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Food Safety, Animal Health, and Environmental Sustainability: A Policy Integration Model

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Abstract- — The inter-linkages between environmental contamination, animal health, and food safety have emerged as critical concerns in the context of rapid industrialization and agricultural intensification. This study develops a policy integration model grounded in the One Health framework, using empirical evidence from Haryana, India. Heavy metals and pesticide residues originating from industrial and agricultural activities were traced across soil, water, livestock feed, and milk, demonstrating systemic transfer through the food chain. Health risk assessment indices, including Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Cancer Risk (CR), indicate potential human health implications. The findings highlight the inadequacy of fragmented governance systems and propose an integrated, multi-sectoral policy model aligned with global sustainability goals. This research contributes to bridging the gap between environmental science and policy design, offering actionable insights for developing economies.

Keywords: Food safety, One Health, Environmental sustainability, Heavy metals, Policy integration, Health risk assessment

I. INTRODUCTION

Food security in the 21st century has evolved beyond the mere availability of food to encompass critical dimensions of safety, nutritional quality, and environmental sustainability. Contemporary global food systems are increasingly shaped by rapid industrialization, urbanization, and climate change, all of which contribute to the emergence of complex food safety risks. Recent global estimates indicate that nearly 600 million people fall ill annually due to contaminated food, resulting in approximately 420,000 deaths worldwide, highlighting food safety as a major public health concern . These risks are further exacerbated in low- and middle-income countries, where regulatory systems and monitoring infrastructures remain underdeveloped.

In developing economies such as India, the challenge is particularly acute due to the coexistence of intensive agriculture and expanding industrial sectors. Haryana, one of India’s leading agricultural states, exemplifies this duality. While contributing significantly to national food production, the region has simultaneously experienced rapid industrial growth, leading to increased discharge of pollutants into soil and water systems. Scientific evidence suggests that heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) persist in the environment, accumulate in agricultural soils, and enter food chains through crops and livestock . These contaminants are non-biodegradable and tend to bioaccumulate and biomagnify across trophic levels, posing long-term ecological and human health risks.

Recent global assessments further indicate that approximately 14–17% of the world’s cropland is contaminated with toxic metals, exposing nearly 1.4 billion people to potential health risks . This highlights the scale of environmental contamination and its direct implications for food safety. Additionally, emerging research (2025–2026) shows that heavy metals are increasingly detected in staple foods—including cereals, vegetables, dairy products, and processed foods—often approaching or exceeding permissible safety limits in industrially influenced regions . Such contamination pathways are strongly linked to anthropogenic activities such as industrial emissions, wastewater irrigation, and excessive agrochemical use.

A critical dimension of this issue is the role of livestock as biological intermediaries. Contaminants present in soil and water are transferred to animal feed and subsequently accumulate in animal-derived products such as milk. This pathway significantly increases human exposure risks, particularly in populations dependent on dairy-based diets. The findings of the present study empirically demonstrate this continuum, where toxicants move systematically from environmental matrices (soil and water) to livestock systems and ultimately to humans through food consumption.

In response to these interconnected challenges, global organizations such as the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have increasingly emphasized the One Health approach, which recognizes the intrinsic linkages between human health, animal health, and environmental integrity. The One Health Joint Plan of Action (2022– 2026) advocates for integrated, multi-sectoral strategies to manage food safety risks through coordinated surveillance, risk assessment, and policy interventions . This approach is particularly relevant in the context of climate change, which is altering the distribution and intensity of foodborne hazards, including chemical contaminants such as heavy metals and pesticides .

Moreover, modern food systems are characterized by increased globalization and complexity, resulting in longer supply chains and higher vulnerability to contamination risks. The FAO highlights that safe food systems depend on the health of ecosystems, animals, and humans collectively, reinforcing the need for integrated governance frameworks. Despite this recognition, existing policy structures in many countries remain fragmented, with environmental regulation, agricultural practices, and public health systems operating in isolation.

Against this backdrop, the present study aims to bridge the gap between environmental science and policy by proposing an integrated model that links food safety, animal health, and environmental sustainability. Using empirical data from Haryana, India, this research provides a comprehensive analysis of contamination pathways and associated health risks, thereby offering a strong foundation for evidence-based policymaking. The study argues that addressing food safety challenges requires a paradigm shift from sector-specific interventions to holistic, systems-based approaches grounded in the One Health framework.

II. LITERATURE REVIEW

2.1 Environmental Contamination and Food Safety

Environmental contamination has emerged as a major determinant of food safety, driven by anthropogenic activities such as industrialization, urbanization, and intensive agriculture. Recent studies indicate that heavy metals and chemical contaminants enter agro-ecosystems through industrial discharge, wastewater irrigation, atmospheric deposition, and excessive agrochemical use, thereby contaminating soil and water systems essential for food production (Zhu et al., 2025; Hernández-Montoya et al., 2026). Heavy metals—particularly cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg)—are among the most hazardous pollutants due to their persistence, non-biodegradability, and bioaccumulative nature. These metals remain in environmental matrices for prolonged periods and continuously cycle through ecosystems, increasing exposure risks (Sanusi et al., 2025). Their toxicity is influenced by physicochemical properties and exposure duration, often resulting in chronic health effects including carcinogenicity and organ damage.

Recent global research highlights that contamination of agricultural soils is widespread and increasing. Crops grown in contaminated soils absorb heavy metals through root uptake and foliar deposition, which significantly affects crop quality and yield (Mititelu et al., 2025). Leafy vegetables, in particular, exhibit high accumulation potential and act as bioindicators of environmental pollution. Furthermore, large-scale reviews show that heavy metal concentrations in food products across Asia and Africa frequently exceed permissible limits, posing significant food safety concerns (Hernández-Montoya et al., 2026).

Beyond primary agricultural produce, contamination has also been reported in processed and commercial food items. Studies demonstrate that heavy metals are present in dairy products, cereals, and processed foods, indicating that contamination is not restricted to farm-level production but persists throughout the food supply chain (Shetty et al., 2025). This widespread presence underscores the systemic nature of contamination in modern food systems.

The health implications of such contamination are severe and multifaceted. Heavy metals have been linked to neurological disorders, renal dysfunction, endocrine disruption, and cancer. For instance, cadmium exposure is associated with increased cancer risk, while mercury accumulation affects neurological and renal systems (Sanusi et al., 2025). Additionally, contaminants such as pesticides and mycotoxins interact with heavy metals, amplifying toxicological effects and contributing to chronic diseases (Journal of Population Therapeutics and Clinical Pharmacology, 2025).

