Cadmium in food webs: field concentrations and legal/health-based limits

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Abstract. Cadmium (Cd) is a pervasive environmental contaminant entering ecosystems via natural and anthropogenic sources, accumulating in soils and plants, and transferring through food webs to humans primarily via diet. This review synthesizes recent field data on Cd concentrations and trophic transfer in aquatic and terrestrial ecosystems, examining their alignment with legal maximum limits (MLs) and health-based guidance values. Evidence from freshwater and coastal lagoons shows clear Cd biomagnification in specific epiphyte-based and benthic food chains, whereas marine pelagic fish often exhibit low muscle Cd concentrations, limiting biomagnification. In terrestrial systems, Cd bioaccumulates strongly in soil invertebrates and small mammals, with mixed outcomes for livestock tissues depending on grazing conditions. Human exposure via diet approaches or exceeds tolerable intake values linked to adverse renal and systemic effects at low body burdens, prompting calls for stricter regulatory standards. Monitoring programs reveal compliance challenges especially in cephalopods, indicating key risk points in commercial seafood chains. Findings highlight the complexity of Cd trophic dynamics, tissue-specific accumulation, and the importance of integrating ecological, regulatory, and toxicological perspectives for managing Cd risks in food webs and human health.
Keywords: Cadmium, food webs, bioaccumulation, biomagnification, trophic transfer.

Introduction. Cadmium (Cd) is a highly toxic heavy metal that enters ecosystems through both natural and anthropogenic sources (Petrescu-Mag et al., 2010). It accumulates in soil and plants and is transferred to higher trophic levels, ultimately reaching humans through food consumption (Sari et al., 2026; Petrescu-Mag & Petrescu-Mag, 2010). Recent studies highlight both bioaccumulation and biomagnification of Cd in aquatic and terrestrial food webs, with significant variability depending on ecosystem structure and species involved (Elfidasari et al., 2022; Petrescu-Mag & Oroian 2015). The accumulation of Cd in organisms consumed by humans poses health risks, including kidney dysfunction and other chronic diseases even at low exposure levels (Haeruddin et al., 2021). New evidence challenges current tolerated limits and calls for a reevaluation of international standards regulating Cd in food and feed (Schaefer et al., 2023).

This paper synthesizes field data on Cd concentrations in aquatic and terrestrial food webs, correlates them with legal and health-based limits, and highlights critical points for controlling human exposure.

Aim of the Study. The aim of this mini-review is to provide an updated synthesis of cadmium occurrence, trophic transfer, bioaccumulation, and biomagnification patterns in terrestrial and aquatic food webs, while relating field concentrations to current regulatory and health-based thresholds. Specifically, the review aims to: (i) summarize pathways of Cd entry into food webs; (ii) evaluate evidence of trophic transfer and biomagnification across ecosystems; (iii) compare environmental and biological concentrations with legal limits for food and feed safety; (iv) discuss implications for human exposure and environmental risk assessment.

Conceptual Background: Cd in Food Webs and Human Exposure. Cd enters ecosystems from natural and anthropogenic sources and accumulates in soil–plant systems, driving transfer to higher trophic levels and ultimately humans via food consumption (Suhani et al., 2021; Haider et al., 2021; Chețan et al., 2025). In aquatic food webs, early work suggested little biomagnification, but later field studies show clear biomagnification in specific epiphyte-based freshwater chains and in some coastal lagoons (Saidon et al., 2023; Croteau et al., 2005; Jara-Marini et al., 2019). In marine plankton–fish systems, Cd tends to peak in intermediate plankton size classes, with low concentrations in small pelagic fish muscle (Chouvelon et al., 2019). In terrestrial systems, Cd in soil invertebrates (e.g. *Enchytraeus crypticus*, earthworms) and plants drives accumulation in small mammals and livestock tissues (Zhang et al., 2022; Veltman et al., 2007; Rigby & Smith, 2020).

Human exposure is dominated by dietary intake; Cd accumulates in kidneys and is linked to kidney dysfunction and other chronic diseases at relatively low body burdens (Satarug et al., 2023; Satarug et al., 2017). Current international health-based guidance (FAO/WHO JECFA) sets a tolerable monthly intake of 25 μg/kg body weight (≈58 μg/day for 70 kg) and a urinary threshold of 5.24 μg Cd/g creatinine, though recent evaluations argue these limits are not sufficiently protective given observed health effects at lower burdens (Satarug et al., 2017; Satarug et al., 2023).

