

# Age-Window Metabolic and Toxicokinetic Vulnerability in Vegetable-Based Baby Foods: Separating Developmental Readiness from Toxicant Susceptibility

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## KEYWORDS

- complementary feeding
- toxicokinetics
- infant neurodevelopment
- baby food formulation
- heavy metal exposure
- vegetable bioaccumulation
- under-2 vulnerability window
- risk-based ingredient classification



## FOOD METALLOMICS

## Age-Window Metabolic and Toxicokinetic Vulnerability in Vegetable-Based Baby Foods: Separating Developmental Readiness from Toxicant Susceptibility

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## Abstract

Guidance on complementary feeding appropriately emphasizes developmental readiness for purées and soft foods, but it often fails to distinguish this from toxicokinetic appropriateness during the under-2 window, when absorption is higher, detoxification and excretion are immature, and neurodevelopment is especially vulnerable to low-dose toxicants. This narrative, conceptual review synthesizes evidence that vegetables, particularly leafy greens and root crops, can bioaccumulate heavy metals at levels that become clinically relevant when delivered as concentrated purées and powders to small body masses. It reframes “introducing vegetables” as distinct exposure scenarios, separating small, intermittent tastes for sensory learning from repeated daily intake of concentrated vegetable-based products used as fortifiers. The intended contribution is a risk-based framework with actionable policy implications and formulation guidance, in which high-accumulating vegetable classes are treated as conditional ingredients requiring batch verification, conservative serving-frequency logic, and transparent disclosure, alongside safer alternatives such as lower-accumulating plant tissues and pharmaceutical-grade synthetic fortification. The central conclusion is that developmental readiness does not imply toxicokinetic suitability, and infant food standards should incorporate age-stratified susceptibility, concentration effects, and cumulative exposure accounting.

## 1 | INTRODUCTION

The current public health guidance on complementary feeding establishes clear developmental milestones for introducing solid foods to infants, with approximately 6 months of age recommended as appropriate for starting complementary feeding when developmental readiness is demonstrated (and not before 4 months).<sup>[1]</sup> This developmental framework emphasizes the timing at which infants acquire neuromuscular competence for consuming pureed foods and the behavioral signs indicating readiness to explore diverse flavors and textures.<sup>[1]</sup>

However, the metabolic and toxicokinetic reality of early childhood creates a fundamentally different set of constraints that must be integrated into evidence-based food formulation practices for infants and toddlers.

The under-2 age period represents a uniquely high-stakes toxicant exposure window characterized by small body mass, rapid growth, immature physiological defenses, and maximal neurodevelopmental sensitivity to low-dose toxicants that would produce negligible effects in older children.<sup>[2]</sup>

This review establishes that while developmental readiness for complementary feeding has been scientifically established around 6 months of age, toxicokinetic appropriateness of *the specific forms, tissue types, concentrations, and consumption frequencies* of vegetable-derived ingredients in baby foods requires distinct and substantially more precautionary evaluation.

The critical insight is that “introducing vegetables” encompasses an enormous range of dietary scenarios—from small, minimally processed vegetable exposures supporting texture and flavor learning in an overall milk-based diet, to repeated daily consumption of concentrated vegetable purées and powders formulated as primary nutritional fortifiers. Only the former aligns with both developmental appropriateness and toxicokinetic safety; the latter systematically increases cumulative exposure per kilogram body weight precisely when children’s absorption and neurodevelopmental sensitivity amplify harm from low-dose toxicants.

## 2 | DEVELOPMENTAL READINESS VERSUS TOXICOKINETIC APPROPRIATENESS

### Developmental Milestones and Complementary Feeding Timing

International guidelines from the WHO, European Food Safety Authority (EFSA), and European Society for Paediatric Gastroenterology, Hepatology, and Nutrition (ESPGHAN) recommend exclusive breastfeeding for the first 6 months of life, with solid foods introduced thereafter when developmental readiness is demonstrated [3].

The earliest developmental skills relevant for consuming pureed complementary foods can be observed between 3 and 4 months of age, while skills for consuming finger foods are observed more commonly at 5-7 months [1]. For nutritional reasons, the majority of infants need complementary foods from around 6 months of age, and developmental readiness includes the infant’s ability to sit upright with minimal support, loss of the extrusion reflex that causes automatic expulsion of food from the mouth, and the infant’s demonstration of interest in food when observing others eating [1].

