Food Quality Control for Sensitive Consumer Segments: Challenges and Approaches in Child Nutrition

Raluca-Anamaria Drideanu[1]*, Mariana Luca[1], Georgiana Magdalena Gheciu Pîrlea[1], Aida-Maria Bengea[1], Gratziela-Victoria Bahaciu[1]

[1]*University of Agronomic Sciences and Veterinary Medicine of Bucharest, 59 Marasti Blvd, District 1, Bucharest, Romania*

Abstract

Ensuring adequate food quality for sensitive consumer groups, particularly children, is a critical challenge in contemporary food science and public health. This review examines the main challenges associated with food quality control in pediatric nutrition, including microbiological hazards, allergen management, nutritional adequacy, and the regulatory frameworks governing food products intended for young consumers. This review shows that current monitoring systems present substantial limitations when applied to child-specific dietary patterns, including school meals, infant formula, and processed foods marketed to younger age groups, with fragmented regulatory harmonization across jurisdictions identified as the most critical systemic gap. Analysis of emerging technological approaches demonstrates that biosensor-based rapid detection systems and risk-based preventive control plans adapted for child-oriented food production show the greatest near-term potential for strengthening quality assurance. Furthermore, the integration of nutritional profiling with safety assessment proves essential, as quality in pediatric nutrition extends beyond hazard elimination to encompass the active promotion of optimal growth and cognitive development. The findings conclude that no single disciplinary approach is sufficient to address the complexity of food safety in this domain. A multidisciplinary, risk-informed framework bridging food technology, pediatric nutritional science, regulatory policy, and consumer education is necessary to strengthen food safety systems across the entire supply chain.

Keywords: allergen detection, biosensors, foodborne pathogens, nutritional profiling, regulatory harmonization, vulnerable populations

1. Introduction

The first years of life represent a period of accelerated physiological development during which dietary intake exerts lasting effects on growth, immune function, and neurodevelopment [1, 2]. Infants and young children are entirely dependent on commercially produced foods infant formula, cereal-based products, and complementary foods to meet their nutritional requirements, making the quality and safety of these products a matter of direct clinical and public health relevance [2]. Unlike the general adult population, this consumer segment has a limited capacity to tolerate exposure to foodborne hazards [2, 3]. Immature hepatic and renal function reduces the ability to metabolize and excrete contaminants, while an underdeveloped immune system increases susceptibility to pathogenic microorganisms [2, 3]. Even low-level or short-term exposure to chemical contaminants during critical developmental windows can result in adverse outcomes that persist well beyond infancy [4].

These biological vulnerabilities translate directly into regulatory obligations across jurisdictions [5]. Infant foods are subject to more stringent

* Corresponding author: Raluca Drideanu, raluca.drideanu@usamv.ro

compositional, microbiological, and contaminant requirements than foods intended for the general population, as reflected in frameworks established by the European Union, the United States and Codex Alimentarius among others [6, 7, 8, 9]. Nevertheless, significant divergences persist between regulatory systems in terms of pre-market approval procedures, permitted ingredients, and maximum contaminant limits [10]. Allergen labeling requirements and the scope of microbiological criteria also vary considerably across jurisdictions [5]. These inconsistencies complicate compliance for manufacturers operating across multiple markets and generate uneven levels of consumer protection globally [5].

Food quality control for infant and toddler products must simultaneously address several distinct hazard categories [11]. Microbial pathogens such as *Salmonella* spp. and *Cronobacter sakazakii* pose severe risks in powdered infant formula and cereal-based products [3, 12]. Chemical contaminants including heavy metals, mycotoxins, and pesticide residues have been widely detected in commercial baby foods across all major markets [4, 13, 14]. Nutritional composition and labeling accuracy are equally critical, as deviations from declared values carry direct consequences for dietary adequacy during sensitive developmental periods [15, 16]. Allergenic substances require both correct label declaration and effective cross-contact management throughout the production chain [17]. No single analytical method is capable of addressing the full spectrum of hazards present in complex infant food matrices, making multi-platform quality control programs essential [11, 18, 19].

The growing complexity of global supply chains further amplifies these challenges [11]. Variability in raw material origins introduces contamination profiles that finished-product testing alone cannot adequately capture [20]. Historical incidents such as the 2008 melamine adulteration crisis demonstrated the capacity of deliberate fraud to evade conventional quality systems and precipitated substantial regulatory reform [21]. Advances in analytical technology including high resolution mass spectrometry, aptamer-based biosensors, and blockchain-enabled traceability systems offer improved tools for detection, monitoring, and supply chain transparency [19, 22, 23]. Aligning these technological capabilities with harmonized international standards remains the central challenge for quality control in infant and child nutrition [10].

