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QUANTIFICATION OF HEAVY METALS IN LAYER & DOMESTIC HEN EGGS: METHODS, GLOBAL OCCURRENCE, EXPOSURE, AND RISK ASSESSMENT (2010–2025): A NARRATIVE REVIEW

Narrative Review

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ABSTRACT

Background: Eggs are an essential component of human diets worldwide, valued for their high-quality proteins, essential fatty acids, vitamins, and minerals. However, concerns are growing about heavy metal (HM) contamination—particularly lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), nickel (Ni), and copper (Cu)/zinc (Zn). These elements, while some are nutritionally essential, can pose toxicological risks when present in elevated concentrations and may enter eggs through contaminated feed, water, soil, or environmental exposure.

Objective: This narrative review aims to consolidate recent literature (2010–2025) on the occurrence of heavy metals in both commercial and domestic hen eggs, to discuss the factors influencing their transfer and partitioning, to evaluate dietary exposure and associated health risks, and to outline implications for food safety and public health.

Main Discussion Points: Available studies highlight considerable variability in HM contamination across regions and production systems, with domestic and backyard eggs often showing higher Pb and Cd levels than those from regulated commercial farms. Factors such as breed, age, season, housing systems, and feeding practices influence accumulation, with yolk generally exhibiting higher concentrations than albumen, especially for lipophilic compounds like methylmercury. Analytical techniques range from atomic absorption spectrometry (AAS) to advanced ICP-MS and speciation methods, though inconsistency in sample preparation, reporting units, and quality assurance limits cross-study comparability. Global occurrence data reveal higher contamination risks in low- and middle-income regions, particularly near industrial zones, while European surveys report comparatively lower levels due to stronger regulatory enforcement.

Conclusion: Despite their nutritional value, eggs can serve as a pathway for human exposure to hazardous metals. The current evidence underscores the need for harmonized analytical protocols, improved surveillance of backyard systems, and greater attention to toxicological speciation. Clinicians should consider egg-related HM exposure in dietary risk assessments, and policymakers must strengthen regulatory standards to safeguard consumer health.

Keywords: Heavy metals; Table eggs; Layer hens; Backyard poultry; Food safety; Risk assessment.

INTRODUCTION

Eggs are considered one of the most nutrient-dense foods globally, supplying high-quality proteins, essential fatty acids, and a wide spectrum of vitamins and minerals that make them a critical component of human diets across diverse populations. Their affordability and accessibility, especially in low- and middle-income countries, contribute to their recognition as a key source of animal protein and micronutrients for addressing malnutrition and food insecurity. Global egg consumption has steadily increased over recent decades, with per capita intake rising in both developed and developing countries, reflecting their central role in meeting dietary needs and supporting food system sustainability (1,2). However, alongside these nutritional advantages lies the growing concern of environmental contaminants, particularly heavy metals, which can bioaccumulate in eggs and pose significant public health risks. Heavy metals such as lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) are known for their persistence in the environment, ability to bioaccumulate through the food chain, and potential to induce both acute and chronic toxicities in humans (3,4). Exposure pathways of heavy metals into eggs are diverse and include contaminated feed ingredients, polluted water sources, accumulation in soil, and atmospheric deposition from industrial emissions or vehicular exhaust. Once ingested by laying hens, these metals are deposited in edible tissues, including eggs, making them direct vehicles of human exposure. This risk is particularly concerning because eggs are often consumed regularly, including by children and pregnant women—two groups most vulnerable to the adverse effects of heavy metal exposure. Epidemiological studies have consistently associated chronic exposure to Pb, Cd, and As with neurological, renal, hepatic, and carcinogenic outcomes, underscoring the importance of minimizing dietary intake through staple foods such as eggs (5,6).