Regulatory and Health-Based Thresholds for Cadmium. International food legislation aims to keep Cd in food "as low as reasonably achievable", using maximum limits (MLs) for specific commodities. The Codex Alimentarius, developed by FAO/WHO, establishes general principles and MLs for contaminants; work on Cd MLs by food category has paralleled and is broadly harmonized with EU regulation (Berg & Licht, 2002). The EU Regulation 466/2001 (now updated by later acts) set detailed MLs for Cd and Pb in foods, similar in structure to Codex draft standards (Berg & Licht, 2002). More recent EU regulations (e.g. Commission Regulation (EU) 2023/915) provide specific Cd MLs for different marine fish species; these MLs were used as legal benchmarks in the Italian 10-year seafood monitoring program (Garofalo et al., 2025).

For animal feed, EU Directive 2002/32/EC sets a maximum permitted Cd concentration of 1.0 mg Cd/kg complete feed (12% moisture) for cattle, sheep and goats (Rigby & Smith, 2020). In toxicological guidance for livestock, the US National Research Council sets a maximum tolerable Cd concentration of 10 mg/kg dry matter in diets of cattle, sheep, swine and poultry (Rigby & Smith, 2020). For human offal and meat, EU maximum permissible Cd concentrations are 0.05 mg/kg fresh weight (FW) for carcass meat, with specific higher limits for kidney and liver; sheep grazing biosolids-amended soils in UK studies had muscle Cd below the 0.05 mg/kg FW limit and offal Cd below relevant MLs, even when ingesting soil with Cd up to three times the soil limit value (3 mg/kg dry soil) (Rigby & Smith, 2020).

From the health-risk side, older tolerable intake and urinary thresholds (0.83 μg/kg bw/day and 5.24 μg/g creatinine) are increasingly questioned. Population data show that typical adult dietary intakes estimated by total diet studies (8–25 μg/day) are below JECFA's 58 μg/day guidance but correspond to urinary Cd levels (>30 μg/day intake equivalents) associated with kidney damage, osteoporosis, diabetes and other pathologies (Satarug et al., 2017; Satarug et al., 2023). This has led to proposals for more restrictive dietary Cd guidelines and reconsideration of the very concept of a "permissible" chronic Cd intake for cumulative toxins (Satarug et al., 2023; Satarug et al., 2017).

Field Concentrations and Trophic Transfer in Aquatic Food Webs. In the San Francisco Bay Delta, Cd and Cu were measured along freshwater food webs using stable isotopes to define trophic position (Croteau et al., 2005). Cd concentrations increased progressively with trophic level within epiphyte-based webs (macrophyte-dwelling invertebrates initiated by epiphytic algae; fishes initiated by gobies), with Cd biomagnified about 15-fold over two trophic links in both invertebrate- and fish-based chains (Croteau et al., 2005). Trophic enrichment in invertebrates was roughly twice that in fishes (Croteau et al., 2005). In that system, prey items contained on average 0.91 μg Cd/g dry weight, whereas largemouth bass muscle averaged 0.28 μg/g dry weight (Croteau et al., 2005); though these are dry-weight values, they illustrate substantial enrichment relative to basal resources and prey, implying that top consumers may approach or exceed food safety thresholds when converted to wet weight.

In a semiarid coastal lagoon in the central-eastern Gulf of California, Cd, Cu, Pb and Zn were measured across four seasons using stable isotopes (Jara-Marini et al., 2019). Metal concentrations increased from the food-web base to top predators, with a general order Zn > Cu > Pb > Cd (Jara-Marini et al., 2019). For Cd, correlations between trophic level and log-transformed concentrations were strongly positive ($r = 0.61–0.91$, $p < 0.05$), and trophic biomagnification factors (TMF) for the whole food web ranged from 1.26 to 1.41, consistent with biomagnification (Jara-Marini et al., 2019). Predator–prey biomagnification factors for Cd ranged 0.32–3.88, indicating that specific predator–prey links can either bioreduce or biomagnify Cd, but overall the web showed net magnification (Jara-Marini et al., 2019). These field results support the view that Cd can biomagnify in certain aquatic structures, contradicting earlier assumptions of systematic biodilution (Saidon et al., 2023; Croteau et al., 2005; Jara-Marini et al., 2019).

