International Journal of Health Sciences and Research
[Indexed, Peer-Reviewed Journal]
Volume 16; Issue: 3; March 2026
Website: www.ijhsr.org
ISSN: 2249-9571

Review Article

Counterfeit Infant Feeding Bottles and Their Implications for Child Health: A Global Review of Chemical, Microbiological, Environmental, and Policy Evidence

Yamee Shah[1], Tekla Hemisha Jacob Lyanda[2], Deepika Anand[3]

[1,2,3]Department of Nutrition and Dietetics, Parul Institute of Applied Sciences, Parul University, Vadodara, Gujarat, India

Corresponding Author: Tekla Hemisha Jacob Lyanda

DOI: https://doi.org/10.52403/ijhsr.20260306

ABSTRACT

Background: Infant feeding bottles are widely used globally; however, increasing evidence indicates that plastic food-contact materials are not chemically inert under realistic conditions involving heating, repeated sterilization, mechanical stress, and prolonged use. Early life, particularly the first 1,000 days, represents a critical developmental window during which low-dose environmental exposures may influence endocrine signalling, immune maturation, metabolic programming, and neurodevelopmental outcomes.
Objective: This review synthesizes peer-reviewed evidence on chemical migration from infant feeding bottles, endocrine-disrupting mechanisms and "regrettable substitution" following bisphenol A (BPA) regulation, microplastic release during routine formula preparation, microbiological contamination risks, and emerging public health challenges associated with counterfeit feeding bottle markets.
Methods: A structured narrative systematic approach was used to identify peer-reviewed literature from PubMed, Scopus, and Google Scholar. Included studies comprised experimental migration research, mechanistic toxicology reviews, epidemiological studies examining bisphenol exposure and child health outcomes, microplastic release investigations, and authoritative regulatory risk assessments. Grey literature and non-indexed sources were excluded to ensure methodological rigor.
Results: Experimental evidence demonstrates increased migration of bisphenols under thermal and mechanical stress conditions. Although regulatory actions reduced BPA use in infant products, structurally related substitutes such as bisphenol S (BPS) and bisphenol F (BPF) exhibit comparable endocrine activity, raising concerns regarding class-based chemical risks. Polypropylene feeding bottles may release substantial quantities of microplastic particles during standard preparation practices, introducing an additional exposure pathway. Concurrently, bottle feeding practices may increase microbiological contamination risk, particularly where material degradation promotes biofilm formation. Counterfeit products further complicate safety assessment due to uncertain composition and regulatory oversight gaps.
Conclusion: Infant feeding bottle safety should be conceptualized within an integrated exposure framework incorporating chemical migration, particulate release, microbiological

hazards, and global market dynamics. Strengthening lifecycle-based testing, class-focused regulatory strategies, counterfeit surveillance, and culturally appropriate caregiver guidance may reduce early-life environmental exposures and improve child health protection.

Keywords: Infant feeding bottles; bisphenol A; bisphenol analogues; endocrine-disrupting chemicals; microplastics; polypropylene; polycarbonate; bottle hygiene; biofilms; counterfeit products; food-contact materials; infant exposure.

INTRODUCTION

Early-Life Vulnerability and Environmental Exposure

The first thousand days of life—from conception through the second year—represent a biologically sensitive window characterized by rapid cellular proliferation, organ maturation, immune programming, and endocrine system development [1]. During this period, even low-dose environmental exposures may exert disproportionate and potentially irreversible effects on long-term health trajectories [2,18]. Developmental toxicology has demonstrated that infancy is marked by immature hepatic detoxification pathways, reduced renal clearance, and higher intake per kilogram body weight, all of which amplify internal dose following exposure to environmental contaminants [2].

Exclusive breastfeeding for the first six months of life remains the global gold standard recommendation because of its protective effects against infection, malnutrition, and chronic disease [1]. Nevertheless, bottle feeding remains prevalent worldwide due to urbanization, maternal employment, sociocultural factors, and aggressive marketing of breast-milk substitutes [1]. Consequently, the safety of infant feeding equipment is not merely a consumer issue but a core public health concern intersecting toxicology, food safety regulation, and child health equity.

Plastic infant feeding bottles have gained widespread adoption because of durability, affordability, transparency, and resistance to breakage compared with glass alternatives. However, accumulating scientific evidence demonstrates that plastic polymers used in food-contact materials are not chemically inert under real-world conditions [3–6]. Heating, mechanical stress, sterilization, and repeated use can induce degradation of polymer matrices, facilitating migration of chemical constituents into food and beverages [3–6]. In infants, such exposures may coincide with periods of endocrine system programming, heightening concern regarding developmental consequences [2].

CHEMICAL MIGRATION FROM INFANT FEEDING BOTTLES

Bisphenol A (BPA): Early Evidence and Regulatory Trigger

Bisphenol A (BPA) is a synthetic monomer historically used in polycarbonate plastics and epoxy resins. Early toxicological studies demonstrated estrogenic activity of BPA, prompting investigation into its migration from baby bottles under common household conditions [2]. One of the seminal studies by Brede et al. reported that dishwashing, boiling, and mechanical brushing significantly increased BPA migration from polycarbonate bottles [3]. Importantly, migration levels increased after repeated use cycles, suggesting cumulative degradation effects [3].

Cao and Corriveau further confirmed that BPA leached into water when bottles were subjected to severe heating conditions, including boiling and prolonged contact times [4]. Their findings indicated that real-world sterilization practices could generate exposure levels exceeding those predicted under standardized laboratory testing [4]. Kubwabo et al. subsequently demonstrated that severe use conditions, including microwave heating and mechanical wear, further elevated BPA release [6].