A critical concept emphasized in recent literature is food chain transfer and biomagnification. Heavy metals introduced into soil and water are absorbed by plants and subsequently transferred to animals through feed consumption, ultimately reaching humans through animal-derived products. This trophic transfer leads to increasing concentrations of contaminants at higher levels of the food chain (Zhang et al., 2024; Shetty et al., 2025). Studies confirm that livestock products such as milk, meat, and eggs often contain detectable levels of heavy metals, reflecting environmental exposure conditions.

Recent advancements in analytical technologies have significantly improved detection and monitoring of contaminants. Techniques such as Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Gas Chromatography-Mass Spectrometry (GC-MS), and emerging machine learning- based systems enable precise quantification of contaminants in food matrices (Hernández- Montoya et al., 2026). These tools are essential for effective risk assessment and regulatory enforcement.

Despite technological progress, challenges persist in mitigating environmental contamination. Current regulatory frameworks are often fragmented, with limited coordination between environmental, agricultural, and public health sectors. This results in inadequate monitoring and enforcement, particularly in developing countries where exposure risks are higher (Zhu et al., 2025).

In response, recent studies advocate for integrated and multidisciplinary approaches that combine environmental management, food safety regulation, and public health strategies. Sustainable interventions such as phytoremediation, improved waste management, and stricter industrial regulations have shown promise in reducing contamination levels (Yang et al., 2025).

Overall, contemporary research clearly demonstrates that environmental contamination is a systemic issue affecting the entire food chain. The persistence and bioaccumulative nature of heavy metals, coupled with increasing industrial pressures, necessitate a shift toward integrated, science-based policy frameworks. This provides a strong foundation for the present study, which aims to bridge empirical evidence with policy integration using a One Health approach.

2.2 Animal Health and Food Chain Transfer

Livestock occupy a critical position at the interface of environmental systems and human food consumption, acting as biological conduits through which environmental contaminants are transferred into the human diet. In agro-industrial landscapes, animals are continuously exposed to pollutants through contaminated feed, water, and soil, making them highly sensitive indicators of environmental quality. This interconnectedness highlights that animal health is not merely a veterinary concern but a central component of food safety and public health.

Recent studies have demonstrated that heavy metals such as cadmium (Cd), lead (Pb), arsenic (As), and mercury (Hg) enter livestock systems primarily through ingestion of contaminated fodder and drinking water (Shetty et al., 2025; Zhang et al., 2024). Once ingested, these toxic elements are absorbed into the bloodstream and distributed across various tissues, including liver, kidneys, and mammary glands. Importantly, dairy animals such as buffalo and cattle can excrete a portion of these contaminants into milk, thereby creating a direct pathway for human exposure. The empirical findings of the present study strongly support this pathway, demonstrating the transfer of toxicants from soil and water to feed and ultimately to milk in both agricultural and industrial regions of Haryana.
The process of bioaccumulation plays a key role in this transfer. Unlike many organic compounds, heavy metals are not metabolized or eliminated efficiently from biological systems. Instead, they accumulate over time, especially in long-lived organisms such as livestock. This accumulation becomes even more concerning when viewed through the lens of biomagnification, where contaminant concentrations increase at successive trophic levels (Witkowska et al., 2021; Sanusi et al., 2025). As a result, animal-derived food products—particularly milk, meat, and eggs—can contain higher concentrations of toxicants than the original environmental sources.

Recent global research further emphasizes that livestock-based food systems are increasingly vulnerable to environmental contamination. A 2024 study in Journal of Hazardous Materials reported that heavy metal concentrations in animal-derived foods are strongly correlated with environmental exposure levels, particularly in regions with high industrial activity (Zhang et al., 2024). Similarly, Shetty et al. (2025) highlighted that dairy products from polluted regions frequently exhibit elevated levels of Pb and Cd, often exceeding recommended safety thresholds. These findings are particularly relevant for countries like India, where milk is a staple component of daily diets, thereby increasing the risk of chronic exposure.

Beyond chemical contaminants, recent literature also highlights the combined effects of multiple stressors on animal health. Exposure to heavy metals can weaken immune responses, disrupt endocrine function, and impair reproductive performance in livestock (Yang et al., 2025). This not only reduces productivity but also increases susceptibility to diseases, thereby compounding food safety risks. Furthermore, interactions between heavy metals and other contaminants, such as pesticide residues, may produce synergistic toxic effects, amplifying their impact on both animal and human health (Hernández-Montoya et al., 2026).

Another important dimension is the role of animal metabolism in modifying contaminant dynamics. While some metals are partially excreted, others are selectively retained in specific tissues. For instance, cadmium tends to accumulate in kidneys, while lead is often deposited in bones and soft tissues. However, during physiological processes such as lactation, these stored contaminants can be mobilized and transferred into milk, increasing the risk of exposure for consumers (Mititelu et al., 2025). This makes dairy products particularly important indicators of environmental contamination.

Advancements in analytical techniques have enabled more precise detection of contaminants in animal-derived products. Techniques such as ICP-MS and GC-MS are now widely used to quantify trace levels of heavy metals and pesticide residues in milk and feed (Zhu et al., 2025). These tools have significantly improved our understanding of contamination pathways and have reinforced the need for regular monitoring of livestock products as part of food safety frameworks.

Despite growing scientific evidence, policy responses remain fragmented. Animal health monitoring systems are often designed to detect infectious diseases rather than chemical contamination, leading to significant gaps in surveillance. Moreover, regulatory standards for contaminants in animal feed and milk vary widely across countries, limiting the effectiveness of global food safety governance (FAO, 2023). This underscores the need for integrated approaches that link environmental monitoring with veterinary and food safety systems.

In this context, the One Health framework provides a valuable paradigm for addressing these challenges. By recognizing the interdependence of environmental, animal, and human health, it promotes coordinated surveillance, risk assessment, and policy interventions. Integrating animal health monitoring into broader environmental and food safety strategies can significantly enhance the detection and mitigation of contamination risks.

In summary, livestock play a pivotal role in mediating the transfer of environmental contaminants into the human food chain. The processes of bioaccumulation and biomagnification amplify these risks, making animal-derived foods critical points of exposure. The findings of this study, supported by recent global research, highlight the urgent need for integrated monitoring systems and policy frameworks that address animal health as a key component of food safety and environmental sustainability.

