



Heavy metals, veterinary antibiotics and microplastics in agroecosystems: Occurrence, co-contamination and remediation approaches: A comprehensive review

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Abstract

Agroecosystems increasingly face complex mixtures of pollutants from diffuse agricultural and peri-urban sources, collectively termed emerging contaminants (ECs), which remain bioactive at trace levels, are poorly regulated and can act as vectors for co-occurring pollutants. This review synthesises the occurrence, fate, toxicity and remediation of heavy metals (HMs), veterinary antibiotics (VAs) and microplastics (MPs, inclusive of nanoplastics (NPs)) in agroecosystems, with emphasis on India, where intensive livestock-crop integration, weak wastewater treatment and high mulch-film use favour co-contamination. Heavy metal through classical rather than emerging pollutants, are included given their sorption and complexation interactions with VAs and MPs. In Indian farmlands, cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As) and nickel (Ni) concentrations span roughly two orders of magnitude and frequently exceed World Health Organization/Food and Agriculture Organization (WHO/FAO) limits in industrial and intensively cropped zones. Veterinary antibiotic residues in manure-amended soils range from sub- $\mu\text{g kg}^{-1}$ to several hundred $\mu\text{g kg}^{-1}$ (tetracyclines, fluoroquinolones, sulfonamides dominant), while MP abundance ranges from ~ 50 to > 1000 particles kg^{-1} , chiefly polyethylene and polypropylene. Microplastics and metals (Pb, Cd, Cr) can act as sorption/complexation partners for antibiotics, enhancing their persistence and mobility, though mechanisms remain incompletely characterised. Co-contamination degrades soil quality, disrupts microbial communities, co-selects resistance genes, suppresses crop productivity and raises human exposure via food and dust. Remediation studies report 60–90 % Cd/Pb immobilisation (biochar-zeolite), 60–94 % ciprofloxacin removal (vetiver grass), 99 % sulfamethoxazole removal (iron-nitrogen (Fe-N)-biochar), 96 % amoxicillin degradation (*Stenotrophomonas* sp. WA5) and 70–95 % quinolone removal (hybrid wetlands). Long-term field data, harmonised risk frameworks and fate data for metabolites, weathered MPs and metal complexes remain limited, warranting priority research attention.

Keywords: agroecosystem; antibiotics; bioremediation; heavy metals; microplastics

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1. Introduction

Ensuring food security for an estimated 9.7 billion people by 2050 has driven unprecedented agricultural intensification. The accompanying surge in synthetic fertilisers, pesticides, plastic mulches, treated wastewater, biosolids and veterinary pharmaceuticals has introduced a wide spectrum of new-age, or “emerging”, contaminants (ECs) into agroecosystems, including pesticide residues, micro- and nano-plastics, engineered nanomaterials, antibiotics and antibiotic-resistance genes (ARGs) and complex contaminants from wastewater, digestate and sludge, together with atmospheric dry and wet deposition (1–3). East Asia, Europe and Brazil are emerging as hotspots for

synthetic fertiliser application. Plastic film mulching simultaneously increases yield and water-use efficiency (WUE), with meta-analyses reporting average yield increases of 24–33 % (4). Parallel use of treated wastewater and biosolids in agriculture has introduced co-contaminants of emerging concern into farmlands. Emerging contaminants can be distinguished from classical pollutants in several ways: they persist in the environment, are weakly or not yet regulated, remain toxic at trace concentrations and often occur as complex mixtures with synergistic or antagonistic effects. Their environmental dissemination alters microbial diversity in soils and aquatic systems and disrupts ecological functions (2). Once mobilised through food chains, irrigation water and drinking-water sources, ECs elevate

public-health risks and frequently exhibit phytotoxic effects on non-target plants (5). Degradation, biotransformation and stability of the resulting intermediates further modulate toxicity in both soil and plant compartments (6). Despite escalating concern, information on the current status, regional specificity and ecological interactions of ECs in agroecosystems remains fragmented (7). Current monitoring underestimates contaminant diversity and data on phytotoxicity and plant-community responses are needed to design effective phytoremediation strategies (8). Addressing these challenges requires integrated approaches that combine stricter regulatory frameworks, responsible stewardship, sustainable agronomic alternatives, advanced waste management such as composting and bioremediation and an explicit One Health perspective linking environmental and human health (9). Against this backdrop, this review critically examines the sources, fate, ecological impact and remediation of three priority contaminant classes, heavy metals (HMs), veterinary antibiotics (VAs) and microplastics (MPs), in agricultural soils, with a particular emphasis on Indian agroecosystems and on quantitative remediation outcomes. While several reviews published during 2024–26 have addressed individual EC classes or global trends, this review distinguishes itself by jointly synthesising HM, VA and MP occurrence, co-contamination interactions and remediation performance with a specific focus on Indian agroecosystems, an underrepresented region in the existing literature and by compiling comparative, quantitative remediation efficiencies across contaminant classes rather than treating each class in isolation.

Methodology of bibliometric analysis

Bibliometric analysis was used to map publication and citation trends. A dataset was compiled from the Scopus database for English-language journal articles published between 2005 and 2026. The Boolean search string applied to the title, abstract and keyword fields was: ("emerging contaminant*" OR "veterinary antibiotic*" OR "microplastic*" OR "heavy metal*") AND (agriculture* OR mitigation OR monitoring). Records were screened in two stages: an initial title/abstract screening to exclude non-English articles, non-journal document types (conference abstracts, book chapters) and studies unrelated to agroecosystems, followed by a full-text screening against inclusion criteria requiring an explicit focus on HMs, VAs or MPs in agricultural soil, water or crop systems. After data cleaning to remove duplicates and irrelevant entries, the refined dataset was analysed in the Bibliometrix R package (Biblioshiny web interface (R version 4.5.3)). Descriptive statistics, network-based keyword co-occurrence analysis and country- and journal-level metrics were generated, supported by word clouds and network maps. After screening, 330 articles were retained: 247 research articles and 83 review articles for descriptive analysis. Of these, approximately 100 references were selected for citation in the main text,

prioritised by direct relevance to HMs, VAs or MPs in agroecosystems, recency (2023–26 publication where possible) and the presence of quantitative occurrence or remediation data, in order to remain within the journal's reference limit. The analysis relied solely on the Scopus database; Web of Science (WoS), PubMed and Dimensions index partially non-overlapping sets of journals, so the bibliometric trends reported here should be interpreted as indicative of Scopus-indexed literature rather than as a fully comprehensive picture of the field and this single-database scope is acknowledged as a limitation of the present analysis.

Publication output was modest before 2019 but increased sharply thereafter, peaking in 2024–25 before easing slightly in 2026 (Fig. 1 and 2). Environmental pollution led contributing journals with 19 papers (IF 7.3), followed by Ecotoxicology and Environmental Safety (12 papers, (IF 6.1). Sustainability (Switzerland) and Water, Air and Soil Pollution each contributed 6 papers, Applied Soil Ecology and Environmental Monitoring and Assessment 5 papers each and Environmental Research 5 papers (IF 7.7). Globally, China accounted for the highest number of publications (542), followed by India (115), the United States (77), Pakistan (62), Australia (55) and the United Kingdom (40); Germany and Italy (38 each), Nigeria (26) and Spain (24) completed the top ten (Fig. 3), reflecting strong contributions from both developed and developing countries. The near five-fold gap between China (542 publications) and India (115) suggests that, despite India's clear regional relevance to this review, the Indian evidence base for ECs in agroecosystems remains comparatively sparse; this likely explains the greater availability of India-specific data for HMs than for VAs and MPs in the sections that follow and is highlighted as a research-capacity gap in the conclusion. From 6790 extracted keywords, 436 met the inclusion threshold. "Antibiotics" was the most frequent (482 occurrences), followed by "pharmaceuticals" (442), "antibiotic-resistance genes" and "wastewater management" (384 each), "adsorption" (293) and "biochar" (209). Other recurrent terms included "emerging pollutants" (56), "heavy metals" (27) [frequency to be verified against the Biblioshiny output; this count appears low relative to the prominence of HMs elsewhere in the review, possibly reflecting keyword-variant splitting, e.g. "heavy metal" vs "HMs" "nanoplastics" (14), "bioremediation" (14) and "agriculture" (12). Co-citation analysis identified two main author clusters (Fig. 4); within the green cluster Davey-Jones, Zhang, Zhou and Zeng emerged as the most-cited authors, while the red cluster reflected an independent thematic community. Overall, the included and excluded research article expressed by PRISMA analysis in Fig. 5. These patterns highlight the dominance of antibiotic-residue, ARG and adsorption/biochar themes in current EC research.

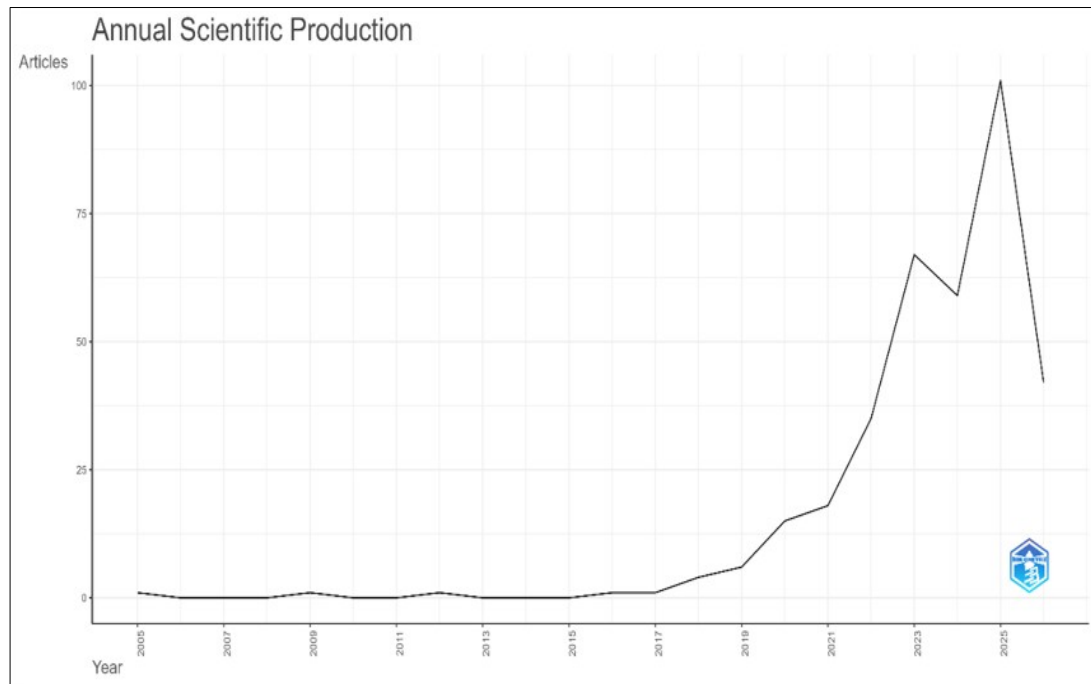


Fig. 1. Annual scientific production on emerging contaminants in agroecosystems, 2005-2026. Number of Scopus-indexed articles published per year (y-axis) plotted against publication year (x-axis); data source: Scopus, extracted and plotted using the Bibliometrix/Biblioshiny R package.

