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Tracing Toxic Chemical Routes and Their Impact on Food Safety Across Production Stages

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Abstract

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Chemical substances exceeding established safety limits have long posed serious threats to human health and the environment, particularly in developing countries. The global food sector is increasingly challenged by toxic chemical contaminants originating from both natural processes and anthropogenic activities. These pollutants can infiltrate all stages of the food production chain, thereby compromising food safety. Among the most concerning are Persistent Organic Pollutants (POPs), such as pesticides and Polychlorinated Biphenyls (PCBs), which are known for their resistance to degradation and long-term ecological impacts. Chemical contamination occurs through multiple pathways, including agricultural practices, industrial emissions, and environmental media such as air, water, and soil. These pathways facilitate the transfer and accumulation of harmful substances in food products. Therefore, strict control measures are essential, particularly in regulating pesticide use, antibiotic application, and food packaging processes to prevent residue accumulation. Ensuring food safety requires coordinated regulatory oversight at both national and international levels. Strengthening monitoring systems and enforcing global standards are crucial steps to reduce exposure risks and maintain the safety and sustainability of the global food supply chain.

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1. Introduction

The regulation and oversight of food systems constitute a fundamental public health function exercised across nations worldwide. Nevertheless, substantial obstacles persist in the effective execution and enforcement of legislative frameworks aligned with international codes and benchmark standards (Ahmad et al., 2019; Aiyar & Pingali, 2020; Vipham et al., 2020). These difficulties are intensified by the unprecedented expansion of the global populace, projected to approach nine billion individuals by mid-century, thereby exerting immense pressure on agricultural output and food manufacturing capacities (Yu et al., 2020). The intensification of large-scale food production, coupled with escalating consumer demand, frequently precipitates deviations from established best practices and statutory obligations. Consequently, food governance has assumed heightened significance, prompting the formulation of diverse intervention strategies aimed at mitigating the repercussions of regulatory non-adherence. Although considerable progress has been made in developing analytical instruments for food surveillance, scholarly evidence indicates that no singular methodology offers an exhaustive or universally applicable remedy for food safety assurance (Nerin et al., 2016). Nonetheless, certain institutions have successfully implemented early detection and warning frameworks designed to identify emergent food safety hazards promptly while enhancing the overall effectiveness of monitoring systems within the food sector (Niu et al., 2021).

The initial phases of the food production continuum present a multitude of safety vulnerabilities. During processing operations, chemical substances may already reside within unprocessed agricultural commodities. This phenomenon arises from ongoing advancements in food technology alongside the persistent reliance on agrochemical inputs. The widespread application of synthetic pesticides and chemical fertilizers markedly elevates contamination risks, with such hazards being particularly pronounced across food manufacturing establishments (Bhalla & Monika, 2019). Moreover, cultivated lands positioned adjacent to concentrated industrial zones remain susceptible to pollutant infiltration via hydrological systems, soil matrices, and atmospheric deposition. Such circumstances may engender a compounded contamination burden resulting from the synergistic accumulation of agrochemical residues and industrial discharges (Bhalla & Monika, 2019; Mandlate et al., 2020).

The detection and quantification of potentially hazardous substances originating from both natural sources and anthropogenic activities can be accomplished through an array of analytical techniques employed within the food sector. Prominent methodologies exhibiting multi-element analytical capabilities for contaminant determination encompass inductively coupled plasma optical emission spectrometry (ICP-OES) and graphite furnace atomic absorption spectrometry (Hossain et al., 2021; Mandlate et al., 2020; Shariatifar et al., 2020). Additional established approaches include inductively coupled plasma mass spectrometry, flame atomic absorption spectrometry, and cold vapor atomic absorption spectrometry (Nerin et al., 2016). These instrumental techniques enable precise identification and measurement of trace-level contaminants across diverse food matrices, thereby supporting risk assessment and regulatory compliance initiatives.