2.3 Human Health Risk Assessment

Human health risk assessment has become an essential component of environmental and food safety research, as it provides a quantitative framework to evaluate the potential impacts of contaminants on human populations. In recent years, increasing attention has been given to chemical contaminants—particularly heavy metals—in food systems due to their persistence, bioaccumulation, and long-term toxicity.

Widely accepted models for assessing human exposure include Estimated Daily Intake (EDI), Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR). These indicators allow researchers to quantify both non-carcinogenic and carcinogenic risks associated with dietary intake of contaminated food (Suresh et al., 2025; Ben Ameur et al., 2025). The EDI estimates the daily intake of contaminants based on concentration levels, ingestion rates, and body weight, thereby providing a baseline measure of exposure. The HQ, derived as the ratio of EDI to the reference dose (RfD), is used to evaluate non-carcinogenic risks, where values greater than one indicate potential health concern . Similarly, the Hazard Index (HI), which represents the cumulative risk of multiple contaminants, offers a more comprehensive understanding of combined exposure effects.

Recent studies emphasize that even when individual contaminants fall within permissible limits, cumulative exposure can still pose significant health risks. For instance, research conducted on seafood and agricultural products has demonstrated that while HQ values may remain below unity, indicating acceptable risk, the combined HI values can approach critical thresholds, especially in populations with high consumption rates (Ben Ameur et al., 2025) . This highlights the importance of considering multi-contaminant exposure rather than isolated assessments.

Carcinogenic risk (CR) assessment further extends this analysis by estimating the probability of developing cancer over a lifetime due to exposure to toxic elements. Acceptable risk levels are generally considered to lie within the range of 10^{-6} to 10^{-4}, beyond which regulatory concern is warranted. Recent studies have reported that exposure to metals such as Pb and Cr through dietary sources may approach or exceed these thresholds in industrially impacted regions (Reyes- Márquez et al., 2024) .

Empirical evidence from global and regional studies indicates that contaminated food and water are major contributors to human exposure. For example, a 2024 study published in Scientific Reports found that heavy metal concentrations in vegetables exceeded FAO/WHO permissible limits, posing both carcinogenic and non-carcinogenic risks to consumers (Chowdhury et al., 2024) . Similarly, research conducted in India and other developing regions has highlighted that prolonged exposure to low levels of heavy metals can lead to chronic health conditions, including kidney damage, neurological disorders, and endocrine disruption (Selvam et al., 2022)

An important consideration in recent literature is the variability of risk across population groups. Children, pregnant women, and individuals with higher dietary intake of contaminated food are particularly vulnerable due to differences in metabolism and exposure rates. Moreover, socio- economic factors and dietary habits significantly influence exposure levels, making localized studies—such as the present research in Haryana—crucial for accurate risk assessment.

The findings of this study , which utilize EDI, HQ, and CR models, align with global research trends, demonstrating that environmental contamination translates directly into measurable human health risks through food consumption. The integration of statistical tools and exposure models provides a robust framework for understanding these risks and highlights the need for evidence-based regulatory interventions.

In summary, human health risk assessment serves as a critical bridge between environmental contamination and public health outcomes. Recent research underscores the importance of cumulative risk evaluation, population-specific exposure analysis, and integration of advanced analytical techniques. These insights reinforce the necessity of incorporating health risk assessment into policy frameworks to ensure safe and sustainable food systems.

2.4 Policy and Governance Gaps:

Despite growing scientific evidence linking environmental contamination, animal health, and food safety, existing policy frameworks remain largely fragmented and insufficient to address these interconnected challenges. Traditionally, governance systems have operated within sector- specific boundaries, with environmental regulation, agricultural practices, and public health policies functioning independently. This approach has resulted in significant gaps in monitoring, coordination, and enforcement.

Recent global assessments highlight that institutional fragmentation is one of the primary barriers to effective food safety governance, particularly in developing countries. Environmental agencies often focus on pollution control, while agricultural departments emphasize productivity, and health systems prioritize disease management. However, the interconnected nature of contamination pathways requires integrated oversight that bridges these domains (FAO, 2023).

The One Health framework, promoted by international organizations such as the FAO, WHO, and UNEP, has emerged as a comprehensive approach to address these challenges. It emphasizes the interdependence of human, animal, and environmental health and advocates for coordinated surveillance and policy integration. However, despite its conceptual strength, implementation remains limited due to structural and operational constraints.

One of the key challenges identified in recent literature is the lack of integrated data systems. Monitoring data related to soil contamination, water quality, livestock health, and food safety are often collected by different agencies using varying methodologies, making it difficult to establish clear linkages and design effective interventions (Zhu et al., 2025). This lack of data harmonization undermines evidence-based policymaking and limits the ability to respond to emerging risks.

Another significant issue is weak regulatory enforcement, particularly in regions experiencing rapid industrialization. Studies have shown that industrial effluent discharge, improper waste management, and excessive agrochemical use continue to contribute to environmental contamination despite existing regulations (Shetty et al., 2025) . In many cases, compliance monitoring is inadequate, and penalties for violations are insufficient to deter harmful practices.

Furthermore, current food safety standards often focus on end-product testing rather than addressing contamination at its source. This reactive approach fails to account for upstream factors such as soil and water quality, which play a crucial role in determining food safety outcomes. Recent research advocates for preventive and risk-based regulatory frameworks that integrate environmental monitoring with food safety systems (Yang et al., 2025).

Socio-economic factors also contribute to governance gaps. Small-scale farmers and livestock producers, who form the backbone of agricultural systems in countries like India, often lack access to resources, training, and infrastructure needed to implement safe practices. This creates disparities in compliance and increases exposure risks among vulnerable populations.

Importantly, climate change is emerging as an additional stressor that complicates governance frameworks. Changes in temperature, precipitation patterns, and extreme weather events can influence the mobility and bioavailability of contaminants, thereby altering exposure pathways and risk levels. This dynamic nature of environmental risks further underscores the need for adaptive and integrated policy approaches.

The findings of this study highlight these governance challenges at the regional level, where industrial and agricultural activities coexist, leading to complex contamination pathways. The observed transfer of toxicants across environmental and biological systems underscores the inadequacy of isolated regulatory approaches.

In response, recent literature strongly advocates for integrated policy models based on the One Health approach, which emphasize:

- Cross-sectoral coordination
- Unified monitoring systems
- Data sharing and interoperability
- Preventive risk management strategies

Such frameworks not only improve regulatory efficiency but also enhance resilience against emerging environmental and public health challenges.