These findings shifted scientific consensus by demonstrating that infant feeding bottles were not chemically inert under typical caregiver practices. Because infants consume large volumes of formula relative to body weight, BPA exposure from bottles became a major regulatory concern [2,19].

Epidemiological studies strengthened the plausibility of health risk. Braun et al. reported associations between prenatal BPA exposure and altered behavioral outcomes in children [7]. Trasande et al. identified associations between urinary BPA concentrations and obesity risk in children and adolescents [8]. Although causality remains complex, such findings reinforced concerns regarding endocrine disruption during sensitive developmental windows [2,7,8].

In response, regulatory agencies implemented precautionary measures. Canada became the first country to declare BPA toxic and ban its use in baby bottles [9]. The European Union adopted Directive 2011/8/EU prohibiting BPA in infant feeding bottles [10]. The United States Food and Drug Administration subsequently removed BPA-based resins from baby bottles and sippy cups [11]. These actions marked a significant shift toward precautionary protection of infant health.

REGRETTABLE SUBSTITUTION: BPA-FREE DOES NOT NECESSARILY MEAN SAFE

Bisphenol S (BPS) and Bisphenol F (BPF)

Following regulatory bans, manufacturers introduced alternative bisphenols, particularly bisphenol S (BPS) and bisphenol F (BPF), marketed under "BPA-free" labeling. However, structural similarity between BPA and its analogues raised immediate toxicological concerns [2].

Rochester and Bolden conducted a systematic review demonstrating that BPS and BPF exhibit endocrine activity comparable to BPA, including estrogenic, anti-androgenic, and thyroid-disrupting effects [12]. Experimental studies have shown that these compounds can bind hormone receptors and interfere with gene expression pathways involved in metabolic and reproductive regulation [12]. Thus, substitution of BPA with structurally related analogues may represent a phenomenon termed "regrettable substitution," whereby one hazardous compound is replaced with another of similar biological activity [12].

Migration studies further demonstrated that BPS and BPF can leach from BPA-free bottles under heating and repeated use conditions [12]. These findings challenge simplistic interpretations of consumer safety labelling and highlight limitations of single-chemical regulatory strategies.

From a toxicokinetic perspective, infants possess immature glucuronidation capacity, potentially prolonging systemic exposure to bisphenols [2]. Physiologically based pharmacokinetic modelling suggests that age-specific metabolism significantly influences internal dose following equivalent external exposure [2]. Consequently, safety thresholds derived from adult toxicology may underestimate infant risk.

MECHANISMS OF ENDOCRINE DISRUPTION

Non-Monotonic Dose–Response Relationships

Endocrine-disrupting chemicals (EDCs) differ from classical toxicants in that low-dose exposures may exert biologically significant effects not predicted by high-dose testing paradigms [2]. Non-monotonic dose–response curves challenge traditional regulatory frameworks that rely on linear extrapolation from high-dose animal studies [2,20].

BPA and its analogues can mimic estrogen by binding to estrogen receptors (ERα and ERβ), alter androgen receptor signaling, and interfere with thyroid hormone pathways [2,12]. These hormonal pathways regulate critical developmental processes including neurogenesis, adipogenesis, pancreatic β-cell development, and immune maturation [2]. Disruption during infancy may therefore have long-term metabolic and neurodevelopmental implications.

Experimental models demonstrate that low-dose BPA exposure can influence adipocyte differentiation and insulin signaling pathways [2]. Such mechanisms are consistent with epidemiological associations linking BPA exposure to obesity risk [8]. While causality remains debated, the convergence of mechanistic and observational evidence underscores biological plausibility [2,8].

Importantly, exposure rarely occurs in isolation. Infants may be exposed to mixtures of bisphenol analogues, phthalates, and other food-contact chemicals simultaneously. Cumulative and mixture effects remain insufficiently characterized in regulatory risk assessment.

MATERIALS & METHODS

Search Strategy and Inclusion Criteria

This review employed a structured narrative systematic approach to identify and synthesize relevant scientific evidence. Peer-reviewed literature was systematically searched using major electronic databases, including PubMed, Scopus, and Google Scholar, to ensure comprehensive coverage of multidisciplinary research spanning toxicology, environmental health, paediatrics, and food-contact material safety. The search strategy incorporated combinations of keywords and controlled vocabulary terms such as "infant feeding bottle," "bisphenol migration," "endocrine-disrupting chemicals," "microplastics infant feeding," and "food contact materials." Boolean operators and database-specific filters were applied to refine results and improve retrieval accuracy.

Studies were considered eligible if they met predefined inclusion criteria aligned with the objectives of this review. These included peer-reviewed experimental investigations evaluating chemical migration from infant feeding bottles under laboratory or simulated real-world conditions; toxicological and mechanistic reviews examining endocrine activity of bisphenols and related analogues; epidemiological studies assessing associations between bisphenol exposure and child health outcomes; and peer-reviewed experimental studies examining microplastic release during formula preparation or bottle usage. Additionally, authoritative regulatory assessments published by recognized agencies were included when supported by rigorous scientific evaluation and DOI-traceable documentation.

To maintain scientific rigor and comply with journal requirements, grey literature, unpublished reports, conference abstracts without full peer review, and non-indexed sources were excluded from analysis. This selection strategy ensured that conclusions were based on validated, reproducible, and peer-reviewed scientific evidence.

Data Synthesis

Due to heterogeneity in exposure conditions, materials tested, and outcome measures, quantitative meta-analysis was not performed. Instead, thematic synthesis was used to integrate findings across chemical, toxicological, microbiological, and regulatory domains. Particular emphasis was placed on studies replicating realistic household conditions, including boiling water sterilization, microwave heating, and repeated mechanical stress [3–6].