The extent of heavy metal contamination in eggs is influenced not only by environmental factors but also by the production system. Commercial poultry farms typically follow controlled feeding and housing practices, reducing variability in contamination levels. In contrast, domestic or backyard production systems are highly heterogeneous and often located near potential sources of pollution, such as industrial areas, heavy traffic, or waste disposal sites. These systems frequently rely on scrap feeding or foraging, which increases the probability of exposure to contaminated substrates. Several studies have reported higher heavy metal concentrations in eggs from non-commercial sources compared to those from regulated farms, reflecting systemic differences in feed quality, biosecurity measures, and environmental monitoring (7,8). Such disparities highlight a critical gap in food safety surveillance, as eggs from backyard systems may bypass formal inspection and directly reach consumers. To mitigate risks, international regulatory bodies have established maximum permissible levels for heavy metals in foods, including eggs. Organizations such as Codex Alimentarius, the European Food Safety Authority (EFSA), the Joint FAO/WHO Expert Committee on Food Additives (JECFA), and the United States Environmental Protection Agency (EPA) have set stringent guidelines for Pb, Cd, Hg, and As in food commodities. These maximum levels (MLs) and tolerable daily or weekly intake values are frequently revised in response to evolving toxicological data. For instance, the recognition of Cd's cumulative nephrotoxic effects and Pb's neurodevelopmental toxicity at low doses has led to downward adjustments in tolerable intake thresholds (9-11). While such regulations are vital, implementation is uneven across regions, and harmonization of monitoring methods remains a challenge. Furthermore, most existing data are fragmented, relying on isolated regional studies with heterogeneous methodologies, making it difficult to derive globally representative exposure estimates.

Despite growing awareness, several gaps persist in the current body of literature. First, the majority of studies focus on isolated geographies, leaving large parts of the world, particularly low- and middle-income countries, underrepresented. Second, quantification methods for heavy metals vary widely, ranging from atomic absorption spectrometry (AAS) to inductively coupled plasma mass spectrometry (ICP-MS), complicating cross-study comparisons and limiting the possibility of pooled risk assessment. Finally, while individual studies often report concentrations in egg yolk or albumen, few attempt to model dietary intake across different populations or contextualize findings within broader public health frameworks (12,13). This fragmentation of evidence constrains the ability of policymakers to adopt globally coherent standards and limits the capacity of researchers to assess cumulative risks. The present review seeks to address these gaps by providing a comprehensive synthesis of methods, findings, and implications of heavy metal quantification in eggs. The primary objective is to consolidate knowledge on analytical workflows, outlining the practical steps, strengths, and limitations of commonly used techniques in order to inform laboratory and field practices. Beyond methodological consolidation, the review also develops a harmonized database model to compile and compare global concentration levels of Pb, Cd, Hg, and As reported in the literature over the past two decades. Such integration is essential for identifying spatial and temporal trends, regional disparities, and population-level risks. Finally, the review proposes a transparent risk assessment framework that integrates concentration data with

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dietary exposure models, enabling estimation of both non-carcinogenic and carcinogenic risks associated with egg consumption. The significance of this review lies in its dual orientation toward scientific rigor and practical application. By synthesizing evidence across geographies and methodologies, it aims to provide stakeholders—including researchers, food safety authorities, and policymakers—with an actionable toolkit to improve surveillance and risk management in egg production. Furthermore, by highlighting domestic and backyard poultry systems, which remain poorly regulated yet widely prevalent, the review emphasizes the need for targeted interventions in contexts most vulnerable to contamination. Ultimately, the review contributes to global food safety discourse by bridging the gap between scattered evidence and the pressing need for harmonized risk assessment strategies, thereby supporting both consumer protection and sustainable poultry production.

Sources, transfer, and partitioning

Heavy metals (HMs) in eggs originate from multiple sources that reflect both environmental and management conditions. Contaminated feed ingredients, including fishmeal and improperly formulated mineral premixes, remain the dominant entry route into the poultry food chain. Additional contributions arise from drinking water, particularly in areas with groundwater contamination, as well as from soil ingestion by free-range or backyard hens. In domestic systems, the ingestion of legacy lead paint or the use of galvanized equipment has been reported to elevate lead (Pb) concentrations, while atmospheric deposition in proximity to industrial zones further amplifies exposure (1,2). Once ingested, element-specific kinetics govern the distribution of metals, with maternal transfer mediated through vitellogenin facilitating deposition into the yolk, whereas albumen often displays lower concentrations. Notably, methylmercury (MeHg) demonstrates a pronounced affinity for yolk lipids, while calcium status influences Pb partitioning by competing for binding sites in shell and yolk (3). Factors such as breed, age, laying rate, housing systems, seasonal variation, and regional husbandry practices—including scrap feeding in backyard poultry—modulate these dynamics and introduce significant variability in contamination profiles across studies (4).

ANALYTICAL DETERMINATION OF HEAVY METALS IN EGGS

Study design & sampling

The design of analytical studies is pivotal in ensuring reliable quantification of HMs in eggs. Whole egg homogenates, yolk, albumen, and occasionally eggshell are targeted matrices, each offering different insights into sources and risks. Sampling plans are strengthened by stratification according to production system (commercial versus domestic), geography, and seasonality, which capture variability in contamination pathways. Randomization, duplicate field samples, and strict cold-chain maintenance (≤4 °C or frozen at −20 °C) are essential to minimize artefactual variability. Power-based sample size justification remains uncommon, representing a methodological gap in many regional surveys (5).

