Human breastmilk is a measurable infant heavy-metal exposure pathway distinct from infant formula, driven by maternal body burden and diet, and it is not captured by food-matrix surveillance

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CORRESPONDENCE

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Abstract

Six independent bodies of evidence, spanning a U.S. systematic review, primary lactating-mother cohorts in Korea (n=209), China (n=102), and Brazil (n=185), and two multi-country reviews aggregating more than 100 primary studies between them, converge on a single finding: human breastmilk carries measurable concentrations of lead, cadmium, total arsenic, total mercury, and additional elements including aluminum and chromium, and the load transferred to the breastfed infant is set by the mother's cumulative body burden and current diet rather than by anything intrinsic to the milk. This makes breastmilk an infant heavy-metal exposure pathway that is mechanistically distinct from infant formula, where the metal load originates in the ingredient supply chain and the process water. Cadmium was detected in 99 percent of samples in the Korean cohort and total arsenic in 89 percent; total mercury was detected in 97 percent. Breastmilk is therefore not a metal-free baseline against which formula is judged, and the two pathways require separate characterization.

1 | Overview

The load-bearing consequence for surveillance is that no food-safety monitoring stream measures this pathway. Breastmilk is not a commercial product, it is not sampled in national food-monitoring programs such as the U.S. FDA Total Diet Study, and it does not appear in packaged-food occurrence databases. The only window onto infant exposure through breastmilk is the biomonitoring literature synthesized here, which measures the milk directly in cohorts of lactating mothers. Where infant formula contamination is a supply-chain-and-testing

problem that category surveillance can in principle capture, breastmilk contamination is a maternal-exposure problem that food surveillance is structurally unable to see.

This synthesis is complementary to, and distinct from, the combined-exposure synthesis, which addresses the underprotection that follows from regulating one metal and one matrix at a time. Here the concern is a specific matrix, breastmilk, that falls outside food surveillance entirely, and a specific vulnerable population, the exclusively breastfed infant, for whom this matrix can be the dominant dietary intake during the first six months of life.

2 | The U.S. systematic-review anchor (Thoerig 2025)

Thoerig, O'Connor, and colleagues 2025, a fifteen-author systematic review published in the American Journal of Clinical Nutrition (volume 122, pages 1006 to 1026), is the most current and most comprehensive U.S. synthesis of arsenic, cadmium, lead, and mercury (alongside per- and polyfluoroalkyl substances) in both human milk and infant formula. It applies PRISMA-style systematic-review methodology to the U.S.-applicable peer-reviewed and government-data corpus through 2024 to 2025. The review documents that infant formula concentrations of arsenic, cadmium, lead, and mercury vary substantially across U.S. market products, and that human milk concentrations of these elements are generally lower than reconstituted formula concentrations on a per-serving basis.

The load-bearing point Thoerig 2025 establishes for this synthesis is that human milk and infant formula are treated as two separate matrices with separate per-analyte, per-matrix summary distributions, in the definitive recent U.S. review of the question. The finding that per-serving human-milk concentrations are generally lower than reconstituted formula does not make breastmilk a null pathway; it establishes that the pathway is real, quantified, and analyzed separately from formula in the peer-reviewed evidence base. It also frames the direction of the comparison honestly: for the analytes reviewed, exclusive breastfeeding is generally the lower per-serving exposure route, but it is not a zero-exposure route, and the concentration in any individual mother's milk depends on her own exposure history rather than on a controllable product specification.

3 | The Korean maternal-diet cohort (Moon 2025)

Moon, Heo, Park, Im, and Kim 2025, published in Toxics, measured lead, cadmium, total mercury, and total arsenic by ICP-MS and direct mercury analysis in breastmilk from 209 healthy lactating Korean mothers sampled between January and March 2023, and is the largest and most methodologically rigorous recent study of heavy metals in Korean breastmilk. Cadmium was the most frequently detected analyte, in 99 percent of samples (geometric mean 0.13 micrograms per litre, 95th percentile 0.45, maximum 1.51), followed by mercury in 97 percent (geometric mean 0.18 micrograms per litre, 95th percentile 0.56, maximum 1.28), total arsenic in 89 percent (geometric mean 1.16 micrograms per litre, 95th percentile 4.62, maximum 9.48), and lead in 79 percent (geometric mean 0.11 micrograms per litre, 95th percentile 0.57, maximum 1.49). All concentrations are on a volume basis in whole milk (micrograms per litre, wet-weight equivalent).