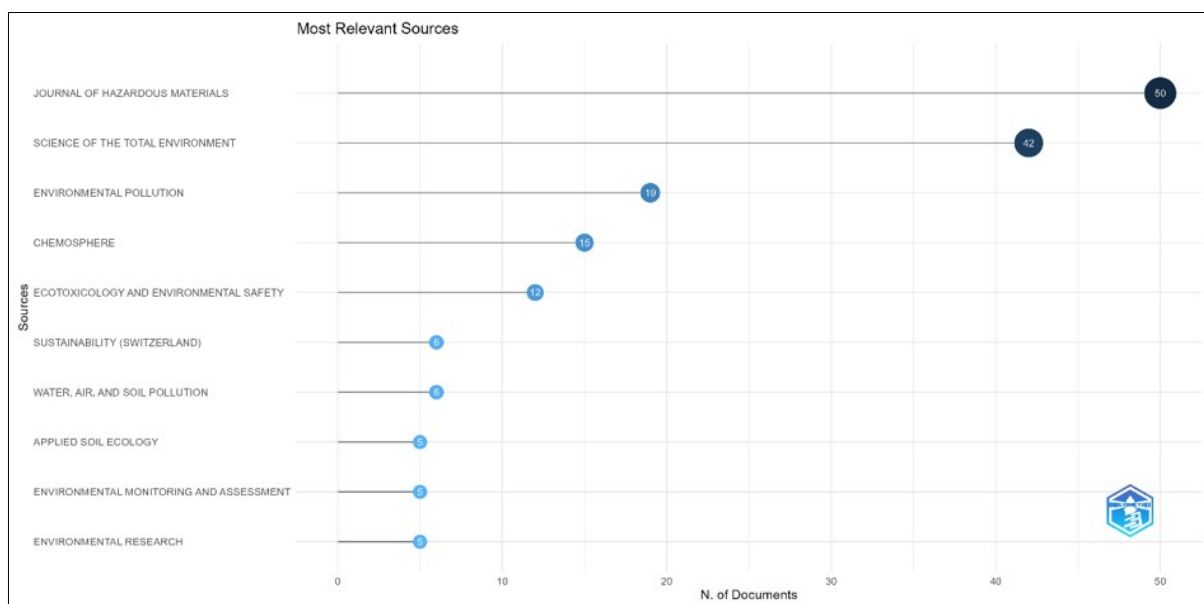
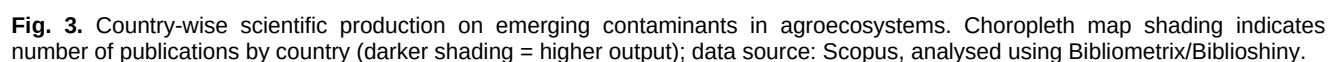


Fig. 2. Most relevant journal sources publishing on emerging contaminants in agroecosystems. Number of documents (x-axis) per journal (y-axis), ranked by publication count; data source: Scopus, analysed using Bibliometrix/Biblioshiny.



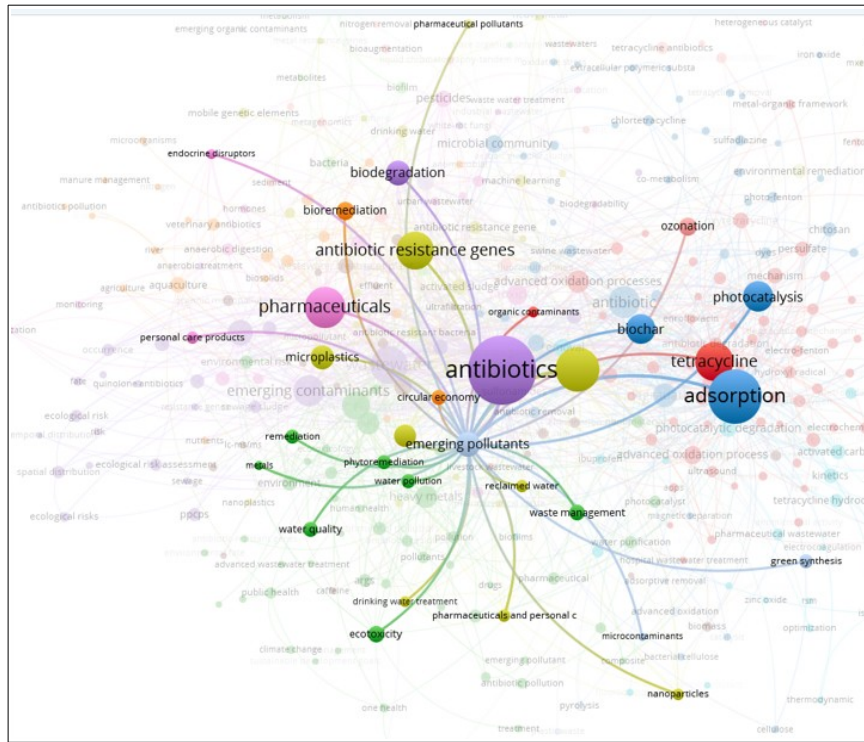


Fig. 4. Keyword co-occurrence network and word cloud for emerging contaminants in agroecosystems, based on 436 keywords meeting the inclusion threshold from 6790 extracted terms; node/word size reflects occurrence frequency and edge proximity reflects co-occurrence strength. Data source: Scopus (2005–2026), analysed using Bibliometrix/ Biblioshiny. Two main author co-citation clusters are distinguished by colour (green and red).

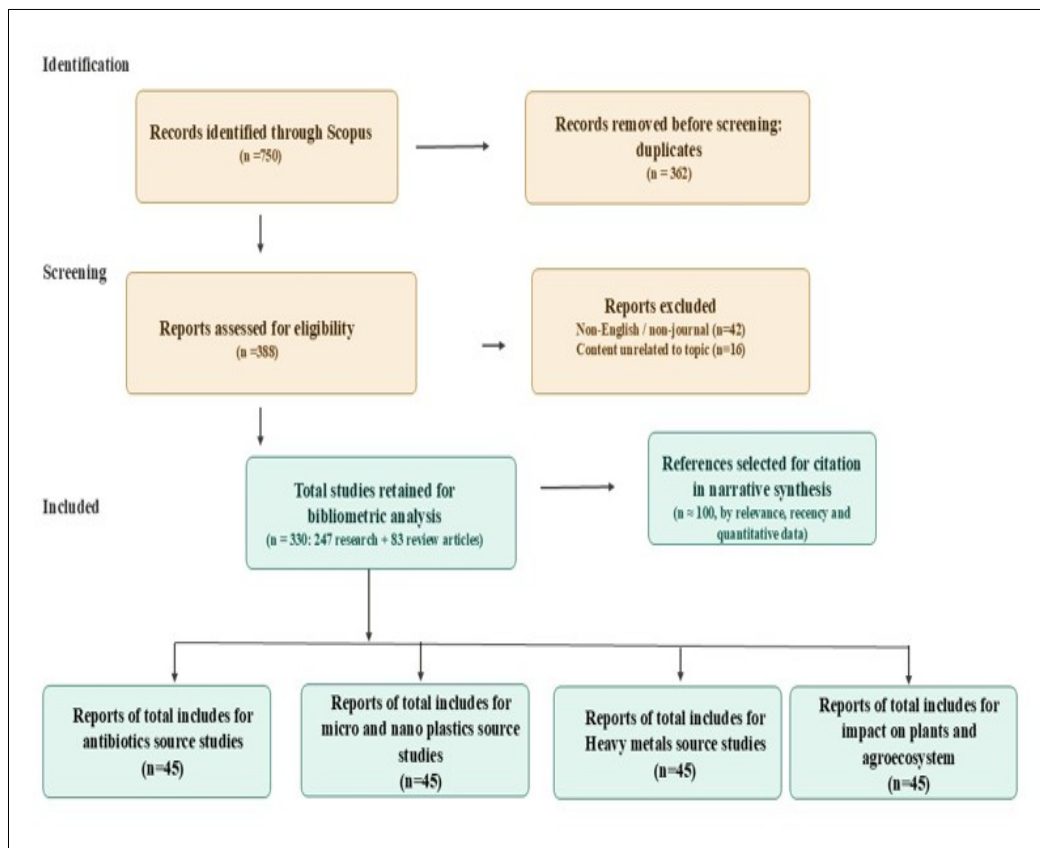


Fig. 5. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) analysis.

Sources, fate and transport of emerging contaminants in agricultural soils

The dominant inputs of ECs to agroecosystems are the recycling of treated wastewater for irrigation; organic manures and amendments enriched in antibiotics, HMs and MPs. Once they enter soil systems, ECs follow multiple pathways and mechanisms, which involve sorption, transformation, redox reaction, bioprecipitation, leaching, mineralisation, rhizosphere attenuation, complexation and transfer through different trophic levels, before entering the food chain (2, 10). The fate of HMs, antibiotics and MPs are discussed in detail in the following subsections.

Heavy metals in the agroecosystem

Heavy metals in agroecosystems originate from both geogenic sources (parent rock, natural weathering) and anthropogenic inputs such as mining, industry, fossil fuel combustion, fertilisers, manures and pesticides (11). Their behaviour is strongly governed by soil pH, organic carbon (C) content, cation-exchange capacity (CEC), redox potential, clay content and organic-matter quality, which together control speciation, mobility and plant-available fractions (11, 12). Low pH and low organic-matter content generally increase HM bioavailability, as documented for Cd in Chinese agricultural soils (13). Indian field studies illustrate the heterogeneity of HM loading. Tea plantation soils in the Western Ghats (Tamil Nadu) showed elevated Pb (9.8 mg kg⁻¹) and Cr (96 mg kg⁻¹) attributed to intensive fertiliser and pesticide use, while nickel (Ni) and Pb remained within guideline limits, indicating that local soil chemistry and management critically modulate risk. Recent national-

scale assessments report Cd of 0.05–14 mg kg⁻¹, Pb of 9.8–185 mg kg⁻¹, Cr of 2.5–96 mg kg⁻¹, arsenic (As) of 1–60 mg kg⁻¹ and Ni of 8–75 mg kg⁻¹ in Indian farmlands, with industrial peri-urban soils, mid-channel river bars and mining-affected sites contributing the highest values (1). Humans are exposed via ingestion of contaminated food and water, inhalation of dust and dermal contact with polluted soils. Chronic exposure can damage kidneys, liver, nervous and endocrine systems and increase cancer risk, even at relatively low doses for Cd, As and Pb (5, 14).

Soil microorganisms are often even more sensitive than plants. Meta-analyses and field studies show that HMs reduce bacterial abundance, microbial biomass, key enzyme activities and overall diversity, thereby disrupting nutrient cycling and organic-matter turnover. Community structure shifts toward metal-tolerant taxa, altering ecosystem functions and potentially reducing soil fertility (15). To characterise contamination and risk, multiple indices and tools are used: geoaccumulation index, contamination and potential ecological risk indices, bioconcentration factors and human health risk indices, supported by bioindicators, biomarkers and advanced analytical instruments such as inductively coupled plasma optical emission spectrometry (ICP-OES), inductively coupled plasma mass spectrometry (ICP-MS) and microwave plasma atomic emission spectrometry (MP-AES) (11). These approaches are essential for prioritising remediation and protecting food safety and human health. The major sources of HMs, along with their effects on soil, plants and humans, are listed in Table 1.