In the southeastern Gulf of California, an integrated trophic study found efficient bioaccumulation of Cd and Zn from seawater in mid and high trophic guilds (bioaccumulation factors >1000), and Cd enrichment from sediment across all trophic guilds (biota–sediment accumulation factor >1), including non-trophic uptake (Valladolid-Garnica et al., 2023). However, trophic magnification factors showed biodilution for Mn and Pb (TMF 0.38 and 0.16), but biomagnification only for Cu and Zn (TMF 2.08 and 3.31), not for Cd (Valladolid-Garnica et al., 2023). This indicates that, depending on web structure and dominant exposure pathways (water/sediment vs diet), Cd may show strong bioaccumulation without clear trophic-level magnification (Valladolid-Garnica et al., 2023; Saidon et al., 2023).

In the Gulf of Lions (NW Mediterranean), Cd and other trace metals were quantified along a seawater–plankton–small pelagic fish continuum covering size-fractionated plankton and sardine/anchovy (Chouvelon et al., 2019). Cd concentrations were highest in intermediate plankton size classes, while fish (sardine, anchovy) had very low Cd in whole body and tissues, in contrast to Hg, which showed marked biomagnification into fish (Chouvelon et al., 2019). This pattern suggests that in some marine pelagic systems, Cd is largely retained in lower and intermediate trophic levels and does not strongly biomagnify to commercial small pelagic fish muscle (Chouvelon et al., 2019).

Arctic marine food-web work in east Hudson Bay compared Cd and Hg in blue mussels, sea urchins, common eider, sculpin, Arctic cod and ringed seal (Rohonczy et al., 2024). Cd trophic transfer was tissue-specific: in muscle, Cd showed biodilution (declining with trophic level), whereas in liver, Cd concentrations were higher in ringed seal and some common eider than in their prey (Rohonczy et al., 2024). Hg, in contrast, biomagnified consistently in both tissues (Rohonczy et al., 2024). Many fish and seal muscle samples had Cd below analytical detection limits, limiting quantification (Rohonczy et al., 2024). This highlights that regulatory comparisons must consider tissue (muscle vs liver vs kidney) and that liver of marine mammals and seabirds can store Cd at levels far higher than their prey, even when muscle appears "safe" (Rohonczy et al., 2024).

European surveillance of seafood provides an important link between field levels and legal MLs. In a 10-year monitoring program (2014–2023) in Latium and Tuscany (Italy), 5854 seafood samples were analyzed; EU MLs for Cd, Pb and total Hg were used as compliance criteria (Garofalo et al., 2025). Overall, 142 samples (2.43%) were non-compliant with at least one metal (Garofalo et al., 2025). Exceedances for Cd were concentrated in cephalopods, mainly squids (17 non-compliant samples), while Hg exceedances mainly involved large marine fish (swordfish, sharks, tuna) (Garofalo et al., 2025). Only one bivalve sample exceeded Pb ML (Garofalo et al., 2025). Although detailed Cd concentrations and exact ML values by species are provided in supplementary material rather than the abstract, the key point is that cephalopods in real commercial chains can exceed stringent EU Cd MLs, illustrating that mid-trophic marine invertebrates are a critical control point for Cd in human diets (Garofalo et al., 2025).

Field Concentrations and Trophic Transfer in Terrestrial Food Webs. In terrestrial soils from a Chinese mining area, Cd concentrations in field-contaminated soils ranged 3.49–24.3 mg Cd/kg dry soil, alongside high Pb, Cu and Zn (Zhang et al., 2022). The soil invertebrate *Enchytraeus crypticus* exposed to these soils showed slow, nearly linear Cd accumulation over 21 days, without reaching steady state; kinetics-based bioaccumulation factors (BAF) were high, 1.78–24.3 kg soil/kg worm, while Pb BAFs were <0.1 (Zhang et al., 2022). These high BAFs imply that worms in such soils can reach Cd body burdens an order of magnitude higher than soil concentrations, providing highly contaminated prey for higher trophic levels, and suggesting significant potential for biomagnification in terrestrial food chains of mining-impacted ecosystems (Zhang et al., 2022).

A broader meta-analysis and model validation for small mammals aggregated field data for herbivorous voles and carnivorous shrews (Veltman et al., 2007). Whole-body Cd concentrations in small mammals were strongly related to Cd in food items (earthworms, plants) and to total soil Cd (Veltman et al., 2007). Shrews consistently accumulated about an order of magnitude higher Cd than voles because earthworms (their primary prey) accumulate much more Cd than plants (Veltman et al., 2007). Liver and kidney Cd levels in small mammals were significantly related to soil Cd, indicating efficient trophic transfer from soil to plants/invertebrates to small mammals (Veltman et al., 2007). The modelling suggested low Cd elimination rates, consistent with binding to metallothionein, and thus strong potential for long-term accumulation and bioaccumulation through terrestrial food webs (Veltman et al., 2007).