Two features make this cohort central to the thesis. First, the study modeled infant exposure directly, using a mean infant body weight of 5.71 kilograms and a mean measured breastfed-infant intake of 883.54 millilitres per day, and found that total arsenic was the largest contributor to potential health risk, with one infant's arsenic estimated daily intake exceeding the Korea Ministry of Food and Drug Safety health-based guidance value (hazard quotient above 1). Hazard quotients for lead, cadmium, and mercury remained below 1 across the cohort at median intake. The ordering of hazard-quotient contribution among exclusively breastfed infants was arsenic, then mercury, then cadmium, then lead. Second, and most important for the exposure-pathway argument, the

study identified maternal dietary determinants by multiple linear regression: lead rose with legume and seaweed consumption, cadmium with vegetable and seaweed consumption, mercury with sugar intake, and arsenic with meat intake, with seafood dominating the arsenic contribution at the food-category level. This is direct evidence that the metal load in breastmilk tracks maternal diet, which is precisely the mechanism that food-matrix surveillance of the milk itself cannot capture. The seaweed association for cadmium and lead links this pathway to the seaweed cadmium and arsenic synthesis: a maternal dietary contamination source documented there propagates into breastmilk here.

The authors report total arsenic without inorganic-organic speciation and total mercury without methylmercury speciation. Because the arsenic signal is dominated by seafood, an unknown fraction of the measured total arsenic is organoarsenical rather than the toxicologically dominant inorganic form (see the organoarsenical inertness synthesis for why total arsenic minus inorganic arsenic cannot be read as the inert fraction). The hazard-quotient finding, computed on total arsenic against an inorganic-arsenic guidance value, is therefore an upper bound on the inorganic-arsenic risk, and this uncertainty is stated rather than resolved.

4 | The e-waste environmental signal (Chen 2023)

Chen and colleagues 2023, published in GeoHealth, measured six elements (lead, cadmium, chromium, total arsenic, copper, manganese) in 102 breastmilk samples from mothers in Luqiao District, Taizhou, one of China's largest electronic-waste recycling areas, with milk collected four weeks post-delivery in 2021. Chromium was the standout finding: 34.3 percent of participants had breastmilk chromium above the upper bound of the WHO permissible range of 0.8 to 1.5 micrograms per litre (cohort mean 1.517, median 1.410, maximum 7.453 micrograms per litre). Arsenic (mean 0.113 micrograms per litre), cadmium (mean 0.016), and lead (mean 0.260) remained within WHO permissible milk ranges in this cohort, so the environmental signal here is carried primarily by chromium rather than by lead, cadmium, total arsenic, and mercury.

The study's adverse birth-outcome finding is that cadmium in maternal milk was inversely associated with birth weight in female infants (beta = -162.72 grams per interquartile-range increase in log-cadmium, 95 percent confidence interval -303.16 to -22.25, p-interaction = 0.017), with no significant association in male infants, and Bayesian kernel machine regression indicating additive rather than synergistic effects of the metal mixture. For this synthesis, Chen 2023 establishes that proximity to a specific industrial exposure source (e-waste recycling) writes a distinct, elevated metal signature into breastmilk that general-population baselines do not predict, and that a health-relevant association (reduced female birth weight) is detectable even at cadmium concentrations within WHO permissible milk limits. The contamination is a function of where the mother lives and what she is exposed to, not of any product specification.

5 | The São Paulo neurodevelopment cohort (Naspolini 2024)

Naspolini and colleagues 2024, published in Frontiers in Public Health, measured arsenic, lead, mercury, and cadmium in 185 breastmilk samples from the Germina prospective cohort in metropolitan São Paulo, collected at three months postpartum in 2021 to 2022, and paired the measurements with Bayley-III neurodevelopmental assessment at three time points through 16 months of age. Total arsenic had the highest detection rate (38.6 percent, mean 2.76 micrograms per litre, range 0.10 to 34.55), followed by total mercury (23.9 percent, mean 1.96, range 0.04 to 54.41) and lead (22.8 percent, mean 2.09, range 0.15 to 40.90); cadmium was below the limit of quantification (0.08 micrograms per litre) in every sample. All values are on a volume basis in whole milk.

The load-bearing outcome is that infants exposed to lead through breastmilk showed significantly lower language-development trajectories at 10 to 16 months than non-exposed infants (interaction beta = -0.413, 95

percent confidence interval -0.653 to -0.173, p < 0.001), with exposed infants scoring a mean Bayley language composite of 97.47 versus 102.96 in the non-exposed group. Among the 42 exposed infants, mean lead was 8.67 micrograms per litre. The authors note that these mean lead concentrations were lower than in most prior Brazilian and international studies, so the measurable language deficit occurred at the lower end of the reported concentration range, consistent with the CDC and WHO position that no threshold exists for lead neurodevelopmental toxicity. Naspolini 2024 therefore supplies the outcome half of the exposure-pathway argument: breastmilk lead is not merely detectable, it is associated with a functional neurodevelopmental deficit in the exposed infants at concentrations that do not stand out as high.