In pursuit of advancing global food safety objectives, authoritative bodies have consistently championed comprehensive ingredient disclosure and transparent labelling practices coupled with ethical marketing conduct. Such measures align harmoniously with the imperatives of international commerce and operational transparency (My et al., 2021). A significant impediment, however, resides in the reality that national regulatory provisions and technical guidelines do not uniformly establish threshold limits for all conceivable chemical contaminants. This discrepancy stems partly from divergent legal statuses accorded to specific chemical agents, substances deemed permissible within one jurisdiction may face outright prohibition elsewhere. Scholars have advocated for the establishment of a unified international agro-commercial chemical governance framework to foster regulatory coherence (Ahmad et al., 2019). Such an initiative would equip participating states with a clear comprehension of chemical safety benchmarks requisite for engagement in transnational food trade, simultaneously cultivating consumer trust as enshrined within the principles of the Codex Alimentarius.

The present review endeavors to furnish a globally oriented synthesis of prevailing patterns concerning food contaminants and their consequential effects upon environmental integrity and human well-being. Central to this examination is an in-depth exploration of chemical contamination trajectories spanning the entirety of food production, from primary agricultural cultivation through successive processing stages to ultimate consumer acquisition. By elucidating these pathways, this work seeks to inform evidence-based policy formulation and operational interventions aimed at safeguarding public health. The subsequent sections delineate specific contamination sources, including transportation-related exposures, cleaning agent residues, food additive applications, packaging material migrations, persistent organic pollutants, pesticide utilization, antibiotic administration in animal husbandry, and heavy metal accumulation, culminating in a discussion of regulatory frameworks and strategic recommendations.

2. Methods

This review employed a systematic and comprehensive literature search methodology to identify relevant scholarly publications addressing chemical contamination pathways and food safety implications across the food production continuum. A structured search was conducted utilizing the Web of Science Core Collection database, encompassing multiple citation indices including the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts & Humanities Citation Index (A&HCI), Conference Proceedings Citation Index (CPCI-S and CPCI-SSH), Book Citation Index (BKCI-S and BKCI-SSH), and the Emerging Sources Citation Index (ESCI). This database was selected based on its established reputation for scientific rigor, extensive multidisciplinary coverage, and frequent application in bibliometric analyses across diverse research domains.

The search strategy incorporated combinations of targeted keywords and Boolean operators designed to capture publications relevant to the review's thematic focus. Primary search terms included "pesticide food contamination" combined with "health effects" or "contamination" as secondary qualifiers. For heavy metal-related content, the search string "heavy metal contamination in food" was deployed. All searches were conducted without language restrictions, although only English-language publications were ultimately included in the synthesis. The temporal scope encompassed publications from January 2010 through March 2021, allowing for an examination of contemporary trends spanning approximately one decade of scientific output.

Inclusion criteria prioritized peer-reviewed journal articles, comprehensive review papers, book chapters, and authoritative reports from international regulatory bodies including the Food and Agriculture Organization (FAO), World Health Organization (WHO), and Codex Alimentarius Commission. Publications addressing persistent organic pollutants, pesticide residues, veterinary antibiotics, heavy metal accumulation, food packaging migration phenomena, and regulatory frameworks governing food safety were deliberately targeted. Exclusion criteria eliminated conference abstracts without full-text availability, non-peer-reviewed commentaries, and publications lacking substantive toxicological or food safety relevance.

Bibliometric trend analyses were performed to visualize publication patterns over time, specifically examining the annual frequency of scientific outputs pertaining to pesticide contamination and heavy metal occurrence in food matrices. Data retrieval and preliminary analysis were completed on March 4, 2021, for pesticide-related literature and March 4, 2021, for heavy metal contamination studies. The search yielded 1,167 pesticide-related publications and a consistently increasing annual output for heavy metal contamination research over the preceding decade.

