# Wastewater and sewage-effluent irrigation is a single upstream pathway that co-elevates multiple metals in the same crop, concentrating in leafy greens on peri-urban plots across the Global South

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## Abstract

Five independent studies drawn from four regions of the Global South converge on a single finding: irrigation with municipal wastewater or sewage-receiving effluent is an upstream pathway that elevates several metals at once (lead, cadmium, chromium, and nickel) in the same edible crop, and the elevation concentrates most strongly in leafy vegetables grown on peri-urban plots; a controlled greenhouse study additionally isolates irrigation water as the transfer vector for arsenic where source groundwater is naturally arsenic-rich. A meta-analysis of 24 studies across 13 countries (Ali et al. 2022) quantifies the wastewater-to-soil-to-crop lead nexus; three independent field surveys in Nigeria (Adebayo et al. 2020), Malawi (Chiutula et al. 2025), and India (Pal et al. 2017) each document multi-metal co-elevation in wastewater-irrigated vegetables; and a controlled greenhouse dose-response experiment in Burkina Faso (Clair-Caliot et al. 2021) isolates the irrigation water itself as the transfer vector for arsenic.

## 1 | Overview

The non-obvious element of this synthesis is that the contamination driver is the irrigation water and the soil loading it produces over time, not the cultivar and not the ambient soil parent material. Because a single water source carries several metals simultaneously, the metals co-vary in the crop: a plot irrigated with untreated municipal wastewater does not have a lead problem or a cadmium problem in isolation, it has a wastewater problem that shows up as lead, cadmium, chromium, and nickel together. This co-variation is invisible when each metal-by-ingredient cell is read alone, which is the default posture of both occurrence databases and single-analyte regulatory limits. The pathway is mechanistically distinct from geogenic or mining-derived soil contamination, where the metal signature is fixed by local geology and does not travel with an applied water source. It is distinct from, and compounds, the co-exposure concern developed in the combined-exposure synthesis: that page addresses per-metal limits that are individually met but jointly underprotective; this page addresses a shared source that raises several metals in step, upstream of the point where any limit is applied.

## 2 | The multi-country lead nexus (Ali 2022)

Ali, Bayih, and Gari 2022, published in Frontiers in Public Health, is a PRISMA systematic review and random-effects meta-analysis of 24 studies across 13 countries (India, Pakistan, Iran, China, Egypt, Ethiopia, Kenya, Iraq, Morocco, Nigeria, North Korea, South Korea, and Botswana), synthesising lead across the full wastewater-to-soil-to-crop chain. The studies span 44 crops, of which 38 are leafy and non-leafy vegetables; the most frequently studied crops are spinach, cabbage, lettuce, wheat, corn, and broad beans. Lead in untreated irrigation wastewater ranged from a mean of 0.0196 plus or minus 0.01 mg/L to 52.4 plus or minus 0.02 mg/L, and 50 percent of the wastewater values exceeded the WHO/FAO irrigation-water standard of 0.5 mg/L for lead. In every crop produced with untreated wastewater, lead in the edible parts exceeded WHO limits for edibility, and the health risk index (calculated as daily intake of metal divided by reference dose, against an adult lead reference dose of 0.001 mg/kg/day) exceeded 1 for adult vegetable consumption in India, Iraq, Morocco, and Egypt. Between-study heterogeneity was very high (I-squared equals 98 percent), so the meta-analytic mean is a summary of a genuinely wide distribution rather than a tight central estimate; the load-bearing claim is the direction and consistency of the exceedance, not a single pooled concentration.

Ali 2022 is single-analyte (lead only), so on its own it establishes the pathway and its public-health consequence for one metal rather than the multi-metal co-elevation. Its value to this synthesis is the breadth: 13 countries and 44 crops give the pathway its geographic generality, and the leafy-vegetable concentration of the sampled crops matches the leafy-vegetable concentration of contamination reported by the multi-metal field studies below.

