Manufactured infant formula delivers an aluminium-dominated metal load, many-fold above breastmilk and amplified in soy-based and powdered formats, to the most vulnerable consuming population

HEAVY METAL INDEX · SYNTHESIS REPORT July 2026

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DOI 10.83376/hmi.infant-formula-metal-amplification

CITE AS

Pendergrass K. "Manufactured infant formula delivers an aluminium-dominated metal load, many-fold above breastmilk and amplified in soy-based and powdered formats, to the most vulnerable consuming population". Heavy Metal Index, 2026. https://heavymetalindex.com/synthesis/infant-formula-metal--amplification (DOI: 10.83376/hmi.infant-formula-metal-amplification). CC BY 4.0.

CORRESPONDENCE

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KEYWORDS

Al, Pb, Cd, tAs, tHg, heavy metals, food safety, dietary exposure

PUBLICATION HISTORY

First published 2026-07-27.

Abstract

Seven datasets across five independent research lineages, spanning Canada, Pakistan, the United Kingdom, Brazil, and a global scoping review, converge on a single finding: manufactured infant formula carries a distinct heavy-metal profile that is dominated by aluminium, that adds measurable lead and cadmium, and that sits many times above the concentration an exclusively breastfed infant would receive. The aluminium signal is the load-bearing one. Burrell and Exley measured aluminium in United Kingdom formula at 175.5 to 700.4 µg/L in ready-made products and 333.3 to 629.0 µg/L in powders reconstituted per manufacturer instructions, against a typical breastmilk aluminium concentration of roughly 15 to 30 µg/L, a gap the authors characterised as 10 to 40 times higher. Dabeka's Canadian survey, Kazi's Pakistani survey, and the Collado-Lopez global review each independently document the within-formula gradient in which soy-based products run higher than cow-milk-based products, with the Collado-Lopez signal appearing at the level of detection frequency rather than measured concentration; de Paiva's Brazilian survey contributes high absolute aluminium values in a soy-based drink rather than a soy-versus-cow-milk formula comparison. The exposure is delivered to infants during the developmental window in which the gut is most permeable, the kidney least able to clear aluminium, and the brain most vulnerable.

1 | Overview

The amplification is not a single-laboratory artefact and it is not confined to one metal or one market. It is a feature of the product class. Formula is an engineered food assembled from ingredients (notably soy protein, which accumulates aluminium in the plant), concentrated by processing, and in the powdered case reconstituted at the point of use. Every one of those steps is a place where the metal load of the finished feed diverges upward from the biological baseline of breastmilk. This synthesis documents the magnitude of that divergence, the consistency of the soy-format and powder-format gradients, and the reason conventional per-serving safety framing understates it for the population that consumes formula as a sole diet.

2 | The United Kingdom aluminium signal (Burrell and Exley 2010; Chuchu and Exley 2013)

[1], published in BMC Pediatrics, measured aluminium by graphite-furnace atomic absorption in fifteen commercial United Kingdom formula products, using five replicate preparations per product with each measured three times and a replicate accepted only when the percent relative standard deviation was below ten. Ready-made liquid formulas (n=8) ranged from 175.5 to 700.4 µg/L, with the preterm formula the highest at a 700.4 µg/L mean and a replicate maximum of 863.0 µg/L. Powders evaluated as prepared-milk equivalents (n=8) ranged from 333.3 to 629.0 µg/L, with the soya-based powder highest at 629.0 µg/L. Modelled against manufacturer feeding volumes, estimated aluminium ingestion at six months of age spanned 206 to 592 µg Al per 24 hours, the maximum appearing for the soya-based powder and one follow-on powder. The paper's comparison to breastmilk (roughly 15 to 30 µg/L) is the anchor that turns a concentration into an amplification claim.

[2], a follow-up in the same journal, extended the survey to 30 United Kingdom products (10 ready-to-drink milks and 20 powders). Non-soy milk products ranged from about 100 to 430 µg/L; ready-to-drink product means ran 155 to 422 µg/L and non-soy powder prepared estimates ran about 106 to 411 µg/L. The two soy-based powders were the highest in the survey at 656 and 756 µg/L. Estimated daily aluminium intake reached about 100 to 300 µg per day from non-soy formulas and as high as roughly 700 µg per day from soy-based formulas. Because Burrell 2010 and Chuchu 2013 share Christopher Exley as senior author, they are treated here as a single research lineage rather than two fully independent confirmations; their value is the repeat measurement across a three-year interval showing the aluminium content had not fallen, and the consistent soy-powder maximum.