Table 1. Source of Heavy metals for agroecosystem and its effect on soil, plant and humans

S. No.	Heavy metal	Category	Source	Effects			Reference
				Plant	Soil	Humans	
1.	Cadmium	Non-essential Toxic	Phosphate fertilisers, wastewater, industrial effluents, pesticides and mining	Hinders root growth, accumulates in crops, toxic at low levels, reduced mineral uptake, photosynthesis affects plant metabolism and reduction in nitrate reductase activity	Accumulation in top soil, Reduced microbial activity and diversity and microbial respiration	Kidney failure, Cardiovascular diseases, Prostate and ovarian cancer, Bone damage and Itai Itai	(14, 16)
2	Lead	Non-essential Toxic	Rapid urbanisation, vehicular emissions, fertiliser, sewage sludge and industrial effluents	Germination inhibited root and shoot growth. Chlorosis reduced crop yield and nutrient imbalance	Soil productivity, nutrient cycling, changes in soil microbial diversity, population size and microbial communities	Brain injury, hearing loss, learning disability, behavioural abnormalities and neurotoxic	(17, 18)
3.	Arsenic	Non-essential toxic	Natural weathering, groundwater, pesticides, mining run off, coal burning, wood and preservatives	Reduces yield, Carcinogenic, Oxidative stress, Uptake via phosphate transporters, DNA and biomolecule damage	Land degradation, Reduced beta glucosidase activity, urease, aryl sulphatase activity and increased microbial metabolic quotient	Carcinogenic, black foot, skin lesions like keratosis and melanosis	(12, 19)
4.	Mercury	Non-essential toxic	Atmospheric wet and dry deposition, industrial waste, fungicides, organic and mineral fertiliser and sewage sludge	Inhibits seed germination, reduced biomass and leaf water content, cellular damage, chloroplast degradation, decrease in palisade and parenchyma cells	Reduce soil enzyme activity, reduced microbial activity and phosphatase suppression	Genotoxic, carcinogenic, neurotoxic, renal toxicity and multiple organ damage	(20, 21)
5.	Chromium	Essential (trace) Glucose metabolism	Industrial chromate production, tanneries, fertilisers, leather industry and electroplating industries	Root and shoot growth inhibition, oxidative damage and osmolyte accumulation	Altered microbial community and speciation	Carcinogenic, respiratory issues and dermal problems	(22, 23)
6.	Nickel	Essential (trace) Urease cofactor Minor metabolic roles	Industrial emission, smelting, fertilisers and natural weathering	Affects plant metabolism and development process	Reduced soil enzyme activity	Dermatitis, lung and nasal cancer	(13, 24)
7.	Copper	Essential (Micronutrient) Enzyme cofactor	Fertiliser, sewage and industrial waste	Inhibits root growth and nutrient imbalance	Reduces microbial activity and affects soil chemistry	Dermatitis and organ toxicity	(13)

DNA: deoxyribonucleic acid.



Mechanism of metal uptake in soil-plant systems

Once HMs enter the soil, they do not undergo degradation but rather transformation and adsorption onto soil minerals and organic matter, resulting in long-term accumulation. Their persistence in soil is governed by their distribution among exchangeable, carbonate-bound, Fe-manganese (Mn) oxide-bound, organic-bound and residual fractions and the soil properties. Sequestration and mobility of metals in the soil are determined by soil pH, cation exchange capacity, clay content, mineralogy, organic matter and redox potential (25, 26). Thus, low pH increases the solubility and mobility of HMs by releasing metals from bound complexes, meanwhile clay and high organic content favour sorption and immobilisation, thereby limiting their movement into groundwater and plants (27). The dissolved metal in the soil solution enters plant roots via apoplastic and symplastic transport. Apoplastic binding is mainly associated with cell wall components (pectin, carboxyl groups), which act as the first barrier and major sorption site for HMs (28). The symplastic pathway involves transport across the plasma membrane via specific and non-specific transporters. Key transporter families include ZIP, Zn-regulated transporter / Fe-regulated transporter-like protein (ZRT/IRT-related proteins), natural resistance-associated macrophage protein (NRAMP), heavy metal ATPase (HMA), ATP-binding cassette transporter (ABC) and cation diffusion facilitator / metal tolerance protein (CDF/MTP), which mediate uptake, translocation and sequestration of Cd and other metals (24, 29). ZRT1/IRT1-type ZIP transporters primarily mediate Zn and Fe uptake but also transport Cd and other non-essential metals. Natural resistance-associated macrophage protein transporters are broad-spectrum divalent cation carriers involved in Mn, Fe and Cd uptake and internal transport (Fig. 6) (17, 18, 29). P1B-type HMAs mediate root-to-shoot transport via xylem loading and vacuolar sequestration of Zn/Cd and related metals. Vacuolar sequestration of metal-chelate complexes (e.g. phytochelatin-Cd) is mediated by ABCC-type ABC transporters, while MTP/CDF transporters contribute to vacuolar sequestration/efflux of Zn, Co, Ni and Cd (24, 30). Non-essential metals frequently hijack nutrient pathways: Cd via Zn/Fe transporters, as via phosphate or silicon (Si) transporters and Cr via sulfate transporters. After entry, metals are chelated by organic acids, nicotianamine or histidine and stored in root vacuoles; the remaining fraction is loaded into the xylem and translocated to shoots. Plants with up-regulated metal transporters, efficient xylem loading and strong shoot deposition act as hyperaccumulators and are exploited for phytoremediation (31). In the rhizosphere,

proton extrusion and other processes can shift pH by 1–2 units, strongly changing metal solubility and bioavailability (32). Root exudation of low-molecular-weight organic acids (citric, oxalic, malic) dissolves mineral phases, displaces adsorbed metals and forms soluble or sparingly soluble complexes, thereby mobilising or immobilising metals depending on the metal-ligand pair. Rhizosphere microorganisms further modulate availability through redox transformations, siderophore production, biosurfactants and organic acids, which can either enhance phytoextraction or immobilise metals and reduce phytotoxicity (33).

Mitigation and remediation strategies

Bioremediation and phytoremediation exploit the natural ability of the living organisms to remove, stabilise or detoxify HMs in soil and water. Phytoremediation is extensively studied for remediating various pollutants which includes phytostabilisation, rhizofiltration and rhizodegradation, phytoextraction, phytodegradation, phytoaccumulation and phytovolatilisation. Accumulation of metals such as Fe, Mn, Zn, Cd, Pb and others in crops grown on sludge- or wastewater-contaminated soils and waters is widely reported, raising food-chain concerns (20, 26). Numerous terrestrial and aquatic plants, including *Brassica* spp., *Thlaspi/Noccaea*, *Pteris vittata*, *Vetiver*, *Agrostis*, *Arabidopsis*, *Helianthus* and *Eichhornia crassipes*, are described as effective metal accumulators or hyperaccumulators for phytoremediation of soil and water (34). Natural hyperaccumulators are often limited by low biomass and slow growth, so chelate-assisted phytoextraction with citric acid is used to enhance metal bioavailability and accumulation in higher-biomass species. Due to concerns about synthetic chelates, organic and mineral amendments such as compost, biochar, lime, zeolite, rock phosphate and iron oxides are increasingly applied to immobilise metals near the soil surface and reduce bioavailability (22). Biochar and biochar-zeolite combinations increase pH, cation-exchange capacity and sorption sites, thereby decreasing mobile Cd, Pb, Zn and other metals (35). Lime similarly raises pH and promotes precipitation of metals as hydroxides, reducing solubility. Bioremediation also exploits bacteria, fungi and other microorganisms to transform or immobilise metals and to assist plants (microbe-assisted phytoremediation) (19). Genetic engineering of plants to overexpress metal transporters, metallothioneins or phytochelatin synthase is highlighted as a powerful route to increase phytoextraction capacity in high-biomass crops and to improve detoxification and sequestration of Cd and other metals (23, 36).

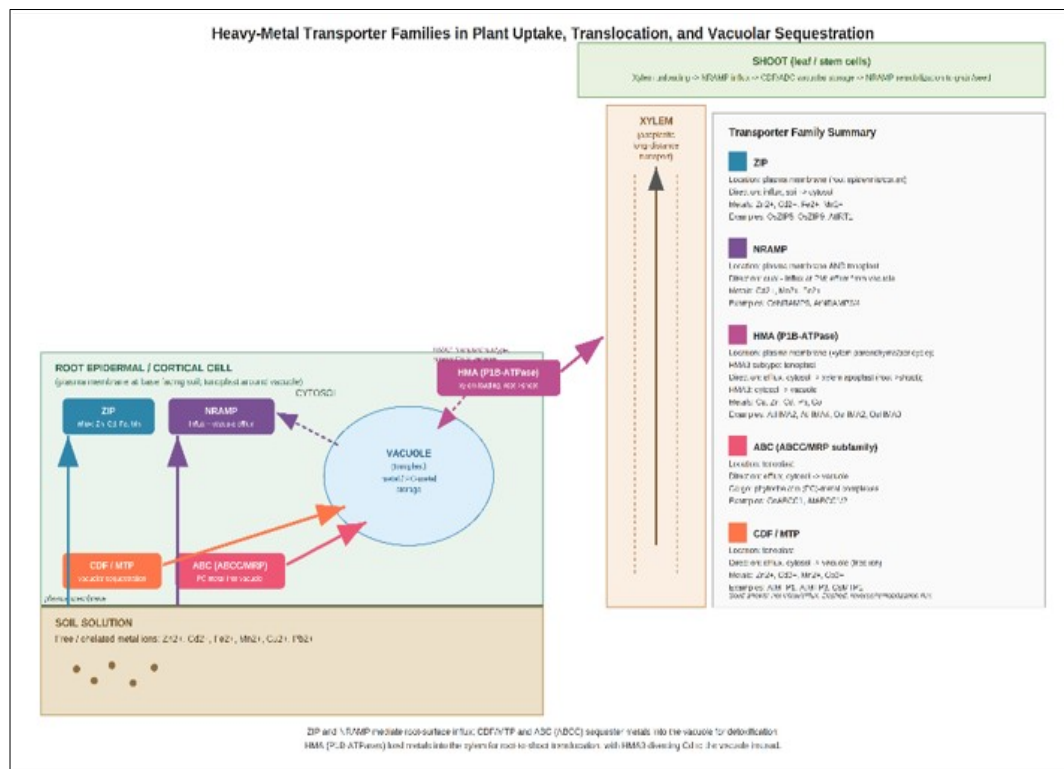


Fig. 6. Synthesising schematic of the five heavy-metal transporter families.

ZIP, NRAMP, HMA, ABC (ABCC/MRP) and CDF/MTP mapped onto their subcellular localisation and direction of transport across the soil-root-xylem-shoot continuum.