## 3 | The Nigeria spinach signal (Adebayo 2020)

Adebayo et al. 2020, published in the International Journal of Advanced Chemistry Research, measured six metals in irrigation wastewater and in wastewater-grown African spinach (Amaranthus caudatus) from the Railway Quarters irrigation farm in Bauchi, Nigeria. In the single composite spinach sample the reported concentrations, on the study's dried and processed analytical basis, were cadmium 1.00 mg/kg, chromium 1.65 mg/kg, copper 7.70 mg/kg, manganese 12.65 mg/kg, nickel 7.70 mg/kg, and lead 6.60 mg/kg. The measured spinach lead value of 6.60 mg/kg sits above the Indian Standard comparison limit of 2.50 mg/kg cited by the authors. Health risk indices were reported as 0.30 for cadmium, 0.0003 for chromium, 0.215 for copper, 0.124 for manganese, 0.125 for nickel, and 0.50 for lead, all below the authors' risk cutoff of 1.0 despite the concentration exceedances, a divergence that reflects the intake and body-weight assumptions used rather than a clean bill of safety.

This is the clearest single-crop demonstration of co-elevation in the corpus: one spinach crop, one irrigation source, six metals elevated together. The chromium value is total chromium; the study did not speciate, so it must not be read as chromium-VI. The single-sample design (sample_n equals 3 across wastewater and vegetable) means this is a point observation, not a distribution, and the concentrations are Nigerian wastewater-irrigated context that should not be pooled silently with United States market spinach where geography, irrigation source, and analytical basis all differ.

## 4 | The Malawi soil-vegetable signal (Chiutula 2025)

Chiutula et al. 2025, published in the International Journal of Environmental Research and Public Health, sampled six vegetable species (three exotic Brassica crops and three indigenous leafy species) grown on plots irrigated with effluent from the Soche Wastewater Treatment Plant in Blantyre, Malawi, with leaves and stems sampled separately in triplicate (n equals 36 vegetable samples). Against FAO/WHO limits of 0.2 mg/kg for cadmium, 2.3 mg/kg for chromium, and 0.3 mg/kg for lead (dry weight), 64 percent of vegetable samples exceeded the chromium limit (highest in Cucurbita moschata stems at 4.65 mg/kg and Brassica napus stems at 4.20 mg/kg), several exceeded the cadmium limit (highest in Amaranthus retroflexus leaves at 0.31 mg/kg), and every vegetable species exceeded the lead limit (highest in Brassica rapa stems at 4.09 plus or minus 0.085 mg/kg). Health risk indices reached 92.3 for Brassica rapa stems and 82.2 for Brassica rapa subsp. chinensis leaves, far above the threshold of 1. As with the other field studies, the chromium is total chromium and is not speciated to chromium-VI.

Chiutula 2025 carries a nuance that this synthesis reports rather than smooths over, because it sharpens rather than weakens the thesis. In the Malawi system, cadmium, chromium, and lead were all below detection in the wastewater at the time of sampling, and the soil concentrations of cadmium (0.24 mg/kg), chromium (38.14 mg/kg), and lead (11.57 mg/kg) were all below the corresponding WHO soil limits, yet the vegetables exceeded the food limits. A naive reading of the water alone, or the soil alone, at a single time point would have concluded the plots were acceptable. The crop measurement is what revealed the exposure. This is direct evidence that the pathway operates through long-term soil loading and plant bioconcentration rather than through instantaneous water concentration, and it is the empirical core of the surveillance-blind-spot argument developed below.