3. Results

3.1. Enduring Organic Contaminants in the Environment

Persistent Organic Pollutants, commonly abbreviated as POPs, represent a class of carbon-based chemical substances that continue to pose significant environmental and public health threats owing to sustained anthropogenic emissions. Despite the formal adoption of the Stockholm Convention on Persistent Organic Pollutants in 2001, a landmark international treaty designed to restrict and ultimately eliminate the production and utilization of these hazardous compounds, the agreement only attained legal enforceability in 2004 (Pius et al., 2019). Even subsequent to this global regulatory milestone, ongoing human exposure to POPs persists, predominantly attributable to intensive industrial operations encompassing waste management activities and manufacturing sectors that continue to employ chemical additives and pesticide formulations (Bruce-Vanderpuije et al., 2019; Pius et al., 2019). These recalcitrant contaminants exist either in gaseous vapor states or adsorbed onto atmospheric particulate matter, facilitating their long-range environmental transport across geographical and political boundaries (Gaur et al., 2018; Volschenk et al., 2019). Prominent categories of POPs include polychlorinated dibenzo-p-dioxins, dibenzofurans, organochlorine pesticides, polycyclic aromatic hydrocarbons, and polychlorinated biphenyls, all of which share the characteristic trait of pronounced environmental persistence due to their inherent resistance to natural degradation processes (Guo et al., 2019; Wang et al., 2019).

Within the African continent, agricultural pesticides constitute the predominant source of persistent organic pollutant emissions, a phenomenon particularly evident in nations where food production and agricultural trade represent substantial contributors to gross domestic product (Bruce-Vanderpuije et al., 2019). Ghana exemplifies this trend, ranking among the foremost consumers of pesticide products regionally. Comprehensive review investigations conducted in Ghana have identified dichlorodiphenyltrichloroethanes as presenting elevated risk profiles across multiple examined food categories, although observed temporal declines in certain contaminant concentrations may plausibly reflect the positive influence of Stockholm Convention implementation (Bruce-Vanderpuije et al., 2019). Notably, demographic cohorts lacking occupational exposure to POPs nonetheless experience considerable contaminant intake through routine dietary consumption patterns, particularly via animal-derived food products. This baseline exposure is further amplified by the ingestion of fruits and vegetables tainted with pesticide residues, underscoring the pervasive nature of POP contamination across diverse food matrices.

Polychlorinated biphenyls, designated by the acronym PCBs, comprise a family of industrially synthesized chemical compounds categorized within the broader POP classification framework. Although initial synthesis occurred during the 1880s, large-scale commercial production commenced in the 1940s and persisted through the late 1970s (Loganathan & Masunaga, 2020). Physically, these substances manifest as transparent materials capable of existing in either solid or liquid states contingent upon ambient conditions. Historical industrial applications of PCBs encompassed their utilization as lubricating agents, plasticizing compounds, and dielectric insulating fluids within capacitors and electrical transformers (Kang et al., 2020). Their classification as persistent organic compounds derives from their remarkable stability under extreme thermal and barometric conditions, coupled with pronounced resistance to environmental breakdown. Structurally, biphenyl configurations may arise through chemical modifications of diverse organic substrates including polymeric materials and crop protection formulations (Deb, 2018; Rusin et al., 2019).

Empirical evidence consistently indicates that the predominant route of human exposure to polychlorinated biphenyls occurs through the consumption of contaminated food items (Rusin et al., 2019). Quantitative analyses have documented the most substantial contamination burdens within aquatic organisms, terrestrial animal meats, avian eggs, and dairy-derived products, findings attributable to the elevated daily intake frequencies characterizing these dietary staples (Kang et al., 2020). The remarkable capacity of PCBs to penetrate and propagate through trophic levels stems from their intrinsic lipophilicity, environmental recalcitrance, and propensity for prolonged bioaccumulation across ecosystem compartments. Notably, long-lived faunal species exhibit heightened PCB sequestration within adipose tissue depots, reflecting cumulative exposure spanning extended temporal horizons.

Historical epidemiological records document significant foodborne intoxication outbreaks attributed to PCB contamination in Japan (1968) and Taiwan (1979), both incidents involving rice, a fundamental dietary staple within these East Asian societies, as the implicated transmission vehicle (Loganathan & Masunaga, 2020). Clinical manifestations observed among affected populations included cutaneous hyperpigmentation, peripheral limb paresthesia, acneiform dermatological eruptions, and abnormal ocular secretions. Subsequent investigations performed in Lanzhou, China, revealed substantially elevated dietary PCB exposures relative to non-industrialized reference regions. Within this assessment, aquatic food products exhibited the highest mean concentrations (0.31 ± 0.30 ng/g), succeeded by eggs (0.08 ± 0.09 ng/g) and various meat items (0.06 ± 0.05 ng/g), collectively indicating considerable intake through staple food consumption (Kang et al., 2020). Corroborating findings from African scholarship affirm that urbanized industrial centers and manufacturing zones account disproportionately for PCB exposure burdens among populations residing within industrialized communities (Ssebugere et al., 2019).