EMERGING DIMENSION: MICROPLASTICS FROM POLYPROPYLENE BOTTLES

Recent research has expanded concern beyond chemical migration to include microplastic particle release. Li et al. conducted experimental simulations of formula preparation using polypropylene infant feeding bottles and reported that millions of microplastic particles per litre could be released under boiling and shaking conditions [13]. Estimated daily ingestion levels for infants ranged in the millions of particles [13].

Although direct human outcome data remain limited, experimental toxicology suggests potential mechanisms including oxidative stress, inflammatory responses, and alterations in gut microbiota composition [14,21]. The World Health Organization has acknowledged microplastics in drinking water as an emerging research area requiring further evaluation [22].

Given that counterfeit bottles may be manufactured from lower-grade or recycled plastics, degradation and particle shedding may be amplified, although counterfeit-specific microplastic research remains sparse. This gap underscores the need for targeted comparative testing.

RESULTS

Microbiological Contamination and Infection Risk

Bottle Feeding as a Microbiological Exposure Pathway

Beyond chemical hazards, bottle feeding introduces significant microbiological risks that may contribute to infant morbidity. Unlike breastfeeding, which delivers sterile nutrition directly from the mother, bottle feeding involves multiple steps including preparation, storage, and cleaning, each representing a potential contamination point [1]. Studies in low-resource settings have demonstrated increased risk of diarrheal disease among bottle-fed infants compared with exclusively breastfed infants [15]. Such infections may exacerbate malnutrition by impairing nutrient absorption and increasing metabolic demands.

Plastic bottle surfaces are particularly susceptible to microbial colonization. Repeated mechanical stress, including brushing during cleaning, can produce microscopic scratches that enhance bacterial adhesion and biofilm formation [16,24]. Biofilms provide protective microenvironments that increase resistance to disinfectants, making thorough sterilization difficult [16]. Experimental studies have identified contamination by pathogens such as Cronobacter sakazakii, Escherichia coli, and Salmonella species in improperly sterilized bottles [16].

The relationship between microbiological contamination and counterfeit products remains understudied but highly plausible. Counterfeit bottles may use inferior plastics that degrade more rapidly, creating porous surfaces conducive to bacterial growth. Furthermore, inconsistent manufacturing standards may introduce contamination during production. These risks may be magnified in settings lacking access to safe water or reliable sterilization equipment.

Heating, Sterilization, and Mechanical Stress as Exposure Drivers

Real-World Preparation Practices

Caregiver practices designed to ensure hygiene may unintentionally increase chemical migration and material degradation. Boiling bottles remains a widely recommended sterilization method, particularly in low- and middle-income countries where electric sterilizers are unavailable [1]. However, thermal stress can weaken polymer matrices and accelerate release of chemical additives [3–6].

Microwave heating introduces additional risks. Studies have demonstrated that microwave radiation can induce localized heating and polymer breakdown, increasing migration of bisphenols into liquids [5]. Similarly, vigorous shaking during formula preparation may enhance mechanical stress and particle release [13]. These findings illustrate the complex interplay between hygiene practices intended to reduce microbiological risk and unintended chemical exposure.

Repeated washing cycles also contribute to cumulative degradation. Dishwasher detergents and mechanical abrasion alter surface integrity, increasing permeability and facilitating chemical leaching [3]. Thus, exposure risk is influenced not only by material composition but also by lifecycle usage patterns.

Microplastics as an Emerging Exposure Pathway

Quantifying Infant Exposure

The recognition that infant feeding bottles may release microplastic particles represents a significant paradigm shift in understanding environmental exposures during infancy. Experimental simulations conducted by Li et al. demonstrated that polypropylene bottles subjected to typical formula preparation conditions released millions of microplastic particles per liter[13]. Exposure estimates suggested that infants consuming formula prepared using these bottles could ingest millions of particles daily [13].

Microplastics may act as vectors for chemical additives or environmental contaminants. Laboratory studies indicate that microplastics can adsorb heavy metals, persistent organic pollutants, and endocrine-disrupting compounds [14]. Upon ingestion, these particles may interact with gastrointestinal tissues, potentially triggering inflammatory responses or altering microbial ecosystems [14].

While definitive human health outcomes remain uncertain, the scale of potential exposure raises concern, particularly given developmental vulnerability during infancy [2]. Current regulatory frameworks do not yet incorporate microplastic release into food-contact material safety assessments, highlighting a significant policy gap.

Counterfeit Infant Feeding Bottles and Global Market Dynamics

Drivers of Counterfeit Markets

Counterfeit infant feeding bottles represent an emerging global challenge driven by economic and regulatory factors [23]. Counterfeit products imitate established brands but circumvent safety testing, certification, and quality control processes. These products are frequently sold through informal markets were affordability pressures and limited regulatory enforcement influence consumer behavior.

Studies examining counterfeit consumer goods indicate that price differentials are a major driver of purchasing decisions, particularly in low-income settings [25]. Certified infant feeding bottles may be significantly more expensive than counterfeit alternatives, incentivizing caregivers to choose lower-cost options despite potential safety risks.

Counterfeit manufacturing may involve recycled plastics, unregulated additives, or unknown polymer compositions. Such variability introduces uncertainty regarding chemical stability and migration behavior. Unlike regulated manufacturers, counterfeit producers are not required to adhere to migration limits or standardized testing protocols.

Health Equity Implications

The proliferation of counterfeit infant feeding bottles reflects broader structural inequities in global health protection. High-income countries benefit from robust regulatory surveillance, laboratory testing infrastructure, and consumer protection frameworks. In contrast, many low- and middle-income countries lack resources to enforce food-contact safety standards effectively.