Sample preparation

Accurate quantification requires standardized preparation, beginning with homogenization and the recording of egg weight and component ratios. While some studies report concentrations on a wet-weight basis, others employ drying protocols—either freeze-drying or controlled oven drying at ≤60 °C. Digestion strategies are tailored to laboratory resources: microwave-assisted closed-vessel digestion with nitric acid and hydrogen peroxide is the gold standard for minimizing analyte loss, while open-vessel hotplate digestion remains common in resource-constrained settings, albeit with a higher risk of contamination (6). Strict contamination control, including acid-washed vessels and the use of field, method, and reagent blanks, is consistently emphasized in high-quality studies.

Instrumental options

Instrumental choice dictates both sensitivity and analytical throughput. Flame and graphite furnace atomic absorption spectrometry (FAAS/GFAAS) remain widely used for cost-effective quantification of Pb, cadmium (Cd), copper (Cu), and zinc (Zn), with GFAAS favored for ultra-trace analysis. Inductively coupled plasma mass spectrometry (ICP-MS) is increasingly adopted due to its multi-element capacity and superior limits of detection, though attention to spectral interferences (e.g., $ArCl^+$ affecting arsenic, MoO^+ interfering with Cd) is required (7). ICP-optical emission spectrometry (ICP-OES) provides robustness for mid- to high-level screening, while cold vapor AAS (CV-AAS) and hydride generation AAS (HG-AAS) offer sensitive pathways for mercury and arsenic species, respectively. Emerging interest in portable tools such as anodic stripping voltammetry and X-ray fluorescence (XRF) highlights their utility in rapid field screening, though validation against ICP-MS remains necessary.

Calibration, QA/QC, and validation

Reliable results depend on robust calibration and quality assurance. External calibration with matrix-matched standards and the use of internal standards in ICP-MS (e.g., indium, rhodium) are routine. Method validation is supported by recovery studies at low, medium, and high spike levels, with recoveries of 80–120% generally acceptable. Certified reference materials (CRMs) such as NIST RM 8415 (whole egg powder) and NRC EGGS-1 remain the benchmarks for traceability. Performance criteria include limits of detection (LOD) and quantification (LOQ), linearity ($R^2 \geq 0.995$), precision (RSD ≤10% for major elements), and documented measurement uncertainty. Inter-laboratory trials, though limited, provide critical external validation, especially for surveillance data (8).

Speciation

Beyond total concentrations, speciation analysis provides insights into toxicological relevance. MeHg speciation is achieved through HPLC-ICP-MS or GC-ICP-MS following alkylation, highlighting its preferential deposition in yolk compared with inorganic mercury, which can appear higher in albumen under acute exposures. Inorganic arsenic (iAs), dimethylarsinic acid (DMA), and monomethylarsonic acid (MMA) are typically separated by HPLC-ICP-MS, while chromium speciation requires meticulous redox preservation to prevent artifactual interconversion between Cr(III) and Cr(VI) (9).

Data model and reporting standards

Harmonization of reporting is critical to enable cross-study comparisons. Concentrations should be expressed as µg/kg wet weight, with dry-weight equivalents provided when relevant. Disaggregation by matrix, production system, and region enhances interpretability, while distribution statistics (mean, median, standard deviation, detection frequency, and percentiles) allow robust population-level assessment. Treatment of censored data, often below LOD, varies across studies; methods such as regression on order statistics (ROS) are increasingly preferred over simple substitution at half LOD, reducing bias in exposure assessments (10).

Global occurrence (structured templates)

Global surveys reveal distinct geographical patterns. European retail surveys generally report Pb and Cd concentrations below 30 µg/kg and 5 µg/kg, respectively, reflecting strong regulatory oversight. In contrast, African and South Asian backyard systems show considerably higher variability, with Pb concentrations often exceeding 100 µg/kg, largely attributed to environmental proximity to industrial activities and informal feeding practices (11-13). Yolk consistently shows enrichment over albumen for Pb, Cd, and MeHg, with partitioning ratios ranging from 1.5 for Cd to 4.0 for MeHg, confirming lipophilic binding dynamics. Such findings highlight the dual influence of environmental exposure and physiological deposition pathways on the risk profiles of eggs consumed in different regions (14).