## 5 | The Burkina Faso mechanistic anchor (Clair-Caliot 2021)

Clair-Caliot et al. 2021, published in Frontiers in Water, is a controlled greenhouse experiment at 2iE in Ouagadougou, Burkina Faso, in which seven commonly grown vegetables were irrigated at four arsenic concentrations (0, 100, 500, and 1,000 micrograms per litre of arsenate) in a 168-pot design (7 species by 4 concentrations by 6 replicates), with total arsenic measured by ICP-MS. At the mid-point irrigation concentration of 500 micrograms per litre, edible-part arsenic concentrations were 6.6 micrograms per gram dry mass in spinach, 3.9 in lettuce, 3.5 in carrot, 2.2 in amaranth, 0.9 in okra, 0.8 in green bean, and 0.2 in tomato. Averaged across all spiked irrigation levels, the edible-part category means were 4.9 micrograms per gram for leafy vegetables, 2.9 for root vegetables, and 0.8 for fruit and pod vegetables. Cancer risk exceeded 1 in 10,000 for green bean, lettuce, and spinach at 500 and 1,000 micrograms per litre, for amaranth at 1,000, and for carrot at all spiked treatments; tomato and okra stayed below that risk level at every concentration.

Two caveats are essential to reading this source honestly. First, the arsenic here is geogenic (the applied arsenate models the naturally arsenic-rich groundwater of the region), not sewage effluent, so Clair-Caliot 2021 is not a sewage-irrigation study; it is included because it is the one source in this set that controls the water concentration experimentally and therefore isolates irrigation water as the transfer vector, which is the mechanistic claim at the center of this synthesis. Second, all values are total arsenic; no inorganic-versus--organic speciation was performed, and the cancer-risk calculation conservatively applied the inorganic-arsenic slope factor to total arsenic. The concentrations are experimental ceiling values under sustained high-arsenic irrigation, not field-survey occurrence data for commercial produce, and must not be used as baseline contamination-profile values. What the study establishes for this synthesis is the dose-response direction and the accumulation ranking (leafy greater than root greater than fruit and pod), established in Clair-Caliot's controlled design; the field surveys, which sampled mainly leafy and some root crops, are consistent with the leafy end of this ordering but did not include fruit and pod vegetables to test the full ranking.

## 6 | The India multi-metal field signal (Pal 2017)

Pal, Bishnoi, and Kaur 2017, published in the International Journal of Engineering Science Technologies and graded B-tier in this corpus, measured cadmium, lead, copper, zinc, chromium, and nickel in vegetables grown on domestic-wastewater-irrigated farmland around Hisar district, Haryana, India, with five samples of each vegetable analysed in triplicate. Spinach carried the highest cadmium (1.30 plus or minus 0.31 mg/kg) and the highest nickel (2.45 plus or minus 0.86 mg/kg); cabbage carried the highest lead (4.23 plus or minus 0.32 mg/kg); carrot carried the highest copper (1.42 plus or minus 0.25 mg/kg); and cauliflower carried the highest zinc (4.26 mg/kg). The study reports a total-chromium maximum of 1.16 mg/kg, with the abstract and discussion disagreeing on whether carrot or radish held that value; this internal inconsistency is noted rather than resolved here. Pal 2017 independently reproduces the leafy-vegetable concentration of the multi-metal signal (spinach highest for two of the six metals) under the same domestic-wastewater pathway, in a fourth country and a fourth research group.

## 7 | The mechanistic explanation

Municipal wastewater and sewage-receiving effluent carry a mixture of metals from domestic, commercial, and light-industrial inputs: lead from plumbing and legacy deposition, cadmium and nickel from batteries, plating, and pigments, chromium from tanning and metal finishing, and, where the underlying groundwater is naturally arsenic-rich, arsenic on top of the anthropogenic load. Because these metals arrive together in a single applied water stream, they load the irrigated soil together. Repeated irrigation over seasons accumulates the metals in the plough layer, and the crop then draws them from that loaded soil through the root system into the edible tissue. The pathway therefore has a shared cause (the water), a shared reservoir (the soil), and a shared uptake step (root-to-shoot transfer), which is why the metals co-vary in the crop rather than varying independently.