The practice of complementary feeding (CF) is a critical period in infant nutrition during which pediatricians and parents must simultaneously consider the infant’s developmental competencies, nutritional requirements, and ability to safely consume and digest diverse foods [4]. Research demonstrates that approximately 87.7% of pediatricians advise initiating CF at 6 months in non-allergic infants, with the most commonly recommended

initiation method being spoon-fed purées [4]. However, this developmental appropriateness—the infant’s capacity to consume and learn from diverse textures and flavors—represents only one dimension of safety assessment. Developmental readiness does not inherently address whether the specific foods selected for early introduction, and their cumulative dose and frequency of consumption, align with the infant’s physiological capacity to handle and detoxify contained contaminants

### Toxicokinetic Vulnerability and Differential Absorption in Infants

Toxicokinetics refers to the absorption, distribution, metabolism, and elimination of toxic substances in the body—processes that differ fundamentally between infants and older children or adults. Young children are vulnerable to the effects of toxic elements (arsenic, cadmium, lead, and mercury) based on higher absorption levels and potentially poorer detoxification capacities [2].

For lead, a classic example of this differential toxicokinetic vulnerability, gastrointestinal absorption in infants is estimated at 50% compared to 5-15% in adults [5]. This approximately 3-10 fold greater bioavailability of lead means that an infant consuming a given amount of lead-contaminated food experiences substantially higher systemic exposure than an adult consuming an identical portion. Similarly, infants show reduced capacity for urinary excretion of various metals and delayed development of metabolic enzyme systems responsible for detoxification [2].

For inorganic arsenic specifically, children exhibit lower degrees of methylation efficiency compared to adults, with studies showing that arsenic methylation in children is considerably lower than in adults, effectively reducing their capacity to convert and excrete less toxic metabolite forms [6]. Cadmium absorption efficiency also varies with age; as calcium and iron bioavailability change through early childhood, competing pathways of absorption shift cadmium uptake efficiency.

The development of physiological defense mechanisms against heavy metals continues throughout early childhood, meaning that the degree of vulnerability is highest in the youngest infants and gradually decreases

through the first 2 years of life. At birth and during early infancy, metallothionein production (a crucial heavy metal-binding protein that facilitates detoxification and excretion) is immature, with developmental increases occurring progressively through early childhood [2]. This physiological immaturity means that low-dose exposures considered safe for older children or adults may produce disproportionate systemic accumulation and toxicant effects in infants.

### 3 | HEAVY METAL BIOACCUMULATION IN VEGETABLES: TISSUE TYPE AND CONCENTRATION CONSIDERATIONS

#### Differential Accumulation Across Vegetable Classes and Plant Tissues

Research consistently demonstrates that leafy vegetables and root crops accumulate substantially higher concentrations of lead, cadmium, and arsenic compared to fruiting vegetables and cereals [7]. Spinach, a commonly consumed leafy green frequently used in baby food formulations, demonstrates particular vulnerability to both cadmium and lead accumulation through specific soil-plant interactions [8].

Within plant tissues, roots generally contain higher heavy metal concentrations than edible shoots and leaves, though metal translocation to edible tissues varies dramatically depending on the metal species and plant variety [9]. The bioconcentration factor (BCF)—a measure of how effectively a plant accumulates metals from soil above environmental background levels—frequently exceeds 1.0 for leafy vegetables exposed to contaminated soils, indicating that these vegetables absorb and concentrate metals to levels higher than soil concentrations [7].

For cadmium specifically, leafy greens including spinach, lettuce, and cabbage are classified as hyperaccumulator species that selectively transport cadmium from soil to edible tissues [10]. Evidence from wastewater-irrigated agricultural areas demonstrates that heavy metal concentrations in vegetables grown under these

conditions often exceed international safety standards, with leafy vegetables showing particularly concerning accumulation patterns [11].

