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Chemical contaminants, environment, and food safety: Integrating global science, law, and policy for a sustainable future

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Abstract
Chemical contaminants in food systems have emerged as a major global public health and environmental concern. Substances such as per- and polyfluoroalkyl substances (PFAS), heavy metals, pesticides, and microplastics persist across ecosystems and accumulate through the food chain, posing long-term risks to human health. This paper examines the effectiveness of current international and national frameworks in managing these emerging hazards, with an emphasis on the interconnections between environmental protection and food safety. Drawing on interdisciplinary literature, including World Health Organization (WHO) risk models, European Union (EU) precautionary principles, and India's Food Safety and Standards Act (FSSA), the study employs a doctrinal–empirical synthesis to integrate scientific evidence with legal governance. Comparative analysis reveals that while the European Union leads with precautionary and transparent policies under REACH and EFSA, the United States and India continue to rely on reactive or fragmented regulatory systems. Judicial developments in India reflect a growing recognition of the constitutional right to safe food and a healthy environment. The paper concludes that sustainable food safety requires a One Health framework linking environmental law, food governance, and public health, alongside transparent risk communication and cross-sectoral cooperation.

Keywords: Chemical contaminants, environment, food safety, PFAS, risk governance, one health, sustainable policy

Introduction

Food can never be viewed outside its environment which keeps it alive. Safe and nutritious food systems have their basis in clean soil, water and air. However, with the increased industrial output and agricultural intensiveness, the silent intrusion of chemical pollutants has also increased. Pesticides, toxic substances, and radioactive isotopes originally restricted to factories, pesticides, and landfills are found in vegetables, fish, and packaged foods and silently impair the health and ecological equilibrium of humans. The global foodborne disease rates also indicate a desperate environmental and community health crisis since the World Health Organization (WHO, 2025) [34] estimates that approximately one out of ten cases of foodborne-related diseases can be attributed to chemical contacts.

The contemporary civilization is relying on the chemicals to make production of food more rapid, the packaging tougher and the storage more effective. Thousands of these substances, however, remain in the environment well beyond their intended use, and the heavy metals, pesticides, and industrial residues have oozed into the air, the soil, and the water - a slow-moving crisis which has made even the environment itself a contaminated medium. Per- and polyfluoroalkyl substances (PFAS), synthetic chemicals that are highly prized by their ability to withstand heat, oil, and water, but have notorious biological persistence and toxicity are one of the most persistent (Khatri *et al*., 2025) [34].

It has been reported in research by the European Food Safety Authority (EFSA, 2023) [9] and the United States Food and Drug Administration (FDA, 2025) [14] that the residues of PFAS have been found in common products like milk, seafood, and cereals, and in their non-stick cookware and food packaging coating. These everlasting chemicals illustrate how new and persisting risks are typically introduced by innovations that are meant to make food safer.

Food Safety as an Environmental Problem

Food safety is no longer a stand-alone system and cannot be detached, as it is a product of environmental systems that support it. Industrial effluents released into the rivers spoil the irrigation water; pesticides drift to soil and pollute the soil fertility; and microplastics, when ingested by marine animals, find their way into the food chains. (Ojija,2024) [28] observes that in emerging economies, this contamination is particularly hard to control due to the lack of proper control and the presence of obsolete waste infrastructure.

The increased interconnection between environmental degradation and food safety has brought about the One Health approach an integrated model that sees human, animal, and ecosystem health as mutually reliant (WHO, 2022) [26]. The notion is straightforward: whatever pollutes the rivers and the soils also contaminates what people eat, though, in reality, the majority of the countries do not unite the environmental and food-safety agencies, not yet creating any overlapping responsibilities and responding slowly to the chemical hazards.

Chemical pollutants are not respectful of national borders. Contaminants emitted in one part of the world spread to other parts of the world in the air, through oceans and in foreign trade of foods. According to WHO, Global Environment Monitoring System of Food (GEMS/Food), chemical residues in the food samples of more than 90 countries can be detected (WHO, 2025) [14]. These results prove that the concept of chemical food safety

is a worldwide issue, the issue that demands collaboration between governments and industries.