The leafy-vegetable concentration of the signal has a physiological basis. Leafy greens combine high transpiration-driven water flux, large edible surface-to-mass ratio, and, for species such as spinach and amaranth, an inherent tendency to accumulate cadmium and other divalent metals in leaf tissue. In Clair-Caliot's controlled ranking, leafy vegetables accumulate more than root vegetables, which accumulate more than fruit and pod vegetables; the three field surveys, which sampled mainly leafy and some root crops, are consistent with the leafy end of this ordering but did not include fruit and pod vegetables to test the full ranking. This is the reason the pathway expresses itself most visibly in spinach, lettuce, amaranth, and the leafy Brassica crops.

The pathway is mechanistically distinct from geogenic and mining-derived soil contamination. In a mining or ore-body setting the metal signature is fixed by local geology and does not travel with an applied water source; the plot is contaminated whether or not it is irrigated. That pathway is treated separately in the mining-impacted freshwater synthesis for aquatic matrices. In the wastewater-irrigation pathway the contamination is a property of the water-and-soil-management history of the plot, which means it can in principle be present on plots whose parent geology is unremarkable and absent on adjacent plots that use clean water. The contamination follows the irrigation, not the cultivar and not the bedrock.

## 8 | Why conventional surveillance misses this

Three features of conventional monitoring cause this pathway to be underdetected. First, occurrence databases and regulatory limits are organized as independent metal-by-ingredient cells. A surveillance program that checks lead in spinach, cadmium in spinach, and chromium in spinach as three separate queries can find each individually within or near its limit and never register that a single upstream cause has raised all three in step. The co-variation, which is the diagnostic signature of the wastewater pathway, is exactly the information that a cell-by-cell reading discards. This is the shared-source counterpart to the additive-exposure problem in combined-exposure-underprotection.

Second, point-in-time water and soil sampling can miss the exposure entirely. Chiutula 2025 is the direct demonstration: in that system the metals were below detection in the wastewater and below WHO limits in the soil at the sampling time, yet the vegetables exceeded the food limits, because the exposure is the integral of years of soil loading and the bioconcentration step, not the instantaneous water concentration. A monitoring program that clears an irrigation source by testing the water, or a field by testing the topsoil once, can pass a plot whose crops are non-compliant.

Third, the pathway concentrates on peri-urban and informal production plots in the Global South that sit outside the formal supply-chain testing that audited markets apply. The five studies here span Nigeria, Malawi, India, Burkina Faso, and 13 countries in the Ali meta-analysis, and in each the produce enters local and regional food systems rather than an audited export channel. For global sourcing, the implication is that origin history (specifically whether a supplying region relies on wastewater irrigation) is a risk factor that a finished-product single-metal test may not surface if only one analyte is checked or if the tested lot happens to sit below a per-metal limit while the co-elevated siblings are not measured.

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

For testing, the operative recommendation is that wastewater-irrigation origin should trigger a multi-metal panel rather than a single-analyte check, because the defining feature of the pathway is co-elevation. Measuring lead alone in a wastewater-sourced leafy green characterizes neither the cadmium, the nickel, the total chromium, nor, in arsenic-rich groundwater regions, the arsenic that the same water delivered. Where feasible, characterization should attach to the crop tissue rather than rely on a one-time water or soil clearance, given the Chiutula demonstration that water and soil can read clean while the crop does not. Total chromium in these studies is not speciated and must not be entered as chromium-VI; a total-chromium exceedance in a wastewater-irrigated crop is a flag for speciation follow-up, not a chromium-VI value.

For regulation, the pathway argues for treating irrigation-water provenance as a category-level risk descriptor for leafy greens and other high-accumulating vegetables sourced from regions with documented wastewater or sewage-effluent irrigation, and for reading per-metal limits in that context as jointly rather than severally informative. The health risk indices in the field studies (exceeding 1 across multiple countries in Ali 2022, and reaching 82 to 92 for Brassica in Chiutula 2025) indicate that in the most affected systems the exceedances are large, not marginal. The field and greenhouse concentrations reported here are context values, not a pooled occurrence distribution, and setting numeric limits from them is out of scope for this synthesis, which reports what the literature supports.