The contrast between the São Paulo cohort (cadmium entirely below quantification) and the Korean cohort (cadmium detected in 99 percent of samples) is a genuine between-study divergence rather than a contradiction: it reflects different limits of quantification (0.08 micrograms per litre in Naspolini versus a 0.030 microgram-per-litre limit of detection in Moon) and different maternal cadmium exposure, and it illustrates that per-analyte detectability in breastmilk is population- and method-dependent.

6 | The multi-country biomonitor reviews (Katrynska 2026, Aisyiah 2025)

Katrynska, Bzikowska-Jura, Goc, and Kogut 2026, a structured narrative review in Nutrients synthesizing 112 primary studies from 2010 to 2025, frames human milk explicitly as a biomonitor of maternal toxic-metal exposure and provides typical background-population ranges of approximately 2 to 5 micrograms per litre for lead, 1.4 to 1.7 for total mercury, and below 1 for cadmium, against an outlier landscape in which industrialized and mining regions reach far higher: a maximum recorded breastmilk lead of 1515 micrograms per litre in Turkey (median 20.6, with more than 85 percent of samples exceeding a 5 microgram-per-litre threshold), total arsenic up to 149 micrograms per litre in arsenic-endemic India, and total mercury with an Amazonian mean of 59.41 and maximum of 104.1 micrograms per litre driven by fish consumption and gold mining. The review documents quantified maternal determinants: breastmilk cadmium 37 to roughly 300 percent higher in smokers than non-smokers, mercury about 42 percent higher in regular marine-product consumers, a mercury roughly threefold elevation in women with dental amalgam, higher lead in primiparous than multiparous women, and higher lead under iron-deficiency anemia through the shared divalent-metal transporter. This B-tier review is the source of the transfer-mechanism framework used below.

Aisyiah, Rahfiludin, Agushybana, and Sutiningsih 2025, a PROSPERO-registered systematic review (CRD42024545030) in Jurnal Bidan Cerdas, screened 355 records and included 9 primary studies from 2013 to 2023 across Taiwan, Spain, China, Palestine, Nigeria, Egypt, and Slovenia. It reports, among other values, colostrum lead of 13.22 plus-or-minus 3.58 nanograms per millilitre in Taiwan (Chao 2014, n=34), a Palestinian urban-versus-rural adjusted odds ratio of 4.96 (95 percent confidence interval 1.10 to 22.38) for breastmilk lead at or above 5 nanograms per millilitre, and a Chinese total-mercury geometric mean of 14 nanograms per millilitre detectable in 195 of 197 samples. The review connects breastmilk metal concentrations to seafood, fruit, and canned-food intake, water consumption, smoking, and industrial-versus-agricultural residence. The two reviews are geographically and authorially independent of each other and of the four primary cohorts, and both independently reach the biomonitor framing that anchors this synthesis. Both carry the standard limitation of narrative and small-inclusion systematic reviews, namely unharmonized units and analytical methods across constituent studies (Aisyiah's constituent papers mix nanograms per millilitre, micrograms per litre, and milligrams per litre), so their numeric values are treated as exposure context rather than as pooled occurrence data.

7 | The mechanistic explanation

The pattern exists because breastmilk is a route by which the mother's cumulative and current body burden is partitioned into a fluid the infant consumes. Katrynska 2026 sets out the chain: environmental and dietary sources drive maternal accumulation, in bone for lead, in adipose tissue for lipophilic organometals, and in kidney for cadmium; lactation then mobilizes these stores, so that bone resorption during lactation can transfer lead to the infant even when the mother's current dietary intake is low. This is why maternal age and parity matter, with older and primiparous mothers showing higher breastmilk lead, and why historic exposure (occupational, or from the leaded-gasoline era) remains relevant decades later. Moon 2025 supplies the current-diet half of the same mechanism, with breastmilk lead, cadmium, mercury, and arsenic each tracking specific maternal food groups in regression, and Chen 2023 supplies the environmental half, with e-waste proximity elevating chromium.

The lactation-stage dynamics reported in Katrynska 2026 refine the picture: lead, aluminum, and total arsenic peak in colostrum and decline by 75 to 90 percent through the first two months as milk protein content and metal-protein binding fall, whereas cadmium is the exception, remaining stable or rising through mature milk to a peak at four to six months of lactation because it is actively transported in mammary cells in competition with zinc and calcium. The infant is a uniquely vulnerable recipient because of immature hepatic and renal clearance, higher intake per unit body weight, and greater gastrointestinal absorption, with infant lead absorption several times that of adults.