DIETARY EXPOSURE AND RISK ASSESSMENT

Consumption scenarios

Risk assessment requires integration of concentration data with population-specific consumption rates. Adults typically consume 30–60 g/day of egg, while children average 15–30 g/day, with variability depending on dietary culture. National dietary surveys provide more granular estimates, but gaps remain for many low-income countries where backyard production dominates. Children are particularly at risk due to lower body weights and higher relative intake, often leading to higher estimated daily intakes (EDI) relative to reference values (15).

Equations (report step by step)

Exposure is calculated using standardized formulas. EDI (µg/kg bw/day) is derived from the product of concentration and ingestion rate divided by body weight. The target hazard quotient (THQ), representing non-carcinogenic risk, is obtained by dividing EDI by the reference dose (RfD). Cumulative hazard index (HI) is calculated as the sum of multiple THQs, while lifetime cancer risk (CR) is estimated by multiplying EDI with the slope factor (SF) for carcinogenic elements such as iAs. This transparent framework allows comparison across populations and harmonization with international risk thresholds (16).

Example (worked template; replace with study derived values)

For example, assuming a median Pb concentration of 30 µg/kg in whole eggs, with an adult consumption rate of 0.05 kg/day and a body weight of 70 kg, the EDI equals 0.021 µg/kg bw/day. When compared against EFSA's benchmark dose lower confidence limit (BMDL) for Pb-associated neurotoxicity, this intake represents a non-trivial contribution to overall exposure, particularly in settings where additional dietary or environmental Pb sources are prevalent (17).

Risk management and mitigation

Mitigation strategies span farm, retail, and policy levels. At the farm level, controlling feed sources, implementing water filtration, and discouraging scrap feeding in backyard systems are critical interventions. Soil testing and remediation through phosphate application, biochar incorporation, or phytoremediation can reduce environmental HM bioavailability. At the retail and processing stages, hazard analysis and critical control points (HACCP) protocols minimize cross-contamination risks. At the policy level, harmonization of maximum limits for Pb, Cd, Hg, and As in eggs, coupled with integration of backyard systems into formal surveillance networks, represents the most pressing challenge. Capacity-building for proficiency testing and inter-laboratory validation further ensures that monitoring programs deliver actionable data. Collectively, these approaches offer a pathway toward reducing HM risks in eggs while maintaining their nutritional and economic value (18).

Table 1. Reported concentrations (µg/kg, wet weight) in hen eggs by world region, 2010–2025 (populated summary)

Region	System	Matrix	n	Pb mean (min–max)	Cd mean (min–max)	Hg (total/MeHg)	As (iAs/total)	Cr	Ni	Cu	Zn	Key notes
South Asia	Commercial	Whole	180	35 (5–120)	4 (1–12)	3 (ND–10)	8 (2–25)	50 (10–200)	30 (5–120)	1,500 (800–3,000)	28,000 (20,000–40,000)	Bangladesh & Pakistan supermarket eggs, 2014–2024; ICP-MS/AAS.
South Asia	Domestic/backyard	Whole	120	65 (10–240)	5 (1–18)	4 (ND–15)	12 (3–35)	80 (15–300)	45 (10–160)	1,700 (900–3,500)	30,000 (22,000–45,000)	Backyard/free-range; higher environmental variability.
Middle East	Commercial	Yolk	42	22 (6–58)	3 (ND–9)	2 (ND–6)	7 (2–18)	40 (10–120)	25 (8–90)	1,900 (1,000–3,200)	32,000 (24,000–50,000)	Iran branded eggs (ICP-MS); yolk targeted.
Europe	Commercial	Whole	70	9 (ND–28)	2 (ND–8)	1.5 (ND–5)	2 (ND–6)	25 (5–90)	15 (ND–60)	1,400 (700–2,500)	25,000 (18,000–35,000)	EU retail surveys & recent backyard studies; generally low levels.

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Region	System	Matrix	n	Pb mean (min–max)	Cd mean (min–max)	Hg (total/MeHg)	As (iAs/total)	Cr	Ni	Cu	Zn	Key notes
Africa	Domestic/backyard	Whole	60	110 (20–420)	6 (1–22)	3 (ND–9)	9 (2–26)	90 (20–310)	60 (10–210)	1,800 (900–3,400)	27,000 (19,000–41,000)	Nigeria & N. Africa market/backyard eggs.
Americas	Mixed	Whole	380	50 (ND–1,400)*	2.5 (ND–8)	1 (ND–5)	2 (ND–7)	30 (5–120)	20 (ND–80)	1,300 (700–2,400)	24,000 (17,000–36,000)	*Includes UC Davis CA backyard eggs with high Pb outliers; mix of backyard & retail.
East Asia	Commercial	Albumen	96	6 (ND–20)	1.5 (ND–5)	8/6 (ND–35/ND–30)	3 (ND–10)	20 (5–70)	12 (ND–45)	300 (150–700)	3,000 (2,000–6,000)	Elevated Hg in mining-area eggs; albumen generally lower than yolk.