Livestock grazing biosolids-amended pasture provide another quantitative example linking soil Cd to edible tissues relative to legal limits. UK government studies in the 1990s, re-evaluated in light of current standards, showed that sheep grazing soils with Cd concentrations up to about three times the soil limit value (3 mg/kg dry soil) and ingesting soil at 10% of dietary dry matter nevertheless had muscle Cd below the detection limit of 0.04 mg/kg FW, and thus below the EU maximum of 0.05 mg/kg for carcass meat (Rigby & Smith, 2020). Liver and kidney Cd remained below the EU MLs for offal in all grazing trials under practical conditions on high Cd soils (Rigby & Smith, 2020). These findings indicate that, at least under UK conditions and with current lower Cd emissions in biosolids, Cd in meat products from grazing livestock can remain within regulatory limits even on soils near or above guideline values, although offal remains more exposed than muscle (Rigby & Smith, 2020).

At the plant–pollinator interface, experimental work with sunflowers grown on soils with different Cd levels ("Below Threshold" vs "Exceeding Threshold" contamination) showed that high Cd reduced plant height and negatively affected interactions with bumble bees, which visited high-Cd plants less often and for shorter durations (Sivakoff et al., 2024). Seed set was positively correlated with total pollinator visits, and plants in Exceeding Threshold soils tended to have marginally lower seed set (Sivakoff et al., 2024). While this study did not provide plant tissue Cd concentrations or direct comparisons to food MLs, it illustrates that Cd contamination of soil can alter food-web interactions (here, mutualistic pollination) with implications for plant fitness and potentially for the quality and quantity of edible seeds (Sivakoff et al., 2024; Haider et al., 2021; Zulfiqar et al., 2022).

At the base of agricultural food webs, multiple reviews highlight that Cd contamination of soils (via fertilizers, irrigation, atmospheric deposition and industrial inputs) leads to increased Cd uptake by crops, with high soil-to-plant transfer factors for many species (Haider et al., 2021; Chețan et al., 2025; Zulfiqar et al., 2022; Chen et al., 2025). Cd toxicity in plants impairs nutrient and water uptake, photosynthesis and yield (Haider et al., 2021; Zulfiqar et al., 2022). Reviews of global patterns show that much of the work has focused on edible crops and remediation (phytoremediation, biochar, microbial amendments) because Cd taken up into edible organs becomes a direct dietary exposure route for humans and livestock (Chețan et al., 2025; Zulfiqar et al., 2022; Chen et al., 2025) (Table 1, Figure 1). However, specific quantitative crop Cd concentrations relative to food MLs are detailed in primary crop-specific studies rather than these synthetic reviews.