2. Materials and methods

This review is based on a comprehensive analysis of scientific literature covering the microbiological, chemical, nutritional, allergenic, and regulatory dimensions of food quality control for infants and young children. Sources were identified through searches conducted in Google Scholar, PubMed, and ScienceDirect, using combinations of the following terms: infant food, baby food, infant formula, food safety, microbiological contamination, Cronobacter sakazakii, Salmonella, heavy metals, mycotoxins, pesticide residues, allergens, ICP-MS, LC-MS/MS, biosensors, blockchain traceability, regulatory framework.

The search covered peer-reviewed journal articles, regulatory documents, and analytical guidelines, and spans publications predominantly from the past ten years (2015-2025), with older foundational studies included where relevant. Regulatory documents were retrieved from the official portals of the European Commission, the U.S. Food and Drug Administration, the Codex Alimentarius Commission, and Chinese national standards authorities. Studies were selected based on the following inclusion criteria: primary data, regulatory analysis, or methodological evaluation directly relevant to at least one of the defined review domains (microbiological safety, chemical contamination, nutritional composition, allergen management, or comparative regulation of infant and toddler foods); and full-text availability in English. Sources providing only general food safety data without specific applicability to infant or young child nutrition were excluded. The retrieved materials were thematically organized and comparatively reviewed to identify key trends, recurring findings, and knowledge gaps relevant to this uniquely vulnerable consumer segment. A total of 49 references were retained for the final synthesis.

3. Results and discussion

3.1 Microbiological safety profiles in children's food products

Infants and young children are disproportionately vulnerable to foodborne pathogens due to their immature immune systems, with infections capable of progressing to septicaemia and meningitis [2, 3]. International regulatory frameworks show broad agreement on zero tolerance criteria for key pathogens in powdered infant formula, though sampling strategies and pathogen coverage differ across jurisdictions [6, 7].

Salmonella spp. and Cronobacter sakazakii are the pathogens of greatest regulatory concern [3, 12]. C. sakazakii is particularly dangerous in neonates under two months of age, where case-fatality rates are high [3]. Its low infectious dose and ability to survive in dry processing environments make it a persistent contamination risk in powdered infant formula production, since low water activity inhibits growth but does not eliminate viable cells [12]. Documented outbreak investigations have reinforced the need for environmental monitoring programs targeting the entire production facility, not only the finished product [3, 12].

The EU requires testing of 30 analytical units for both pathogens under Regulation (EC) No 2073/2005, while Codex Alimentarius mandates 60 units for Salmonella [6, 7]. China's GB 29921 uses fewer units but requires 100 g portions for Cronobacter [21]. The US FDA does not set colony-forming unit limits for finished products; instead, it relies on preventive controls under 21 CFR Parts 106 and 107 [8].

Process hygiene indicators reveal further differences [2]. The EU defines absence criteria for Enterobacteriaceae and limits for Bacillus cereus in cereal-based infant foods [6]. Surveillance data confirm B. cereus occurrence in commercial products, while molecular methods have proven more sensitive than conventional culture for its detection [24]. China sets explicit quantitative limits for aerobic plate count and total coliforms - parameters not uniformly regulated in the EU or US [21]. The lack of fully harmonized global criteria complicates compliance for multinational manufacturers and underscores the need for risk-based approaches tailored to infant vulnerability [2].

3.2 Chemical contaminants and maximum permissible limits

Chronic exposure to chemical contaminants during infancy-even at low concentrations - can impair neurological development and organ function [2]. Heavy metals, mycotoxins, and pesticide residues are the primary categories of concern, and their regulation has evolved as toxicological evidence has accumulated [4, 13, 14].

Lead, cadmium, inorganic arsenic, and mercury have been detected in commercial baby food products globally, with rice - and fish-based products showing the highest contamination levels [4, 20]. Market monitoring confirms the continued relevance of analytical surveillance [25]. The EU sets strict maximum limits for these metals, while the US adopted action levels through the "Closer to Zero" initiative [4, 26].