The term pesticide functions as an umbrella designation encompassing diverse categories of chemical agents including plant growth modulators, fungicidal compounds, herbicidal formulations, insecticidal preparations, rodenticidal substances, molluscicidal products, and nematicidal treatments (Kumar et al., 2018; Zikankuba et al., 2019). Deployed extensively throughout global agricultural systems, these chemical interventions serve to suppress pest populations responsible for crop diseases and yield diminution. Applications may occur across the entirety of food production trajectories, spanning primary cultivation, post-harvest storage, transportation logistics, distribution networks, processing facilities, and ultimate consumer-level handling (Bhalla & Monika, 2019; Kosamu et al., 2020; Tudi et al., 2021; Volschenk et al., 2019; Zikankuba et al., 2019). Significantly, pesticide effects extend beyond intended target organisms to impact non-target species inhabiting adjacent ecological niches (Deb, 2018; Xu et al., 2021). Agricultural sector expansion has paralleled progressive intensification of pesticide utilization patterns. First-generation pesticide formulations, originating during the 1860s, were ultimately abandoned owing to pronounced toxicological liabilities, with synthetic organic alternatives emerging in the subsequent decade (Kumar et al., 2018). However, widespread manufacturing and deployment only attained substantial momentum during the 1940s, coinciding with industrial acceleration across both developed and developing economies.

The transboundary atmospheric conveyance of pesticide residues renders these compounds pollutants capable of traversing local, regional, and international jurisdictions (Sharma et al., 2019; Taiwo, 2019). Human health consequences stemming from pesticide intoxication are considerable, with annual global mortality estimates attributable to direct or indirect ingestion ranging between 250,000 and 370,000 fatalities (Bhalla & Monika, 2019). Temporal analyses reveal Japan's position as the preeminent global pesticide consumer during the 2010-2014 period, exemplifying pronounced national dependency upon chemical pest management strategies in contexts where economically viable alternatives remain scarce. Among the most extensively investigated pesticide categories are organophosphorus compounds, for which microbial biodegradation pathways offer promising remediation avenues (Chiocchetti et al., 2019; Massoud et al., 2019). Lactic acid bacterial strains, specifically *Lactobacillus bulgaricus* and *Streptococcus thermophilus*, have demonstrated demonstrable pesticide-degrading capacities (Chiocchetti et al., 2019; Massoud et al., 2019). Complementary enzymatic systems, including phosphodiesterases, methyl parathion hydrolases, and organophosphorus acid anhydrolases, further contribute to organophosphate breakdown. Additionally, fermentative processes mediated by *Saccharomyces cerevisiae* yeast present viable strategies for pesticide residue attenuation or elimination within food matrices (Santarelli et al., 2018). Consequently, rigorous risk assessment protocols must be systematically implemented across food production enterprises and retail establishments to evaluate residual pesticide burdens (Raymundo-Pereira et al., 2021; Santarelli et al., 2018).

