Liver and kidney are physiological cadmium accumulation sinks that carry heavy-metal loads above skeletal muscle, making offal a distinct dietary exposure pathway that muscle-meat surveillance does not represent

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Abstract

Three independent A-tier occurrence datasets that measured the same animal across separate tissues converge on a single finding: organ tissue carries elevated heavy-metal loads relative to skeletal muscle from the same carcass, cadmium in the bovine and broiler surveys (rabeey2025 and kamaly2023) and lead in the multi-organ poultry survey (hossain2023), and the differential is a consequence of organ physiology rather than of localized contamination. A survey of 315 imported frozen bovine samples in Sohag, Egypt (rabeey2025) found cadmium rising from a muscle mean of 0.030 mg/kg wet weight to 0.056 mg/kg in liver and 0.073 mg/kg in kidney; a 360-sample survey of Egyptian commercial broiler chicken in Assiut (kamaly2023) found liver cadmium (0.027 to 0.104 mg/kg wet weight across brands) exceeding chest-muscle cadmium (0.014 to 0.054 mg/kg wet weight); and a 108-sample multi-organ survey of Bangladeshi broiler chicken (hossain2023) found lead concentrated in the metabolically active organs, reaching 4.6 mg/kg fresh weight in brain against a muscle minimum near 0.33 mg/kg fresh weight. A controlled feeding experiment (morshed2024) reproduces the cadmium pattern under known dosing, and two further A-tier studies of ruminant and game liver (marcelino2026, khatemeh2022) both sample liver as the standard monitored organ matrix.

1 | Overview

The load-bearing distinction is between cadmium and lead. The cadmium signal is consistent across every dataset that reported a cadmium tissue breakdown (rabeey2025, kamaly2023, and morshed2024 under controlled dosing): liver and kidney exceed muscle, by roughly 2.4 times at the mean in the one balanced occurrence survey (rabeey2025) and by a larger factor only under morshed2024's high-dose experimental feeding. The lead signal is real but variable and does not follow a single tissue hierarchy, and one A-tier dataset (kamaly2023) inverts it. The synthesis therefore rests firmly on cadmium as an organ-accumulation phenomenon and treats lead as a secondary, more environmentally contingent pathway. Total mercury behaves differently again: in the one dataset that measured it across tissues (rabeey2025), mercury was highest in muscle, not organs, which is a direct counterexample to any assumption that offal is uniformly the higher-metal cut for every analyte.

This finding is distinct from the muscle-focused occurrence work that dominates meat surveillance. National monitoring programmes and most published meat surveys report muscle values because muscle is the dominant edible fraction by mass. Offal is a separate matrix with its own concentration distribution, and a muscle value cannot stand in for a liver or kidney value. The gap matters because organ meats are consumed deliberately (liver, kidney, gizzard, heart) and enter processed products (pâté, liverwurst, meat purees, pet and infant meat blends) where muscle-derived safety assumptions do not transfer.

2 | The imported bovine signal (Rabeey et al. 2025)

Rabeey, Sabala, Zakaria, and Sallam 2025, published in Scientific Reports, analyzed 315 imported frozen bovine samples (105 muscle, 105 liver, 105 kidney) collected from markets in Sohag, Egypt, with source countries described as Brazil, India, and the United States, by atomic absorption spectrophotometry. This is the cleanest within-carcass tissue comparison in the anchor set because it holds species, market, and method constant across a balanced tissue design.

For cadmium the tissue hierarchy is unambiguous. The muscle mean was 0.030 mg/kg wet weight (range 0.007 to 0.100), the liver mean 0.056 mg/kg wet weight (range 0.010 to 0.390), and the kidney mean 0.073 mg/kg wet weight (range 0.011 to 0.211). Kidney cadmium was roughly 2.4 times muscle cadmium and liver cadmium roughly 1.9 times muscle cadmium at the mean. Notably, none of the liver or kidney samples exceeded the author-cited maximum permissible limits (0.50 mg/kg for liver, 1.0 mg/kg for kidney), whereas 24 of 105 muscle samples (22.9 percent) exceeded the tighter muscle limit of 0.05 mg/kg. The organs carried more cadmium in absolute terms but sat within their higher category-specific limits, which is itself a regulatory feature worth stating precisely: the limits are looser for offal because the baseline is understood to be higher.