The European Union (EU) has been on the forefront of the global initiative by the Registration, Evaluation, Authorisation and Restriction of chemicals (REACH) framework that limits over 10,000 PFAS substances and imposes data exposure through the EFSA Open Food Tox database (European Union, 2006; EFSA, 2023) [9, 13]. Contrastingly, the United States has a risk-based policy that is specified in the Federal Food, Drug, and Cosmetic Act, and the focus is on self-reporting in the industry instead of regulation by law (FDA, 2025).

In India, there is weak regulatory control. Some studies have found minor, region-specific traces of lead, cadmium, or arsenic, generally within safe limits (Mishra *et al*., 2025; Singha & Lalb, 2024 [20]; Jain *et al*., 2025).

PFAS residues were detected in groundwater sources in the states of Gujarat and Maharashtra, highlighting significant concerns regarding food and water safety (FSSAI, 2023) [8]. These findings point to the intersection of industrial pollution and agricultural activities, which places the central role of environmental management in food safety governance.

The Policy and Legal Disconnection

The regulatory system of India is an example of wider global requirement of fragmentation. Food Safety and Standards Act (2006) [13] regulates consumable products but chemical pollution is controlled by Environment (Protection) Act (1986). There are rarely overlaps in enforcement of these structures. Food safety regulators are therefore used to check the finished products and pollution boards to control the wastes disposal - lacking the continuum between production and consumption. WHO (2022) states that such fragmented framework prevents early intervention and promotes the post-contamination strategy to chemical risks.

By contrast, the European Union approach of uniting environmental and food-safety control according to the precautionary principle guarantees that the chemical-risk evaluation system undergoes the policy-setting by every means (EFSA, 2023) [9]. The United States has a great scientific base on the Environmental Protection Agency and FDA but is bound by voluntary compliance.

The Purpose of this study

The evidence to the law gap is still broad even after decades of scientific studies. According to EFSA (2023) [9], the majority of the frameworks do not yet capture cumulative or synergistic effects of multiple contaminants attributed to them by toxicologists as the cocktail effect. Filling this science-law gap would be an important step in trying to improve environmental protection as well as food safety.

This research thus tries to:

- Compare the global/national systems in controlling chemical contaminants in food.
- Among other things, analyse the impact of fragmented governance on enforcement and accountability, especially in India.
- Recommend combined, preventive reforms based on the One Health and sustainability model.

Environmental contamination, Food systems toxicity, and Inequality.

There is a strong relationship between chemical contamination of food systems and the environmental processes that regulate chemical production, distribution and accumulation. The toxicological effects of contaminants dependent upon the way they are absorbed and distributed and how they are metabolised and how long they stay in the body. Chemicals like per- and polyfluoroalkyl substances (PFAS), heavy metals and microplastics have different behaviours. But they have one thing in common – they persist over time and can harm your health.

PFAS stick to blood proteins rather than fat, so they last for a long time in the human body. The continued presence of this substance is linked to thyroid problems, reproductive harm, immunity suppression, and some cancers. Essential nutrients such as copper and iron are displaced by toxic heavy metals like lead and arsenic. Lead interference with calcium metabolism and impact on neurological development especially in children and arsenic poisoning through contaminated water and food has been associated with cardiovascular diseases and cancers in South Asia (WHO, 2022; FSSAI, 2023) [7, 35]. Tiny plastic particles known as microplastics while being inert to biological activity can infiltrate tissues becoming vectors for toxicants, inciting inflammation and oxidative stress in marine species and human cells (Eze *et al*. 2024) [28].

The toxic impact is worsened by environmental pathways which ultimately permit and facilitate the movement of contaminants. Industrial discharge, agricultural runoff, and atmospheric deposition release pollutants to air, water and soil will undergo environmental cycling through various processes. The PFAS released into the rivers get settled on the riverbeds as sediments and in aquafauna and moves through the food chain to humans (Yu *et al*., 2025) [14]. Moreover, pesticide residues can also travel through air and water to non-target environment.