Quantitative assessments indicate that developed nations account for approximately 80% of worldwide annual pesticide production, with agricultural activities responsible for an estimated 70-80% of total usage (Kumar et al., 2018). Vegetable crop applications alone represent roughly 25% of pesticide consumption within industrialized countries (Zikankuba et al., 2019). Remarkably, merely 0.1% of applied pesticide quantities successfully reach intended target pests, with the residual 99.9% dispersing into surrounding environmental compartments including food systems, hydrological resources, and atmospheric reservoirs (Deb, 2018). Environmental transport mechanisms encompass surface water runoff, volatilization and vapor-phase movement, substrate leaching, and osmotically driven redistribution under aerodynamic influences (Kumar et al., 2018; Zikankuba et al., 2019). Contemporary inventories document approximately 1,400 discrete pesticide entities (Bari & Yeasmin, 2018). Although certain formulations, exemplified by DDT, have long been subject to prohibitory regulations within numerous jurisdictions, bioaccumulation persists within aquatic ecosystems owing to protracted environmental residence times (Mazzoni et al., 2018). Consequently, rigorous transboundary monitoring protocols and harmonized regulatory standards remain imperative (Taiwo, 2019). Risk evaluations have illuminated the heightened hazardous potential associated with chemical mixture effects arising from multiple concurrent exposure pathways (Margenat et al., 2019). Organochlorine pesticides, distinguished by their ubiquity, persistence, hydrophobicity, and degradation resistance, exhibit pronounced chemical stability and semi-volatility, facilitating atmospheric transport and preferential accumulation within lipid-rich biological tissues. Their lipophilic nature dictates predominant occurrence within fatty food categories, fish, meat, and dairy products, with several African nations, including Togo, Nigeria, and Ghana, continuing to report concentrations exceeding internationally established maximum permissible thresholds (Taiwo, 2019).

3.2. Pesticide Contamination in Food: Regulatory Standards and Human Health Risks

Routine dietary intake inevitably entails concomitant exposure to pesticide residues, given the pervasive application of these agrochemicals throughout global food production systems. The ubiquity of pesticide utilization across agricultural landscapes translates directly into measurable contaminant burdens within consumable food commodities, thereby establishing ingestion as the predominant non-occupational exposure pathway for the general populace. Consequently, the assessment and regulation of pesticide concentrations in foodstuffs constitute fundamental pillars of contemporary food safety governance frameworks. National regulatory authorities across diverse geopolitical jurisdictions have promulgated predetermined maximum allowable thresholds for pesticide residues, aligned with technical guidance disseminated by tripartite international bodies, namely the Food and Agriculture Organization, the World Health Organization, and the Codex Alimentarius Commission (Zikankuba et al., 2019). These threshold values, designated as Maximum Residue Limits, serve as benchmarks against which compliance with good agricultural practices and consumer safety assurances are evaluated.

Within the European context, the European Food Safety Authority assumes a pivotal role as an independent scientific advisory body tasked with conducting comprehensive risk evaluations pertaining to pesticide residues and other food-associated hazards (European Food Safety Authority, 2011, 2019). Functioning effectively as a gatekeeping entity vis-à-vis the European Commission, EFSA undertakes rigorous peer-reviewed assessments of novel chemical substances proposed for agricultural deployment, subsequently formulating recommendations regarding acceptable maximum residue concentrations in diverse food commodities. This deliberative process incorporates exhaustive due diligence investigations encompassing toxicological profiles, environmental fate characteristics, and potential human health ramifications associated with candidate compounds

(European Food Safety Authority, 2011, 2019). Upon satisfactory completion of these evaluative procedures, EFSA's scientific determinations inform regulatory decisions concerning substance approvals and the establishment of legally enforceable residue ceilings across European Union member states.

In circumstances where detected pesticide residue concentrations surpass established Maximum Residue Limits, comprehensive risk characterization necessitates comparative analysis against toxicological reference values, specifically the Acceptable Daily Intake and the Acute Reference Dose (Zikankuba et al., 2019). The Acceptable Daily Intake, as formally articulated within scholarly and regulatory discourse, denotes the quantity of a given pesticide, expressed in milligrams per kilogram of body weight, to which human populations may be subjected daily via oral ingestion throughout an entire lifetime without incurring appreciable health detriments, predicated upon the totality of scientific knowledge available at the juncture of evaluation (Nasreddine & Parent-Massin, 2002; Zikankuba et al., 2019). This chronic exposure benchmark integrates uncertainty factors accounting for interspecies variability and intraspecies sensitivity differentials, thereby furnishing a conservative estimate protective of vulnerable demographic subgroups including pediatric populations, geriatric cohorts, and immunocompromised individuals.