Lead in this dataset was elevated across all three tissues but did not stratify strongly by tissue: muscle mean 0.684 mg/kg wet weight, liver mean 0.763 mg/kg, kidney mean 0.716 mg/kg. Liver and kidney sat marginally above muscle, but the near-uniformity means this dataset does not support a strong lead-as-organ-sink claim on its own. Total mercury ran in the opposite direction, with muscle highest (mean 0.312 mg/kg wet weight) and kidney lowest (mean 0.167 mg/kg wet weight), and the authors report total mercury without methylmercury speciation. The authors calculated target hazard quotients below 1.0 and a total target hazard quotient of 0.752 for muscle and 0.257 for liver under average Egyptian adult consumption, so regulatory-limit exceedance for lead and mercury coexisted with modeled risk indices below concern thresholds.

3 | The Egyptian broiler signal (Kamaly and Sharkawy 2023)

Kamaly and Sharkawy 2023, published in Environmental Science and Pollution Research, measured twelve metals by ICP-MS in 360 samples of broiler chest muscle, thigh muscle, and liver from six commercial brands in Assiut, Egypt. For cadmium it reproduces the organ-accumulation pattern found in the bovine data from a different laboratory, a different species, and a different Egyptian province: liver cadmium ranged 0.027 to 0.104 µg/g wet weight across brands, above chest-muscle cadmium at 0.014 to 0.054 µg/g wet weight (1 µg/g equals 1 mg/kg). Seventeen percent of samples exceeded the FAO/WHO cadmium limits, and liver was consistently at the higher end of the tissue range.

This study also supplies the synthesis's most important internal contradiction, and it is reported here rather than smoothed over. For lead, the pattern inverts: chest muscle carried 2.560 to 5.552 µg/g wet weight, thigh muscle 0.334 to 1.082 µg/g, and liver only 0.146 to 0.952 µg/g. Lead exceeded FAO/WHO limits in 94 percent of all samples, with chest-muscle lead several times higher than liver lead. A chest-muscle lead concentration above liver is not consistent with physiological soft-tissue accumulation, in which the liver would be expected to carry more; the most parsimonious reading is exogenous or feed-associated contamination loading onto muscle in this particular supply chain, an interpretation the authors support by noting aluminum concentrations (chest muscle 8.610 to 21.985 µg/g wet weight) far above European norms and pointing to regional feed and environmental sources. The lesson for the synthesis is that lead in edible meat can be dominated by an environmental-contamination term that overwhelms the physiological-distribution term, which is exactly why lead does not produce a stable organ-versus-muscle hierarchy across datasets while cadmium does.

4 | The multi-organ poultry signal (Hossain et al. 2023)

Hossain, Nesha, Chowdhury, and Rahman 2023, published in PLOS ONE, measured lead, cadmium, and chromium (plus iron, copper, and zinc) in six edible body parts (breast muscle, liver, gizzard, heart, kidney, brain) of 18 broiler chickens from six Dhaka markets, 108 samples in total, by flame atomic absorption spectrometry. Lead ranged from 0.33 mg/kg fresh weight, at its lowest in muscle, to 4.6 mg/kg fresh weight in brain, roughly six times the FAO/WHO maximum allowable concentration, with kidney also elevated. Cadmium ranged 0.004 to 0.125 mg/kg fresh weight and was mostly at or below regulatory limits.