Cereal-based infant foods are particularly susceptible to mycotoxin contamination [13]. Multiple mycotoxins including aflatoxins and deoxynivalenol have been detected simultaneously in the same product, raising concerns about cumulative exposure [13, 27]. EU limits for aflatoxins in infant foods are more stringent than those for general food categories, though regulatory divergence between jurisdictions remains notable [14]. While deoxynivalenol concentrations in commercial products often fall within legal limits, co-occurrence with other mycotoxins is a persistent risk [28].

EU regulatory frameworks apply particularly stringent pesticide residue limits in infant foods, with default maximum residue levels set at 0.01 mg/kg as a precautionary measure, reflecting the vulnerability of this consumer segment [14]. The US and China apply broader limits without infant-specific adjustments, creating uneven levels of consumer protection across markets [4]. The analytical complexity of monitoring multiple pesticide residues in diverse food matrices, combined with the variability of environmental contamination across growing regions, makes routine multi-residue screening an essential component of quality control programs [2].

3.3 Nutritional adequacy benchmarks and labeling compliance

Compositional standards for infant formula must reflect current knowledge of early-life nutritional needs [15, 9]. While macronutrient ranges are

broadly aligned across jurisdictions, micronutrient specifications and mandatory additives vary considerably [10]. Table 1 summarizes key compositional benchmarks [8, 9, 15, 21, 29].

Table 1. Nutritional composition requirements for infant formula across regulatory jurisdictions (per 100 kcal)

Nutrient	Unit	Codex CXS 72 (Min-Max)	EU 2016/127 (Min-Max)	US FDA 21 CFR 107 (Min-Max)	China GB 10765 (Min-Max)	Source
Protein (milk-based)	g	1.8-3.0	1.8-2.5	1.8-4.5	1.8-3.0	[9, 29, 8, 21]
Total fat	g	4.4-6.0	4.4-6.0	3.3-6.0	4.4-6.0	[9, 29, 8, 21]
Carbohydrate	g	9.0-14.0	9.0-14.0	NS[1]	9.0-14.0	[9, 29, 8, 21]
Iron	mg	0.45-NS	0.3-1.3	0.15-3.0	0.42-1.5	[9, 29, 8, 21]
Calcium	mg	50-NS	50-140	60-NS[1]	50-146	[9, 29, 8, 21]
Zinc	mg	0.5-NS	0.5-1.0	0.5-NS[1]	0.5-1.5	[9, 29, 8, 21]
Vitamin D	µg	1.0-2.5	2.0-3.0	1.0-2.5	2.0-5.0	[9, 29, 8, 21]
Vitamin A	µg RE	60-180	70-114	75-225	60-150	[9, 29, 8, 21]
DHA[2]	mg	Not mandatory	20 (minimum, mandatory)	Not mandatory	Not mandatory	[29, 9, 8, 21]
Choline	mg	7-50	25-50	7 (minimum; no upper limit specified)	20-100	[9, 29, 8, 21]

[1]NS = not specified.
[2]DHA = docosahexaenoic acid.

The EU framework is the most restrictive: it sets both minimum and maximum values for nearly all nutrients and uniquely mandates DHA at a minimum of 20 mg/100 kcal [15]. Iron ranges differ substantially the FDA allows 0.15-3.0 mg/100 kcal, while the EU caps it at 1.3 mg/100 kcal, reflecting different views on fortification and gastrointestinal tolerability in term infants [15, 30]. The EU and China both prohibit sucrose and fructose, requiring lactose to constitute at least 90% of carbohydrates in milk-based formulas; the US permits corn syrup solids and sucrose [10].

Labeling compliance data reveal widespread inaccuracies [16, 31]. A survey of 43 complementary food products from Cambodia, Indonesia, and Senegal found no product meeting EU tolerance thresholds for all nine analyzed nutrients; 88.4% had at least one missing label value, and only 54.8% achieved acceptable macronutrient accuracy [16]. In the US market, surveys of complementary and toddler foods haveidentified discrepancies between declared and actual nutrient content, including caloric and macronutrient values [31]. Such deviations are particularly concerning in infant and toddler nutrition, where dietary planning depends on accurate label data to avoid both under- and over-supply of critical nutrients during sensitive developmental windows [16, 31].

3.4 Food allergen prevalence and management strategies

Allergen declaration is a key component of food safety labeling in pediatric nutrition [32, 17]. Food allergy affects approximately 6-8% of children in industrialized countries, though prevalence estimates vary considerably depending on diagnostic method and geography [33]. Challenge-confirmed diagnoses consistently yield lower rates than self-reported data, making oral food challenge the accepted diagnostic standard in epidemiological studies [33]. Table 2 presents challenge-proven food allergy prevalence across major population-based studies [33, 34].