ZIP and NRAMP mediate influx of divalent metal cations (Zn^{2+} , Cd^{2+} , Fe^{2+} , Mn^{2+}) across the root plasma membrane; NRAMP additionally mediates efflux from the vacuole during remobilisation. CDF/MTP and ABC (ABCC/MRP subfamily) transporters sequester free ions and phytochelatin-metal complexes, respectively, into the vacuole across the tonoplast for detoxification. HMA (P1B-type ATPases) load metals from the cytosol into the xylem apoplast for long-distance root-to-shoot translocation, with the HMA3 subtype instead diverting Cd^{2+} to the vacuole. Representative genes and transported metal ions for each family are listed in the accompanying summary panel.

Veterinary antibiotics in the agroecosystem

Veterinary antibiotics are central to modern livestock production but their extensive use has made agroecosystems key reservoirs of antimicrobial residues and resistance. In many developed countries, livestock consume about 50–80 % of all antibiotics produced, reflecting intensive, high-density farming and relatively easy drug access (37–39). Globally, an estimated 73 % of antimicrobials are used in food animals, with consumption projected to rise from about 93000–99000 t in 2017–20 to roughly 104000–107000 t by 2030, driven largely by expanding poultry and pig sectors (38, 40, 41). Asia is the dominant consumer and antimicrobial use hotspot, with especially rapid growth forecast in South and Southeast Asia where demand for poultry meat and other animal protein is increasing sharply. Tetracyclines are the most widely used veterinary antimicrobials and are expected to increase by around 9 % by 2030, while other commonly used classes include sulfonamides, macrolides, penicillins, cephalosporins and quinolones, many of which are also critically important in human medicine (42–44). Much of the administered dose is excreted unmetabolised, so manures and slurries applied to fields introduce active compounds and resistant bacteria into soils and waters, where they can persist, select for resistance and move through runoff

and leaching. This contamination links farm environments, wildlife and human communities, facilitating horizontal transfer of resistance genes and raising concerns over antimicrobial resistance (AMR) as a One Health problem (45). Although many high-income regions, notably the European Union (EU), have banned growth promotion uses and tightened VA regulations, growth promotion and routine prophylaxis remain common in several tropical and emerging economies, including India and China, where regulatory capacity and farm-level stewardship are weaker (46). Projections that antimicrobial use in food animals will keep rising, especially in Africa and Asia, highlight the need for region-specific interventions: stricter regulation of non-therapeutic uses, improved surveillance, better farmer and veterinarian education and investment in alternatives such as vaccines and enhanced biosecurity to safeguard agroecosystem health and slow AMR emergence (47). Veterinary antibiotics are introduced into terrestrial and aquatic environments primarily through animal excretion, land application of manure and discharge from aquaculture operations (48). The major pathways through which VAs enter and persist in the environment are illustrated in Fig. 7.

India-specific data remain limited relative to global monitoring datasets, consistent with the

publication gap noted in the bibliometric analysis, but available surveys of manure-amended Indian agricultural soils report antibiotic residues typically ranging from sub- $\mu\text{g kg}^{-1}$ to several hundred $\mu\text{g kg}^{-1}$, dominated by tetracyclines, fluoroquinolones and sulfonamides, reflecting the widespread use of manure and biosolids on organic and conventional farms alike (46, 49, 50). On the regulatory side, India's antimicrobial

use in livestock is addressed primarily through the National Action Plan on Antimicrobial Resistance rather than through soil- or produce-specific contaminant limits, which as discussed further in the cross-cutting considerations section leaves a policy gap between AMR strategy and agricultural-soil monitoring that is not unique to India but is particularly consequential given the country's scale of livestock production.



Fig. 7. Schematic of entry pathways for veterinary antibiotics into the agroecosystem, from source (livestock excreta, manure and aquaculture effluent) through soil and water compartments to plant uptake and human exposure.

Mechanism of antibiotics uptake in soil and plant system

Veterinary antibiotics enter agroecosystems mainly via manure, biosolids and contaminated irrigation water, then partition between soil solids and pore water according to their speciation, hydrophobicity and sorption to minerals and organic matter. Antibiotics that avoid strong sorption and remain dissolved in pore water, such as many sulfonamides and some macrolides, are readily intercepted by roots, whereas strongly sorbing fluoroquinolones and tetracyclines form a persistent reservoir on soil colloids that can still supply low concentrations over time (51–53). The primary entry route is through roots, where uptake occurs via passive transport with water flow for neutral, mobile molecules and via carrier- and energy-dependent processes for several tetracyclines, sulfonamides and fluoroquinolones, as shown by inhibition with respiratory blockers and aquaporin inhibitors in maize and other species (54). Once inside roots, the ionic state of each compound at cytosolic pH governs ion trapping and distribution between apoplast and symplast, leading tetracyclines to translocate efficiently to shoots (often root-to-leaf concentration ratios approaching 1: 1) while sulfonamides tend to accumulate in roots (52). Field and pot studies and meta-analyses indicate that, for many compounds,

internal distribution follows leaf > stem > root, reflecting xylem-driven transport and high transpiration, especially in leafy vegetables and rice irrigated with contaminated water. Soil organic matter, pH, dissolved organic matter and long-term manuring modulate sorption and persistence, thereby controlling long-term bioavailability, while plant species, growth stage and transpiration rate determine uptake magnitude and tissue residues (55). Although some biotransformation occurs, many parent antibiotics persist in plant tissues, so residues detected from trace to hundreds of mg kg^{-1} raise concerns about food-chain exposure and antibiotic resistance selection, highlighting the need to better understand soil-solution-plant interactions and to manage antibiotic inputs to agricultural soils (56).

Non-target terrestrial organisms, such as earthworms and arthropods, suffer sub-lethal to lethal effects, which compromise biodiversity and soil ecosystem services. Terrestrial wildlife, including scavengers and predators, may ingest residues through contaminated carcasses or water sources, raising ecological and toxicological concerns (57). Compounds such as tylosin and ciprofloxacin negatively impact soil respiration, microbial biomass and enzymatic activities, while certain residues, e.g., sulfadiazine, accumulates in crops like tomatoes and wheat, posing phytotoxic risks

(31). The mobility of antibiotics in soils depends on physicochemical properties like solubility and stability, along with soil characteristics such as organic matter content and pH. Leaching into groundwater introduces antimicrobial residues into drinking water supplies, compounding public health risks and propagating AMR (58). Waterborne contamination via surface runoff or direct discharge from aquaculture and livestock operations leads to bioaccumulation in aquatic organisms and introduces harmful transformation products through

processes like photolysis and microbial degradation (59, 60). The environmental overuse of antibiotics fosters resistant bacteria and resistance genes (ARGs), which disseminate through manure, water and soil, complicating therapeutic options and inflating healthcare costs. These trends underscore the urgent need for a One Health approach to align environmental, animal and human health perspectives (45, 61). A detailed overview of environmental impacts and antibiotic usage in globe is provided in Table 2a and 2b.

Table 2a. Impact on antibiotics in environment

S. No	Antibiotic class	Examples	Sources	Pathway	Impact	Remediation	Reference
1.	β -Lactams	Amoxicillin, cloxacilin, oxacillin and amoxicillin	Veterinary farms	Runoff and untreated wastewater	Resistant microbes, endocrine disorders, aquatic toxicity, soil contamination and reduced microbial diversity	Biodegradation, Microalgae-based technology (<i>Coelastrum</i> sp.), nano remediation, Activated sludge process, MBR, AOP and biochar application	(53)
2.	Aminoglycosides	Amikacin, apramycin, gentamycin and streptomycin	Veterinary use	Wastewater discharge and runoff	Microbial disruption, bioaccumulation and resistance development	Biodegradation, photolysis, constructed wetlands and phytoremediation	(9)
3.	Tetracycline	Chlortetracycline, doxycycline, oxytetracycline and tetracycline,	Animal husbandry and aquaculture	Wastewater discharge	Microbial disruption, N-fixing inhibition, bioaccumulation, algal impacts and GHG emissions	Hydrolysis, biodegradation, constructed wetlands, bioreactors and photodegradation	(44,50)
4.	Sulfonamide	Sulfachloropyridazine, Sulfadiazine, Sulfamethazine, Sulfamethoxazole	Livestock	Manure and slurry	Persistence, bioavailability, resistance and human/ecological risks	Hydrolysis Biodegradation, constructed wetlands, bioreactors and Photodegradation	(49, 61)
5.	Enrofloxacin	Fluoroquinolones (FQs)	Aquaculture runoff.	Runoff, leaching	Oxidative stress in fish, immunity reduction, soil enzyme inhibition and productivity loss	Advanced oxidation processes, UV treatment and adsorption desorption technology	(60)
6.	Cephalexin	-	Veterinary clinics and livestock farms	Wastewater, manure	Resistance, soil degradation, aquatic toxicity and fish reproduction interference	Advanced oxidation processes (AOPs) nanoremediation and biodegradation	(62)
7.	Doxycycline	Vibramycin, doxycin	Veterinary farms	Wastewater and manure	Plant uptake, soil disruption and harm to aquatic species	Phytoremediation, adsorption and bioaugmentation	(63)
8.	Gentamicin	Aminoglycoside	Animal agriculture	Soil leaching	Resistance, soil toxicity, nitrification inhibition and aquatic toxicity	Biodegradation, activated C and vermifiltration	(64)
9.	Sulfamethoxazole	Sulfonamide	Livestock and aquaculture	Effluent runoff	Resistance genes, nutrient cycling impact and bioaccumulation	Constructed wetlands, ozonation and biochar amendment	(9)

10	Clindamycin	Lincosamide	Veterinary hospitals and livestock farms	Wastewater and manure	Soil microbial reduction and bioaccumulation	Bioremediation, advanced filtration and microbial fuel cells	(65)
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AOP: advanced oxidation processes; C: carbon; FQ: fluoroquinolones; GHG: greenhouse gas; MBR: membrane bioreactor; N: nitrogen; UV: ultraviolet.