As a result, infants in resource-constrained settings may face disproportionately higher exposure to hazardous materials. This unequal distribution of risk aligns with broader patterns of environmental health inequity, where vulnerable populations experience greater exposure to unsafe products due to socioeconomic constraints.

DISCUSSION

Overview of Principal Findings

This review demonstrates that infant feeding bottle safety must be understood within a multidimensional exposure framework integrating chemical migration, endocrine disruption, microplastic release, microbiological contamination, and counterfeit market dynamics. Experimental evidence consistently shows that heating, repeated sterilization, and mechanical stress increase migration of bisphenol compounds from plastic bottles [3–6]. Regulatory bans targeting bisphenol A (BPA) have reduced exposure in some regions [9–11]; however, substitute compounds such as bisphenol S (BPS) and bisphenol F (BPF) demonstrate comparable endocrine activity [12]. Emerging research further reveals that polypropylene bottles can release microplastic particles under routine formula preparation conditions [13]. These overlapping exposure pathways raise important toxicological and policy implications.

Developmental Toxicology and Early-Life Susceptibility

Infancy represents a uniquely vulnerable developmental stage characterized by rapid organ maturation, endocrine system calibration, and immune programming [1,2]. During this period, small perturbations in hormonal signaling may produce long-term physiological consequences [2]. Bisphenols function as endocrine-disrupting chemicals (EDCs) capable of binding estrogen receptors and interfering with androgen and thyroid signaling pathways [2,12]. Because endocrine systems rely on tightly regulated feedback mechanisms, even low-dose exposure may alter transcriptional processes critical for growth and neurodevelopment [2].

Non-monotonic dose–response relationships complicate traditional toxicological assumptions that “higher dose equals greater effect” [2]. EDCs may exert biologically meaningful effects at low concentrations not predicted by high-dose testing paradigms [2]. This phenomenon challenges regulatory thresholds derived primarily from adult toxicology studies. Given that infants have higher intake per kilogram body weight and immature glucuronidation pathways, internal exposure may exceed adult-equivalent dose under similar environmental concentrations [2].

Epidemiological studies linking urinary BPA concentrations with metabolic outcomes in children further support biological plausibility [7,8]. While causality remains complex due to confounding variables, convergence between mechanistic and observational evidence underscores the need for precautionary risk reduction during early life.

Regrettable Substitution and Chemical Class Considerations

The transition from BPA-containing bottles to “BPA-free” alternatives illustrates a classic case of regrettable substitution. Systematic reviews confirm that BPS and BPF retain estrogenic and anti-androgenic properties similar to BPA [12]. Migration studies demonstrate that these analogues can leach under heating and repeated use conditions [12]. Consequently, single-chemical bans may shift rather than eliminate endocrine risk.

A broader regulatory approach considering structural classes of bisphenols may provide stronger long-term protection. Class-based regulation could reduce iterative replacement of one compound with another of comparable biological activity. Such approaches align with contemporary toxicological thinking emphasizing cumulative and mixture effects [2].

Microplastic Exposure: An Emerging Dimension of Risk

Recent experimental evidence indicates that polypropylene infant feeding bottles may release substantial quantities of microplastic particles during formula preparation [13]. Boiling water sterilization, vigorous shaking, and repeated heating cycles increase particle shedding [13]. Estimated ingestion levels for formula-fed infants reach millions of particles per day [13].

Although direct longitudinal human health data remain limited, laboratory studies suggest potential mechanisms including oxidative stress, inflammatory responses, and alterations of gut microbiota composition [14]. Microplastics may also act as carriers for sorbed contaminants or residual additives, potentially increasing internal chemical burden [14]. While definitive clinical implications require further investigation, the scale of potential exposure warrants precautionary evaluation.

Current food-contact regulations largely focus on chemical migration thresholds and rarely address particulate release. Incorporating microplastic testing into material safety assessment frameworks represents an important research and policy frontier.

Microbiological Risk and Infection Pathways

Chemical safety must be interpreted alongside microbiological risk. Bottle feeding introduces multiple contamination points, including formula preparation, storage, and cleaning [1]. Surface degradation caused by repeated mechanical brushing can facilitate bacterial adhesion and biofilm formation [16]. Biofilms increase resistance to disinfection, complicating sterilization efforts [16].

Studies in low-resource settings demonstrate increased diarrheal incidence among bottle-fed infants compared with exclusively breastfed infants [15]. Infection can impair nutrient absorption and exacerbate growth faltering, linking feeding equipment safety to broader nutrition outcomes [15]. Counterfeit bottles manufactured from inferior polymers may degrade more rapidly, potentially amplifying both chemical and microbiological risks.

Importantly, hygiene practices intended to reduce microbial contamination—such as boiling—may simultaneously increase chemical migration [3–6]. This dual-risk interaction underscores the need for balanced public health messaging that integrates both chemical and microbiological considerations.

Counterfeit Market Dynamics and Health Equity

Counterfeit infant feeding bottles reflect structural inequities in global consumer protection systems. Informal markets in low- and middle-income countries frequently distribute products lacking safety certification. Price differentials between authentic and counterfeit bottles incentivize purchase of lower-cost alternatives, particularly among economically vulnerable populations.

Counterfeit manufacturing often involves recycled plastics or unregulated additives, increasing uncertainty regarding chemical composition and migration behavior. Limited laboratory infrastructure in some regions constrains regulatory enforcement capacity. As a result, infants in resource-constrained settings may face disproportionate exposure risk, reinforcing environmental health inequities.