Table 2. Challenge-proven food allergy prevalence in children by allergen and geographic region (%).

Allergen	Australia (HealthNuts, 1 yr)	Europe (EuroPrevall cohort)	Meta-analysis	Asia	Source
Cow's milk	1.5	0.5-1.2	~1.0	0.3-3.0	[33, 11]
Egg	9.0-9.5	0.1-2.2	~1-2	0.5-2.5	[33]
Peanut	3.0-3.1	<0.5	~0.5	0.1-0.3	[33]
Wheat	-	<1.0	~0.5	Variable	[11]
Soy	-	<0.5	~0.3	Variable	[11]
Tree nuts	-	<0.5	~0.5	Low	[11]
Fish	-	Variable	~0.3	Higher in Asia	[35]
Any food allergy	10-11	-	6.5-8.0	1-3	[11, 33, 34]

Prevalence varies substantially by region [33, 34]. The Australian HealthNuts study found ~9.5% egg allergy and 3% peanut allergy at one year [34], while European rates are generally lower [33]. In Asia, fish and shellfish allergies are more prevalent than peanut allergy, consistent with regional dietary patterns [35]. These differences implicate early dietary exposure as a key driver of sensitization [36, 37].

Egg allergy often resolves during childhood, whereas peanut allergy typically persists [35]. The LEAP trial showed that early peanut introduction significantly reduced allergy risk at age five compared to avoidance [37], and subsequent reviews support early exposure as a strategy for promoting oral tolerance [36].

From a regulatory standpoint, the EU mandates labeling of 14 allergens under Regulation (EU) No 1169/2011, while the US requires declaration of nine, including sesame under the FASTER Act [29, 8]. Precautionary allergen labeling (PAL) - statements such as "may contain" - is used when cross-contact risk exists during production [32], but its application is largely unregulated, with no agreed quantitative thresholds across jurisdictions [17]. The VITAL (Voluntary Incidental Trace Allergen Labeling) initiative has proposed reference doses for specific allergens to support risk-based PAL decisions, though adoption remains voluntary and inconsistent globally [17]. Without standardized thresholds, inconsistent PAL use creates conflicting signals: consumers may unnecessarily avoid safe products or, conversely, underestimate genuine risk when labeling is applied erratically [32]. Quantitative, risk-based allergen management frameworks are needed to standardize decision-making from raw material sourcing through to final product labeling [17, 35]. matrix, and applicable regulatory thresholds [11, 18, 19]. Increasingly stringent limits for toxic metals have driven adoption of high-sensitivity instrumentation and more rigorous validation standards [18]. Table 3 compares the main analytical platforms used in children's food quality control [18, 19].

3.5 **Analytical methods for quality control assessment**

No single analytical method covers the full range of chemical, microbiological, and allergenic hazards in infant foods [11, 18, 19]. Method selection depends on the target analyte, food

Table 3. Performance characteristics of principal analytical methods used in children's food quality control.

Method	Target Analytes	LOD[1] Range	Recovery (%)	Analysis Time	Key Strength	Source
ICP-MS[2]	Heavy metals (Pb, Cd, As, Hg)	0.02-2.81 µg/kg	80-119	2-5 min/sample	Ultra-trace multi-element detection	[18]
LC-MS/MS[3]	Mycotoxins (multi-residue)	0.001-0.1 mg/kg	85-129	10-30 min/run	Simultaneous multi-analyte detection	[19]
HPLC-FLD/DAD[4]	Vitamins (A, D, E, K, B-complex)	~0.01 µg/mL	90-105	20-35 min	Reliable quantitative analysis	[38]
ELISA[5]	Allergens, mycotoxins	1-5 ppm (allergens)	73-106	30-100 min	Cost-effective, high-throughput screening	[39]
Real-time PCR[6]	Allergens, pathogens	0.1-1 ppm (allergens); 1-10 CFU[7]	-	2-16 hours	High sensitivity in processed matrices	[39]
NIR[8] spectroscopy	Composition, adulteration	Variable (matrix-dependent)	-	Seconds-minutes	Non-destructive, rapid at-line monitoring	[40]
Biosensors	Pathogens, contaminants	Low CFU levels	-	15-60 min	Portable, rapid detection	[41]

[1]LOD = limit of detection.
[2]ICP-MS = inductively coupled plasma mass spectrometry.
[3]LC-MS/MS = liquid chromatography tandem mass spectrometry.
[4]HPLC-FLD/DAD = high-performance liquid chromatography with fluorescence detection/diode array detection.
[5]ELISA = enzyme-linked immunosorbent assay.
[6]PCR = polymerase chain reaction.
[7]CFU = colony-forming units.
[8]NIR = near-infrared.