Table 2b. Global veterinary antibiotic consumption

Rank/Region	Country	Estimated AMU (tonnes)	Intensity (mg/PCU)	Percentage of Global AMU	National surveillance reporting	Reference
1	China	32776	-	56 % of Asia's 58377 t	No routine national report to WOAHO/OIE	(41)
2	Brazil	-	-	Top 5 (combined 58 % with China, India, USA, Australia)	No routine national report	(41)
3	India	-	-	Top 5 (combined 58 % with China, Brazil, USA, Australia)	No routine national report	(41)
4	USA	-	-	Top 5	Reports via FDA/NARMS	(41)
5	Australia	-	-	Top 5	Reports via national AMU program	(41)
-	Thailand	-	337.8 (highest reported, 2020)	-	Reports to regional/WOAHO systems	(41)
-	Norway	-	4.4 (lowest reported, 2020)	-	Full EU/ESVAC reporting	(41)
-	Pakistan (broiler sector)	2184 (2020) → 3143 projected (2030)	462.6 (farm-level broiler survey)	44 % projected relative increase (largest of any country)	No national system; farm-level surveys only	(41,53)
Species intensity (global, 2020)	-	-	Sheep 243.3; Pigs 173.1; Cattle 59.6; Chicken 35.4	-	-	(41)
Global total (species-weighted, FAO-PCU method)	-	99502 (2020) → 107472 projected (2030)	79.3 → 85.6 projected	100 %	31 EU countries (ESVAC) + 9 others report routinely	(41)
Global total (revised biomass-adjusted method)	-	76060 (2019–21 avg.: cattle 40697; pigs 31120; chicken 4243)	-	-	Cross-validated against WOAHO's 76704 t (2018, sales-based)	(39)
Global total (LBC method, FAO 2025)	-	110777 (2019 baseline) → 143481 projected (2040, BAU)	-	29.5 % projected increase by 2040	-	(50)

AMU: antimicrobial use; PCU: population correction unit; WOAHO: World Organisation for Animal Health; BAU: business as usual; LBC: livestock biomass correction; OIE: Office International des Epizooties; FDA: Food and Drug Administration; NARMS: National Antimicrobial Resistance Monitoring System; EU: European Union; ESVAC: European Surveillance of Veterinary Antimicrobial Consumption; FAO: Food and Agriculture Organization

Mitigation of antibiotics in the environment

Mitigating the environmental footprint of veterinary antibiotic use requires an integrated, One Health framework combining antimicrobial stewardship, on-farm prevention and downstream waste management, consistent with WHO's push to optimise antimicrobial use across human and animal health systems (66). World Health Organization and partner agencies now emphasise reducing routine antimicrobial use in food animals through disease prevention, vaccination, functional nutrition and improved husbandry rather than metaphylactic or growth-promoting applications, aligning

with global AMR strategies. Well-studied probiotics (*Lactobacillus acidophilus*, *Bifidobacterium bifidum*, *Bacillus subtilis*) support gut microbial balance, immunity and growth in poultry and livestock (67, 68). Vaccines against major livestock and poultry diseases (e.g., foot and mouth disease, bovine viral diarrhoea, Newcastle disease, infectious bronchitis) reduce disease incidence and antibiotic reliance (69). Phytochemical additives such as essential oils and turmeric offer antimicrobial and anti-inflammatory benefits but face standardisation, cost and regulatory constraints (63, 70).



Systemically, strong biosecurity and farm management improved housing, sanitation, early disease detection and immunomodulatory strategies lower infection pressure and antibiotic demand (47). Nutrient-rich diets and clean water further build resilience. Quarantine, sanitation, vector/rodent control and staff hygiene prevent disease spread and reduce therapeutic antimicrobial needs (71). Precision livestock farming enables real-time health monitoring, supporting earlier intervention over routine prophylaxis (72). Beyond prevention, environmental mitigation relies on advanced waste treatment. Composting, anaerobic digestion and pyrolysis degrade antibiotic residues and resistance genes (ARGs) in manure (49). Anaerobic digestion achieves > 99 % degradation of compounds like sulfadimethoxine under optimised conditions. Constructed wetlands enable microbial, chemical and photolytic degradation of antibiotics and aid ARG attenuation (16, 44). Engineered biochars (e.g., Fe-N-BC) show high adsorption capacity for sulfonamides like sulfamethoxazole. Thermal treatments and advanced oxidation processes (ozonation, ultraviolet (UV), UV/H₂O₂) transform recalcitrant antibiotics into safer byproducts, serving as effective polishing steps (73). Nutrient recovery methods (struvite precipitation, ammonia stripping) recover phosphorus (P) and N while removing > 80 % of several antibiotic residues (16). Bioremediation include the biosorption, biodegradation, mycoremediation and phytoremediation offers a biologically driven alternative to costly, selectivity-limited physicochemical methods, aided by advances in genomics and bioengineering (74). Biosorption passively binds antibiotics to microbial/fungal biomass; biodegradation uses microbial enzymes to cleave antibiotic structures (58). Mycoremediation employs fungi (e.g., white rot species) to decompose pharmaceuticals, while phytoremediation uses plants for antibiotic uptake and degradation. *Coriopsis gallica* efficiently removes fluoroquinolones like levofloxacin (75). *Bacillus subtilis* degrades 76 % of tetracycline in 5 days; *Stenotrophomonas* sp. WA5 removes 96 % of amoxicillin in 14 days (76). *Lactarius deliciosus* biomass adsorbs 216.4 mg g⁻¹ chlortetracycline, 121.2 mg g⁻¹ doxycycline and 23.2 mg g⁻¹ tetracycline at 25 °C. Intercropping *Lolium multiflorum* and *Brassica juncea* removes tetracyclines, sulfonamides and quinolones from soil (2.38–54.40 % efficiency) (21). *Phragmites australis* removes sulfamethoxazole and ofloxacin via root uptake; *Lemna minor* and *Salvinia molesta* metabolise ciprofloxacin and sulfamethoxazole in water (77). Vetiver grass achieves 89–100 % tetracycline and 60–94 % ciprofloxacin removal (78). Hydroponic studies show low antibiotic concentrations stimulate plant growth while higher levels inhibit it; *Acorus calamus* shows the highest removal efficiency via root uptake and rhizosphere microbial activity (*Aeromonas*, *Bacillus*, *Staphylococcus*) (79). Genetic engineering, immobilised enzymes, hybrid wetlands and photocatalysts (e.g., cuprous oxide (Cu₂O)/BC) further enhance degradation efficiency (80), though complex contaminant mixtures and toxic intermediates still constrain long-term performance,

underscoring the need for optimised microbial consortia and field-scale validation (64, 74).

Microplastics and nanoplastics in agroecosystem

Agroecosystems are increasingly recognised as major sinks for micro and NPs, with loading to agricultural land via sludge and organic fertilisers already estimated to be of the same order as, or higher than, inputs to the oceans, making terrestrial systems a dominant global reservoir (81). These plastics enter fields through multiple pathways, including plastic mulching films, sewage sludge and sludge-based fertilisers, organic amendments and composts, polymer-coated fertilisers and pesticides, irrigation with contaminated or treated wastewater and atmospheric deposition of airborne particles and fibres (82, 83). Among these sources, plastic mulching is consistently identified as the primary contributor in modern agriculture: long-term mulched fields in China show strong linear relationships between regional mulch film consumption and macroplastic residues and time-dependent increases in soil MPs from tens to over 1000 particles kg⁻¹ as films fragment under UV radiation, weathering and mechanical disturbance (84). Greenhouse and intensively mulched soils usually contain substantially higher MP abundances than open-field or non-mulched systems. China is reported as the largest global consumer of agricultural plastic mulch, helping explain particularly high soil burdens there (84). Sewage sludge and sludge-derived composts represent a secondary but very important source, because wastewater treatment plants efficiently trap MPs in sludge: successive sludge applications (typically 20–40 t ha⁻¹) cause stepwise increases in soil MP counts, with clear positive correlations between number of applications or sludge rate and MP abundance and long-term experiments show that sludge-derived particles can persist in topsoils for decades (85). Atmospheric deposition is increasingly recognised as a major diffuse input to farmland, with regional mass-balance studies indicating that dry and wet fallout can account for a substantial fraction of total MP loading, complementing inputs from treated wastewater, textile and packaging fragments, tire wear and inadequate waste management (86). Within this context, the rhizosphere and phyllosphere function as critical interfaces where MPs interact with roots, soil biota and above-ground plant surfaces, influencing particle retention, transformation and potential entry into food webs (87). Once present at these interfaces, plant uptake of MPs and nanoplastics (MPs/NPs) proceeds through a multi-stage, size-dependent pathway system rather than a single mechanism, comprising crack-entry, apoplastic diffusion and symplastic transport, whereby the crack-entry route facilitates initial entry of larger particles, the apoplastic pathway enables passive intercellular movement and the symplastic mechanism drives intracellular penetration and deeper translocation of smaller particles (88). Root entry is largely enabled by natural, transient fissures forming at sites of lateral root emergence and within the actively dividing root apical meristem, where the Casparian strip has not yet fully

developed; submicrometer- and micrometer-scale polystyrene and polymethyl methacrylate particles have been shown to exploit these cracks to reach the stele and accumulate within xylem, with detection inside xylem conduits within 2 hr and migration to cortical tissues within twelve hours under transpiration-driven flow, effectively bypassing the traditional apoplastic barrier posed by the endodermal Casparian strip (89). Once past the epidermis and cortex, particles reach the endodermis and central vascular cylinder, from where transpiration-driven mass flow plays a pivotal role in regulating their translocation to above-ground tissues (90). In addition to root-mediated uptake, foliar entry occurs via two routes: absorption through the leaf cuticle and through stomata, with stomatal uptake from ambient air reaching the apoplastic pathway before further internal transport (91). Additional pathways proposed across the literature include adhesion onto root surfaces, endocytosis and entry through plasmodesmata (92), alongside aquaporin-mediated entry (90), though several of these remain context-dependent and method-sensitive rather than universally established, particularly with respect to long-distance transport to aboveground parts under field-realistic soil conditions (92). Uptake efficiency is further modulated by particle-level properties: NPs in the 50–150 nm range show markedly higher frequency in intercellular layers and are also detected in leaves, with their smaller size favouring apoplastic transport as a key route for uptake and translocation (93), while movement is additionally regulated by rhizosphere mucilage trapping and hydrophobic interactions between particles and cell walls, allowing retention within cell-wall pores and bidirectional migration along vascular pathways with water and nutrient flow (94). Collectively, these mechanisms position MP/NP translocation as a physicochemically governed, tissue-dependent process with direct implications for food-chain transfer, warranting closer mechanistic integration alongside co-occurring antibiotic and heavy-metal contaminants in future remediation and risk-assessment frameworks.

Impact of microplastics on the agroecosystem

Agronomic practices such as tillage also contribute to the widespread presence of MPs in agricultural soils. Accumulated MPs disturb soil by causing physical perturbations and altering physico-chemical properties, which in turn influence soil structure, gas exchange, field capacity, water holding capacity and biogeochemical cycling of nutrients. The magnitude of the effect mainly depends on the concentration of fragmented plastic particles, the duration of the exposure, quantity of MPs and type of polymer used in plastic production. Their major impact on soil biota includes changes in microbial community composition and effects on earthworms and other invertebrates, which can disrupt microbial diversity and impair the ecosystem functions these community's support. They are reported to alter N metabolism and have negative impacts on animal growth, reproduction and behaviour (88). Increase in soil pH induces leaching of chemical additives from the MPs which converts

organic N to ammoniacal N. However, soil pH is influenced by an array of factors. In addition, Soil macro- and micro-fauna aids in the widespread occurrence of these MPs. Further it enters the plant system reduces root growth, transpiration rate, delay germination rate and inhibits water absorption ultimately leading to reduced biomass and yield production. It is of critical concern since it can adsorb other contaminants from the environment such as pesticides, HMs, organic pollutants, pathogens etc acting as a vector enhancing contaminant availability and toxicity (85). Low density polyethylene and polylactic acid from MPs reduce the rice yield by 32.1 and 32.9 %, grain protein level 4.5 and 2.8 % and reduction in lysine level by 91.1 and 63.6 %, respectively. Besides N assimilation is enhanced by MPs in roots and stem but not in leaves and exhibited microbial N functionality and disturbed N metabolism (89). High density as well as low density polyethylene MPs affects photosynthetic activity of the plants, alters tissue composition and biomass production. Crop uptake raises concern about human dietary exposure. Chronic exposure of these MPs is observed in human blood, placenta and other tissues (81). Cumulative effect of MPs on agroecosystem illustrated in Fig. 8, standardisation and quantification protocol could be explored further for deep understanding and for policy frameworks.