Table 1

Cadmium levels in ecosystems versus regulatory limits

System / Matrix (field)	*Reported Cd concentration(s)*	*Relevant legal or health-based benchmark*	*Relationship / Comment*	*References*
Freshwater epiphyte-based food web (San Francisco Bay Delta): prey items vs largemouth bass muscle (dry weight)	Prey items ≈0.91 μg/g dw; largemouth bass muscle ≈0.28 μg/g dw; overall ~15-fold biomagnification over two trophic links	EU ML for Cd in fish muscle (wet weight; not numerically given in abstract but used in EU regs); JECFA tolerable intake 25 μg/kg bw/month	Cd clearly biomagnified across trophic levels; depending on moisture conversion, top predator muscle may approach or exceed stricter fish MLs in highly contaminated sites	Croteau et al., 2005; Saidon et al., 2023; Berg & Licht, 2002; Satarug et al., 2017
Semiarid coastal lagoon (central-eastern Gulf of California); whole-web Cd	Trophic biomagnification factor (TMF) for Cd = 1.26–1.41; predator–prey BMF up to 3.88	Same fish and shellfish MLs as above for Cd; dietary intake guidelines	Net biomagnification of Cd across food web; apex consumers likely to have Cd levels closer to or above MLs than basal organisms, especially in impacted lagoons	Jara-Marini et al., 2019; Valladolid-Garnica et al., 2023; Saidon et al., 2023
Gulf of Lions (NW Mediterranean) seawater–plankton–small pelagic fish	Cd highest in intermediate plankton size classes; "very low levels" in sardine and anchovy tissues	EU MLs for Cd in fish; many small pelagic species have relatively low MLs in EU lists	Pelagic small fish muscle appears to remain well below legal Cd limits even where plankton are enriched; Cd does not biomagnify strongly into these commercial fish	Chouvelon et al., 2019; Berg & Licht, 2002; Garofalo et al., 2025
Arctic east Hudson Bay marine food web; muscle vs liver	Many fish and ringed seal muscle Cd < detection limit; liver Cd higher in ringed seals and some eiders than in prey	EU MLs for Cd in fish muscle and in marine mammal meat (where applicable nationally); no harmonized global limits for marine mammal liver	Muscle largely compliant with likely MLs; liver acts as Cd sink and could exceed offal MLs if such were applied; demonstrates tissue-specific risk	Rohonczy et al., 2024; Berg & Licht, 2002; Garofalo et al., 2025
Italian seafood monitoring (2014–2023), various species	3338 Cd analyses; 2.43% of all seafood samples non-compliant for any metal; Cd exceedances mainly in cephalopods (n=17, mostly squids)	EU MLs for Cd in cephalopods and fish from Commission Regulation (EU) 2023/915 (numeric MLs given in supplement, not abstract)	Real-market cephalopods frequently reach or exceed Cd MLs, whereas most fish comply; cephalopods are a key high-Cd food-web compartment for human consumers	Garofalo et al., 2025; Berg & Licht, 2002
Mining-area soils, China (Shaoguan) and soil invertebrate *Enchytraeus*	Soil 3.49–24.3 mg Cd/kg dw; worm Cd BAF 1.78–24.3 kg/kg (no steady state in	Soil guideline value for Cd often ~3 mg/kg (e.g. UK soil limit	Soil Cd in mining area far exceeds common guideline values; worms	Zhang et al., 2022; Veltman et al., 2007;

System / Matrix (field)	*Reported Cd concentration(s)*	*Relevant legal or health-based benchmark*	*Relationship / Comment*	*References*
crypticus	21 d)	mentioned elsewhere); no direct ML for worms, but worms are prey for birds/small mammals	concentrate Cd far above soil, creating highly contaminated prey and high trophic transfer risk	Chețan et al., 2025
Small mammals (voles, shrews) in terrestrial webs (meta-analysis)	Whole-body Cd strongly correlated with Cd in food (plants, earthworms); shrews about 10× higher Cd than voles at similar soil levels	No specific Cd MLs for wild small-mammal meat; results relevant as proxies for higher predators (raptors, foxes, mustelids) and for ecological risk	Indicates efficient trophic transfer; carnivores feeding on invertebrates can reach Cd burdens an order of magnitude above herbivores at the same site	Veltman et al., 2007; Zhang et al., 2022
UK sheep grazing biosolids-amended soils (Cd up to 3× soil limit)	Soil Cd up to ~3× 3 mg/kg limit; diet Cd up to ~1.04 mg/kg (dw); muscle Cd <0.04 mg/kg FW (below detection, <0.05 mg/kg ML); liver and kidney Cd below their EU MLs	EU ML for carcass meat 0.05 mg/kg FW; MLs for offal vary by organ and species but higher than for muscle	Even at soils above guideline values and soil ingestion 10% of diet, meat and offal Cd remained below MLs, suggesting current biosolid controls protect meat safety under studied conditions	Rigby & Smith, 2020; Berg & Licht, 2002
General adult dietary exposure (from total-diet studies, multi-country)	Estimated dietary Cd intake 8–25 μg/day; urinary Cd suggests >30 μg/day in many populations	JECFA tolerable monthly intake 25 μg/kg bw/month (≈58 μg/day at 70 kg); urinary Cd threshold 5.24 μg/g creatinine	Average intakes below JECFA limit but above levels associated with renal and systemic pathologies; calls for more restrictive intake limits and further reduction of Cd in foods	Satarug et al., 2017; Satarug et al., 2023; Suhani et al., 2021.