In conclusion, addressing policy and governance gaps requires a paradigm shift from fragmented, sector-specific approaches to holistic, integrated systems. Strengthening institutional coordination, improving data integration, and adopting preventive regulatory strategies are essential for ensuring food safety, protecting animal health, and achieving environmental sustainability.

III MATERIALS AND METHODS:

3.1 Study Area:

The present investigation was carried out in two districts of Haryana, India—Panipat and Rohtak—which were deliberately selected to represent contrasting environmental settings influenced by industrial and agricultural activities. Panipat is recognized as a major industrial hub, with a high concentration of textile, petrochemical, and manufacturing industries that contribute significantly to environmental pollution through effluent discharge, atmospheric emissions, and improper waste management. In contrast, Rohtak is predominantly characterized by intensive agricultural practices, where the extensive use of fertilizers and pesticides represents the primary source of environmental stress. This contrast provides an ideal framework for comparative analysis, enabling the assessment of how different anthropogenic pressures influence contamination patterns across ecosystems (Daulta et al., 2018; Singh et al., 2024).

The selection of these two regions allows for a more comprehensive understanding of contamination dynamics, as industrial zones are typically associated with elevated levels of heavy metals, while agricultural regions are often linked to pesticide accumulation. Previous studies have emphasized that such dual-system comparisons are essential for identifying the relative contributions of different pollution sources and for understanding the interaction between environmental compartments (Kumar et al., 2023; Shetty et al., 2025).
To capture the movement of contaminants across the food chain, a total of 40 samples were systematically collected, comprising:

- 10 soil samples
- 10 water samples
- 10 livestock feed samples
- 10 buffalo milk samples

Each sample category was equally represented to maintain balance and ensure comparability across different matrices. The inclusion of multiple environmental and biological components was intentional, as it allows for tracing the progression of contaminants from primary sources (soil and water) to intermediate carriers (feed) and ultimately to human-consumable products (milk). Such multi-matrix sampling approaches are widely recommended in environmental health studies for identifying contamination pathways and assessing cumulative exposure risks (Mititelu et al., 2025).

Sampling locations within each district were carefully selected to ensure adequate spatial coverage and to represent typical environmental conditions. Sites were chosen based on proximity to industrial activities, agricultural fields, and livestock-rearing areas. This approach helps minimize sampling bias and improves the reliability of the results by capturing variations in contamination levels across different micro-environments (Zhu et al., 2025).

Furthermore, the inclusion of buffalo milk as a sampling component is particularly significant in the Indian context, where dairy consumption is high and milk serves as a major dietary staple. As a biological product, milk reflects both recent exposure and cumulative accumulation of contaminants in livestock, making it an effective indicator of environmental pollution and a critical link in assessing human health risks (Giri et al., 2021).

Overall, the study design integrates environmental and biological sampling within a comparative framework, enabling a holistic evaluation of contamination pathways and supporting the development of evidence-based strategies for food safety and environmental management.

3.2 Sample Collection and Analysis

All samples were collected following standardized and quality-controlled protocols to minimize external contamination and ensure analytical reliability. Adherence to uniform sampling and preparation procedures is essential in environmental toxicology studies, as it directly influences the accuracy and reproducibility of results (Zhu et al., 2025; Mititelu et al., 2025).

Soil samples were collected from the upper layer (0–15 cm), which represents the most active zone for contaminant accumulation and plant uptake. The samples were air-dried under controlled conditions, ground, and sieved to achieve uniform particle size. This homogenization step is crucial for improving analytical precision and ensuring representative measurements (Kumar et al., 2023).

Water samples were collected in pre-cleaned, sterilized amber bottles to prevent photodegradation and contamination. The samples were filtered to remove suspended particles and preserved at low temperatures until analysis. Proper storage and filtration are critical for maintaining the integrity of dissolved contaminants, particularly heavy metals and pesticide residues (Singh et al., 2024).

Livestock feed samples were collected from feeding sites and finely ground to obtain a homogeneous matrix. Homogenization ensures that contaminant distribution within the sample is consistent, thereby improving the reliability of analytical results. Feed is an important intermediate in the food chain, reflecting contamination from both soil and water sources (Shetty et al., 2025).

Milk samples were obtained from clinically healthy buffalo under hygienic conditions to avoid external contamination. The samples were stored and transported under controlled temperatures to preserve their physicochemical properties. Milk is widely regarded as a sensitive bio-indicator of environmental contamination, as it reflects both recent exposure and cumulative accumulation of toxic substances in livestock (Giri et al., 2021; Mititelu et al., 2025).

Overall, the standardized sampling and preparation procedures adopted in this study ensured consistency across all matrices and provided a reliable foundation for subsequent chemical analysis and risk assessment.

3.3 Pesticide Residue Analysis Using GC–MS:

Pesticide residues in soil, water, feed, and milk samples were quantified using Gas Chromatography–Mass Spectrometry (GC–MS), a highly sensitive technique capable of detecting multiple pesticide classes—including organophosphates, organochlorines, and pyrethroids—at trace levels (Hernández-Montoya et al., 2026; Shetty et al., 2025). The analytical range typically spans from µg/kg to mg/kg, depending on sample matrix and compound properties.

Sample preparation was carried out using a modified QuEChERS protocol, which is widely recognized for its efficiency, reproducibility, and suitability for multi-residue analysis. The method involved extraction using acidified acetonitrile, followed by salt-induced phase separation and dispersive clean-up. This approach ensures high recovery rates (generally 70– 120%) while minimizing matrix interference (Anastassiades et al., 2003; AOAC, 2019).

Table 1: Target Pesticides and Analytical Characteristics:

Pesticide	**Chemical Class**	**Typical Detection Range (mg/kg)**	**Detection Limit (mg/kg)**	**Environmental Relevance**
Chlorpyrifos	Organophosphate	0.01 – 2.5	0.001	Widely used insecticide, persistent in soil and milk
Malathion	Organophosphate	0.05 – 15.0	0.002	High agricultural usage, dominant residue
Cypermethrin	Pyrethroid	0.01 – 1.0	0.001	Common in crop protection
DDT	Organochlorine	0.01 – 1.5	0.001	Persistent organic pollutant

Lambda-cyhalothrin	Pyrethroid	0.005 – 0.8	0.001	Stable and bioaccumulative

Instrumental analysis was performed under optimized GC–MS conditions using selective ion monitoring (SIM) to enhance sensitivity and specificity. The method allows simultaneous detection of multiple pesticide residues with high precision and low variability.

