal, identifiable, or confidential data were collected or processed in the course of this study. All sources were obtained from publicly accessible scientific databases and cited appropriately to ensure academic integrity.

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