The practical implication for baby food formulation is stark: if vegetables are to be used as primary ingredients or fortification agents in products for infants, the selection of plant tissue type and vegetable variety has profound implications for the magnitude of heavy metal exposure. Using whole spinach purée—in which roots may still be present and all tissues are concentrated in high-calorie purée form—delivers substantially higher metal concentrations than using only the leafy portions or selecting alternative vegetables with documented lower accumulation capacity. The tissue-specific distribution of metals within plants also means that for some metals, selective harvesting practices or processing methods could reduce metal content, though such considerations are rarely if ever incorporated into baby food manufacturing.

#### Concentration and Processing Effects in Commercial Products

Commercial baby food products typically deliver vegetable-derived nutrients in concentrated form, as purées that reduce the volume of food while maintaining or increasing the density of both beneficial and potentially harmful constituents. A standard serving of commercial vegetable purée (100-120 grams) delivers the nutritional and contaminant content of substantially larger quantities of fresh vegetables. For an infant consuming 100 grams of concentrated spinach purée, the dose of accumulated cadmium or lead is approximately equivalent to what an adult might receive from consuming 150-250 grams of fresh spinach—but delivered to a body mass that is 10-15 times smaller.

This concentration effect amplifies cumulative exposure per kilogram of body weight precisely during the age period when absorption efficiency is highest and detoxification capacity is most immature. Additionally, some commercial processing methods may alter metal bioavailability without reducing total metal content.

For example, processing that removes cellular structure may increase the proportion of metals in readily absorbable forms. The matrix effects created during commercial food processing—the way the food matrix affects metal speciation and bioavailability—have received little systematic study in baby food products.

A critical distinction exists between “vegetables in complementary feeding” when interpreted as small portions (10-30 grams) of minimally processed vegetable foods supporting texture and flavor learning within a predominantly milk-based diet, versus “vegetables in baby foods” when interpreted as concentrated purées delivering 50-100+ grams per serving as nutritional fortifiers or primary food components. These represent fundamentally different toxicological scenarios despite both being labeled “complementary feeding.”

#### 4| THE UNDER-2 WINDOW OF NEURODEVELOPMENTAL SENSITIVITY AND TOXICANT-INDUCED HARM

##### Lead, Cadmium, and Arsenic: Neurodevelopmental Effects During Critical Windows

Comprehensive reviews of prospective cohort studies spanning 34 different cohorts across 18 countries provide strong support for the contention that higher levels of prenatal and childhood exposure to arsenic, cadmium, lead, and mercury are linked with adverse cognitive, motor, behavioral, and mental health outcomes in children [12].

The critical window for neurodevelopmental toxicant sensitivity extends from fetal development through early childhood, with maximal vulnerability occurring in the 0-3 year age range when active synaptogenesis, axonal extension, and myelination are occurring at their fastest rates [12]. Prenatal cadmium exposure significantly decreased Full-Scale Intelligence Quotient (FSIQ) in children aged 5-9 years, with a 50% increase in cadmium exposure resulting in a 0.44-point drop in FSIQ—a seemingly small effect that becomes substantial at the population level [13]. Joint exposure to lead, mercury, cadmium, and arsenic reduced gross motor development by 17.78%, decreased language

ability by 55.36%, and decreased general developmental milestones by 13.36% in children aged 3-4 years [14].

These are not rare, extreme exposure scenarios; these effects occur at exposure levels within the range typical for children in areas with contaminated food supplies or water sources. The dose-response relationship for lead’s neurotoxic effects demonstrates measurable cognitive impairment at blood lead levels as low as 5 micrograms per deciliter ( $\mu\text{g}/\text{dL}$ )—a level considered “safe” by previous regulatory standards but now recognized as producing detectable neurobehavioral effects [15].

Importantly, children exhibit markedly higher susceptibility to lead’s neurotoxic effects compared to adults at equivalent exposure levels, with the developing brain particularly vulnerable to lead’s interference with calcium signaling, glutamate neurotransmission, and synaptic plasticity [15]. For arsenic, prenatal and early childhood exposure shows associations with reduced cognitive performance, particularly affecting attention and working memory at environmental exposures occurring through food and water contamination [12]. The mechanisms underlying these neurotoxic effects involve oxidative stress generation, mitochondrial dysfunction, impaired antioxidant enzyme activity, and disruption of normal cellular signaling pathways—effects that occur at substantially lower thresholds in developing brain tissue than in mature brain [16].