For consumers, the finding is specific to a production context rather than to a food type in general. Leafy greens are not inherently high in these metals; leafy greens grown on plots irrigated with untreated municipal wastewater or sewage-receiving effluent are. A consumer eating spinach, lettuce, cabbage, or amaranth produced on peri-urban plots irrigated with wastewater, as a daily staple, faces a materially higher and multi-metal exposure than a consumer eating the same species from clean-water production, and the field-study concentrations (for example spinach lead at 6.60 mg/kg in Bauchi and spinach cadmium at 1.30 mg/kg in Hisar, both on a dried analytical basis) sit above common food comparison limits. This is a production-and-origin quality signal, not a reason to avoid leafy vegetables as a class. Where cooking is relevant, Clair-Caliot 2021 found that cooking arsenic-contaminated vegetables in arsenic-free water removed on average 39 percent of the arsenic and that steaming rather than boiling reduced arsenic by roughly 8-fold to 18-fold in staple foods, a mitigation that applies to the water-soluble fraction and does not substitute for clean-water production. The organic label does not address this pathway, for the reasons developed in organic-certification-not-protective: the metals enter through the irrigation water and soil, not through synthetic agricultural inputs that organic certification governs.

## 10 | Uncertainty and limits of this synthesis

The evidence base is real but geographically and methodologically specific. Four of the five sources are single-region field or greenhouse studies from the Global South, and their absolute concentrations are context values on varying dried and processed analytical bases; they are not a pooled occurrence distribution and are not transferable as contamination-profile typical values for commercial retail produce. The Ali 2022 meta-analysis provides the breadth but for lead only and with very high heterogeneity (I-squared equals 98 percent). The Clair-Caliot 2021 anchor is experimental high-dose and models geogenic rather than sewage arsenic. The multi-metal co-elevation claim rests principally on the three field surveys (Adebayo, Chiutula, Pal), of which two are A-tier and one is B-tier, and one of those (Adebayo) is a single-composite-sample observation. Total chromium is reported throughout without speciation, so the pathway's chromium-VI burden is unquantified. The synthesis is therefore strong on the existence, direction, and mechanism of the pathway, and appropriately weak on any transferable numeric magnitude for a specific commercial crop.

The corpus does not yet contain a controlled field study that measures the same metal panel in wastewater--irrigated versus clean-water-irrigated plots of the same cultivar in the same season, which would isolate the irrigation variable directly under field conditions rather than by cross-study inference or greenhouse spiking. Nor does it contain a commercial retail survey testing whether wastewater-origin produce reaches audited supply chains at measurable frequency. Both are candidate targets for a Journal of Food Metallomics synthesis and would materially strengthen the numeric and supply-chain-relevance components of this finding.

## 11 | What downstream pages this synthesis updated

Consistent with the downstream-propagation rule, this synthesis is linked from the leafy-green and vegetable ingredient and product pages named in its frontmatter as the literature anchor for the wastewater-irrigation origin-risk descriptor: spinach, leafy-greens, leafy-vegetables, lettuce, cabbage, carrot, and wheat on the ingredient side, and spinach, leafy-vegetables-other, root-tuber-vegetables, and non-root-vegetables on the product side. These pages carry the pathway as an origin-and-production risk descriptor and explicitly do not adopt the field-study concentrations as retail typical values, per the transferability limit stated above. Where a downstream ingredient page needs a numeric contamination-profile edit, that edit is deferred to a synthesis pass over commercial-market occurrence data rather than executed from these context values, and that deferral is the specific blocker recorded here rather than a generic implication statement.

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REVIEW

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## STATUS AND LICENCE



## DATA AVAILABILITY

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

## COMPETING INTERESTS

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