Mitigation and management strategies

Source reduction

Numerous studies have been conducted to quantify MPs in crop systems. On the mitigation front, alternatives to plastic mulches are being actively explored to reduce the MPs concentration in soil caused by polyethylene mulches. As a mitigating approach, biodegradable films are directly incorporated into the soil thereby eliminating the residue issue of plastic mulches. Direct incorporation improves soil physical, chemical, biological properties which enhance microbial biodiversity, control weeds and soil moisture maintenance. Complete mineralisation of these biodegradable films has to be achieved for a clean soil. High carbon-nitrogen (C : N) ratio alters biogeochemical cycling and shifts soil microbial diversity and communities. Ecotesting on earthworms has raised concerns about the complete degradability of biodegradable films. Alternative materials are emerging, such as an atrazine-integrated poly (vinyl alcohol) /xanthan gum active film developed for herbicide-releasing mulch applications, which achieved a tensile strength of 42.73 MPa, blocked UV radiation and was capable of degrading within 30 days (90). As a part of source reduction, management of sewage sludge is crucial in controlling the entry of MPs in agricultural soils. Conventional treatment of sewage sludge fails to reduce the load of MPs. 78–99.9 % removal of MPs has been achieved in membrane bioreactor technology with sludge incineration (91). It is also reported that redirection of sludge towards bricks manufacturing could be a feasible solution in phasing out MPs in agroecosystem due to biosolids application (92). Government policies, strict

regulation and awareness campaigns can register the impact of plastic pollution.

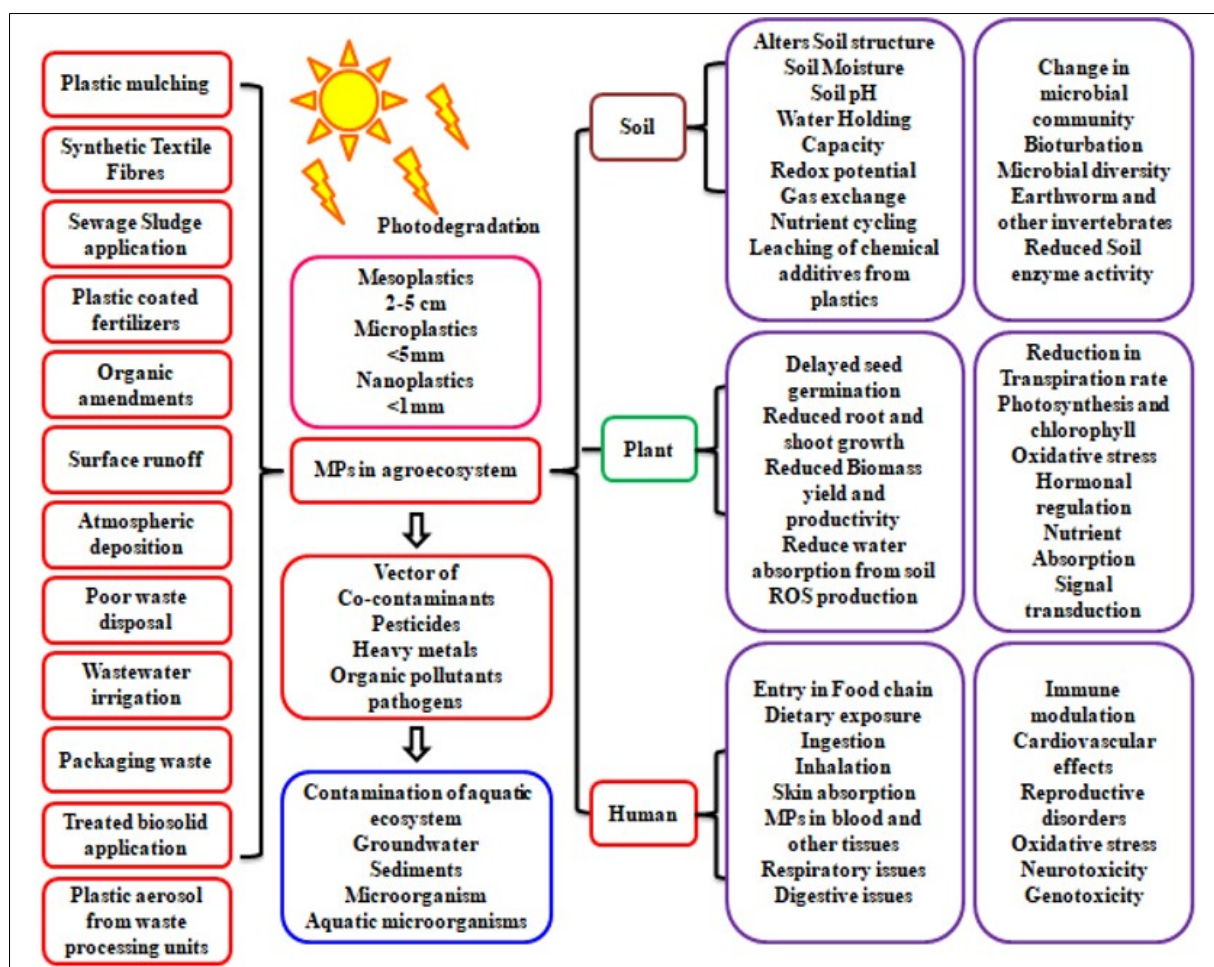


Fig. 8. Schematic of the fate and transport of microplastics and nanoplastics in the agroecosystem, from source inputs (mulch films, sewage sludge, irrigation water) through soil transport processes to plant uptake and trophic transfer.

Management of contaminated sites

Bioremediation and phytoremediation are tested against eliminating the MP load from the soil. Biochar is widely used as a soil amendment which stabilises soil aggregates, improves porosity, moisture retention, regulation of pH and nutrient levels enhances microbial diversity in contaminated soils (50, 93). Biochar increased the crop yield by 30–80 % despite the high MP concentration which favours crop production by mobilising phosphorous by 46 % and increasing organic carbon by 35 % and declines antibiotic resistance genes by enhancing beneficial microbes (94). It is also introduced to remediate co-contaminated soil (MPs and HMs). In this case, it reduces the bioavailability of cadmium by 14–15 %. Apart from this, earthworms are also introduced into the soil aiming for the degradation of MPs by exopolysaccharides generated by the gut microbes of earthworm and their mucus (41). *Lumbricus terrestris* can fragment low-density polyethylene (LDPE) plastics in the gizzard can depolymerise polylactic acid (PLA) and polybutanoic acid particles thereby increasing the particle accumulation from 8.4–18.8 % (39). Thus,

bioremediation has the potential to degrade MPs in a sustainable manner (95, 96) (Table 3).

Co-contaminant interactions in agroecosystems

Although the preceding sections treat HMs, VAs and MPs separately for clarity, agroecosystems rarely receive a single contaminant class in isolation: manures, biosolids and irrigation water typically co-deliver metals, antibiotics and plastic residues together and their combined fate differs from that predicted by single-contaminant studies. Three interaction mechanisms are particularly well documented. First, sorption competition and complexation: MP surfaces and metal oxides/cations provide sorption sites and complexing ligands that can bind antibiotics, altering their bioavailability, mobility and persistence relative to single-contaminant systems; the direction of the effect (enhanced retention versus enhanced co-transport) depends on the specific metal, antibiotic and plastic polymer involved and remains inconsistently characterised in agricultural soils specifically. Second, co-selection of resistance genes: co-exposure to metals and antibiotics can favour bacteria carrying both metal-resistance and antibiotic-resistance determinants, particularly where resistance genes are

genetically linked on the same mobile genetic elements, so that metal contamination in manure-amended soils may indirectly sustain antibiotic-resistance gene pools even where antibiotic residues themselves have degraded. Third, MPs as vectors and microbial habitat: the plastisphere biofilm that forms on MP surfaces can concentrate metals, antibiotics and resistant bacteria

simultaneously, potentially facilitating their co-transport through soil profiles and into drainage water. Despite the mechanistic plausibility of these interactions, quantitative, field-scale evidence that partitions the combined toxicity or transport behaviour of multi-contaminant mixtures in agricultural soils remains limited and this is identified as a priority research gap in the conclusion.

Table 3. Comparative performance of bioremediation strategies for emerging agroecosystem contaminants

Contaminant type	Representative contaminant / case	Remediation approach	Reported result	Matched technology category	Relative cost*	Field applicability*	Approx. technology readiness*	Ref
Heavy metal	Cd, Pb, Hg, Zn, Fe and Cr	Phytoremediation	Not quantified in source	Phytoremediation	Low (minimal infrastructure; plant-based)	Field-validated at pilot/farm scale (soil/runoff)	Moderate-High (field pilots exist)	(23, 34)
Heavy metal	Cd, Pb, Ni and Zn	Immobilisation using amendments (Biochar-Zeolite)	Reduced bioavailable Cd by 14–15 %	Adsorption (biochar/activated C) - soil immobilisation variant, not water treatment	Low (biochar/zeolite low-cost)	Full-scale for soil amendment; distinct from water-treatment adsorption	High (biochar amendment well-established agronomically)	(35, 97)
Heavy metal	Pb	Bioremediation (biosorption)	61 %	Bioaugmentation / targeted microbial degradation	Low (low-cost inputs; strain maintenance needed)	Lab/pilot scale predominantly; limited field validation	Low-Moderate (emerging)	(17)
Antibiotics	Amoxicillin	Biodegradation	88.7 % at 72 hr	Bioaugmentation / targeted microbial degradation	Low (low-cost inputs; strain maintenance needed)	Lab/pilot scale predominantly; limited field validation	Low-Moderate (emerging)	(98)
Antibiotics	Chlortetracycline, doxycycline, tetracycline	Biosorption	216.4 mg g ⁻¹ (pH 4.0); 121.2 mg g ⁻¹ (pH 3.0); 23.2 mg g ⁻¹ (pH 7.0)	Adsorption (biochar/activated C) - fungal-biomass biosorption variant	Low (biomass-based sorbent, low material cost)	Lab-scale; full-scale biosorption columns not yet field-validated for antibiotics	Low-Moderate (emerging for antibiotics; adsorption itself is mature)	(76)
Antibiotics	Tetracyclines, sulfonamides, quinolones	Phytoremediation / intercropping	2.38–54.40 % removal	Phytoremediation	Low (minimal infrastructure; plant-based)	Field-validated at pilot/farm scale for soil and agricultural runoff	Moderate-high (field pilots exist)	(21)
Antibiotics	Ciprofloxacin	Phytoremediation	60–94 % removal	Phytoremediation	Low (minimal infrastructure; plant-based)	Field-validated at pilot/farm scale	Moderate-High (field pilots exist)	(78)
Antibiotics	Sulfamethoxazole	Engineered microbial remediation (genetically modified strain)	44 % removal	Bioaugmentation / targeted microbial degradation-GMO variant, additional regulatory constraints	Low input cost, but GMO containment/r regulatory costs not captured here	Lab-scale only; field release of GM strains raises separate regulatory barriers	Low (early-stage; GMO status lowers practical readiness further)	(80)
Microplastics/ Nanoplastics	LDPE, PLA particles	Earthworm-assisted degradation	Particle accumulation increased 8.4–18.8 %	Vermifiltration-soil fauna variant; Table 2 rating derived from water-based vermifiltration, not soil	Low (low-cost, low-energy)	Pilot/small-scale; niche application	Low-Moderate (emerging)	(39)
Microplastics/ Nanoplastics	Soil MPs	Earthworm-mediated remediation	Shannon diversity improved by 4 %	Vermifiltration - soil fauna variant; Table 2 rating derived from water-based vermifiltration, not soil	Low (low-cost, low-energy)	Pilot/small-scale; niche application	Low-moderate (emerging)	(41)
Emerging contaminants	Pharmaceuticals, herbicides, PPCPs	Phytoremediation	60–95 %	Phytoremediation	Low (minimal infrastructure; plant-based)	Field-validated at pilot/farm scale	Moderate-High (field pilots exist)	(95)