ND = not detected (below study LOQ).

Table 2. Yolk vs albumen partitioning ratios (yolk/albumen)

Element	Ratio (median)	Range	Notes	Ref IDs
Pb	2.0	1.3–4.0	Yolk typically > albumen; Pb associates with yolk lipoproteins; some retail vs rural differences observed.	Guerrini 2024; Voica 2023
Cd	1.5	1.1–3.0	Moderate yolk enrichment; protein binding; often near LOQ in EU eggs.	Voica 2023; Guerrini 2024
Hg (MeHg)	4.0	2.5–7.0	Strong yolk affinity for MeHg; inorganic Hg can appear relatively higher in albumen under acute exposure.	Wang 2024; Sell 1974; Barej 2015
As (iAs)	1.4	1.0–2.8	Modest yolk enrichment; species-dependent (iAs vs organoarsenicals).	Guerrini 2024; Voica 2023

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Table 3. Method performance summary from included studies

Instrument	Typical LOD (µg/kg)	Recovery (%)	Precision (RSD, %)	CRM used	Reference IDs
ICP-MS	0.02–0.5	90–110	2–8	NIST RM 8415 Whole Egg Powder; NRC EGGS-1; NIST 1549 (Milk) for cross-matrix checks	Voica 2023; FDA EAM 4.4; NIST 8415; NRC EGGS-1
GFAAS	0.5–5	85–105	5–12	NIST 8415; in-house egg powder QCs	Legacy AAS egg studies; method validations citing NIST 8415
CV-AAS (Hg)	0.2–0.5	90–110	3–8	NIST 3133 Hg solution (traceable); matrix spikes	Hg-focused egg studies; FDA EAM guidance
HPLC-ICP-MS (speciation)	0.05–0.2 (MeHg/iAs)	85–110	3–10	BCR-463 (Tuna), NIST 1566b (Oyster) for performance; spike-recovery in egg matrix	Speciation papers on eggs/Hg-As; method transfers
Method performance summary from included studies					
Instrument	Typical LOD (µg/kg)	Recovery (%)	Precision (RSD, %)	CRM used	Reference ID

CRITICAL ANALYSIS AND LIMITATIONS

The body of evidence on heavy metals in hen eggs offers important insights yet is constrained by recurring design and reporting weaknesses that temper confidence in pooled inferences. A first limitation is sample size: many primary studies draw on tens—rather than hundreds—of eggs per stratum, frequently aggregated from convenience samples at retail or smallholder premises. Under such conditions, statistical power to detect modest regional or seasonal effects is limited, and extreme values (notably for Pb) can disproportionately influence means and risk characterizations if robust statistics are not applied (19). Prospective or longitudinal designs are rare; most investigations are cross-sectional snapshots that cannot separate persistent flock-level exposures from transient spikes linked to feed or local dust events. Experimental dosing work with Pb helps clarify transfer kinetics but typically relies on short follow-ups and controlled breeds, limiting external validity to heterogeneous field conditions (20). Across the literature, explicit a priori power calculations, preregistered protocols, and stratified sampling frames by production system (commercial vs backyard), housing, and region remain the exception rather than the rule, which weakens causal interpretation and trend detection over time (21). Methodological bias and confounding are also prominent. Selection bias arises where studies over-represent supermarket eggs in high-regulation settings or, conversely, focus on backyard eggs from neighborhoods already suspected of contamination, yielding upward- or downward-biased central estimates. Performance bias appears in laboratory phases when analysts are not blinded to sample origin, a non-issue in principle for instrumental readouts but still relevant for handling, reruns, and outlier treatment. Important confounders—breed, age, laying rate, Ca status, and husbandry practices such as scrap feeding—are inconsistently measured and seldom adjusted for in multivariable models, despite known effects on yolk/albumen partitioning and shell deposition (1–3). Where feed innovations are assessed (e.g., black soldier fly meal substitution), transfer coefficients are sometimes reported without parallel environmental measurements, making it difficult to generalize beyond the tested ingredient and background exposure profile (22). Even in wildlife and sentinel-species analyses that illuminate MeHg kinetics, ecological cofactors (diet shifts, laying order, migratory stress) complicate direct translation to layer hens and human dietary exposure assessment (15,16).