Complementing the chronic exposure framework embodied by the Acceptable Daily Intake, the Acute Reference Dose constitutes an additional toxicological safeguard specifically addressing short-term, high-intensity exposure scenarios. This parameter is derived with particular consideration for population segments exhibiting heightened susceptibility, encompassing infants, young children, and women of reproductive age. Operationally defined, the Acute Reference Dose represents the quantum of pesticide exposure, within a singular 24-hour interval, at which adverse health sequelae may manifest among the most sensitive constituents of a given population (Zikankuba et al., 2019). The incorporation of this acute exposure metric into regulatory risk assessment protocols acknowledges the toxicological reality that certain pesticide compounds elicit deleterious effects following brief, elevated exposures rather than exclusively through cumulative, protracted intake patterns. This dual-threshold paradigm, encompassing both chronic and acute reference values, enhances the protective scope of contemporary food safety governance mechanisms.

Member states affiliated with the World Health Organization have instituted nationally applicable contaminant threshold limits designed to align with recommendations promulgated under the auspices of the Codex Alimentarius Commission (Codex Alimentarius International Food Standards, 2021). The Codex framework establishes internationally recognized Maximum Residue Limits spanning an extensive array of pesticide-food commodity pairings, thereby facilitating regulatory harmonization and promoting equitable trade practices within global agricultural markets. As illustrated in tabular compilations of Codex standards, permissible residue concentrations exhibit substantial variation contingent upon the specific pesticide-commodity combination under consideration (Codex Alimentarius International Food Standards, 2021). For instance, abamectin residues are restricted to 0.02 mg/kg in citrus fruits and soya beans yet permitted at concentrations up to 2 mg/kg in head cabbages, reflecting differential application patterns and residue dissipation kinetics across diverse crop matrices. Similarly, tebuconazole tolerances range from 0.05 mg/kg in tomatoes to 5 mg/kg in rice, underscoring the commodity-specific nature of residue limit determinations.

The establishment and enforcement of science-based Maximum Residue Limits, coupled with rigorous adherence to Acceptable Daily Intake and Acute Reference Dose parameters, constitute indispensable components of comprehensive pesticide risk management architectures. Nevertheless, substantial challenges persist in ensuring uniform implementation across heterogeneous regulatory landscapes, particularly within developing economies characterized by constrained analytical infrastructure and limited enforcement capacities. The transboundary movement of food commodities necessitates sustained international cooperation and capacity-building initiatives to bridge regulatory asymmetries and safeguard consumer populations irrespective of geographic provenance. Furthermore, ongoing surveillance programs must be augmented to monitor temporal trends in residue occurrence, detect emergent exposure patterns, and inform iterative refinement of permissible thresholds in alignment with evolving toxicological understanding and consumption behaviors.

4. Conclusion

Investigations into chemical toxicity within food systems are essential and must be reinforced through rigorous toxicological research to enhance food quality and safeguard consumer health. Adverse human health consequences arising from heavy metal accumulation, antibiotic residues, and persistent organic pollutants necessitate robust regulatory frameworks supported by sound scientific evidence and stringent monitoring protocols. Although bioremediation strategies have demonstrated effectiveness in mitigating contaminant burdens, further inquiry is required to evaluate their long-term sustainability and economic viability as routine control measures within food industry operations. This review has identified numerous research trajectories warranting deeper exploration to refine understanding of chemical toxicology in alimentary contexts. Strengthened regulatory harmonization across jurisdictions, particularly within developing economies, remains critical for protecting vulnerable populations including children, pregnant individuals, and subsistence farming communities from preventable chemical exposures.

Future research should examine contaminant transfer pathways along farm-to-consumer chains in developing nations, where infrastructural gaps amplify exposure risks. Comparative toxicological assessments across geographic regions and low-concentration threshold development represent pressing priorities. This review highlights pronounced research asymmetries, with heavy metal studies concentrated in Asia despite European Union advancements through REACH legislation. Methodological replication within underexplored African contexts would yield insights regarding culturally mediated exposures, staple food contamination profiles, and agro-climatic influences on contaminant dynamics. Enhanced epidemiological surveillance of chemical-associated foodborne illnesses and robust econometric methodologies quantifying financial burdens are urgently needed. Finally, collaborative engagement with food industry stakeholders to address practical contamination reduction challenges would strengthen translational relevance and foster sustainable solutions aligned with global best practices.

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