ICP-MS is the standard method for heavy metal quantification in baby food, offering simultaneous multi-element detection at concentrations well below current regulatory thresholds, with typical limits of detection in the range of 0.02-2.81 µg/kg depending on the element [18]. The use of collision cell or dynamic reaction cell technology further reduces polyatomic interferences that are common in complex food matrices [18]. However, high fat, protein, or carbohydrate content can still suppress analyte signals, requiring matrix-matched calibration standards and, where feasible, isotope dilution for accurate quantification [18].

LC-MS/MS has replaced single-compound methods for mycotoxin monitoring due to its multi-residue capability and well-documented validation performance across infant food matrices [19]. Matrix effects remain a source of variability and are managed using isotope-labeled internal standards and matrix-matched calibration [42].

HPLC-FLD/DAD remains the reference method for vitamin quantification in infant formula, with high specificity for both fat- and water-soluble vitamins, though its analyte scope is narrower than LC-MS/MS [38]. For allergen detection, ELISA is widely used for routine screening, but protein denaturation during thermal processing can reduce antibody recognition and cause false negatives [39]. PCR-based methods are more robust in processed matrices since DNA is less susceptible to thermal degradation than proteins [39]. The absence of harmonized quantitative allergen thresholds further complicates result interpretation [17].

NIR spectroscopy enables non-destructive, rapid compositional monitoring without sample preparation, making it well suited for at-line process control in infant formula production [40]. Biosensor platforms-including electrochemical and optical systems-offer portable, rapid pathogen detection at low CFU levels, with potential applications in resource-limited settings [41]. The shift toward multi-platform analytical workflows reflects both technological progress and growing regulatory complexity in infant food safety [11, 18, 19].

3.6 Comparative regulatory frameworks for children's food safety

National regulatory systems for children's food safety reflect distinct philosophies on risk management, pre-market scrutiny, and additive control [5]. Differences in compositional specifications and approval requirements have practical consequences for multinational manufacturers and became particularly apparent during the 2022-2023 US infant formula shortage, when foreign products were temporarily admitted under relaxed requirements [43]. The Codex Alimentarius Commission provides a voluntary international reference framework, which jurisdictions may adopt or exceed [9].

The EU framework anchored in Delegated Regulation (EU) 2016/127 and Regulation (EU) No 609/2013 is among the most comprehensive globally [29]. It sets nutrient ranges with both floors and ceilings, mandates DHA at ≥20 mg/100 kcal, restricts sucrose and fructose, and limits additives to a positive list under Regulation (EC) No 1333/2008 [29]. Fourteen allergens must be labeled under Regulation (EU) No 1169/2011, and pesticide residue limits are set at very low levels [29].

China overhauled its regulatory system after the 2008 melamine crisis [21]. Since 2016, all infant formula products require registration with the State Administration for Market Regulation, with full formulation disclosure prior to market entry [21]. The updated standard GB 10765-2021 revised nutrient specifications, prohibited sucrose and fructose, and tightened contaminant limits - substantially reducing the number of approved products and strengthening compliance [21].

The US model is more permissive: manufacturers must notify the FDA at least 90 days before launching a new formula, but pre-market approval is not required [44]. Ingredient safety can be self-determined under the GRAS framework, a provision that came under considerable scrutiny during recent supply disruptions [10]. The US permits a wider range of carbohydrate sources and does not mandate DHA [10]. Japan mandates labeling of major allergens and supports standardized immunoassay- and DNA-based detection methods, contributing to methodological consistency [45]. Australia and New Zealand operate under FSANZ, applying standards broadly aligned with Codex Alimentarius recommendations [9].

The contrast between China's centralized registration model, the EU's precautionary approach, and the US industry-led system reflects broader trade-offs between innovation, market access, and infant protection [5]. Without international harmonization, these structural differences generate uneven consumer protection and significant compliance burdens for globally operating manufacturers [5, 10].