Addressing counterfeit distribution requires coordinated action among customs authorities, public health agencies, and international regulatory bodies. Surveillance systems incorporating risk-based inspection strategies may enhance detection without imposing unrealistic burdens on caregivers.

Regulatory Disparities and Policy Implications

High-income countries have implemented precautionary measures including BPA bans and revised tolerable intake thresholds [9-11,17]. The European Food Safety Authority's reassessment of BPA reflects evolving scientific recognition of low-dose endocrine effects [17]. However, enforcement gaps persist globally. Harmonized international standards and improved laboratory capacity are necessary to ensure equitable protection.

Policy approaches should move beyond narrow single-chemical evaluation toward cumulative risk assessment models integrating bisphenol analogues, microplastics, and microbial contamination. Enhanced transparency in polymer composition and labelling standards may also improve consumer awareness.

Research Priorities

Despite growing evidence concerning chemical migration, endocrine activity, microplastic release, and microbiological contamination associated with infant feeding bottles, several important research gaps remain. A key priority is the comparative evaluation of authentic and counterfeit bottle materials under identical laboratory conditions. Most migration and toxicological studies have examined regulated commercial products, whereas counterfeit bottles often lack standardized polymer disclosure and safety documentation. Direct side-by-side testing under controlled stress conditions would provide clearer insight into whether counterfeit materials exhibit higher rates of chemical leaching, polymer degradation, or particulate shedding. Such evidence would support more targeted regulatory enforcement and surveillance strategies.

Another critical area involves the development of standardized stress-testing protocols that more accurately replicate real-world usage patterns. Current regulatory testing frequently employs fixed temperature and contact-time scenarios that may not reflect household practices such as repeated boiling, microwave heating, vigorous shaking, and mechanical brushing [3–6]. Incorporating dynamic lifecycle testing models that simulate cumulative wear and thermal stress over time could improve exposure estimation accuracy. Standardization across jurisdictions would also enhance comparability of safety assessments.

Biomonitoring studies evaluating infant exposure to bisphenol analogues and related additives represent an additional research priority. Although urinary biomarker studies have documented widespread bisphenol exposure in general populations [2], infant-specific biomonitoring linked directly to feeding practices remains limited. Prospective studies measuring exposure biomarkers alongside detailed feeding equipment histories would provide stronger evidence regarding dose–response relationships in early life. Integration of physiologically based pharmacokinetic (PBPK) modelling could further refine understanding of age-specific metabolism and internal dose variability.

Moreover, mixture toxicology models assessing cumulative exposure warrant greater emphasis. Infants using plastic feeding bottles may be simultaneously exposed to bisphenol analogues, plasticizers, stabilizers, and microplastic particles. Traditional single-compound regulatory evaluation may underestimate real-world biological effects when substances act additively or synergistically [2]. Developing mixture-based assessment frameworks aligned with modern toxicological principles would strengthen regulatory decision-making.

Longitudinal cohort studies linking early-life exposure to developmental outcomes are also urgently needed. While experimental and mechanistic studies provide biological plausibility, long-term observational research could clarify associations with neurodevelopment, metabolic programming, immune function, and growth trajectories. Multicentred cohort designs incorporating environmental exposure assessment, developmental screening, and socioeconomic variables would offer more comprehensive insight into potential long-term implications.

Addressing these research priorities would significantly strengthen the evidence base guiding regulatory policy, clinical recommendations, and public health communication. A coordinated international research agenda integrating toxicology, epidemiology, materials science, and health systems research is therefore essential.

Practical Risk Reduction Strategies

While regulatory frameworks evolve and research gaps are addressed, interim exposure minimization strategies may help reduce potential risks associated with infant feeding bottle use. Caregivers can be encouraged to purchase feeding bottles from verified retailers or licensed pharmacies whenever feasible, as formal supply chains are more likely to distribute products meeting established safety standards. Although economic constraints may limit purchasing options in certain contexts, awareness of counterfeit risks can support more informed decision-making.

Routine inspection and timely replacement of bottles that exhibit visible signs of degradation are also important. Surface clouding, discoloration, scratches, or persistent odors may indicate polymer breakdown, which has been associated with increased chemical migration under stress conditions [3–6]. Replacing damaged bottles reduces the likelihood of enhanced leaching or microbial adhesion.

Thermal exposure management represents another practical consideration. Although sterilization remains essential for microbiological safety, avoiding prolonged contact between very high-temperature liquids and plastic surfaces may reduce polymer degradation. Allowing boiled water to cool slightly before mixing formula may strike a balance between microbial protection and material preservation, provided safe preparation guidelines are followed. Adherence to evidence-based sterilization protocols recommended by health authorities remains critical to minimizing infection risk [1].

Importantly, such guidance should be delivered through culturally appropriate infant and young child feeding (IYCF) programs integrated within maternal and child health services. Clear, non-alarmist communication is essential to prevent confusion or unintended discouragement of necessary feeding practices. Public health messaging should emphasize risk reduction rather than risk elimination, acknowledging that complete avoidance of environmental exposure is unrealistic in many settings.

Integrating practical safety guidance into existing nutrition counselling platforms may enhance caregiver confidence and promote safer feeding environments without imposing unrealistic expectations. This balanced approach aligns with broader goals of protecting infant health while respecting diverse socioeconomic realities.

Integrative Perspective

Infant feeding bottle safety cannot be understood in isolation from broader environmental exposure systems, as infants are simultaneously exposed to multiple interacting hazards arising from chemical migration, particulate release, microbiological contamination, and globalized supply chains that facilitate counterfeit product distribution. These exposure pathways operate within complex socioeconomic and regulatory contexts that influence both product availability and caregiver behavior. Consequently, risk assessment must move beyond a narrow material-specific focus toward an integrated systems perspective that accounts for cumulative exposures across environmental, behavioral, and market domains [1–3].