Mixed contaminants + pharmaceuticals	HMs + pesticides	Bioremediation (multi-organism consortia)	65–97 %	-	-	-	-	(96)
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C: carbon; Cd: cadmium; Pb: lead; Hg: mercury; Zn: zinc; Fe: iron; Cr: chromium; Ni: nickel; HMs: heavy metals; MPs: microplastics; LDPE: low-density polyethylene; PLA: polylactic acid; GM: genetically modified; GMO: genetically modified organisms; PPCP: pharmaceuticals and personal care products.

Cross-cutting considerations: Regulation, detection, risk assessment, climate and economics

1. Regulatory frameworks of India currently lacks contaminant-specific statutory limits for most ECs in agricultural soil, comparable to the produce- and effluent-focused standards administered by the Food Safety and Standards Authority of India (FSSAI) and the Central Pollution Control Board (CPCB); veterinary antibiotic use is addressed indirectly through India's National Action Plan on Antimicrobial Resistance rather than through agricultural-soil monitoring requirements and no dedicated regulatory threshold for MPs in soil or irrigation water currently exists. This regulatory gap is not unique to India: harmonised, contaminant-specific soil thresholds for VAs and MPs are similarly absent or inconsistent internationally. Analytical methods of detection and quantification remain a practical bottleneck across all three contaminant classes. Heavy metals are routinely quantified by ICP-MS/ICP-OES following acid digestion, offering high sensitivity and reasonable inter-laboratory comparability. Veterinary antibiotics require liquid chromatography-tandem mass spectrometry (LC-MS/MS) with matrix-matched calibration to control for soil organic matter interference and multi-residue methods capable of resolving tetracyclines, sulfonamides and fluoroquinolones simultaneously are still being refined. Microplastic quantification is the least standardised of the three: extraction (density separation, digestion), identification (Fourier transform infrared spectroscopy (FTIR), Raman, pyrolysis- as gas chromatography-mass spectrometry (GC/MS)) and size-fraction reporting vary widely between studies, complicating cross-study comparison and likely contributing to the wide abundance ranges reported in the MPs section above; adoption of harmonised protocols is needed before regional or temporal trends can be compared with confidence.
2. Risk assessment of existing risk-assessment frameworks for agricultural soils were largely developed for single contaminants and do not formally accommodate mixture toxicity, additive or synergistic dose-response relationships, or the resistance-gene dimension of combined metal-antibiotic exposure discussed above. Adapting mixture risk-assessment approaches used in aquatic ecotoxicology (e.g., concentration-addition and independent-action models) to soil-plant-human exposure pathways for HM-VA-MP co-contamination is an open methodological need rather than a solved problem.

3. Climate change interactions of rising temperatures, altered precipitation intensity and more frequent drought-flood cycles are expected to modify contaminant behaviour in agroecosystems: warmer soils generally accelerate microbial degradation of antibiotics but can also increase metal desorption and bioavailability under fluctuating redox conditions, intensified rainfall increases surface runoff and leaching of both metals and MPs and drought-induced soil cracking can create preferential flow paths that bypass sorption sites intended to retain contaminants. These interactions are rarely addressed in the remediation studies reviewed here, most of which were conducted under controlled, non-fluctuating conditions.
4. Economic considerations of most data are seldom reported alongside removal efficiency, which limits judgements about field deployability. As a general pattern, phytoremediation and biochar-based amendments are typically lower-cost and more scalable to farm level than engineered microbial or nanomaterial-based approaches, but require longer treatment times and are more sensitive to site-specific conditions; the trade-off between cost, treatment duration and removal efficiency should be reported explicitly in future primary studies to support technology selection by farmers and regulators.

4. Conclusion

Heavy metals (HMs), veterinary antibiotics (VAs) and microplastics (MPs) co-occur widely in manure- and biosolid-amended agroecosystems, individually and jointly threatening soil health, crop productivity, ecosystem stability and public health. Their diffuse sources, persistence and capacity for sorption- and resistance-gene-mediated interaction distinguish this problem from classical single-pollutant pollution and substantially complicate monitoring, risk assessment and remediation. Among strategies evaluated, biochar-zeolite amendments for heavy metal immobilisation, engineered biochars and constructed wetlands for antibiotic removal and hybrid plant-microbe systems for MP and mixed-contaminant degradation show the strongest reported performance. However, these results derive predominantly from laboratory- or pilot-scale studies under controlled conditions and should be read as indicators of technological potential rather than field-ready guarantees. Priority research should focus on several interconnected fronts. Long-term, field-scale validation of remediation technologies is needed, with standardised reporting of cost and treatment duration alongside removal efficiency, to enable meaningful cross-study



comparison and support technology transfer. Equally important is mechanistic and quantitative characterisation of heavy metal-antibiotic-MP interactions, including sorption competition and resistance-gene co-selection, studied under realistic agricultural conditions rather than idealised single-contaminant systems. Harmonised analytical protocols particularly for MP extraction and identification remain essential to enable cross-regional comparability, currently a major barrier to synthesis in this field. Finally, mixture-toxicity risk-assessment frameworks require adaptation to soil-plant-human exposure pathways, with explicit attention to India and other under-represented regions, alongside closer integration of climate-change projections into remediation design, given the sensitivity of sorption, desorption and microbial degradation to temperature and moisture fluctuations. Sustained interdisciplinary collaboration is essential to manage rising co-contaminant pressures and safeguard ecosystem services, food safety and public health.

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Authors' contributions

SP¹ contributed to conceptualisation, performed literature search, formal analysis, investigation, methodology, visualisation and writing-original draft. PPC and BA performed literature search, data curation, writing review and editing. SP², BK, MD, NS and SR contributed to conceptualisation, supervision, writing review and editing. All authors read and approved the final manuscript. [SP¹ stands for Sengottian Priyatharshini and SP² stands for Sellaperumal Pazhanivelan].

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Paperpal in order to maintain language consistency in the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Aziz S, Zaib S, Iqbal A, Chuadhry MA, Shahzad S, Dhara B, et al. Emerging contaminants and their influence on plants: An in-depth review. *Environ Toxicol Pharmacol* 2026;121:104872. <https://doi.org/10.1016/j.etap.2025.104872>
2. Carter LJ, Adams B, Berman T, Cohen N, Cytryn E, Elder FC, et al. Co-contaminant risks in water reuse and biosolids application for agriculture. *Environ Pollut* 2025;375:126219. <https://doi.org/10.1016/j.envpol.2025.126219>
3. Tiwari D, Kumar R, Yadav M, Gupta GK, Singh SK, Dhapekar NK, et al. Holistic analysis of Ganga basin water quality: a statistical approach with WQI, HMCI, HMQI and HRI indices. *RSC Adv* 2025;15:3290–316. <https://doi.org/10.1039/D4RA06144F>
4. Li SW, Chang M, Huang X, Li H, Li HB, Ma LQ, et al. Coupling *in vitro* assays with sequential extraction to investigate cadmium bioaccessibility in contaminated soils. *Chemosphere* 2022;288:132655. <https://doi.org/10.1016/j.chemosphere.2021.132655>
5. Anas M, Altun V, Khattak WA, Khan A, Ercişli S, Khan KA, et al. Environmental geochemistry of emerging contaminants: impacts on agroecosystem function, food security and human health. *Environ Geochem Health* 2026;48:117. <https://doi.org/10.1007/s10653-026-03007-z>
6. Tiwari A, Tiwari N, Tiwari U. Assessing the phytotoxicity of emerging pollutants on vegetable crops grown with sewage effluent. *Sci Total Environ* 2025;989:179865. <https://doi.org/10.1016/j.scitotenv.2025.179865>
7. Pathak VM, Verma VK, Rawat BS, Kaur B, Babu N, Sharma A, et al. Current status of pesticide effects on environment, human health and its eco-friendly management as bioremediation: A comprehensive review. *Front Microbiol* 2022;13:962619. <https://doi.org/10.3389/fmicb.2022.962619>
8. Lee Y-Y, Cho K-S, Yun J. Phytoremediation strategies for co-contaminated soils: overcoming challenges, enhancing efficiency and exploring future advancements and innovations. *Processes* 2025;13:132. <https://doi.org/10.3390/pr13010132>
9. Gautam M, Nimesh S, Sharma C. Nano-bioremediation, a new approach to degrade veterinary antibiotics from environment. *Int J Mod Phys B* 2025;39:2550134. <https://doi.org/10.1142/S0217979225501346>
10. Hou R, Zhang J, Fu Q, Li T, Gao S, Wang R, et al. The boom era of emerging contaminants: A review of remediating agricultural soils by biochar. *Sci Total Environ* 2024;931:172899. <https://doi.org/10.1016/j.scitotenv.2024.172899>
11. Saleem M, Pierce D, Wang Y, Sens DA, Somji S, Garrett SH, et al. Heavy metal(oid)s contamination and potential ecological risk assessment in agricultural soils. *JoX* 2024;14:634–50. <https://doi.org/10.3390/jox14020037>
12. Rashid A, Schutte BJ, Ulery A, Deyholos MK, Sanogo S, Lehnhoff EA, et al. Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. *Agronomy* 2023;13:1521. <https://doi.org/10.3390/agronomy13061521>
13. Alengebawy A, Abdelkhalek ST, Qureshi SR, Wang MQ. Heavy metals and pesticides toxicity in agricultural soil and plants: ecological risks and human health implications. *Toxics* 2021;9:42. <https://doi.org/10.3390/toxics9030042>