Hossain is the anchor that carries the lead component of the thesis, because it shows lead concentrating in the metabolically active non-muscle organs (brain and kidney) rather than in muscle. The contrast with kamaly2023, where muscle lead was highest, is the clearest single illustration that lead distribution is supply-chain dependent: in the Bangladeshi birds the elevated lead tracked the organs, while in the Egyptian birds it tracked muscle. The authors attribute the Bangladeshi contamination to tannery-waste-derived poultry feed and flag a lead recovery of 115 percent, slightly above the conventional acceptable ceiling, which introduces a modest risk of upward bias in the absolute lead values. Target hazard quotients for lead remained between 0.037 and 0.073 for adults and children, below 1.0, even though brain lead exceeded the regulatory maximum, which again separates limit-exceedance framing from hazard-quotient framing.

5 | Mechanistic confirmation under controlled dosing (Morshed et al. 2024)

Morshed et al. 2024 is a Research Square preprint (evidence tier B) reporting a 28-day experiment in which broiler chickens were fed feed deliberately adulterated with graded lead, cadmium, and chromium, then had metals measured in muscle, bone, liver, kidney, and lung. Because the dose is known and controlled, this study isolates the physiological-distribution term that the occurrence surveys can only infer. At the highest cadmium dose group, cadmium deposition (mg/kg dry basis) rose from muscle 6.57 to liver 43.36, with kidney at 8.72 and bone at 20.72; at an intermediate dose the liver value (6.49) was again above muscle (1.26). Liver cadmium exceeded muscle cadmium by roughly a factor of seven at the top dose. The study therefore confirms, under experimental control, the differential that rabeey2025 and kamaly2023 observe in commercial product.

Three caveats keep this source in a supporting rather than load-bearing role. It is a preprint with only three birds per dose group; the feed adulteration was deliberate and high-dose, so the absolute concentrations are not ambient retail baselines; and the rendering of the results table in the available PDF is internally inconsistent, with the visible values placing liver above bone at the highest cadmium dose while the abstract states bone was highest. The direction of the liver-over-muscle cadmium effect is robust to these problems, but the precise numbers are not used here as occurrence values.

6 | Liver as the routinely monitored matrix (Marcelino 2026, Khatemeh 2022)

Two further A-tier studies establish liver as the tissue that veterinary and food-chain monitoring actually samples, which is itself evidence that liver is where these metals are expected to be found. Marcelino et al. 2026, in Frontiers in Veterinary Science, reports a twenty-year (2003 to 2023) post-mortem programme measuring thirteen elements by ICP-MS in the livers of 346 free-living Heck cattle, red deer, and Konik horses at the Oostvaardersplassen reserve, Netherlands. The lead reference interval reached an upper bound of 4.6 mg/kg dry weight in Heck cattle liver, while cadmium sat mostly below the limit of quantification (0.1 mg/kg dry weight) in this relatively clean environment. This last point is important for honesty about the thesis: liver is the accumulation sink, but the absolute cadmium load depends on environmental exposure, and in a clean setting liver cadmium can be below quantification even though the physiological preference for liver over muscle is unchanged. The study also documents statistically significant declining lead trends across all three species (p less than 0.01), consistent with reduced environmental lead inputs over two decades.

Khatemeh and Imani Baran 2022, in Veterinary Research Forum, measured lead, cadmium, and chromium by flame atomic absorption in sheep liver from an abattoir in Tabriz, Iran. Uninfected sheep liver carried lead at 0.12, cadmium at 0.07, and chromium at 0.40 µg/g wet weight (n=10). These values are below typical EU maximum levels for liver and give an independent Middle Eastern ruminant-liver baseline. Neither of these two studies measured muscle from the same animals, so they do not themselves demonstrate the organ-over-muscle differential; they contribute organ-specific occurrence baselines and corroborate that liver is the standard sampled matrix for these metals.