From a toxicological standpoint, plastic food-contact materials represent dynamic systems rather than chemically inert structures. Repeated heating, mechanical abrasion, ultraviolet exposure, and cleaning processes alter polymer stability and facilitate migration of monomers, additives, and degradation byproducts into food matrices [4–6]. Studies examining bisphenol compounds demonstrate that migration rates increase under realistic use conditions, challenging earlier assumptions derived from simplified laboratory testing [4,5]. Moreover, the transition toward "BPA-free" materials has highlighted limitations of single-chemical regulatory approaches, as structurally similar analogues such as bisphenol S (BPS) and bisphenol F (BPF) exhibit comparable endocrine activity and receptor-binding properties [7]. These findings underscore the importance of adopting class-based regulatory strategies that address chemical families rather than isolated compounds.

The recognition of microplastic release from polypropylene infant feeding bottles further expands the conceptualization of exposure risk. Experimental studies simulating formula preparation have demonstrated substantial particle release, with estimated ingestion levels reaching millions of particles per day in formula-fed infants [8]. Although long-term clinical implications remain under investigation, emerging evidence suggests that microplastics may interact with gastrointestinal tissues, influence microbiota composition, and serve as vectors for adsorbed environmental contaminants [9]. The inclusion of particulate exposure within food-contact safety frameworks therefore represents an emerging priority for both research and regulatory innovation.

Microbiological risk must also be considered alongside chemical hazards. Bottle feeding introduces multiple contamination pathways, including improper cleaning, inadequate sterilization, and environmental exposure during preparation. Biofilm formation on degraded plastic surfaces can increase microbial persistence and resistance to disinfection, particularly when bottles exhibit microstructural damage resulting from repeated use [10]. The dual nature of thermal sterilization simultaneously reducing microbial risk while potentially increasing chemical migration illustrates the need for integrated risk communication strategies that avoid oversimplified messaging.

Counterfeit feeding bottle distribution adds another layer of complexity. Globalized manufacturing and informal market networks enable rapid dissemination of products that may bypass safety testing and certification standards. Counterfeit materials frequently lack traceable polymer composition, making toxicological characterization difficult and increasing uncertainty regarding chemical stability. These dynamics disproportionately affect low- and middle-income countries, where regulatory enforcement capacity may be limited and affordability pressures influence consumer purchasing behaviour [11]. Addressing counterfeit risks therefore requires coordinated international surveillance strategies that combine regulatory oversight with consumer education initiatives.

From a developmental biology perspective, infants represent a uniquely sensitive population due to higher intake relative to body weight, immature detoxification pathways, and hormonally sensitive developmental windows [12]. Exposure to endocrine-disrupting chemicals during critical periods may influence gene expression, metabolic programming, and neurodevelopmental trajectories [12]. Recognizing this vulnerability reinforces the ethical imperative to minimize avoidable environmental exposures during early life.

Integrated policy approaches grounded in health equity principles are therefore essential. Regulatory agencies should prioritize harmonization of safety standards, adoption of lifecycle testing protocols that replicate real-world usage, and expansion of surveillance mechanisms targeting informal markets. Public health interventions should emphasize culturally appropriate education strategies that empower caregivers without generating unnecessary fear or stigma. Importantly, promoting breastfeeding where feasible remains a central strategy for reducing exposure to feeding equipment-related hazards while supporting optimal infant nutrition outcomes [1].

By situating counterfeit feeding bottles within this broader exposure ecosystem, this review highlights that early-life environmental safety represents both a scientific responsibility and a global public health priority. Protecting infants from preventable exposure requires collaboration among researchers, clinicians, regulators, manufacturers, and communities. Advancing multidisciplinary research, strengthening regulatory frameworks, and promoting informed caregiving practices together offer the most promising pathway toward safer feeding environments and improved child health outcomes worldwide.

CONCLUSION

Synthesis of Evidence Across Exposure Domains

This review demonstrates that infant feeding bottle safety must be evaluated through an integrated exposure framework that considers chemical migration, endocrine-disrupting activity, microplastic release, microbiological contamination, and counterfeit product distribution as interconnected rather than isolated phenomena. Evidence from experimental migration studies confirms that plastic food-contact materials are dynamic systems whose chemical stability is influenced by heating, mechanical abrasion, and repeated sterilization cycles. While regulatory bans on bisphenol A (BPA) in infant feeding bottles have reduced direct exposure in several high-income countries, the emergence of structurally similar substitutes such as bisphenol S (BPS) and bisphenol F (BPF) raises concerns regarding persistent endocrine activity. This pattern illustrates the limitations of substance-by-substance regulatory strategies and underscores the need for broader class-based assessment models.

Simultaneously, emerging research on microplastic release from polypropylene feeding bottles reveals an additional dimension of exposure that extends beyond chemical leaching alone. Under realistic preparation conditions, bottles may shed substantial quantities of microscopic particles, introducing a particulate exposure pathway whose long-term health implications remain under investigation. Although definitive epidemiological data linking microplastic ingestion to specific infant outcomes are currently limited, laboratory findings suggesting oxidative stress, inflammatory responses, and potential interaction with gut microbiota justify precautionary consideration. Incorporating particulate release into food-contact safety evaluation may represent a necessary evolution of regulatory science.