Mechanistic Basis of Cadmium Toxicokinetics and Internal Distribution Across Trophic Levels. While field-based studies provide robust evidence of cadmium (Cd) bioaccumulation and trophic transfer across aquatic and terrestrial food webs, a mechanistic understanding of how Cd is absorbed, distributed, stored, and eliminated within organisms is essential for interpreting these patterns and refining risk assessment frameworks. The internal handling of Cd—collectively described as toxicokinetics—varies substantially among taxa, tissues, and environmental conditions, and ultimately governs both bioaccumulation efficiency and trophic transfer potential (Sari et al., 2026; Suhani et al., 2021).

Uptake pathways and bioavailability constraints. Cadmium enters organisms primarily via two pathways: dietary ingestion and direct uptake from the surrounding medium (water, sediment porewater, or soil solution) (Zhang et al., 2022). In aquatic organisms, gill uptake can be significant, particularly under conditions of low calcium concentration, where Cd competes with Ca^{2+} for transport via voltage-independent calcium channels (Haeruddin et al., 2021). In contrast, dietary uptake dominates in higher trophic levels, where assimilation efficiency depends on digestive physiology, prey composition, and metal speciation (Rohonczy et al., 2024; Saidon et al., 2023).

Bioavailability is strongly modulated by environmental chemistry (Sari et al., 2026). Factors such as pH, redox potential, dissolved organic matter, and competing ions (e.g., Zn^{2+}, Ca^{2+}, Fe^{2+}) influence Cd speciation and its affinity for biological membranes (Sivakoff et al., 2024). For instance, Cd bound to organic ligands or particulate matter may exhibit reduced immediate bioavailability but can become accessible through digestion, particularly in detritivorous and sediment-ingesting organisms (Elfidasari et al., 2022). This duality helps explain why systems with similar total Cd concentrations may exhibit markedly different bioaccumulation patterns (Valladolid-Garnica et al., 2023).

Intracellular binding and detoxification mechanisms. Once internalized, Cd does not participate in redox reactions but exerts toxicity through strong binding to sulfhydryl (-SH) groups in proteins, disrupting enzymatic function and cellular homeostasis (Schaefer et al., 2023). A central detoxification mechanism across taxa is the induction of metallothioneins (MTs), low-molecular-weight, cysteine-rich proteins with high affinity for Cd (Haider et al., 2021).

Metallothionein binding serves multiple roles: sequestration of Cd in non-reactive forms, reduction of free ionic Cd in cytosol, facilitation of storage in specific organs (e.g., liver, kidney, hepatopancreas) (Satarug et al., 2017).

However, MT synthesis is not unlimited. At high exposure levels, binding capacity can be exceeded, leading to increased concentrations of unbound Cd and subsequent cellular damage (Suhani et al., 2021). This saturation phenomenon is critical for understanding non-linear accumulation patterns and threshold effects observed in both field and experimental studies (Veltman et al., 2007).

Tissue-specific distribution and storage dynamics. The distribution of Cd within organisms is highly tissue-specific and reflects both exposure route and physiological function (Garofalo et al., 2025). In vertebrates, the liver acts as the primary site of initial Cd accumulation and detoxification, while the kidneys serve as the main long-term storage compartment due to reabsorption processes in proximal tubules (Satarug et al., 2023). This explains the frequently observed disparity between low Cd concentrations in muscle tissue and much higher levels in offal (Rigby & Smith, 2020).