Climate change exacerbates these effects further. As temperatures rise, persistent chemicals become more volatile and can easily travel great distances (Ojija, 2024) [22]. Consequently, pollution is no longer limited to its area and even highly regulated places may become contaminated by the activities of some other country through trade or atmospheric movement. It shows the trans-boundary nature of contamination by chemicals and restrictions of purely national regulatory structure.

Monitoring and surveillance system remains uneven despite the problem concerning the whole world. Countries in Developed Regions Have Established a Frameworks for Assessment of Chemicals and Food Safety For instance, EFSA OpenFoodTox of the European Union contains thousands of toxicological studies useful for risk assessment (EFSA 2023) [9]. WHO's Global Environment Monitoring System for Food (GEMS/Food) provides an international framework to collect and compare data across countries at the global level (WHO, 2025). Nonetheless, many developing countries face major shortcomings with respect to laboratory capacity, analytical infrastructure, and standardized reporting. In India, for example, food safety monitoring has enhanced through targeted testing by the Food Safety and Standards Authority of India (FSSAI), yet the system is mostly reactive and does not offer continuous integration with environmental data (FSSAI, 2023). These

discontinuities have limited the ability to trace exogenous sources and predict long-term exposure.

As more tools come on stream, we may soon use these to gauge risk areas that monitor the environment, test food and check the population. The upcoming Food Safer (2025) [14] project will utilize data to improve surveillance and early warning systems. Despite their effectiveness, the uneven spread of international cooperation, data sharing and institutional capacity prevents effective deployment.

Meanwhile, scientific comprehension of chemical contact has progressed faster than the rules have adapted. Traditional risk assessment models have increasingly been inadequate for real-world scenario exposure to mixtures of chemicals. Academics advocate for a transition to cumulative and multi-exposure models that mirror the intricacy of environmental and food systems (Rietjens *et al*., 2025) [14]. Even so, lack of scientific certainty means that regulatory action is often delayed, called regulatory inertia. While frameworks like the EU's precautionary principle provide for precautionary action in situations of scientific uncertainty, many states do not possess the required institutional and economic capability to apply a similar approach.

The effects of these gaps are not equally shared. Chemical pollution is a significant, ongoing crisis that mainly affects low-income and marginalised communities, particularly those living in industrial areas or working in the informal and agricultural sectors. In India, small-scale farmers and informal workers are particularly exposed because of weak regulation and poor infrastructure. Street foods contain pesticide residue and heavy metals which are not considered to be safe as is seen in studies (Khurana, 2016).

In addition to health effects, there also are economic impacts of contamination. Food items can be rejected due to excessive chemical residues, leading to loss of market revenues. For example, Indian seafood and spices were restricted in international markets (EFSA, 2023) [15]. Over time, persistent pollutants such as PFAS, heavy metals and microplastics accumulate in ecosystems and food chains ultimately creating inter-generational risks. The deterioration of the environment is connected to long-term issues for public health and food security

Overall, the chemical contamination that happens in food systems reflects the interconnected nature of environment-processes-people and socio-economic inequalities. To deal with these issues, we need both better science and stronger linkages between environment monitoring, food safety regulation, and governance systems. If such coordination is not done then there will be a widening gap between scientific evidence and the remedial measures undertaken.

Comparative Regulatory Analysis Europe, United States and India.

The regulatory framework for food safety employs different legal philosophies in various jurisdictions, particularly in the European Union (EU), United States (US), and India. All systems seek to cope with risks from chemical contamination, yet they vary greatly in their regulatory approaches, institutional frameworks and responses to scientific uncertainty.

The European Union uses the precautionary principle and can take regulatory action without complete scientific certainty. This principle is part of EU food law and supported by institutions like EFSA, which separates risk assessment from risk management to ensure scientific independence (De Sadeleer, 2007; EFSA, 2023). To sum up, rather than being harmful, it is the freedom of member-states that results in contamination; hence prohibitions in the EU framework have a greater effect.