Table 2: Method Validation Parameters (GC–MS Analysis)

Parameter	**Observed Range / Value**	**Acceptable Standard (SANTE, 2022)**
Recovery (%)	72 – 115%	70 – 120%
Relative Standard Deviation	< 12%	≤ 20%
Limit of Detection (LOD)	0.001 – 0.01 mg/kg	≤ 0.01 mg/kg
Limit of Quantification (LOQ)	0.005 – 0.02 mg/kg	≤ 0.05 mg/kg
Linearity (R^2)	> 0.99	≥ 0.99

3.3 Heavy Metal Analysis Using ICP–MS:

Heavy metals, including Al, As, Cd, Cu, Fe, Pb, and Co, were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP–MS), which is widely used for multi-element detection due to its ability to measure metals at very low concentrations, typically in the µg/L to ng/L range (Zhu et al., 2025; Mititelu et al., 2025). This makes it particularly suitable for environmental and food samples where contaminants are often present at trace levels.

To prepare the samples, a wet acid digestion method was applied to break down organic matter and release metal ions into solution. Each sample was treated with a mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) and subjected to controlled heating. The digestion was carried out in two steps: first at around 70°C, which helps initiate the decomposition of organic components, followed by heating at approximately 135°C to achieve complete digestion and obtain a clear solution. This gradual heating process improves digestion efficiency and reduces the risk of losing volatile elements (Alloway, 2013).After digestion, the samples were diluted with deionized water, filtered to remove any remaining particulates, and stored in acid-cleaned containers before analysis. Care was taken to use high-purity reagents and clean labware to avoid external contamination and ensure reliable measurements.

The ICP–MS system was operated under optimized conditions, allowing simultaneous detection of multiple metals with limits of detection typically between 0.001 and 0.01 mg/L. The method provides high sensitivity, a broad working range, and minimal interference, making it suitable for accurately quantifying metals across different sample types (Suresh et al., 2025).

Table 3: ICP–MS Method Performance Parameters

Parameter	**Observed Range / Value**	**Standard Reference**
Limit of Detection (LOD)	0.001 – 0.01 mg/L	≤ 0.01 mg/L
Limit of Quantification (LOQ)	0.005 – 0.02 mg/L	≤ 0.05 mg/L
Recovery (%)	85 – 110%	80 – 120%
Relative Standard Deviation	< 10%	≤ 15%
Linearity (R^2)	> 0.99	≥ 0.99

3.4 Health Risk Assessment

Human health risks from consuming contaminated milk were assessed using three commonly used indicators: Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Cancer Risk (CR). These metrics help convert measured contaminant levels into meaningful estimates of human exposure and potential health effects, making them widely used in food safety and environmental studies (Suresh et al., 2025; Ben Ameur et al., 2025).

The Estimated Daily Intake (EDI) was used to estimate how much of each metal an individual might consume daily through milk. This was calculated using the measured concentration of metals in milk along with average consumption rates and body weight. For adults, milk intake is typically assumed to be around 0.2–0.5 L per day, with an average body weight of 60–70 kg, allowing exposure to be standardized across populations (WHO, 2022). The calculated EDI values were then compared with internationally accepted safety limits, such as the Provisional Tolerable Daily Intake (PTDI), to determine whether exposure levels were within safe bounds.

To understand non-carcinogenic effects, the Hazard Quotient (HQ) was calculated by comparing the estimated exposure (EDI) with the reference dose (RfD). An HQ value of less than 1 indicates that the exposure is unlikely to cause harm, whereas a value greater than 1 suggests a potential health concern, particularly if exposure continues over a long period. Previous studies have shown that metals such as iron, aluminum, and lead can often exceed this threshold in contaminated environments, pointing to possible cumulative health risks (Sanusi et al., 2025).

For long-term effects, particularly cancer risk, the Cancer Risk (CR) index was applied. This metric estimates the probability of developing cancer over a lifetime due to exposure to specific contaminants. Acceptable risk levels generally fall within the range of 10^{-6} to 10^{-4}, and values approaching or exceeding this range may require regulatory attention, especially for toxic elements like arsenic and lead (Reyes-Márquez et al., 2024).

Table 4: Health Risk Assessment Parameters

Parameter	**Unit**	**Typical Range Used**	**Reference Standard**
Milk ingestion rate	L/day	0.2 – 0.5	WHO (2022)
Body weight	kg	60 – 70	WHO (2022)
RfD (Pb, As, etc.)	mg/kg/day	Element-specific	USEPA/WHO
Acceptable HQ	—	< 1	USEPA guideline
Acceptable CR	—	$10^{-6} – 10^{-4}$	USEPA guideline

IV. RESULTS:

4.1 Pesticide Residues across Environmental and Biological Matrices

Pesticide residues were detected across all sampled matrices—soil, water, feed, and milk—with clear spatial variation between the industrial (Panipat) and agricultural (Rohtak) regions. Quantitative analysis indicates both active-use pesticides (e.g., Malathion, Chlorpyrifos) and persistent compounds (e.g., DDT) present above recommended safety limits.

Table 5: Pesticide Concentration in Panipat

Pesticide	Soil (mg/kg)	Water (mg/L)	Feed (mg/kg)	Milk (mg/L)
Malathion	12.45	>11	Trace	ND
Chlorpyrifos	0.057	0.16	~2.0	~2.1
Cypermethrin	0.42	Trace	Trace	ND
DDT	0.96	Trace	Trace	Present
Lambda-cyhalothrin	Trace	ND	Trace	ND

Key Observations:

- Highest contamination observed in water (Malathion >11 mg/L)
- Chlorpyrifos present across all matrices, including milk (~2.1 mg/L)
- Persistent pesticide DDT detected in soil and milk, indicating long-term contamination
- Overall higher contamination burden, reflecting industrial influence.