Microbiological contamination further complicates risk assessment. Bottle feeding introduces multiple potential contamination points, and degradation of plastic surfaces may facilitate microbial adhesion and biofilm formation. In low-resource settings, inadequate access to clean water and sterilization equipment may amplify infection risk. Notably, hygiene practices intended to reduce microbial contamination, such as repeated boiling, may simultaneously increase chemical migration. This dual-risk dynamic highlights the complexity of balancing chemical and microbiological safety in real-world contexts.

Developmental Vulnerability and Ethical Imperative

Infants constitute a uniquely sensitive population due to higher intake relative to body weight, immature detoxification capacity, and hormonally sensitive developmental windows. Endocrine-disrupting chemicals can interfere with receptor-mediated signaling pathways that regulate growth, neurodevelopment, and metabolic programming. The presence of non-monotonic dose response relationships further complicate risk assessment, as low-dose exposures may exert biologically significant effects not predicted by traditional toxicological models. Although uncertainties remain, the convergence of mechanistic evidence and exposure plausibility strengthens the argument for precautionary risk minimization during early life.

From an ethical perspective, minimizing avoidable environmental exposures during infancy represents a public health priority grounded in principles of developmental protection and intergenerational equity. The potential for cumulative and mixture exposures including bisphenol analogues, additives, and microplastic particles reinforces the need for comprehensive safety frameworks that reflect real-world exposure complexity rather than isolated compound evaluation.

Counterfeit Products and Structural Inequities

The proliferation of counterfeit infant feeding bottles reveals broader structural inequities within global consumer protection systems. Informal markets, fragmented supply chains, and economic disparities contribute to uneven distribution of exposure risk. In many low- and middle-income countries, limited laboratory infrastructure constrains regulatory surveillance capacity, allowing uncertified products to circulate widely. Counterfeit bottles may contain variable polymer compositions or unregulated additives, increasing uncertainty regarding chemical stability and safety.

Addressing counterfeit risks therefore requires more than technical material testing. It demands coordinated regulatory enforcement, strengthened customs inspection systems, improved traceability mechanisms, and cross-border collaboration. At the same time, public health messaging must avoid stigmatizing caregivers who rely on lower-cost products due to economic necessity. Health equity considerations must guide both policy development and risk communication strategies.

Regulatory Evolution and Policy Directions

The regulatory response to BPA exposure demonstrates that precautionary action is possible when scientific evidence converges with public health advocacy. However, the experience of regrettable substitution highlights the need for more comprehensive chemical class evaluation frameworks. Future regulatory evolution should incorporate:

- Class-based assessment of structurally related endocrine disruptors
- Lifecycle stress-testing protocols simulating realistic household use
- Standardized evaluation of microplastic release
- Mixture-based risk assessment methodologies
- Harmonization of international safety standards

Integrating these components into food-contact material regulation would better reflect contemporary scientific understanding of cumulative exposure dynamics. Furthermore, enhanced global cooperation could reduce disparities in product safety enforcement.

Research and Innovation Pathways

Advancing infant feeding safety requires sustained multidisciplinary research efforts. Comparative testing of authentic versus counterfeit products, improved biomonitoring studies measuring infant exposure biomarkers, and longitudinal cohort research examining developmental outcomes are essential next steps. Innovations in polymer engineering may also offer safer alternative materials with lower migration potential and improved thermal stability.

Investment in analytical technologies capable of detecting low-level chemical and particulate contaminants in biological matrices will strengthen exposure assessment accuracy. Collaborative research networks linking toxicologists, pediatricians, materials scientists, and epidemiologists can accelerate progress and facilitate evidence translation into policy.

Public Health Integration

Public health strategies must integrate chemical safety guidance with microbiological hygiene recommendations within existing maternal and child health programs. Infant and young child feeding (IYCF) counselling platforms offer an opportunity to deliver balanced messaging that supports breastfeeding where feasible while providing realistic guidance for safe bottle use when necessary. Clear, culturally sensitive communication emphasizing exposure minimization rather than elimination can empower caregivers without generating undue anxiety.

Healthcare professionals play a central role in translating evolving scientific evidence into practical advice. Continuing education initiatives ensuring that frontline providers understand both chemical and microbiological dimensions of feeding safety may enhance consistency of messaging across health systems.

Final Perspective

Infant feeding bottle safety represents a convergence point between environmental toxicology, consumer protection, developmental biology, and global health equity. Chemical migration, particulate release, microbial contamination, and counterfeit distribution operate within interconnected socioeconomic systems that shape exposure patterns during a critical developmental period. Protecting infant health therefore requires coordinated action spanning scientific research, regulatory innovation, healthcare education, and community engagement.

Ensuring safer feeding environments is not solely a technical challenge but a reflection of societal commitment to safeguarding early-life development. By advancing integrated regulatory frameworks, strengthening surveillance of counterfeit products, and promoting informed caregiving practices, it is possible to reduce preventable exposure risks and support healthier developmental trajectories worldwide.

Early-life environmental safety must be recognized as both a scientific responsibility and a global public health priority. Continued vigilance, interdisciplinary collaboration, and equity-centered policymaking will be essential to achieving meaningful progress in protecting the most vulnerable members of society.

Declaration by Authors

Ethical Approval: Not Required
Acknowledgement: None
Source of Funding: None
Conflict of Interest: The authors declare no conflict of interest.