7 | The mechanistic explanation

The consistency of the cadmium finding follows from cadmium physiology. Absorbed cadmium is transported to the liver, where it induces and binds metallothionein, a low-molecular-weight metal-binding protein; cadmium--metallothionein complexes are then released and filtered by the kidney, where they are reabsorbed in the proximal tubule and retained. The kidney and liver are therefore the two organs where cadmium is concentrated and stored over the animal's lifetime, with a biological half-life measured in years, while skeletal muscle has no comparable storage mechanism and holds cadmium only at low steady-state levels. This is why rabeey2025 finds kidney above liver above muscle for cadmium, why kamaly2023 finds liver above muscle, and why morshed2024 reproduces liver above muscle under controlled dosing. The differential is a property of how the mammalian and avian body handles cadmium, not a property of any one supply chain, which is what makes it generalizable across species and geography in a way that a contamination-driven signal would not be.

Lead partitions differently. Lead in the body is dominated by bone, which acts as the long-term reservoir, with soft-tissue lead (liver, kidney, brain) reflecting more recent exposure. Because soft-tissue lead tracks recent intake rather than lifetime accumulation in a single dedicated organ, the tissue that shows the highest lead depends on the exposure route: feed-borne or environmental lead can load onto whichever tissue is most exposed in a given supply chain. This explains why the anchor datasets disagree about lead tissue rank (organs highest in hossain2023, muscle highest in kamaly2023, near-uniform in rabeey2025) even though they agree about cadmium. The morshed2024 experimental data, in which bone carried a large share of the cadmium and lead load, is consistent with bone as a reservoir compartment that edible-tissue surveys do not sample.

Total mercury, measured across tissues only in rabeey2025, was highest in muscle. Methylmercury binds to sulfhydryl groups in muscle protein, so muscle can hold as much or more mercury than liver, which is the mechanistic reason the mercury result runs opposite to the cadmium result and a reminder that "organ meat is higher in heavy metals" is analyte-specific rather than universal.

8 | Why conventional meat surveillance misses this

Meat monitoring is built around muscle. Muscle is the dominant edible fraction by mass, the cut that most consumers eat most often, and the matrix that national residue-monitoring programmes and the majority of published meat surveys report. Offal enters these datasets inconsistently: liver is sampled in veterinary and environmental monitoring (as marcelino2026 and khatemeh2022 illustrate) but is under-represented in retail food-safety surveys relative to how often it is eaten, and kidney, gizzard, heart, and brain are rarer still. The consequence is that the tissue with the higher cadmium concentration, and with lead behavior that can diverge sharply from muscle, is the tissue least likely to appear in a routine surveillance stream.

The regulatory architecture partly acknowledges this: maximum levels for cadmium and lead in liver and kidney are set separately from, and looser than, the muscle limits, precisely because the baseline in offal is understood to be higher. But looser category-specific limits are not the same as characterization. A product formulator who reads a muscle occurrence value and applies it to an offal-containing product (liverwurst, pâté, mixed-organ meat purees, blended pet or infant meat products) inherits the muscle distribution rather than the offal distribution and understates cadmium exposure by roughly two to two-and-a-half times at the mean, based on the rabeey2025 occurrence differential; morshed2024's larger high-dose differential confirms the direction of this effect under experimental control but is not a real-product magnitude.

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

For testing, offal must be treated as a distinct matrix with its own occurrence distribution rather than as an extension of muscle. A cadmium result on muscle does not bound the cadmium result on liver or kidney from the same animal, and any product whose formula includes organ meat should be characterized against liver and kidney occurrence data directly. Because cadmium is the analyte with the stable organ-accumulation signal, it is the priority analyte for offal-containing products; lead should be tested as well but interpreted with the understanding that its tissue distribution is supply-chain dependent and cannot be predicted from physiology alone.

For regulation, the separate and looser maximum levels for cadmium and lead in liver and kidney are consistent with the physiology documented here, and this synthesis supports keeping offal in its own regulatory category rather than harmonizing it to muscle limits. The caution runs the other way as well: the fact that offal sits within its higher category-specific limits (as in rabeey2025, where no liver or kidney sample exceeded its cadmium limit while 22.9 percent of muscle samples exceeded the tighter muscle limit) means limit-compliance data on offal can look reassuring while absolute cadmium intake per gram is higher than for muscle. Exposure assessment, not limit-compliance counting, is the appropriate frame.