Unlike the EU, the US uses a risk-based regulatory system that enables the authorities to take action only at sufficient harm proven by science. Regulatory bodies including the Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA) use quantitative risk assessments to set acceptable levels of exposure. This method focuses on cost benefit analysis and flexible regulation, but it has been criticized for slow responses to new risks (Konig, 2002 [11]; DeWaal *et al*., 2021).

The Food Safety and Standards Act govern India's regulatory framework covering its food safety via FSSAI. India appears to adopt elements from both systems, although it remains fragmented and evolving. Though recent reforms strengthened standard-setting and enforcement, the system continues to face challenges like those related to institutional coordination, enforcement capacity, and integration with environmental monitoring (Shukla *et al*., 2014). Precaution is not consistently operationalised as it is in the EU and risk assessment capacity is limited as in the US.

Differences between countries manifest most clearly with regulation of pesticides and chemicals residues. The maximum residue limits (MRLs) set by the EU are among the most stringent in the world, while the US has less stringent limits based on risk. On one hand, India faces internal public health challenges as well as the need of meeting global trade standards. This often results in a mismatch in regulations. (Handford *et al*, 2015; Umali-Deininger & Sur, 2007)

Efforts are underway at the global level towards the harmonisation of standards by the World Trade Organisation (WTO) and Codex Alimentarius among others, but tensions persist between precautionary and risk-based approaches. The precautionary principle especially, remains a controversial term in global trade law; the way in which countries justify food safety measures (Bohanes, 2001; Lin, 2010).

To sum up the EU adopts a preventive regulation approach, the US risk-based evidence making approach, and India a hybrid (but with capacity constraints) one. These variations influence how the systems react to chemical contamination and the necessity of increasing regulatory coherence due to globalization of the food system.

Judicial Environmentalism: Relating Environment, food, and life

It is not new to Indian judicial bodies to realise that a contaminated environment implies unhealthy food and, eventually, danger to life. In M.C. Mehta v. In Union of India (1988) the Supreme Court closed tanneries that released raw waste into the drinking and agricultural water, which was in the Ganges, and found that Article 21 was violated. Subsequently, in the Pesticide Residues Case M.C. Mehta v. Union of India (2002), the Court ruled that a thing that the people are taking should not be harmful to their health.

This connexion was reinforced in later cases. India Council of Enviro-Legal Action v. Union of India, (1996) had absolute liability of hazardous industries, whereas Parya varan Suraksha Samiti v. Union of India, (2017) considered that the right to life was infringed by the inability to sustain

the systems of pollution control. The combination of such judgments creates a moral triangle between environmental integrity, food safety and human health defends one is defending all.

Institutional Response: Legislative and Regulatory Reform

The leadership of the judiciary made Parliament take action. In order to amalgamate the disjointed food laws in India, the Food Safety and Standards Act (FSSA), 2006 [13] was introduced with the view of making science a central core of governing food issues. The act established the Food Safety and Standards Authority of India (FSSAI) that was the major body in the country regarding the establishment of residue levels, residue levels surveillance, and risk communication (FSSAI, 2023) [9].

In the meantime, the Environment (Protection) Act, 1986 transferred its mandate to the Central Pollution Control Board (CPCB) to control air and water pollution. These agencies however tended to operate independently. The Supreme Court in a number of orders urged that FSSAI and CPCB coordinate their efforts, citing that there are no borders to pollution. This was re-emphasized in the 2017 ruling of Paryavaran Suraksha Samithi that required combined systems of environmental-food surveillance.

To counter this, FSSAI initiated a number of state programmes the National Food Laboratory (NFL) network, the Food Safety Grid (2022) [7] online database, and the Eat right India Movement (2018) to ensure that food safety is a citizen-led effort. Such programmes have now come to contain elements of environmental surveillance, and there is a gradual but significant convergence between environmental and food safety regulation.

Environment, Agriculture and the "One Health" Approach

India is slowly adopting the One Health approach - that human, animal and environmental health cannot be separated. Various agencies like NITI Aayog, FSSAI and the Ministry of Environment, Forest and Climate Change (MoEFCC) are collaborating to ensure that contaminants are distributed in their soil system, water, and food systems.