Table 6: Pesticide Concentration in Rohtak

Pesticide	**Soil (mg/kg)**	**Water (mg/L)**	**Feed (mg/kg)**	**Milk (mg/L)**
Malathion	15.06	>11	Trace	ND
Chlorpyrifos	0.013	0.002	~2.0	~1.9
Cypermethrin	0.17	Trace	Trace	ND
DDT	0.72	Trace	Trace	Present
Lambda-cyhalothrin	Trace	ND	Trace	ND

Key Observations (Rohtak):

- Highest soil contamination (Malathion ~15 mg/kg), indicating intensive pesticide use
- Lower water contamination compared to Panipat

- Chlorpyrifos detected in milk (~1.9 mg/L), confirming food chain transfer
- Presence of DDT suggests persistence despite agricultural dominance

- Comparative Insight:
- Panipat: Higher contamination in water and milk → industrial + environmental loading
- Rohtak: Higher contamination in soil → agricultural input-driven
- Chlorpyrifos is the only pesticide consistently detected across all matrices
- Malathion dominates environmental contamination but does not significantly transfer to milk
- Detection in milk confirms soil → water → feed → milk pathway

These findings align with reported contamination trends in agro-industrial regions, where mixed pollution sources contribute to multi-matrix exposure (Shetty et al., 2025; Mititelu et al., 2025).

4.2. Heavy Metal analysis:

The distribution of pesticide residues was quantified across multiple environmental and biological matrices, including soil, water, livestock feed, and milk, to capture the progression of contaminants through the food chain. The results reveal measurable concentrations of both actively used pesticides (e.g., Malathion and Chlorpyrifos) and persistent compounds (e.g., DDT) in all matrices, with distinct spatial variation between the industrial region (Panipat) and the agricultural region (Rohtak). Notably, higher concentrations of pesticides were observed in soil and water samples, with Malathion reaching values above 11 mg/L in water and up to ~15 mg/kg in soil, indicating significant agricultural input. The detection of residues in feed and milk further confirms the transfer of contaminants across trophic levels. These findings are consistent with previous studies highlighting the persistence and mobility of pesticide residues in agro- environmental systems (Shetty et al., 2025; Mititelu et al., 2025).

Table 7: Heavy Metal Concentration in Panipat (Industrial Region)

Metal	Soil (mg/kg)	Water (mg/L)	Feed (mg/kg)	Milk (mg/L)
Iron (Fe)	High (~natural + industrial)	~9000	Moderate	High
Aluminum (Al)	High	Moderate	Moderate	Elevated
Lead (Pb)	Elevated	Present	Low	Elevated
Arsenic (As)	Trace	Trace	ND	Low
Cadmium (Cd)	ND	ND	ND	ND
Copper (Cu)	Moderate	Low	Low	Trace
Cobalt (Co)	Trace	Trace	ND	ND

Key Observations:

- Fe and Al dominate across all matrices, indicating both geogenic and industrial inputs
- Pb consistently detected, especially in soil and milk → strong industrial signature
- Milk shows elevated Fe, Al, and Pb, confirming biological transfer
- Minimal presence of Cd and Co suggests limited contribution from these metals

Table 8: Heavy Metal Concentration in Rohtak (Agricultural Region):

Metal	Soil (mg/kg)	Water (mg/L)	Feed (mg/kg)	Milk (mg/L)
Iron (Fe)	High (~natural)	~9000	Moderate	Elevated
Aluminum (Al)	Moderate –High	High	Moderate	Elevated
Lead (Pb)	Moderate	Elevated	Low	Moderate
Arsenic (As)	Trace	Trace	ND	Low
Cadmium (Cd)	ND	ND	ND	ND
Copper (Cu)	Moderate	Low	Low	Trace
Cobalt (Co)	Trace	Trace	ND	ND

Key Observations:

- High Fe levels across all matrices, likely influenced by natural geology
- Al and Pb levels relatively elevated in water, indicating possible agricultural runoff
- Lower overall contamination compared to Panipat, but still significant
- Milk contamination present, confirming exposure through feed and water

- Comparative Insight:
- Panipat: Higher levels of Pb, Al, and Fe, especially in soil and milk → strong industrial contribution
- Rohtak: Elevated Fe and Al, but comparatively lower Pb → mixed natural and agricultural influence
- Water acts as a key transport medium, with high Fe (~9000 mg/L) in both regions
- Feed shows reduced concentrations, indicating partial attenuation during plant uptake
- Milk confirms final transfer stage, with detectable levels of Fe, Al, and Pb

This distribution pattern supports the concept of bioaccumulation and trophic transfer, where metals persist in environmental matrices and progressively move into biological systems (Witkowska et al., 2021; Zhang et al., 2024).

V. POLICY INTEGRATION MODEL:

The empirical evidence generated in this study clearly demonstrates that contamination pathways are continuous and interconnected, spanning environmental matrices, livestock systems, and human food consumption. This systemic movement of pesticides and heavy metals underscores a critical limitation of existing governance structures, which largely operate in isolation. In response, this study proposes a data-driven Policy Integration Model grounded in the One Health framework, designed to align environmental regulation, food safety, and public health systems within a unified governance structure.

5.1 Conceptual Foundation: One Health and Global Policy Alignment

The proposed model is anchored in the One Health Joint Plan of Action (2022–2026) developed by FAO, UNEP, WHO, and WOAH, which emphasizes that human health outcomes are inseparable from environmental and animal health systems (FAO et al., 2022). This approach is further reinforced by the World Health Organization (WHO, 2022), which advocates risk-based food safety frameworks integrating environmental monitoring with human exposure assessment.

At a broader level, the model aligns with the United Nations Sustainable Development Goals (SDGs), particularly:

- SDG 2 (Zero Hunger) – ensuring safe food systems
- SDG 3 (Good Health and Well-being) – reducing exposure to toxic contaminants
- SDG 6 (Clean Water and Sanitation) – improving water quality
- SDG 12 (Responsible Consumption and Production) – minimizing pollution
- SDG 13 (Climate Action) – addressing environmental drivers of contamination
- These global frameworks collectively emphasize that food safety must be addressed as a systems-level issue, rather than a sector-specific concern.

5.2. Integrated Monitoring and Data Systems (Data-Driven Approach)

The results of the present study clearly indicate that contamination is not confined to a single environmental compartment but is distributed across soil, water, feed, and milk. For instance, pesticide residues such as Chlorpyrifos were consistently detected across all matrices (~2.0–2.1 mg/L in milk), while heavy metals such as Fe (~9000 mg/L in water) and Pb (elevated in milk) demonstrate clear cross-matrix transfer. These findings provide direct empirical evidence that fragmented monitoring systems fail to capture real exposure pathways.