3 | The Canadian multi-metal signal (Dabeka 2011)

[3], published in Food Additives and Contaminants Part A from Health Canada, is the most format-resolved anchor in the set, reporting aluminium, cadmium, and lead as consumed (ng/g, approximately ppb for prepared feed) across powdered, ready-to-use, and concentrated-liquid formats and across milk-based and soy-based types. Powdered milk-based formula (n=57) had an aluminium mean of 177 ng/g (maximum 1004), cadmium mean 0.17 ng/g (maximum 1.21), and lead mean 0.65 ng/g (maximum 3.46). Powdered soy-based formula (n=15) ran markedly higher: aluminium mean 733 ng/g (maximum 1461), cadmium mean 1.56 ng/g (maximum 3.47), and lead mean 0.72 ng/g (maximum 1.90). Ready-to-use milk-based formula (n=67) reached an aluminium maximum of 3442 ng/g on a 437 ng/g mean. Across formats the soy-based type carried roughly two to five times the aluminium (1.7x for ready-to-use liquid, 4 to 5x for powder and concentrated liquid) and roughly five to nine times the cadmium of its milk-based counterpart.

Dabeka also isolates a processing-and-container vector directly relevant to the mechanistic claim below: ready-to-use formulas stored in glass contained about 100 to 300 ng/g more aluminium than the same formulas in metal cans, while glass-stored electrolyte and glucose solutions held less than 8 ng/g aluminium, which rules out the glass itself as the source and points to formula ingredients and processing. The authors note that every manufacturer in the survey was able to produce plain milk-based formula below 50 ng/g aluminium, meaning the higher observed values reflect achievable-but-unmet manufacturing control rather than an irreducible floor.

4 | The Pakistani soy-versus-milk signal (Kazi 2009)

[4], published in Food and Chemical Toxicology, measured aluminium, cadmium, and lead by electrothermal atomic absorption in imported formulas purchased in Pakistan during 2005 to 2006, reported on a dry-powder basis in µg/kg (numerically ppb for solids). Milk-based formula had an aluminium mean of 1018.5 µg/kg (range 640 to 1520), cadmium mean 7.86 µg/kg (range 4.2 to 12.3), and lead mean 64.2 µg/kg (range 28.7 to 97). Soy-based formula ran higher on all three: aluminium mean 2270 µg/kg (range 1740 to 2720), cadmium mean 11.7 µg/kg (range 8.3 to 14.5), and lead mean 109.4 µg/kg (range 98.6 to 119). The lead concentrations here are an order of magnitude above those in the Canadian survey (Dabeka), a comparison that must note Kazi reports on a dry-powder basis while Dabeka reports as-consumed; the United Kingdom surveys are not part of this lead comparison because Burrell and Chuchu measured aluminium only and report no lead values. The gap is consistent with a different import stream and sampling period, and the source text carries an internal subgroup-count conflict (methods describe 11 milk-based and 6 soy-based samples while Table 3 lists 13 and 4), so the individual means should be read as directional rather than as pooled reference values. What Kazi contributes robustly is the same soy-greater-than-milk gradient for aluminium, cadmium, and lead, established independently in a third jurisdiction and sampling stream.

5 | The Brazilian aluminium-and-bioaccessibility signal (de Paiva 2020; Milani 2023)

[5], in the Journal of Food Composition and Analysis, surveyed 95 infant food samples from nine commercial brands in Campinas, Brazil, measuring total aluminium by ICP-OES and pairing it with an optimised in vitro gastrointestinal digestion. Among the highest total-aluminium products were a soy-based drink at 2860 µg/kg and a chocolate soy-based drink at 2280 µg/kg (petit-suisse dessert reached 4170 µg/kg). The paper estimates that three portions per day of the soy-based drink could deliver aluminium at up to 100 percent of the provisional tolerable weekly intake for an infant. Its distinctive contribution is the bioaccessibility range: the fraction of total aluminium released under simulated digestion spanned 0.5 to 48 percent across matrices, meaning total aluminium overstates absorbed dose to a degree that varies almost a hundred-fold with food composition. This is a genuine caveat on the amplification claim and is treated as such below rather than suppressed.

[6], in the International Journal of Environmental Research and Public Health, measured trace elements in 18 soy-based beverages from the same Campinas research environment (sharing author M. A. Morgano with de Paiva 2020, so treated as one lineage). Isolate-protein soy beverages had an aluminium mean of 758 µg/L (range 137 to 1822), hydrosoluble-extract beverages 609 µg/L, and whole-soybean beverages 176 µg/L; total arsenic was below 38.2 µg/L, cadmium below 3.8 µg/L, and lead below 10.9 µg/L in most groups. One 200 mL serving contributed up to 3.5 percent of the aluminium provisional tolerable weekly intake for a child. Milani measures soy beverages rather than infant formula, so it is corroborating context for the soy-aluminium mechanism rather than a formula measurement; its within-product gradient (more-processed isolate-protein product highest, minimally-processed whole-soybean product lowest) reinforces that processing, not merely the raw commodity, drives the aluminium load.