##### Behavioral and Neurodevelopmental Disorder Associations

Beyond measurable reductions in IQ and developmental milestones, heavy metal exposures during early childhood show associations with behavioral disorders and neurodevelopmental conditions that reflect altered brain development. Children with Autism Spectrum Disorder demonstrate significantly elevated urinary levels of coproporphyrin and altered porphyrin profiles indicating heavy metal burden, with lead levels significantly higher in ASD children compared to neurotypical controls [17]. Hair analysis of children with severe autism showed significantly higher levels of copper, vanadium, cobalt, nickel, arsenic, cadmium, and

lead compared to control groups, with these effects more pronounced in children under 7 years of age [18].

The cumulative impact of lead, mercury, cadmium, and arsenic shows synergistic effects on gross motor, language ability, and general developmental outcomes, with children exposed to mixtures of these metals showing greater impairment than would be predicted from individual metal exposures alone [14]. Heavy metal load measured in urine accounted for 32% of variance in social behavior outcomes in children, with those displaying the lowest social behaviors showing a sixfold increase in odds of high heavy metal loads [19].

The association between heavy metal exposure and dyslexic risk reveals that toxic metals including mercury, cadmium, silver, and lead exacerbate developmental dyslexia risk, while the exposure window for these effects includes the entire 0-36 month period [20]. These neurodevelopmental and behavioral outcomes underscore why early childhood represents such a uniquely vulnerable exposure window: the developing brain is simultaneously undergoing rapid neuroplasticity and maturation while simultaneously lacking mature physiological defenses against toxicant-induced disruption of this critical developmental process.

## 5. THE PARADOX OF BABY FOOD PRODUCT FORMULATION: HEALTH HALO VS. TOXICOKINETIC REALITY

### Vegetable-Based Fortification as Industry Standard

The global baby food and infant nutrition market has adopted widespread use of vegetable-derived ingredients as fortification agents and primary food components, driven by market perception of vegetables as inherently healthy and by marketing signals emphasizing “natural,” “organic,” and “plant-based” nutrition [21]. Baby food product lines frequently feature vegetable purées prominently in marketing, with brands emphasizing that vegetables provide essential micronutrients and represent healthful early taste development [21].

Parents choosing commercial baby food products identify perceived healthiness as a primary purchasing criterion, and manufacturers have responded by developing vegetable-forward products marketed to support optimal nutrition [21]. The challenge is that this industry formulation strategy was developed without systematic consideration of heavy metal bioaccumulation in specific vegetable varieties or the toxicokinetic vulnerabilities that characterize infancy.

Most baby food manufacturers do not routinely conduct heavy metal testing of their vegetable-based products, and even when testing is performed, the assessment typically focuses on meeting regulatory maximum residue limits that were established for general population consumption rather than for vulnerable subpopulations such as infants. The regulatory framework itself creates perverse incentives: compliance with existing regulations appears to demonstrate safety, yet those regulations do not account for age-specific absorption efficiency, body mass, developmental stage, or cumulative exposure from multiple sources.

Critically, an infant consuming multiple servings daily of vegetable-based baby food products may receive cumulative exposures to lead, cadmium, or arsenic that far exceed what would be considered appropriate for an older child or adult, yet such exposure remains compliant with current regulatory standards that do not distinguish by age group or cumulative dietary sources.

### Distinguishing Categories of Vegetable Introduction: Three Levels of Practice

For purposes of establishing metabolically appropriate guidance, it is essential to distinguish between three fundamentally different approaches to vegetable introduction in the 0-24 month age range:

**Level 1: Texture and Flavor Learning (Developmentally and Toxicokinetically Appropriate).**

Small portions (10-30 grams per serving) of minimally processed vegetables introduced 2-3 times weekly as part of a predominantly milk-based diet (representing <5% of daily calories).

These exposures support neurodevelopmental learning regarding diverse textures and flavors without creating substantial cumulative heavy metal burden. This approach aligns with both developmental readiness principles and toxicokinetic safety.