3.7 Challenges and emerging approaches for sensitive consumer segments

Quality control for infant foods is uniquely demanding: regulatory thresholds are exceptionally low, food matrices are analytically complex, and supply chains are increasingly global [11]. Contamination levels considered acceptable in foods intended for the general adult population may produce significant adverse developmental outcomes in infants, given the markedly reduced tolerance thresholds characterizing this age group [1].

Matrix effects are a persistent obstacle in trace analysis [46]. The high fat, protein, and carbohydrate content of infant foods generates variable instrumental backgrounds that can suppress or amplify signals unpredictably [46]. Collision cell ICP-MS, isotope dilution, and matrix-matched calibration are required to meet current detection limits, but these techniques are not universally accessible [18]. In allergen testing, spray-drying and extrusion denature proteins used in immunoassay targets, increasing false-negative risk with direct safety implications [39].

Supply chain complexity introduces additional sources of uncertainty [20, 2]. Single-point finished-product testing cannot capture the full variability introduced by different raw material origins - arsenic in rice-derived ingredients, heavy

metals in soy-based components, and mycotoxins in cereal flours [20]. Raw material sourcing from multiple suppliers and geographic origins means that contamination profiles can shift batch-to-batch, making upstream testing and supplier qualification essential complements to finished-product analysis [20]. The 2008 melamine adulteration incident in China demonstrated how deliberate fraud can systematically evade nitrogen-based quality checks, and prompted major structural reforms in both national and international regulatory oversight [21].

Several emerging technologies have been progressively incorporated to address these gaps [11]. Aptamer-based biosensors demonstrate high sensitivity and specificity for pathogen detection in complex food matrices [22, 47]. LAMP-based molecular methods enable rapid, sensitive pathogen identification without centralized laboratory infrastructure [48]. Blockchain traceability systems can improve supply chain transparency, data integrity, and consumer trust [23, 49]. NIR and advanced biosensor approaches also support real-time compositional monitoring at production scale [40].

Advances have been recorded across multiple dimensions - in detection sensitivity, supply chain transparency, and understanding of infant-specific risk - but regulatory harmonization continues to lag behind both technological development and the growing complexity of global infant food supply chains [10]. Aligning standards across jurisdictions, particularly for contaminant limits, allergen thresholds, and additive approval criteria, remains a prerequisite for consistent protection of this uniquely vulnerable population [10].

4. Conclusions

This review examined food quality control across seven interconnected dimensions of infant and child nutrition, revealing both the progress achieved and the structural gaps that remain [2, 11]. Microbiological safety frameworks converge on zero-tolerance criteria for *Salmonella* spp. and *Cronobacter sakazakii*, yet meaningful differences persist in sampling plans, hygiene indicator requirements, and pathogen scope across the EU, US, China, and Codex Alimentarius [6, 7, 21, 8]. Chemical contaminant regulation has advanced significantly, driven by accumulating toxicological evidence, but heavy metals, mycotoxins, and pesticide residues continue to be detected in commercial infant foods globally, and permissible limits remain inconsistent across jurisdictions [4, 20, 13, 14]. Nutritional labeling compliance data indicate that declared and actual nutrient content frequently diverge, with implications for dietary adequacy during developmentally critical periods [16, 31]. Allergen management is further complicated by the absence of harmonized quantitative thresholds for precautionary labeling, reducing the reliability of risk communication to consumers [32, 17]. Analytical capabilities have expanded substantially, with ICP-MS, LC-MS/MS, and emerging biosensor platforms enabling multi-hazard detection at increasingly low concentrations, though access to advanced instrumentation remains uneven across regulatory and industrial settings [18, 19, 41].

Several limitations of the current evidence base warrant acknowledgment [11]. Many surveillance studies are geographically restricted or based on small product samples, limiting the generalizability of contamination prevalence data [20]. Labeling compliance assessments are largely cross-sectional and may not capture temporal variability in product formulation [16]. Additionally, the regulatory documents analyzed reflect standards at specific points in time, and ongoing revisions - particularly in the context of post-shortage US reforms and evolving EU nutrient specifications - may alter the comparative landscape [10, 43].

Future priorities should include the development of internationally harmonized contaminant limits and allergen thresholds tailored specifically to infant exposure profiles [2, 17]. Wider adoption of blockchain-based traceability and real-time biosensor monitoring could strengthen supply chain oversight beyond what finished-product testing alone can achieve [22, 23]. Longitudinal studies linking early contaminant exposure to developmental outcomes are needed to inform more precise, risk-based regulatory thresholds for this uniquely vulnerable population [4, 2].

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