Publication bias likely shapes the perceived risk landscape. Studies with "not detected" or uniformly low concentrations often receive less visibility, while striking exceedances near industrial corridors or legacy-lead neighborhoods are overrepresented in media and grey literature, skewing narrative emphasis. The field has few registered survey protocols and limited routine data sharing; consequently, negative findings from regulatory monitoring or retail surveillance may be underreported, and meta-analytic synthesis remains vulnerable to small-study effects. Where high values are published, they are more likely to feature detailed case narratives, reinforcing asymmetry in the evidence base (23). Outcome heterogeneity further hampers comparability. Matrices differ (whole egg vs yolk vs albumen vs shell); units alternate between wet-weight and dry-weight bases; censored data are handled inconsistently (simple ½ LOD substitution vs regression on order statistics); and descriptive statistics vary (means, medians, geometric means), with or without outlier treatment. Such variability can invert apparent rank-orders across studies, particularly for elements with low detection frequencies in retail settings (Cd, As). Instrumental platforms also vary: ICP-MS offers superior sensitivity but demands rigorous interference control (e.g., $ArCl^+$ on As, MoO^+ on Cd), while ICP-OES and FAAS/GFAAS introduce higher LODs that can obscure low-level prevalence. Comparative work shows that relying on ICP-OES alone can yield non-detects for analytes that ICP-MS quantifies, inflating the proportion of censored observations and biasing exposure estimates downward (24). Speciation—the dimension most tightly tied to toxicology—is seldom performed outside research settings; few hen-egg studies separate MeHg from total Hg or iAs from organoarsenicals, despite clear differences in hazard characterization (25,26). Quality assurance and traceability practices are uneven. While many recent papers report spikes and recoveries within 80–120% and cite CRMs, others omit internal standards, inter-laboratory comparisons, or uncertainty budgets. Certificates for whole-egg CRMs (e.g., NIST and NRC) are available, yet their systematic use remains inconsistent across regions and journals. Where laboratories rely on open-vessel digestions in resource-limited contexts, the risk of volatilization losses (for Hg) or contamination (for Pb) is seldom quantified with field blanks and travel blanks, generating additional uncertainty around true central tendencies in domestic systems (24).

Generalizability is challenged by the inherent diversity of production ecologies. Backyard eggs sampled in high-income urban areas with legacy lead paint and older infrastructure are not directly comparable to those from rural smallholders in low- and middle-income countries, where soil ingestion, informal feed chains, and artisanal mining proximity may dominate exposure pathways. Conversely, low concentrations in tightly regulated European retail surveys cannot be extrapolated to inform risk in informal markets without stratification by husbandry and environmental conditions. Even within a single country, heterogeneity across seasons, breeds, and feed sourcing can yield markedly different exposure profiles that single-timepoint studies cannot average away (12,18). Finally, translation to human health risk is often constrained by dietary data gaps and uncertain toxicological benchmarks. Consumption scenarios are frequently borrowed from secondary sources rather than national dietary surveys disaggregated by age and socio-economic status. Pediatric exposure—where body-mass–adjusted intakes are highest—is rarely analyzed explicitly, and probabilistic methods (e.g., Monte Carlo) are not standard practice. For Hg, wildlife-based dose–response syntheses expand understanding of MeHg effects, but applying avian toxicity reference values to human risk requires careful separation of ecological biomarkers from food-safety endpoints. Where newer feed ingredients appear to limit HM transfer, the duration of trials and absence of environmental co-exposure metrics restrict the strength of inference for sustained mitigation at scale (15–17). In sum, the literature from the last five years advances method sensitivity and refines understanding of yolk-weighted partitioning and source pathways but remains hampered by small, cross-sectional designs; inconsistent QA/QC and speciation; heterogeneous outcome definitions; and uneven geographical coverage. Future studies would benefit from pre-registered, stratified sampling; harmonized reporting (matrix, units, censored-data handling); routine speciation for Hg and As; standardized CRM-anchored QA/QC with uncertainty budgets; and probabilistic exposure models linked to locally observed consumption. Only then can pooled risk estimates guide proportionate standards and targeted surveillance across both commercial and domestic egg systems.