#### Level 2: Nutritional Supplementation (Developmentally Appropriate but Toxicokinetically Questionable)

Moderate portions (50-100 grams per serving) of vegetable-based baby foods consumed daily as significant nutritional contributors (representing 15-25% of daily food intake). This approach accelerates texture learning and provides micronutrients but creates substantially elevated cumulative dietary exposure to metals accumulated in vegetable tissues, particularly if high-accumulating varieties (leafy greens, root vegetables) are selected.

#### Level 3: Vegetable-Based Fortification (Developmentally Appropriate but Toxicokinetically Inappropriate)

Concentrated vegetable purées or powders used as primary fortification agents in commercial baby foods, resulting in repeated daily consumption of standardized, high-concentration vegetable products (often representing 40-60% of product composition). This approach, now common in commercial baby food products, creates the highest per-kilogram body weight exposure to accumulated metals precisely when absorption efficiency is maximal and detoxification capacity is minimal.

Current industry practice has progressively shifted from Level 1 toward Levels 2 and 3, driven by marketing imperatives and the perception that greater vegetable content equals greater nutritional benefit. This shift has occurred *without toxicokinetic evaluation* of whether such concentrated, frequent vegetable consumption is physiologically appropriate for infants and toddlers.

## 6 | EVIDENCE-BASED PRINCIPLES FOR FOOD FORMULATION: CONDITIONAL RATHER THAN DEFAULT USE OF HIGH-ACCUMULATING VEGETABLES

### Crop Selection and Plant Tissue Specificity

Evidence from agricultural toxicology and plant physiology demonstrates that not all vegetables carry equivalent heavy metal burdens. Fruiting vegetables (tomatoes, peppers, squash, beans), cereals (rice, oats, wheat), and legumes (lentils, chickpeas) show substantially lower accumulation of lead, cadmium, and arsenic compared to leafy vegetables and root crops [22].

Risk-based ingestion rates derived from health risk assessment methodologies indicate that tree leaves, herbs, flowers, and brassica vegetables should be consumed at the lowest rates due to their high potential arsenic contamination, with cancer risk targets indicating safe ingestion rates ranging from 0.13 grams per day for tree leaves to 3.8 grams per day for fruiting vegetables [22].

These recommendations, derived from formal risk assessment processes, provide a scientific basis for food formulation guidance: if vegetables must be included in baby foods, fruiting vegetables and legumes should be prioritized over leafy greens and root vegetables. When leafy vegetables are used, tissue selectivity matters—using only leaf tissue (avoiding roots and stems where metal accumulation is often highest) would reduce metal content. Within plant varieties, genetic variation in accumulation capacity exists; breeding or cultivar selection for lower metal uptake, while not yet widely implemented for baby food ingredients, represents a feasible long-term mitigation strategy [7].

### Conditional Ingredient Classification and Verification Requirements

The fundamental metabolically appropriate reframing is to classify high-accumulating vegetable classes (leafy greens, root vegetables, brassicas) as *conditional ingredients* requiring explicit verification and conservative use in baby food products, rather than as default health-promoting bases for frequent consumption.

Conditional ingredient classification would mean: (1) heavy metal testing of every production batch before inclusion in products for infants; (2) explicit limitation of serving size and consumption frequency recom-

mendations on product labeling; (3) preferential use in Level 1 complementary feeding scenarios (small portions, texture learning) rather than in concentrated fortification formulations; (4) transparent disclosure of heavy metal testing results to consumers and healthcare providers.

By contrast, lower-accumulating vegetables and synthetic micronutrient fortification would require no such conditional restrictions and could be used more liberally in baby food formulations.

This conditional classification approach reflects the precautionary principle appropriate for vulnerable populations: when uncertainty exists regarding whether a food component at specified consumption levels aligns with toxicokinetic safety, conservative verification and use restrictions are warranted until evidence demonstrates safety. Currently, most baby food products containing high-accumulating vegetables do not employ any such conditional classification, testing, or disclosure framework.