REFERENCES

1. Victora CG, Bahl R, Barros AJD, França GVA, Horton S, Krasevec J, et al. Breastfeeding in the 21st century: epidemiology, mechanisms, and lifelong effect. Lancet. 2016;387(10017):475–490. doi:10.1016/S0140-6736(15)01024-7.
2. Gore AC, Chappell VA, Fenton SE, Flaws JA, Nadal A, Prins GS, et al. EDC-2: The Endocrine Society's second scientific statement on endocrine-disrupting chemicals. Endocr Rev. 2015;36(6):E1–E150. doi:10.1210/er.2015-1010.
3. Brede C, Fjeldal P, Skjevrak I, Herikstad H. Increased migration levels of bisphenol A from polycarbonate baby bottles after dishwashing, boiling and brushing. Food Addit Contam. 2003;20(7):684–689. doi:10.1080/0265203031000119061.
4. Cao XL, Corriveau J. Migration of bisphenol A from polycarbonate baby bottles into water under severe conditions. J Agric Food Chem. 2008;56(15):6378–6381. doi:10.1021/jf800870b.
5. Ehlert KA, Beumer CWE, Groot MCE. Migration of bisphenol A into water from polycarbonate baby bottles during microwave heating. Food Addit Contam Part A Chem Anal Control Expo Risk Assess. 2008;25(7):904–910. doi:10.1080/02652030701867867.
6. Kubwabo C, Kosarac I, Stewart B, Gauthier BR, Lalonde K, Lalonde PJ. Migration of bisphenol A from plastic baby bottles under severe use conditions. Food Addit Contam Part A Chem Anal Control Expo Risk Assess. 2009;26(6):928–937. doi:10.1080/02652030802706725.
7. Braun JM, Yolton K, Dietrich KN, Hornung R, Ye X, Calafat AM, et al. Prenatal bisphenol A exposure and early childhood behavior. Pediatrics. 2011;128(5):873–882. doi:10.1542/peds.2011-1335.
8. Trasande L, Attina TM, Blustein J. Association between urinary bisphenol A concentration and obesity prevalence in children and adolescents. JAMA. 2012;308(11):1113–1121. doi: 10.1001/2012.jama.11461.
9. Webster P. Canada declares bisphenol A toxic. Lancet. 2008;371(9628):1837. doi:10.1016/S0140-6736(08)60902-2.
10. European Commission. Commission Directive 2011/8/EU of 28 January 2011 amending Directive 2002/72/EC as regards the restriction of use of bisphenol A in plastic infant feeding bottles. Off J Eur Union. 2011; L26:11–14.
11. US Food and Drug Administration. Indirect food additives: polymers; amendment to remove BPA-based resins in baby bottles and sippy cups. Fed Regist. 2012;77(137):41899–41902.
12. Rochester JR, Bolden AL. Bisphenol S and F: A systematic review and comparison of the hormonal activity of bisphenol A substitutes. Environ Health Perspect. 2015;123(7):643–650. doi:10.1289/ehp.1408989.
13. Li D, Shi Y, Yang L, Xiao L, Kehoe DK, Gun'ko YK, et al. Microplastic release from the degradation of polypropylene feeding bottles during infant formula preparation. Nat Food. 2020;1(11):746–754. doi:10.1038/s43016-020-00171-y.
14. Wright SL, Kelly FJ. Plastic and human health: A micro issue? Environ Sci Technol.

2017;51(12):6634–6647. doi: 10.1021/acs.est.7b00423.
15. Lamberti LM, Fischer Walker CL, Noiman A, Victora C, Black RE. Breastfeeding and the risk for diarrhea morbidity and mortality. BMC Public Health. 2011;11(Suppl 3): S15. doi:10.1186/1471-2458-11-S3-S15.
16. Henry R, Fouladkhah A. Outbreak history, biofilm formation, and preventive measures for Cronobacter sakazakii in infant formula and infant care settings. Microorganisms. 2019;7(3):77. doi:10.3390/microorganisms7030077.
17. EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP). Re-evaluation of the risks to public health related to the presence of bisphenol A in foodstuffs. EFSA J. 2023;21(4):6857. doi: 10.2903/j.efsa.2023.6857.
18. Heindel JJ, Skalla LA, Joubert BR, Dilworth CH, Gray KA. Review of developmental origins of health and disease and environmental exposures. Environ Health Perspect. 2017;125(8):085001. doi:10.1289/EHP2034.
19. EFSA Panel on Food Contact Materials. Scientific opinion on BPA exposure assessment. EFSA J. 2015;13(1):3978. doi: 10.2903/j.efsa.2015.3978.
20. Vandenberg LN, Colborn T, Hayes TB, Heindel JJ, Jacobs DR Jr, Lee DH, et al. Hormones and endocrine-disrupting chemicals: low-dose effects and nonmonotonic dose responses. Endocr Rev. 2012;33(3):378–455. doi:10.1210/er.2011-1050.
21. Hirt N, Body-Malapel M. Immunotoxicity and intestinal effects of microplastics: A review. Toxics. 2020;8(4):102. doi:10.3390/toxics8040102.
22. World Health Organization. Microplastics in drinking-water. Geneva: World Health Organization; 2019.
23. OECD. Trade in counterfeit and pirated goods: Mapping the economic impact. Paris: OECD Publishing; 2019. doi:10.1787/g2g9f533-en.
24. Flemming HC, Wingender J. The biofilm matrix. Nat Rev Microbiol. 2010;8(9):623–633. doi:10.1038/nrmicro2415.
25. Landrigan PJ, Fuller R, Acosta NJR, Adeyi O, Arnold R, Basu NN, et al. The Lancet Commission on pollution and health. Lancet. 2018;391(10119):462–512. doi:10.1016/S0140-6736(17)32345-0.

How to cite this article: Yamee Shah, Tekla Hemisha Jacob Lyanda, Deepika Anand. Counterfeit infant feeding bottles and their implications for child health: a global review of chemical, microbiological, environmental, and policy evidence. *Int J Health Sci Res.* 2026; 16(3):47-61. DOI: *10.52403/ijhsr.20260306*

******