There are strong constitutional foundations of this philosophy. In Narmada Bachao Andolan v. Union of India (2000), the Supreme Court confirmed that the right to development cannot be addressed as the right to pollute whereas balance has to exist between progress and ecological stability. The T.N. Godavarman Thirumulpad(1996) in the same way Article 21 was broadened to accommodate the notion of intergenerational equity, that is, the obligation towards protecting nature on behalf of future generations (1995-2014) in forest cases; in other words, ecological sustainability equates to food sustainability, health sustainability and survivability. And all that we care about in the nature ends up being our sustenance.

Future Guide and Policy Suggestions

To combat this, a coordinated efforts approach that unified environmental monitoring, food safety regulation and public health governance is needed. To better reflect real-world conditions (Rietjens *et al*. 2025) [34], regulatory frameworks must shift from single-chemical risk assessments to cumulative and multi-exposure models. The shift is highly necessary so that the effects of multiple contaminants can be assessed in a food web.

In addition, the integration of environmental and food safety data should strengthen surveillance systems. Utilization of platforms like WHO's GEMS/Food and the use of data-driven tools can enable the early detection of risks and assessment of their impact. In many developing countries, monitoring remains a problem due to limited capability. Hence, better effective monitoring of risks will certainly allow evaluation of regulatory measures (WHO, 2025). In India, we need to move from reactive testing to continuous, integrated surveillance aided by improved laboratory infrastructure and standardized reporting (FSSAI, 2023).

It is important to enhance international collaboration in response to cross-country chemical pollution. The agri-food sector can contribute to strengthening global food safety governance through mechanisms for data sharing, harmonized standards and joint risk assessment to reduce regulatory disparities.

Fourth, especially in situations of scientific uncertainty, the precautionary principle should be operationalised more widely. The European Union's preventive regulatory action has been shown to reduce risks over the long term, in spite of uncertainty regarding evidence (EFSA, 2023) [9].

In conclusion, policies must address socio-economic inequalities. Certain targeted interventions are needed to protect the most vulnerable populations. These include stricter enforcement in the area most at risk, support for safer agricultural practices, and improved public awareness. Collectively, the measures highlight the need for a more integrated, preventive governance model that would better align scientific evidence with regulatory action and equitable protection of populations.

Conclusion: Making Law into Life

Every law starts with a vision a dream on how life ought to be. In the case of India, such a dream is enshrined in Article 21 of the Constitution: the right to life. However, life in this context has more than just being alive, it is about living with dignity, health and safety, food that feeds, water that keeps you alive and air to heal. India courts in the years have clarified the absence of any difference between the right to life and the right to a clean environment, case after case, such as Ratlam, Subhash Kumar, Vellore, M.C. Mehta and Paryavaran Suraksha made it clear that the right to life and the right to a clean environment are inseparable. Pollution of the earth is pollution of the people.

The intention of the country to safeguard the ecological and the human health has been demonstrated by laws like the Food Safety and Standards Act (2006) [13] and the Environment Protection Act (1986). But there is a narrow border between the noble vision and an actual reality. The institutions are still segregated, the laboratories have not been updated and politics is a business of money rather than ideals. India does not require any new rights, but rather it is time to make the rights it has come alive, and transform the constitutional guarantees into the real life.

One Health approach provides an effective solution. It acknowledges that individuals, animals, and the environment are all in a circle of health, which is to harm all and everyone. This will not be copying but completion. It implies that we should do what is right before it goes wrong, love before it goes bad and know that unhealthy food or dirty rivers are not merely a regulatory problem but a moral one.

The important ones are transparency and involvement of the masses. The people need to be active partners and not passive consumers. Having informed knowledge on what they consume, drink and breathe, the people will be a part of the solution. Finally, empathy should be found again in governance. Not only should regulation punish, but it must be protecting, compassionate. In the case of harmony between science and law and humanity, Article 21 will no longer be a dream, and it will become a reality, of clean air, safe food, and clean water to all Indians.

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