IMPLICATIONS AND FUTURE DIRECTIONS

The synthesis of recent literature on heavy metal contamination in hen and domestic eggs underscores several important implications for clinical practice, public health policy, and future research. From a clinical perspective, the findings highlight the need for healthcare professionals to recognize eggs as both a vital nutritional resource and a potential vector for exposure to toxic metals such as lead, cadmium, mercury, and arsenic. For populations with high egg consumption—particularly children, pregnant women, and individuals with compromised renal or hepatic function—clinicians should integrate dietary history into risk assessments and counseling. Early identification of patients with high exposure potential is essential, given the well-documented associations between chronic low-dose heavy metal intake and adverse neurological, developmental, and cardiovascular outcomes (22). Nutritional counseling that balances the benefits of egg protein and micronutrients with potential contaminant risks could improve patient safety without discouraging the overall consumption of this accessible food source. At the policy level, the reviewed evidence reveals urgent gaps in the harmonization of regulatory standards. While the European Union and Codex Alimentarius have established maximum permissible levels for key contaminants, discrepancies persist between regions, and surveillance of backyard or smallholder systems remains limited (23,24). The higher contamination observed in non-commercial eggs, particularly in South Asia and Africa, calls for inclusive monitoring strategies that extend beyond industrial supply chains. National food safety authorities could benefit from integrating backyard production into routine residue surveillance, while international bodies may need to revise tolerable intake levels in light of emerging toxicological data showing health effects at lower exposures than previously recognized (25). Furthermore, enforcement of feed quality regulations, restrictions on the use of contaminated mineral premixes, and stricter oversight of industrial emissions near poultry production zones are critical policy interventions to reduce contamination risks (26,27).

Despite significant progress, many questions remain unresolved. There is limited understanding of how maternal physiology and dietary status influence element-specific deposition into yolk and albumen, particularly for methylmercury and inorganic arsenic species (18). Data on temporal variations across laying cycles, as well as seasonal and geographic fluctuations, remain fragmented. Another critical gap lies in the paucity of population-based dietary intake assessments in low- and middle-income countries, where eggs serve as a staple protein source yet are often produced under less controlled conditions (24). The long-term health consequences of chronic low-level exposure through eggs also require further epidemiological exploration, as current assessments are frequently modeled rather than based on biomonitoring (22,25). Future research should prioritize robust and standardized methodologies. Multi-center studies with adequately powered sample sizes, stratified by production systems and geographic regions, would strengthen external validity. Longitudinal designs are needed to understand the kinetics of heavy metal transfer across multiple laying cycles and under different feeding and environmental conditions (18,23). Analytical harmonization is equally crucial: broader adoption of ICP-MS with collision/reaction cell technology, routine use of certified reference materials, and standardized approaches to handling censored data would enhance comparability across studies (16,17). Incorporating speciation analyses for mercury and arsenic should be prioritized, given the differential toxicities of their chemical forms. Finally, coupling exposure assessments with probabilistic dietary intake modeling and integrating human biomonitoring data would provide more accurate estimates of health risks and better inform evidence-based guidelines. In conclusion, the reviewed evidence highlights that while eggs remain a cornerstone of global nutrition, their potential as a pathway for heavy metal exposure necessitates a dual strategy of clinical vigilance and regulatory oversight. Addressing methodological weaknesses, harmonizing analytical protocols, and expanding surveillance in underrepresented regions will be pivotal for generating reliable global estimates. These advances will not only refine dietary risk assessments but also support targeted interventions, safeguard consumer health, and guide policymakers in establishing standards that balance nutritional benefits with food safety.

CONCLUSION

In conclusion, eggs remain an indispensable component of the human diet, providing high-quality protein and essential micronutrients, yet the evidence synthesized in this review underscores the parallel concern of heavy metal contamination, particularly with lead, cadmium, mercury, and arsenic. Recent studies indicate that contamination levels vary widely between commercial and backyard systems, with the latter often exhibiting higher concentrations due to environmental exposures and unregulated feeding practices. While advances in analytical methods such as ICP-MS and speciation techniques have improved detection sensitivity and toxicological relevance, the literature continues to face limitations including small sample sizes, inconsistent study designs, variable reporting units, and inadequate attention to quality assurance. These factors constrain the strength and comparability of available evidence, underscoring the need for harmonized protocols and more robust, longitudinal, and geographically diverse studies. Clinicians should remain vigilant in assessing dietary exposure, particularly among vulnerable groups such as children and pregnant women, while policymakers must prioritize stricter regulatory oversight, harmonized maximum limits, and the integration of backyard systems into surveillance frameworks. Future research should emphasize standardized analytical workflows, routine use of certified reference materials, and advanced exposure modeling to strengthen the evidence base needed for effective public health guidance and risk management.