## 7 | ALTERNATIVE FORMULATION APPROACHES: MOVING BEYOND VEGETABLE-BASED FORTIFICATION

### Micronutrient Diversification and Fortification

Micronutrient fortification using bioavailable mineral and vitamin forms produced through pharmaceutical-grade manufacturing provides an evidence-based alternative to plant-based fortification that eliminates the heavy metal contamination risk inherent in using bioaccumulative plant tissues. While some consumer segments are likely to perceive supplementation strategies negatively (viewing it as less “natural”), the toxicokinetic reality is that iron, zinc, and other essential minerals delivered to infants do not carry the burden of accumulated environmental contaminants that plant-based fortification inevitably delivers.

Multiple governmental health agencies, including the FDA and EFSA, have approved numerous synthetic nutrient sources for use in infant formulas and baby

foods, recognizing that safety, efficacy, and purity can be standardized and verified in ways that are difficult to achieve with plant-derived ingredients [23]. The “Closer to Zero” initiative launched by the USDA, FDA, and other federal agencies specifically calls for reduction of arsenic, lead, cadmium, mercury, and chromium in foods intended for vulnerable populations, particularly young children [24].

Thus, these public health initiatives implicitly support reconsidering the reliance on plant-based fortification agents that inherently carry these contaminants [24]. Food brands could achieve equivalent or superior nutritional outcomes while substantially reducing toxicant exposure by transitioning to supplemental micronutrient fortification for infant products.

### Flavor Enhancement and Sensory Development Without Vegetable Fortification

An emerging evidence base demonstrates that the primary benefit of early vegetable exposure—supporting flavor learning and hedonic acceptance of vegetables later in childhood—can be achieved through small, diverse vegetable exposures without requiring concentrated vegetable fortification. Flavor exposure during complementary feeding appears to facilitate acceptance of diverse foods when novel vegetables are experienced in varying contexts and with repeated exposure opportunities [25].

Importantly, this flavor-learning benefit does not require high quantities or concentrated forms of vegetables; small portions of diverse, minimally processed vegetables support this developmental outcome. Additionally, spices and herbs increase vegetable palatability and acceptance without adding substantial contaminant burden, as these plant components are used in smaller quantities and accumulate metals differently than the primary consumed crop tissues [26]. Food brands could develop appealing children’s products through flavor enhancement strategies—using herbs, spices, and small vegetable portions to support taste development—rather than relying on concentrated vegetable purées as primary fortification agents. This approach would maintain the developmental benefits of early vegetable exposure while substantially reducing toxicant burden.

## 8 | RECOMMENDATIONS FOR INTEGRATED, AGE-APPROPRIATE FOOD SAFETY IN INFANT NUTRITION

### Regulatory and Manufacturing Framework Revisions

Current food safety regulatory frameworks, while establishing maximum residue limits for individual contaminants, do not adequately address age-specific vulnerabilities in young children or cumulative dietary exposure. Regulatory agencies should establish infant-specific (0-24 months) maximum residue limits for lead, cadmium, arsenic, and mercury that account for higher bioavailability, lower detoxification capacity, and maximal neurodevelopmental sensitivity during this life stage.

Such age-stratified standards, while more stringent than current regulations, would align with the scientific evidence regarding toxicokinetic and developmental vulnerability. Additionally, food manufacturers should be required to conduct heavy metal testing of vegetable-based ingredients used in products for infants under 24 months and to disclose testing results and estimated dietary exposures associated with recommended serving sizes. Transparent labeling indicating the heavy metal content of baby foods, similar to nutritional labeling requirements, would allow healthcare providers and parents to make informed choices regarding cumulative exposure from multiple sources.

Industry self-regulation through *voluntary reformulation* toward lower-accumulating vegetables and synthetic fortification could be incentivized through regulatory recognition and market differentiation for products meeting enhanced safety standards. Furthermore, food brands formulating products for infants should adopt precautionary ingredient classification systems that identify high-accumulating vegetable varieties as conditional rather than default components, requiring explicit verification of safety before inclusion.

### Clinical Guidance and Healthcare Provider Education

Pediatricians, nurses, and other healthcare providers advising families on complementary feeding should receive education distinguishing between (a)

developmental readiness for complementary feeding—appropriately occurring around 6 months of age, and (b) toxicokinetic appropriateness of specific food forms and consumption frequencies.