For consumers, the quantitative statement is specific. Using the rabeey2025 imported-bovine means, a 100 g serving of beef kidney carries roughly 7.3 µg of cadmium and a 100 g serving of beef liver roughly 5.6 µg, against roughly 3.0 µg for a 100 g serving of muscle, so a person who eats organ meat regularly (for example weekly liver or kidney) takes in on the order of two to two-and-a-half times the cadmium per gram of a muscle eater. Because cadmium has a biological half-life of years and accumulates in the human kidney over a lifetime, the relevant population is frequent, long-term offal consumers rather than the occasional eater, and the relevant metric is cumulative weekly intake rather than any single meal. This is not a statement that organ meat is unsafe; the anchor studies' own hazard-quotient calculations remained below 1.0 at their modeled consumption rates. It is a statement that organ meat is a quantitatively distinct cadmium pathway, that the difference from muscle is real and physiologically grounded, and that consumers managing cadmium intake (including smokers, whose baseline cadmium burden is already elevated, and individuals with reduced kidney function) have reason to account for offal frequency specifically.

The combined-exposure synthesis is directly relevant here: offal cadmium adds to other dietary cadmium sources, and a per-food limit-compliance frame does not capture the aggregate. As with the organic-certification null finding, production method does not address this pathway, because cadmium enters the animal through feed and environment and concentrates in liver and kidney through physiology regardless of husbandry label.

10 | What this synthesis does not yet rest on

The occurrence evidence is geographically skewed toward supply chains with elevated environmental contamination. Four of the six anchors are from Egypt, Bangladesh, and Iran, regions where the feed and environmental metal burden is higher than in tightly regulated markets; the one clean-environment A-tier study (marcelino2026, Netherlands) found liver cadmium mostly below quantification. The organ-over-muscle differential is expected to persist in cleaner supply chains because it is physiological, but the absolute loads reported here should not be read as European or North American retail baselines. A balanced within-carcass tissue survey from a low-contamination market would strengthen the absolute-magnitude component of this finding and is a candidate for a Journal of Food Metallomics contribution.

Kidney is under-sampled relative to liver across the corpus. Only rabeey2025 provides a balanced muscle-liver-kidney design; the physiology predicts kidney should be the highest-cadmium edible tissue, and rabeey2025 confirms it, but a single dataset carries the kidney claim. Additional balanced designs that include kidney would move the kidney-specific finding from single-source to multi-source support.

Species coverage is uneven. The direct within-carcass comparisons are cattle (rabeey2025) and chicken (hossain2023, kamaly2023, morshed2024); sheep (khatemeh2022) and game (marcelino2026) are liver-only. Pork, a major offal source globally, is absent from the anchor set. The physiological mechanism is not species-specific, but a porcine within-carcass comparison would close an obvious gap.

11 | Provisional status

This synthesis was established 2026-07-27 on six anchor sources, of which three independent A-tier datasets (rabeey2025, hossain2023, kamaly2023) provide direct within-study organ-versus-muscle comparisons that support the thesis, one B-tier experimental study (morshed2024) confirms the cadmium mechanism under controlled dosing, and two A-tier studies (marcelino2026, khatemeh2022) supply organ-specific baselines. The cadmium organ-accumulation finding is robust across species, geography, and method and is grounded in well-established cadmium-metallothionein physiology; the lead component is weaker and explicitly contingent, with one A-tier dataset inverting the expected hierarchy; the mercury observation is a single-dataset counterexample warning against generalizing the pattern across analytes. Resynthesis triggers fire on the next two independent A-tier sources confirming or contradicting the organ-versus-muscle cadmium differential, on any balanced within-carcass survey from a low-contamination market, or on the addition of porcine or kidney-inclusive tissue comparisons.

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STATUS AND LICENCE

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.

DATA AVAILABILITY

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

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