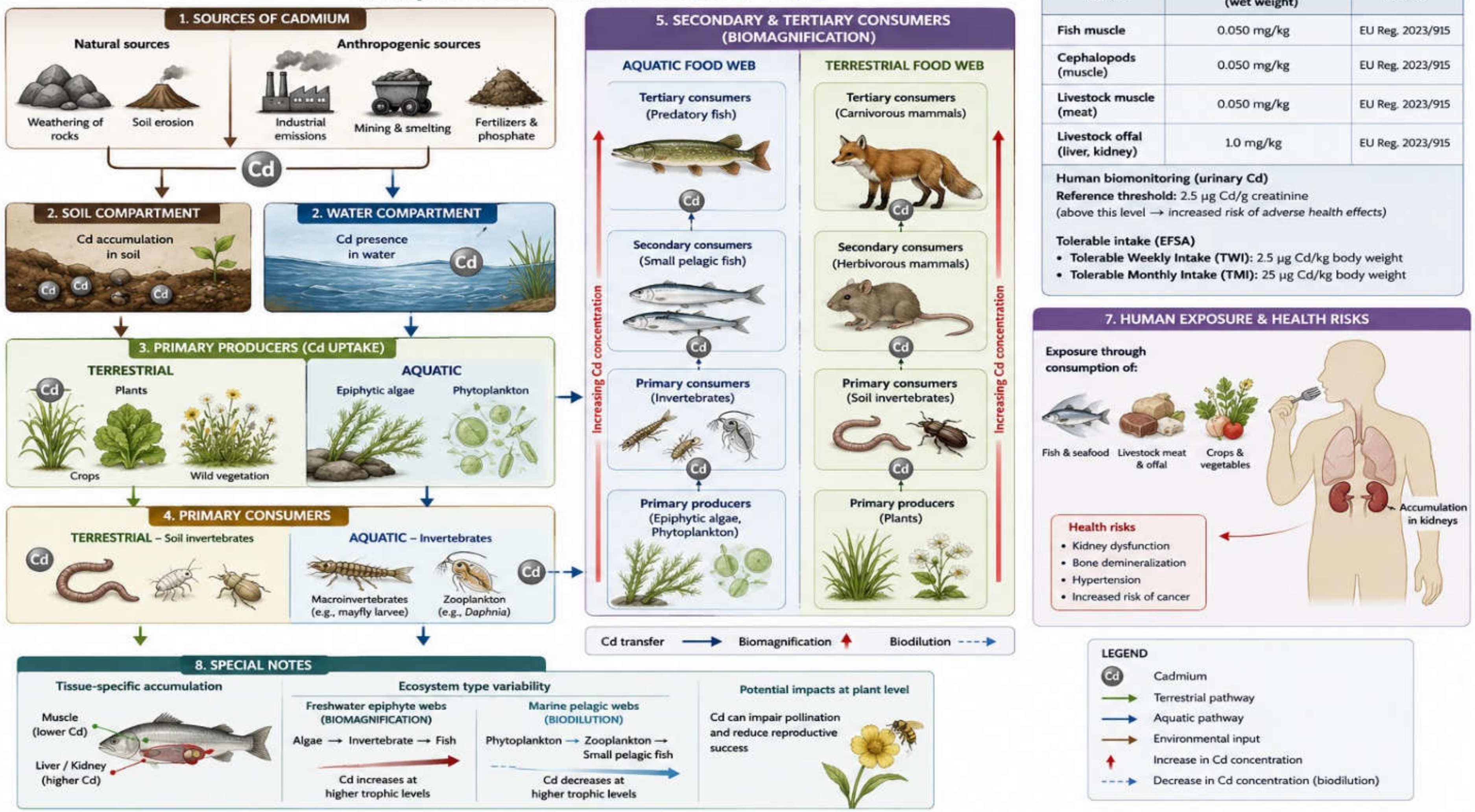
In invertebrates, analogous functions are performed by organs such as the hepatopancreas (in mollusks and crustaceans), which can accumulate Cd to concentrations orders of magnitude higher than surrounding tissues (Zhang et al., 2022). The presence of intracellular granules and lysosomal sequestration further contributes to long-term storage and reduced immediate toxicity, but also enhances trophic transfer when these tissues are consumed (Saidon et al., 2023).

These tissue-specific patterns have direct implications for food safety: organisms that appear compliant with regulatory limits based on muscle tissue analysis may still represent significant exposure risks when whole-body consumption or organ meats are considered (Garofalo et al., 2025; Berg & Licht, 2002).

Elimination kinetics and biological half-life. A defining characteristic of Cd is its extremely slow elimination rate (Veltman et al., 2007). Biological half-lives in vertebrates can span years to decades, reflecting strong intracellular binding and limited excretory pathways (Satarug et al., 2023). Elimination occurs primarily via renal excretion and, to a lesser extent, via bile and feces, but these processes are inefficient for Cd compared to other metals (Schaefer et al., 2023).

In lower organisms, elimination rates are generally faster but still insufficient to prevent accumulation under chronic exposure (Zhang et al., 2022). The imbalance between uptake and elimination results in progressive bioaccumulation over time, particularly in long-lived species and higher trophic levels (Rohonczy et al., 2024). This kinetic constraint underpins the cumulative nature of Cd toxicity and explains why even low environmental concentrations can lead to significant body burdens (Satarug et al., 2017; Veltman et al., 2007).