Current complementary feeding guidance appropriately emphasizes developmental readiness signals and nutrient adequacy but provides minimal guidance on heavy metal contamination risks or consideration of cumulative dietary exposures. Updated clinical guidance should recommend that infants' first vegetable exposures be small portions (10-30 grams) of diverse vegetables from rigorously tested manufacturers—supporting texture and flavor learning while minimizing heavy metal burden.

Healthcare providers should also advise parents that commercial baby food products formulated as concentrated vegetable purées or fortified with high-accumulating vegetables represent a different category of food than small-portion vegetable tasting. The former may warrant caution regarding cumulative exposure in the absence of rigorous testing and ongoing remediation strategies, while the latter aligns with developmental appropriateness. Education should emphasize that the presence of regulatory approval or compliance with current federal maximum residue limits does not inherently indicate suitability for frequent daily consumption by infants during their window of maximal toxicokinetic vulnerability.

Finally, healthcare providers should counsel caregivers to diversify infants' early food experiences across multiple food groups rather than concentrating on vegetable-based products, recognizing that nutrient adequacy can be achieved through varied whole-food exposures without reliance on concentrated vegetable preparations that carry a higher risk of heavy metal contamination. In parallel, providers should encourage restraint in the frequent use of likely high-accumulating vegetable categories and advocate that manufacturers of infant-targeted foods adopt safer-by-design formulation, sourcing, and batch-verification practices that reduce the intrinsic heavy-metal risk of concentrated vegetable-based products.

## Public Health and Research Priorities

Population-level biomonitoring of heavy metals in young children, stratified by infant feeding practices and types of commercial baby foods consumed, would provide epidemiological evidence linking specific feeding practices to systemic heavy metal burden.

Currently, such population-level data remain limited, creating a knowledge gap that impedes evidence-based policy development. Research prioritizing assessment of heavy metal bioavailability from processed baby foods—how the food matrix and processing methods affect absorption of accumulated metals—would provide mechanistic understanding of health risk. Long-term neurodevelopmental follow-up of children with varying early dietary exposures to heavy metals could establish causal relationships between infant feeding practices and later developmental outcomes.

Additionally, agricultural and food science research sectors should prioritize the development of vegetable varieties with inherently lower heavy metal accumulation capacity, combined with improved agronomic practices that minimize soil metal availability.

Finally, research examining alternative sources of micronutrients for infant fortification—including lower-accumulating plant varieties, cultivated microorganisms, and optimized synthetic forms—would support transition toward safer food formulation practices without compromising nutritional adequacy. These research directions, guided by the “One Health” principle recognizing connections between environmental contamination, agricultural practices, and human health outcomes, could advance both food safety and sustainable food production systems.

## 9 | CONCLUSION

The evidence synthesized in this review supports a defensible and practically consequential distinction: the age at which an infant can eat puréed foods safely is not equivalent to the age at which it is physiologically appropriate to routinely ingest concentrated, bio-accumulative plant tissues without undue toxicant risk.

The under-2 period is characterized by exposure amplification per kilogram body weight, higher fractional absorption for certain metals, and incompletely matured detoxification and excretory pathways, occurring concurrently with rapid neurodevelopment that is highly sensitive to low-dose toxicant disruption.

Within this context, the prevailing market trend toward vegetable-forward products, particularly those relying on leafy greens, brassicas, and root vegetables as primary ingredients or fortifiers, can convert a conceptually “healthy” ingredient class into a systematic driver of cumulative metal exposure.

A scientifically defensible approach is therefore conditional rather than default: high-accumulating vegetable classes should be treated as ingredients that require verification, conservative dosing logic, and transparency, while manufacturers should preferentially pursue lower-accumulating crop classes, tissue selectivity, and fortification strategies that achieve nutritional targets without importing environmental contaminants.

Clinically, guidance should explicitly differentiate small, intermittent vegetable exposures that support flavor and texture learning from repeated daily consumption of concentrated commercial purées and powders that can dominate an infant’s non-milk caloric intake. Regulatory and industry frameworks that incorporate age-stratified vulnerability, cumulative dietary exposure, and concentration effects would better align infant feeding practices with the toxicokinetic realities of early life, reducing preventable neurodevelopmental risk while preserving the legitimate developmental benefits of complementary feeding.

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