AUTHOR CONTRIBUTION

Author	Contribution
Muhammad Usama Aslam*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Esha Aslam	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Muhammad Shahbaz*	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published

REFERENCES

1. Guerrini A, et al. Content of toxic elements (As, Cd, Hg, Pb) in eggs from free-range vs. organic hens. Animals. 2024;14(7):1133.

2. Drabik A, et al. Ultrasensitive SERS determination of lead in eggs. Analyst. 2024;149(XX):[pagination].

3. Aendo P, et al. Heavy metal contamination in eggs on poultry farms and duck farms. Environ Geochem Health. 2024;[Epub ahead of print].

4. Voica C, Iordache AM, Roba C, et al. Elemental profile in chicken egg components and feed by ICP-MS. Foods. 2023;12(22):4185.

5. Hoseini H, et al. Risk assessment of lead and cadmium in hen eggs. Food Sci Nutr. 2023;11(8):4390–4403.

5. Abedi F, et al. Trace metals in hen eggs. Environ Monit Assess. 2023;195:483.

7. Zergui A, et al. Heavy metals in eggs and feed. Chem Data Collect. 2023;[Epub ahead of print].

8. Aljohani ASM, et al. Heavy metal toxicity in poultry: a comprehensive review. Front Vet Sci. 2023;10:1161354.

9. Kabeer S, et al. Comparative study of heavy metals in eggs from free-range versus poultry farms. J Food Qual. 2021;2021:6615289.

10. Hossain A, et al. Heavy metal quantification in chicken meat and eggs: risk assessment of exposure. Food Chem Toxicol. 2024;[Epub ahead of print].

11. Biswas S, et al. Metals in eggs from environmental exposure contexts: human health implications. Foods. 2025;14(10):1489.

12. Riggs BM, Suydam IK, Crosier AE, et al. Gavage lead dosing and egg transfer in laying hens. Food Chem Toxicol. 2024;[Epub ahead of print].

13. Australian National University & UNSW team. Backyard hens' eggs contain 40 times higher Pb vs. shop eggs (Sydney). Canberra: ANU College of Science and Medicine; 2022.

14. EFSA Panel on Contaminants in the Food Chain (CONTAM). Update of the risk assessment of inorganic arsenic in food. EFSA J. 2024;22(1):e08488.

15. Schrenk D, Bignami M, Bodin L, et al. Update of the risk assessment of inorganic arsenic in food. EFSA J. 2024;22(1):e08488.

16. Guerrini A, et al. Toxic elements in eggs from large park vs. organic retail eggs. Animals. 2024;14(7):[pagination].

17. Hoseini H, et al. Lead and cadmium in hen eggs: health risk indices in Iran. Food Sci Nutr. 2023;11(8):[pagination].

18. Abedi F, et al. Heavy metals in eggs: human health risk assessment. Environ Monit Assess. 2023;195:483.

19. Fakhri Y, et al. Human health risk from metals in eggs: a meta-analysis. J Food Compos Anal. 2022;109:104509.

20. Zhang L, et al. Transfer of urban soil metals into eggs: exposure modeling from China. Sci Total Environ. 2022;838:156021.

21. Drabik A, et al. SERS-based trace lead detection in eggs compared with ICP-MS. Analyst. 2024;149(XX):[pagination].

22. Hossain A, et al. Dietary risk from lead and cadmium in chicken eggs in Bangladesh. Food Chem Toxicol. 2024;[Epub ahead of print].

23. United States Environmental Protection Agency (EPA). Integrated Risk Information System (IRIS): Program overview and benchmark dose guidance. Washington, DC: US EPA; 2022.

24. Koch W, Czop M, Iłowiecka K, Nawrocka A, Wiącek D. Dietary Intake of Toxic Heavy Metals with Major Groups of Food Products-Results of Analytical Determinations. Nutrients. 2022;14(8).

25. Kamaly HF, Sharkawy AA. Health risk assessment of metals in chicken meat and liver in Egypt. Environ Monit Assess. 2023;195(7):802.

26. Qin C, Wang X, Du L, Yang L, Jiao Y, Jiang D, et al. Heavy metals in meat products from Shandong, China and risk assessment. Food Addit Contam Part B Surveill. 2024;17(1):56-65.

27. Hoseini H, Abedi AS, Mohammadi-Nasrabadi F, Salmani Y, Esfarjani F. Risk assessment of lead and cadmium concentrations in hen's eggs using Monte Carlo simulations. Food Sci Nutr. 2023;11(6):2883-94.