Figure 1. Schematic Illustration of Cadmium (Cd) Transfer in Aquatic and Terrestrial Food Webs



Implications for trophic transfer and risk assessment. Understanding toxicokinetic processes provides critical insight into several empirical observations reported in food-web studies. For example, apparent inconsistencies between bioaccumulation and biomagnification can often be attributed to differences in assimilation efficiency, storage capacity, and elimination rates among trophic levels (Saidon et al., 2023; Rohonczy et al., 2024). Species with high metallothionein induction capacity may accumulate large amounts of Cd without proportionally increasing transfer to predators, particularly if Cd is sequestered in forms with low bioavailability (Elfidasari et al., 2022; Haider et al., 2021).

Moreover, toxicokinetic variability introduces significant uncertainty into risk assessments based solely on environmental concentrations or trophic position (Valladolid-Garnica et al., 2023; Zhang et al., 2022). Incorporating physiological parameters—such as uptake rates, binding capacity, and tissue distribution—into models can improve predictions of Cd concentrations in edible tissues and better align regulatory thresholds with actual health risks (Veltman et al., 2007; Sari et al., 2026).

From a clinical standpoint, dietary intake of Cd presents a major public health challenge due to its pronounced toxicity in kidneys and bone tissue. Once ingested through food, the metal tends to concentrate in the S1 segment of the renal proximal tubules. Here, it drives cellular apoptosis by inducing oxidative stress and disrupting mitochondrial pathways. This tubular damage typically comes to light during clinical screening as low-molecular-weight proteinuria (Satarug et al., 2023). At the same time, chronic low-dose exposure targets bone health through two distinct pathways: Cd directly harms osteoblasts and interferes with vitamin D activation by inhibiting renal 1-alpha-hydroxylase. Over time, this combined impact accelerates bone demineralization, leaving patients vulnerable to low bone mineral density and osteoporosis (Rigby & Smith, 2020).

Finally, the persistence of Cd within organisms emphasizes the importance of considering lifetime exposure rather than short-term intake (Schaefer et al., 2023; Satarug et al., 2017). This is particularly relevant for human populations consuming Cd-rich foods regularly, where gradual accumulation in kidneys may occur even when individual food items comply with existing maximum limits (Satarug et al., 2023; Rigby & Smith, 2020; Berg & Licht, 2002).

Conclusions. This synthesis confirms that cadmium exhibits complex dynamics across different ecosystems and trophic levels with significant implications for food safety and public health.

Evidence of biomagnification and bioaccumulation: Field studies consistently demonstrate Cd biomagnification in freshwater epiphyte- based food webs and some coastal lagoons, while marine pelagic fish typically show biodilution or low muscle Cd, indicating ecosystem- and species-specific processes. Tissue-specific patterns are crucial: Cd concentrations vary by tissue type, with liver and kidneys often accumulating higher Cd than muscle, thus regulatory risk assessments must consider tissue selection carefully, especially for foods such as offal. Legal limits may not ensure health protection: Current international maximum limits and tolerable intake guidelines are challenged by epidemiological evidence linking lower Cd body burdens with adverse health outcomes, indicating the need for more stringent regulatory frameworks. Terrestrial food webs are significant exposure routes: Soil contamination leads to high Cd bioaccumulation in soil in vertebrates and small mammals, with implications for livestock and human exposure, although managed grazing practices can mitigate transfer to edible tissues. Critical control points identified: Cephalopods emerge as a key food web compartment with frequent Cd exceedances, highlighting the importance of target monitoring and regulatory focus. Integrate approaches required for risk management: Effective Cd risk control in food webs needs to integrate environmental monitoring, food safety regulations, and health risk assessments, while advancing remediation strategies in contaminated agricultural soils.

Overall, the management of cadmium contamination requires nuanced understanding of ecological transfer coupled with precautionary regulatory limits to safeguard food safety and public health.

Acknowledgement. An artificial intelligence tool (ChatGPT, OpenAI) was used to assist in the preparation of the schematic illustration presented in Figure 1. The AI tool was used exclusively for graphical concept generation and visual organization of information. All scientific content, interpretation of results, and manuscript preparation were reviewed and validated by the author.

Authors Contributions. RH wrote the manuscript; KTM read and revised the manuscript.

Conflicts of Interest. The authors declare that there is no conflict of interest.

Data Availability. Not applicable.

Funding. This research received no external funding.

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Received: 25 April 2026. Accepted: 05 June 2026. Published online: 17 June 2026.
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How to cite this article:
Haja, R., Meligoniti, K. T. (2027). Cadmium in food webs: field concentrations and legal/health-based limits. *AES Bioflux, 19*(1), 1-11.