Currently, environmental monitoring in India—primarily conducted by the Central Pollution Control Board (CPCB) under programs such as the National Water Quality Monitoring Programme—focuses largely on water and air quality. However, this study shows that water contamination directly translates into food contamination, highlighting a critical disconnect between environmental and food safety surveillance systems.

To address this, the proposed model recommends a multi-matrix, integrated monitoring framework, supported by standardized analytical tools (ICP-MS, GC-MS) and unified data platforms.

Table 9: Data across sectors and policy gap:

Matrix	Key Findings from Study	Policy Benchmark (WHO/CPCB/FAO)	Gap Identified	Policy Action Required
Water	Fe ~9000 mg/L; Malathion >11 mg/L	WHO drinking water guidelines; CPCB water quality standards	Monitoring exists but not linked to food systems	Integrate water data with agriculture & dairy surveillance
Soil	Malathion up to ~15 mg/kg; DDT present	FAO soil contamination guidelines	Limited routine monitoring in India	Establish soil contamination surveillance in agricultural zones
Feed	Moderate pesticide and metal residues	No uniform global standard for feed contamination	Weak regulation and monitoring	Introduce feed quality standards linked to environmental data
Milk	Chlorpyrifos ~2 mg/L; Pb elevated	WHO/FAO food safety limits	End-product testing only	Shift to source-based monitoring (soil–water–feed linkage)
Cross-matrix link	Soil → Water → Feed → Milk transfer confirmed	One Health framework (FAO/WHO)	Sectoral data silos	Develop integrated “farm-to-fork” digital monitoring system

This table clearly demonstrates that data exists across sectors, but integration is missing, which is the core governance gap identified in this study.

Building on this, the model proposes:

- Real-time data integration platforms linking CPCB, FSSAI, and veterinary databases
- Geospatial mapping of contamination hotspots
- Routine multi-matrix sampling (soil–water–feed–food) rather than isolated testing Such a system would allow early identification of contamination pathways, rather than delayed detection at the consumption stage.

5.3. Risk-Based Regulatory Frameworks

The findings of this study provide strong quantitative support for transitioning toward risk-based regulatory frameworks, as recommended by WHO (2022). The detection of contaminants in milk—particularly Pb and pesticide residues—indicates direct human exposure, which cannot be adequately addressed through conventional permissible-limit approaches alone.

Health risk assessment tools such as Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Cancer Risk (CR) offer a more realistic understanding of exposure. For example, regular consumption of contaminated milk (0.2–0.5 L/day as per WHO standards) can lead to chronic accumulation of toxicants, even when individual concentrations appear moderate.

A key observation from this study is that:

- Some contaminants (e.g., Malathion) show high environmental presence but low biological transfer
- Others (e.g., Chlorpyrifos, Pb) show consistent transfer into milk, making them higher- risk pollutants

This highlights the need for prioritization based on transfer potential and toxicity, rather than concentration alone.

Table10: Risk across contaminants

Contaminant	Environmental Presence	Detection in Milk	Health Risk Category (WHO)	Policy Priority
Lead (Pb)	Moderate–High	Elevated	High (no safe limit)	Immediate control (industrial source)
Chlorpyrifos	Present in all matrices	~2 mg/L	Moderate–High	Regulate agricultural usage
Malathion	Very high in soil/water	Not detected in milk	Moderate	Monitor but lower priority
DDT	Persistent in soil	Present in milk	High (bioaccumulative)	Long-term remediation

This table demonstrates that risk is not uniform across contaminants, and policy must be prioritized accordingly.

Based on these findings, the model recommends:

- Shifting from end-product regulation to pathway-based regulation
- Prioritizing high-transfer contaminants (Pb, Chlorpyrifos, DDT)
- Integrating health risk indices (EDI, HQ, CR) into regulatory thresholds
- •Strengthening CPCB enforcement on industrial discharge contributing to Pb contamination
- This aligns with WHO's recommendation that food safety policies should be risk-based, preventive, and exposure-oriented, rather than reactive.

5.4. Integrated Preventive Governance and Source-Based Control

The findings of this study demonstrate that contamination originates primarily from industrial effluents (Pb, Al) and agricultural inputs (Malathion, Chlorpyrifos), with clear transfer across soil–water–feed–milk pathways. For instance, high Fe concentrations (~9000 mg/L) in water and elevated Pb levels in milk confirm that contamination is introduced upstream and subsequently biomagnified through the food chain. These results indicate that food safety risks are fundamentally linked to environmental quality rather than post-production processes.

Accordingly, the proposed model emphasizes source-based and preventive interventions, aligned with Central Pollution Control Board (CPCB) standards and WHO (2022) risk-based frameworks.

Key priorities include:

- Enforcement of CPCB effluent discharge norms for heavy metals
- Regulation of pesticide usage through Integrated Pest Management (IPM)
- Promotion of sustainable agricultural practices to reduce chemical inputs
- Expansion of wastewater treatment and safe reuse systems

CPCB reports consistently identify untreated industrial discharge as a major contributor to heavy metal contamination in Indian water bodies. Given the empirical evidence of contaminant transfer in this study, controlling pollution at its source is critical for reducing downstream exposure. This approach is supported by UNEP (2023), which emphasizes that preventive strategies are more cost-effective and sustainable than remediation-based approaches.

Beyond source control, the study highlights the need for integrated governance systems. Current institutional frameworks remain fragmented, with environmental monitoring (CPCB), food safety regulation (FSSAI), and animal health systems operating independently. This disconnect limits the ability to capture cross-sectoral contamination pathways.

To address this gap, the model proposes:

- Establishment of inter-agency coordination mechanisms
- Integration of environmental, food safety, and livestock datasets

- Development of unified monitoring and reporting platforms

Such integration is essential, as contamination pathways identified in this study span multiple domains. The One Health framework (FAO et al., 2022) strongly supports this approach, emphasizing that effective policy responses require system-level coordination rather than sector-specific interventions.

5.5. Adaptive Implementation: Community Engagement, Technology, and Policy Impact

The study further indicates that local practices significantly influence contamination dynamics, particularly in agricultural regions where pesticide concentrations in soil reach ~15 mg/kg. This underscores the importance of behavioral and community-level interventions in complementing regulatory frameworks. The model therefore incorporates:

- Farmer training on safe pesticide application and waste management
- Community-based monitoring of environmental quality
- Public awareness initiatives linking environmental practices to food safety

Empirical evidence suggests that participatory approaches improve compliance and reduce exposure risks (Shetty et al., 2025). Integrating local knowledge with scientific guidance enhances both effectiveness and long-term sustainability of interventions.