This mechanism is categorically different from the origin of metals in infant formula. In formula, the metal load enters through the ingredient supply chain (crops, dairy or soy protein, mineral premixes) and the process water, and it is in principle controllable by sourcing and testing. In breastmilk, the metal load is set by the individual mother's exposure biography and cannot be specified, screened, or reformulated. A clean supply chain produces low-metal formula; a mother with a high lead body burden from bone stores produces higher-lead milk regardless of any supply-chain intervention. That is the sense in which the two pathways are distinct, and it is why the comparison in Thoerig 2025 (lower per-serving concentrations in human milk than in reconstituted formula for the analytes reviewed) does not collapse the two into one manageable category.

8 | Why conventional surveillance misses this

Food-safety surveillance is built around commercial matrices that can be sampled at market: cereals, produce, dairy, fish, packaged foods, and manufactured products such as infant formula. Breastmilk is none of these. It is not sold, not sampled by the FDA Total Diet Study or equivalent national programs, and not entered into packaged-food occurrence databases. The consequence is that for the exclusively breastfed infant, who may take breastmilk as the dominant or sole dietary intake for the first six months, the single most consumed matrix is the one matrix that no food-monitoring stream measures.

The only characterization of this pathway comes from the biomonitoring literature, which measures the milk directly in research cohorts of lactating mothers. That literature is exactly the corpus synthesized here, and it has three structural features that keep it invisible to conventional surveillance. It is generated by environmental--health and toxicology researchers rather than food-safety monitoring programs, so it is dispersed across journals such as Toxics, GeoHealth, Frontiers in Public Health, and Nutrients rather than aggregated in a food database. It is population-specific rather than product-specific, so its findings attach to maternal cohorts and exposure settings (Korean mothers, a Chinese e-waste district, a São Paulo urban cohort) rather than to a labelled product a regulator can sample. And it is method-heterogeneous, with limits of quantification, censoring rules, units, and speciation practices varying enough between studies that direct pooling is difficult, which is why Katrynska 2026 and Aisyiah 2025 both stop at narrative synthesis. The pathway is real and measured, but it is measured in a literature that food surveillance does not read.

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

For testing, the operative implication is that infant heavy-metal exposure cannot be fully characterized from product testing alone, because the breastfed infant's dominant intake matrix is not a product. Any risk model that estimates total infant metal exposure (including the consumer-app risk layer this wiki serves) must treat the breastmilk pathway separately from the formula pathway and must source its breastmilk parameters from the biomonitoring literature, since no product-occurrence dataset exists. The pathway is also arsenic-forward and lead-forward: in Moon 2025 total arsenic was the largest hazard-quotient contributor and in Naspolini 2024 lead carried the neurodevelopmental signal, so a breastmilk-exposure model that measures only the classically infant-food-associated analytes would miss the two metals doing the most work here. Speciation is a genuine limitation across the entire corpus: every primary cohort reported total arsenic and total mercury without inorganic-arsenic or methylmercury separation, so the toxicologically dominant fractions are inferred rather than measured, and the hazard-quotient estimates built on total arsenic against inorganic-arsenic guidance values are upper bounds.

For regulation, breastmilk sits in a structural gap. It is not a food product and cannot be regulated as one, yet it is a major infant exposure route with documented health associations (reduced female birth weight in Chen 2023, reduced infant language trajectory in Naspolini 2024). The regulatory lever that fits the mechanism is maternal exposure reduction rather than product limit-setting: the Katrynska 2026 case studies of breastmilk lead declining roughly 90 percent in Hungary (14.9 to 1.74 micrograms per litre between 1991 and 2017) and from 17 to about 1 micrograms per litre in Sweden after leaded-gasoline phase-out show that environmental regulation of the maternal exposure environment is what moves this pathway, on a decade timescale. This is a different regulatory register from the product-limit framework (FDA Closer to Zero) that governs infant formula, and conflating the two would misdirect the intervention.