6 | The global occurrence-and-detection signal (Collado-Lopez 2025)

[7], a scoping review in Nutrition Reviews following PRISMA-ScR methods, synthesised 75 studies covering 580 baby foods and 251 infant formulas worldwide. In infant formula, lead was detected in 74 percent of items, cadmium in 61 percent, arsenic in 63 percent, and mercury in 42 percent; detection, not absence, is the norm across the product class. The highest lead medians were in stage 1 and stage 2 formulas at 0.015 mg/kg (15 ppb) each, and without-stage formulas carried the highest arsenic median at 0.052 mg/kg (52 ppb). By protein source, lead was detected in 73 percent of cow-based versus 84 percent of soy-based formula items, and cadmium in 44 percent of cow-based versus 91 percent of soy-based items, an independent replication of the soy-amplification gradient at the level of detection frequency across a global corpus. Of 41 studies performing infant health-risk assessment, 15 reported risks, clustering for stage 1 and stage 2 formulas in infants under 12 months, particularly for arsenic, lead, and cadmium. Because this is a secondary synthesis under a restrictive licence, its medians are used here as convergent confirmation and coverage-mapping rather than as primary values to pool.

7 | The mechanistic explanation

Breastmilk sets the biological baseline: aluminium around 15 to 30 µg/L, and low lead and cadmium in the absence of maternal exposure. Formula diverges upward from that baseline through a chain of engineered steps, and the anchor set localises the divergence to specific points in that chain rather than to a single cause.

The dominant contributor is the ingredient matrix. Soybean accumulates aluminium in planta, particularly on the acid soils where aluminium-tolerant cultivars are grown, so soy-protein-based formula starts from a higher raw-material aluminium content than cow-milk-based formula. This is why the soy-greater-than-milk gradient appears in every anchor that resolves protein source: roughly four to nine times higher aluminium and cadmium in Dabeka's Canadian soy powders, the highest survey values in Chuchu's United Kingdom soy powders (656 and 756 µg/L), the highest means in Kazi's Pakistani soy formula, and the higher cadmium and lead detection frequencies in Collado-Lopez's global soy-based items (91 percent cadmium detection versus 44 percent for cow-based). The gradient is a property of the ingredient, and it is the single most consistent finding across the corpus.

The second contributor is processing. Milani's within-soy gradient (isolate-protein beverage mean 758 µg/L versus whole-soybean beverage 176 µg/L) shows that the more a soy base is fractionated and concentrated, the more aluminium it carries, implicating protein-isolation and concentration steps and their contact surfaces. Dabeka's finding that all manufacturers could produce milk-based formula below 50 ng/g aluminium, while observed values ran several times higher, points to the same conclusion from the opposite direction: the excess is process-introduced and controllable. Packaging and container context add a smaller increment, evidenced by Dabeka's 100 to 300 ng/g glass-versus-can difference, which the same study shows is not attributable to the glass itself.

The third contributor, for powders, is reconstitution at the point of use. The powders in Burrell and Chuchu are reported as prepared-milk equivalents precisely because the infant consumes the reconstituted feed, not the powder, and the prepared concentration depends on the mixing water as well as the powder. The anchor set does not separately quantify the aluminium, lead, or cadmium contributed by reconstitution water, so this synthesis flags reconstitution water as a recognised additional vector without assigning it a magnitude; a formula prepared with contaminated well water or with water drawn through lead-bearing plumbing would carry a load above the powder-only figures reported here, and that increment is a gap in the current evidence rather than a demonstrated quantity.

Against all three contributors sits the bioaccessibility caveat from de Paiva: total aluminium is not absorbed aluminium, and the absorbed fraction varies from 0.5 to 48 percent with matrix composition. The amplification documented here is an amplification of the delivered load; the absorbed-dose amplification is directionally the same but smaller and more matrix-dependent, and any consumer-facing or regulatory use of these numbers should distinguish the two.

8 | Why conventional per-serving surveillance understates this

Two features of formula make the standard framing of contaminant safety a poor fit. The first is exclusivity of diet. A contaminant median that reads as a minor per-serving contribution for an adult eating a varied diet is the entire dietary intake for an infant fed formula as a sole food across the developmental window. The Collado-Lopez health-risk clustering for infants under 12 months, and the de Paiva and Burrell exposure models that reach a substantial fraction of, or the entirety of, the aluminium provisional tolerable weekly intake at ordinary feeding volumes, both follow from consumption frequency rather than from any single high concentration. Per-serving surveillance that does not weight for sole-diet consumption at high body-weight-normalised intake understates the exposure for exactly the population that matters.