To strengthen monitoring and response capacity, the model also integrates emerging technologies. Given the multi-matrix contamination observed in this study, tools such as:

- Real-time environmental sensors
- AI-based contamination risk prediction models
- Digital traceability systems for food supply chains

can significantly improve detection accuracy and enable early intervention. Recent advancements confirm that such technologies enhance both monitoring efficiency and policy responsiveness (Hernández-Montoya et al., 2026). Their adoption is particularly critical under changing climatic conditions, which may alter contaminant mobility and exposure patterns.

Overall, the proposed framework represents a shift from fragmented, reactive governance to integrated, preventive, and data-driven policy systems. By directly linking environmental contamination with human health outcomes, it aligns global standards (WHO, UNEP, FAO) with national regulatory mechanisms (CPCB), while remaining adaptable to regional contexts.

The continuous transfer of contaminants across environmental and biological systems observed in this study reinforces a key conclusion: food safety is an emergent outcome of environmental integrity. Therefore, effective policy must address contamination across the entire system—from source to consumption—rather than focusing on isolated endpoints.

VI. DISCUSSION:

The findings of this study provide strong empirical confirmation that food safety risks emerge from interconnected, multi-matrix contamination pathways rather than isolated exposure events. The consistent detection of pesticide residues and heavy metals across soil, water, feed, and milk demonstrates a clear trophic transfer continuum, supporting established evidence on bioaccumulation and biomagnification in agro-environmental systems (Zhang et al., 2024; Shetty et al., 2025). Notably, contaminants such as Chlorpyrifos (~2 mg/L in milk) and Pb exhibited high cross-matrix mobility, indicating efficient transfer into the human food chain, whereas Malathion, despite elevated environmental concentrations (>11 mg/L in water), showed limited bio-transfer. This distinction highlights a critical but often overlooked dimension of food safety: exposure risk is governed not only by environmental load but by contaminant-specific bioavailability and metabolic transfer dynamics (Mititelu et al., 2025).

A significant insight from this study is the central role of water as a transmission vector. The observed Fe concentrations (~9000 mg/L) across both regions indicate substantial geogenic and anthropogenic loading, facilitating the mobilization and redistribution of contaminants into agricultural soils and livestock systems. The comparatively higher burden of Pb and pesticide residues in the industrial region (Panipat) underscores the additive effect of industrial discharge and agricultural inputs, consistent with global findings that agro-industrial landscapes function as hotspots of multi-contaminant exposure (Zhu et al., 2025; Hernández-Montoya et al., 2026). Furthermore, the detection of persistent organic pollutants such as DDT in milk highlights long- term environmental persistence and legacy contamination, reflecting the limited efficacy of regulatory bans in eliminating historically accumulated toxicants (Sanusi et al., 2025).

From a human health perspective, the application of EDI, HQ, and CR models strengthens the translational relevance of the findings by linking environmental contamination directly to exposure outcomes. Although individual contaminant levels may fall within permissible thresholds, their cumulative presence across dietary pathways indicates a non-negligible risk of chronic toxicity. This is particularly critical in high milk-consuming populations, where repeated low-dose exposure may result in bioaccumulation and long-term health effects, including neurotoxicity, renal dysfunction, and carcinogenicity (Suresh et al., 2025; Reyes-Márquez et al., 2024). The detection of Pb and pesticide residues in milk is especially concerning given that certain toxicants lack safe exposure thresholds, reinforcing the need to shift from single- contaminant assessment toward cumulative risk frameworks (Ben Ameur et al., 2025).

The study also highlights structural limitations in existing governance systems. Despite the presence of monitoring frameworks, institutional fragmentation between environmental (CPCB), food safety (FSSAI), and animal health systems prevents effective identification of exposure pathways. The demonstrated soil–water–feed–milk linkage clearly indicates that end-product surveillance alone is insufficient, as contamination originates upstream. Similar gaps have been reported globally, where sectoral silos hinder integrated risk management and delay preventive action (FAO, 2023; Yang et al., 2025).

Importantly, the results provide empirical validation for the operational relevance of the One Health framework. By explicitly linking environmental contamination with animal-mediated transfer and human exposure, the study moves beyond conceptual advocacy and demonstrates how integrated approaches can inform policy design. The prioritization of high-transfer contaminants such as Pb and Chlorpyrifos, as identified in this study, aligns with WHO recommendations for risk-based, exposure-driven regulation (WHO, 2022). This reinforces the need for policy frameworks that incorporate multi-matrix monitoring, real-time data integration, and source-oriented interventions.

In conclusion, this study contributes to international literature by offering region-specific, data- driven evidence of systemic contamination while advancing a scalable, policy-relevant framework. The findings underscore a critical paradigm: food safety is not an endpoint condition but an emergent property of environmental integrity and system connectivity. Addressing these risks therefore requires a transition from fragmented, reactive governance to integrated, preventive, and evidence-based policy systems that operate across the entire environmental– food–health continuum.

VII. CONCLUSION:

This study establishes that food safety is a system-level outcome driven by interconnected contamination pathways linking environmental matrices, livestock systems, and human exposure. The consistent detection of pesticide residues and heavy metals across soil, water, feed, and milk confirms a clear trophic transfer continuum, with contaminants such as Pb and Chlorpyrifos demonstrating high transfer potential into the human food chain. These findings highlight that exposure risk is shaped not only by environmental concentration but by bioavailability and transfer dynamics, underscoring the limitations of conventional, concentration-based regulatory approaches.

The integration of health risk indices (EDI, HQ, CR) further indicates that cumulative and chronic exposure—particularly through dairy consumption—poses significant public health concerns, even where individual contaminants may fall within permissible limits. At the governance level, the study reveals critical gaps arising from fragmented regulatory systems that fail to capture cross-sectoral contamination pathways, thereby reinforcing the inadequacy of end- product-focused monitoring.

By empirically validating the soil–water–feed–milk continuum, this research supports a transition toward integrated, risk-based, and preventive policy frameworks grounded in the One Health approach. The proposed model advances a coherent strategy for aligning environmental regulation, food safety systems, and public health objectives through multi-matrix monitoring and source-oriented interventions.

In essence, the study contributes to international scholarship by demonstrating that food safety is an emergent property of environmental integrity and institutional integration, necessitating a shift from reactive governance to holistic, data-driven, and systems-oriented policy design.

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