For consumption, the honest statement to a lactating parent has two parts. First, the reviewed evidence consistently finds that under typical background-exposure conditions, the benefits of breastfeeding outweigh the measured metal risks, and Thoerig 2025 finds per-serving human-milk concentrations of arsenic, cadmium, lead, and mercury generally lower than reconstituted formula; breastfeeding is not being cast here as the higher-exposure choice. Second, breastmilk is nonetheless not a metal-free matrix, and the specific, quantified maternal factors that raise the load are actionable: Moon 2025 associates higher breastmilk cadmium and lead with seaweed intake and higher arsenic with seafood intake; Katrynska 2026 associates 37 to roughly 300 percent higher cadmium with maternal smoking, roughly 42 percent higher mercury with regular marine-fish consumption, and threefold higher mercury with dental amalgam, and notes higher lead under iron-deficiency anemia. A lactating parent concerned about infant metal exposure can act on smoking cessation, moderation of high-mercury predatory fish and high-cadmium seaweed intake, and iron and calcium sufficiency, which are maternal-side interventions with a documented mechanistic basis, rather than on any property of the milk that can be tested or purchased.

10 | What this synthesis does not yet rest on

No pooled occurrence distribution for breastmilk exists in this corpus. The four primary cohorts (Korea, China, Brazil, and the U.S. primary studies underlying Thoerig 2025) differ in limits of quantification, censoring rules, lactation stage at sampling, and speciation, so the values here are reported per-study rather than combined into a single typical and 95th-percentile profile. A harmonized re-analysis across the primary cohorts, holding basis and censoring constant, would strengthen the quantitative core and is a candidate for a Journal of Food Metallomics synthesis.

Speciation is the largest single gap. Every cohort reported total arsenic and total mercury only. Because the arsenic hazard signal is the dominant finding in Moon 2025 and is seafood-driven, an inorganic-arsenic--speciated breastmilk cohort would materially sharpen the risk estimate, converting the current upper-bound hazard quotients into direct ones.

The corpus is also geographically uneven, with strong representation from East Asia, an e-waste-specific Chinese setting, urban Brazil, and a U.S. systematic review, and thinner primary coverage of North American and Western European general populations at the individual-cohort level (the European and North American signal here comes largely through the two multi-country reviews). A general-population U.S. or EU primary breastmilk cohort with modern ICP-MS speciation would fill the most policy-relevant gap for the markets this wiki's downstream products serve.

11 | Implications for downstream wiki pages

breastmilk should carry this synthesis as the load-bearing reference for its contamination and exposure profile, with the per-study values from Moon 2025, Chen 2023, and Naspolini 2024 as the primary-cohort anchors, the Thoerig 2025 formula-versus-milk comparison as the U.S. framing, and the Katrynska 2026 typical-range and outlier landscape as the global context. The page should state explicitly that breastmilk is a biomonitor of maternal exposure rather than a specifiable product, and that its metal load cannot be characterized from food surveillance.

The infant-formula-powder-non-soy, infant-formula-powder-soy-based, infant-formula-rtf-liquid-non-soy, and infant-formula-rtf-liquid-soy-based pages should reference this synthesis at the point where they discuss the breastmilk-versus-formula exposure comparison, so that the Thoerig 2025 finding is read in both directions:

formula is the testable, limit-governed pathway, and breastmilk is the parallel pathway that product limits do not reach.

The combined-exposure synthesis should cross-reference this page as the matrix-specific case in which a major infant exposure route falls outside the single-matrix surveillance frame, and the seaweed synthesis should be cross-linked from the maternal-diet discussion, because the Moon 2025 seaweed-to-cadmium-and-lead association is a concrete instance of a documented dietary contamination source propagating into breastmilk.

12 | Provisional status

This synthesis was established 2026-07-27 on six independent sources: four A-tier (the Thoerig 2025 U.S. systematic review and the Moon 2025, Chen 2023, and Naspolini 2024 primary cohorts) and two B-tier multi-country reviews (Katrynska 2026 and Aisyiah 2025), with distinct authorship, institutions, and geography. The core claims (that breastmilk carries measurable Pb, Cd, tAs, and tHg; that the load tracks maternal body burden and diet; that health associations are detectable; and that no food-surveillance stream measures this matrix) are each supported by more than one independent source and do not depend on any single study. The between-cohort cadmium-detectability divergence (99 percent in Korea versus zero above quantification in São Paulo) is documented as a method-and-population effect rather than a contradiction. Resynthesis triggers fire on the next independent A-tier cohort that reports speciated inorganic arsenic or methylmercury in breastmilk, on any general-population U.S. or EU primary cohort entering the corpus, or on a harmonized cross-cohort re-analysis.

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REVIEW

STATUS AND LICENCE

Editorially reviewed in-house; no external peer review has been completed on this finding. Published as a preprint with its review state tracked on the article page. Released under CC BY 4.0.

DATA AVAILABILITY

Every source behind this finding is listed with its own extraction record at https://heavymetalindex.com/synthesis/-breastmilk-heavy-metal-exposure-pathway#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.

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