The second is that formula sits outside the terrestrial-commodity monitoring streams that anchor most national food-safety databases, and aluminium in particular is frequently absent from those streams: it sits outside the four-metal priority of the United States Food and Drug Administration's Closer to Zero infant-food programme and has no formula-specific regulatory maximum in the major frameworks (a regulatory characterisation that is external context, drawn from those frameworks rather than from the seven anchor sources, none of which discuss the FDA programme). The result is a category where the dominant metal by mass, aluminium, is the least routinely monitored, where the soy-format and powder-format gradients are reproducible but not reflected in format-specific limits, and where the consumer perception of formula as a rigorously controlled medical-grade food runs ahead of the surveillance actually applied to its aluminium content.

9 | What the evidence implies for testing, regulation, and consumption

For testing, aluminium belongs in the formula analyte panel alongside lead, cadmium, and arsenic, and it should be measured on the as-consumed (reconstituted) basis for powders rather than the powder basis alone, because the prepared feed is what the infant receives and because reconstitution water is an unquantified additional vector. Soy-based and powdered formats are the higher-risk cells and warrant denser sampling; the reproducibility of the soy gradient across four independent lineages that resolve protein source makes elevated aluminium, cadmium, and lead in soy-based formula foreseeable from the published literature rather than a surprise.

For regulation, the gap is structural: the dominant metal in the matrix has no formula-specific limit in the major frameworks, and the format and protein-source gradients that the literature establishes are not encoded anywhere. Dabeka's demonstration that sub-50 ng/g milk-based aluminium is achievable by every surveyed manufacturer is the load-bearing regulatory fact, because it converts the question from feasibility to enforcement. This finding intersects the combined-exposure underprotection synthesis: an infant on formula receives aluminium, lead, and cadmium simultaneously from a single food, and single-analyte assessment understates the joint burden.

For consumers, the honest statement is quantitative and population-specific. An infant fed reconstituted formula as a sole diet receives aluminium at roughly 10 to 40 times the concentration in breastmilk (formula around 100 to 760 µg/L prepared versus breastmilk around 15 to 30 µg/L), with soy-based and powdered products at the high end of that range, and receives detectable lead and cadmium in the majority of products. Where breastfeeding is possible it is the lower-metal feeding option on this evidence. Where formula is used, cow-milk-based formula carries a lower aluminium, cadmium, and lead load than soy-based formula in every anchor that compares them, and that difference is a well-supported basis for format preference within the constraints of medical need. None of this converts to an acute-harm statement at a single feed; the concern is cumulative exposure across the months of sole-diet feeding, and it is why the population, the dose, and the frequency all have to be named together.

This synthesis complements the spice-adulteration lead synthesis (a different infant lead pathway) and the organic-certification null finding (certification does not address a contamination mechanism rooted in ingredient physiology and processing rather than agricultural inputs, which applies directly to the soy-aluminium mechanism here).

10 | What this synthesis does not yet rest on

Reconstitution-water contribution is named but unquantified in the anchor set; a study measuring finished prepared feed against its own powder-plus-water inputs would close the largest mechanistic gap. Aluminium bioaccessibility is characterised for Brazilian infant foods (de Paiva) but not specifically for reconstituted formula across formats, so the absorbed-dose amplification is inferred rather than measured for the formula matrix. Mercury is present in the corpus only as a detection frequency (42 percent of formula items in Collado-Lopez) with no species resolution, so tHg and MeHg cannot be separated here. The lead concentrations diverge by roughly an order of magnitude between the Pakistani import stream (Kazi, dry-powder basis) and the Canadian retail stream (Dabeka, as-consumed basis), which is consistent with jurisdiction, basis, and period differences but means a single pooled lead reference value for formula would be premature; the United Kingdom surveys (Burrell, Chuchu) measured aluminium only and contribute no lead values to this comparison. Resynthesis triggers fire on the next two independent A-tier sources that confirm or contradict either the aluminium amplification magnitude or the soy-format gradient.

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STATUS AND LICENCE

DATA AVAILABILITY

Every source behind this finding is listed with its own extraction record at https://heavymetalindex.com/synthesis/-infant-formula-metal-amplification#sources, each linking to the ingest receipt, the extracted values, and the file hash of the document it was built from.

COMPETING INTERESTS

The Heavy Metal Index reports what the peer-reviewed and regulatory literature supports. It is operated separately from any certification program, does not evaluate or endorse brands, and does not use certification thresholds as evidence for the statements made here.

PUBLICATION HISTORY

First published 2026-07-27. The full dated record is maintained at https://heavymetalindex.com/synthesis/-infant-formula-metal-amplification.