14. Mubeen S, Ni W, He C. Agricultural strategies to reduce cadmium accumulation in crops for food safety. *Agriculture* 2023;13:471. <https://doi.org/10.3390/agriculture13020471>
15. Liu YR, Van der Heijden MG, Riedo J, Sanz-Lazaro C, Eldridge DJ, Bastida F, et al. Soil contamination in nearby natural areas mirrors that in urban greenspaces worldwide. *Nat Commun* 2023;14:1706. <https://doi.org/10.1038/s41467-023-37428-6>
16. Subramanian P, Pandian K, Pakkiyam S, Dhanuskodi KV, Annamalai S, Padanillay Chidambaram, et al. Biochar for heavy metal cleanup in soil and water: a review. *Biomass Conv Bioref* 2025;15:11421–41. <https://doi.org/10.1007/s13399-024-05989-1>
17. Dhevagi P, Priyatharshini S, Ramya A. Biosorption of lead ions by exopolysaccharide producing *Azotobacter* sp. *JEB* 2021;42:40–50. <https://doi.org/10.22438/jeb/42/1/MRN-1231>
18. Gupta M, Dwivedi V, Kumar S, Patel A, Niazi P, Yadav VK, et al. Lead toxicity in plants: mechanistic insights into toxicity, physiological responses of plants and mitigation strategies. *Plant Signal Behav* 2024;19:2365576. <https://doi.org/10.1080/15592324.2024.2365576>
19. Parida T, Riyazuddin S, Kolli SK, Chakraborty A, Srinivas N, Kundu P, et al. Phytoremediation of heavy metal(loid)s with integral involvement of the endogenous metal-chelators: present state-of-the-art and future prospect. *Discov Environ* 2024;2:139. <https://doi.org/10.1007/s44274-024-00170-x>
20. Rabha S, Dhaneesh KV. The impact of heavy metal accumulation on agricultural soils and its mitigation. *UPJOZ* 2024;45:77–89. <https://doi.org/10.56557/upjoz/2024/v45i204567>
21. Cui E, Cui B, Fan X, Li S, Gao F. Ryegrass (*Lolium multiflorum* L.) and Indian mustard (*Brassica juncea* L.) intercropping can improve the phytoremediation of antibiotics and antibiotic resistance genes but not heavy metals. *Sci Total Environ*. 2021;784:147093. <https://doi.org/10.1016/j.scitotenv.2021.147093>
22. Viana RD, Chagas JK, Paz-Ferreiro J, de Figueiredo CC. Enhanced remediation of heavy metal-contaminated soils using biochar and zeolite combinations with additives: A meta-analysis. *Environ Pollut*. 2025;367:125617. <https://doi.org/10.1016/j.envpol.2024.125617>
23. Bhat SA, Bashir O, Haq SA, Amin T, Rafiq A, Ali M, et al. Phytoremediation of heavy metals in soil and water: An eco-friendly, sustainable and multidisciplinary approach. *Chemosphere*. 2022;303:134788. <https://doi.org/10.1016/j.chemosphere.2022.134788>
24. Panda A, Fatnani D, Parida AK. Uptake, impact, adaptive mechanisms and phytoremediation of heavy metals by plants: Role of transporters in heavy metal sequestration. *Plant Physiol Biochem*. 2025;221:109578. <https://doi.org/10.1016/j.plaphy.2025.109578>
25. Carter LJ, Ben Mordechay E, Chefetz B, Chen Z, Cui X, Gan J, et al. Contaminants of emerging concern in agricultural soils: current understanding, overlooked issues and future priorities. *Plants People Planet*. 2026:ppp3.70158. <https://doi.org/10.1002/ppp3.70158>
26. Khan IU, Qi SS, Gul F, Manan S, Rono JK, Naz M, et al. A Green Approach Used for Heavy Metals 'Phytoremediation' Via Invasive Plant Species to Mitigate Environmental Pollution: A Review. *Plants*. 2023;12:725. <https://doi.org/10.3390/plants12040725>
27. Gantayat RR, Elumalai V. Salinity-Induced Changes in Heavy Metal Behavior and Mobility in Semi-Arid Coastal Aquifers: A Comprehensive Review. *Water*. 2024;16:1052. <https://doi.org/10.3390/w16071052>
28. Cheng Z, Wang C, Tang F, Zhou Y, Zhu C, Ding Y, et al. The cell wall functions in plant heavy metal response. *Ecotoxicol Environ Saf*. 2025;299:118326. <https://doi.org/10.1016/j.ecoenv.2025.118326>
29. Yang Y, Chen S, Liu H, Chen H, Lu Z, Qiao G, et al. Plant ZIP transporter: functional analysis on metal uptake, transport and homeostasis. *Plant Physiol Biochem*. 2025;229:110336. <https://doi.org/10.1016/j.plaphy.2025.110336>
30. Li D, He T, Saleem M. Metalloprotein-Specific or Critical Amino Acid Residues: Perspectives on Plant-Precise Detoxification and Recognition Mechanisms under Cadmium Stress. *Int J Mol Sci*. 2022;23:1734. <https://doi.org/10.3390/ijms23031734>
31. Liu N, Yang C, Wang Y, Lv Y, Wang Y, Wang Q, et al. Functional Analysis of Key Transporter Genes Involved in Cadmium Uptake and Translocation in Wheat. *Agronomy*. 2025;15:2515. <https://doi.org/10.3390/agronomy15112515>
32. Xiong M, Qi L, Li X, Yue Z, Yang Y, Han F, et al. Rhizosphere-driven alteration of cadmium bioavailability under Cd stress. *Soil Sci Soc Am J*. 2025;89:e70061. <https://doi.org/10.1002/saj2.70061>
33. Agarwal P, Vibhandik R, Agrahari R, Daverey A, Rani R. Role of Root Exudates on the Soil Microbial Diversity and Biogeochemistry of Heavy Metals. *Appl Biochem Biotechnol*. 2024;196:2673–93. <https://doi.org/10.1007/s12010-023-04465-2>
34. Bortoloti GA, Baron D. Phytoremediation of toxic heavy metals by Brassica plants: A biochemical and physiological approach. *Environ Adv*. 2022;8:100204. <https://doi.org/10.1016/j.envadv.2022.100204>
35. Rahimi M, Bertalan-Balázs B, Adelinia A, Ebrahimi E, Ojani M. Impact assessment of Zeolite, Ca-bentonite and Biochar amendments on Cd bioavailability and fractions in polluted calcareous soils. *Environ Earth Sci*. 2024;83:506. <https://doi.org/10.1007/s12665-024-11803-y>
36. Marques DN, Thiengo CC, Azevedo RA. Phytochelatins and Cadmium Mitigation: Harnessing Genetic Avenues for Plant Functional Manipulation. *Int J Mol Sci*. 2025;26:4767. <https://doi.org/10.3390/ijms26104767>
37. Alabi MA, Chenia HY, Lin J. Antibiotic Use in Livestock: A Driver of Resistance in Africa and the Path to Safer Alternatives. *MicrobiologyOpen*. 2025;14:e70122. <https://doi.org/10.1002/mbo3.70122>
38. Van Boeckel TP, Brower C, Gilbert M, Grenfell BT, Levin SA, Robinson TP, et al. Global trends in antimicrobial use in food animals. *Proc Natl Acad Sci USA*. 2015;112:5649–54. <https://doi.org/10.1073/pnas.1503141112>
39. Meng K, Harkes P, Lwanga EH, Geissen V. Microplastics exert minor influence on bacterial community succession during the aging of earthworm (*Lumbricus terrestris*) casts. *Soil Biol Biochem*. 2024;195:109480. <https://doi.org/10.1016/j.soilbio.2024.109480>
40. Mulchandani R, Wang Y, Gilbert M. Global trends in antimicrobial use in food-producing animals: 2020 to 2030. *PLOS Glob Public Health*. 2023;3:e0001305. <https://doi.org/10.1371/journal.pgph.0001305>
41. Rehman SU, Hussain M, De Castro F, Benedetti M, Aprile A, Fanizzi FP, et al. Microplastics in Agricultural Soil: Fate, Impacts and Bioremediation by Earthworms. *J Plant Nutr Soil Sci*. 2025;188:873–93. <https://doi.org/10.1002/jpln.70013>



42. Gaballah MS, Guo J, Sun H, Aboagye D, Sobhi M, Muhmood A, et al. A review targeting veterinary antibiotics removal from livestock manure management systems and future outlook. *Bioresour Technol.* 2021;333:125069. <https://doi.org/10.1016/j.biortech.2021.125069>
43. Li S, Zhu Y, Zhong G, Huang Y, Jones KC. Comprehensive Assessment of Environmental Emissions, Fate and Risks of Veterinary Antibiotics in China: An Environmental Fate Modeling Approach. *Environ Sci Technol.* 2024;58:5534–47. <https://doi.org/10.1021/acs.est.4c00993>
44. Conde-Cid M, Núñez-Delgado A, Fernández-Sanjurjo MJ, Álvarez-Rodríguez E, Fernández-Calviño D, Arias-Estévez M, et al. Tetracycline and Sulfonamide Antibiotics in Soils: Presence, Fate and Environmental Risks. *Processes.* 2020;8:1479. <https://doi.org/10.3390/pr8111479>
45. Danasekaran R. One Health: A Holistic Approach to Tackling Global Health Issues. *Indian J Community Med.* 2024;49:260–3. https://doi.org/10.4103/ijcm.ijcm_521_23
46. Kuppusamy S, Venkateswarlu K, Megharaj M, Lee YB. Risks of veterinary antibiotics contamination in Indian organic farmlands: A reality unfolded. *Environ Adv.* 2024;15:100509. <https://doi.org/10.1016/j.envadv.2024.100509>
47. Paramitadevi YV, Priadi CR, Rahmatika I, Rukmana A, Moersidik SS. Integration of water, sanitation and hygiene program with biosecurity: a One Health approach to reduce the prevalence and exposure of antibiotic-resistant bacteria in the livestock community. *Int J One Health.* 2023;181–93. <https://doi.org/10.14202/IJOH.2023.181-193>
48. Akhter S, Bhat MA, Ahmed S. Antibiotic residue contamination in the aquatic environment, sources and associated potential health risks. *Environ Geochem Health.* 2024;46:387. <https://doi.org/10.1007/s10653-024-02146-5>
49. Pham MN, Nishimura F, Lan JC, Khoo KS. Recent advancement of eliminating antibiotic resistance bacteria and antibiotic resistance genes in livestock waste: A review. *Environ Technol Innov.* 2024;36:103751. <https://doi.org/10.1016/j.eti.2024.103751>
50. FAO Livestock Biomass Conversion Study Authors. The future of antibiotic use in livestock. *Nat Commun.* 2025. <https://doi.org/10.1038/s41467-025-56825-7>
51. Gbadegesin LA, Tang X, Liu C. Transport of Veterinary Antibiotics in Farmland Soil: Effects of Dissolved Organic Matter. *Int J Environ Res Public Health.* 2022;19:1702. <https://doi.org/10.3390/ijerph19031702>
52. Nkoh JN, Shang C, Okeke ES, Ejeromedoghene O, Oderinde O, Etafo NO, et al. Antibiotics soil-solution chemistry: A review of environmental behavior and uptake and transformation by plants. *J Environ Manage.* 2024;354:120312. <https://doi.org/10.1016/j.jenvman.2024.120312>
53. Sodhi KK, Kumar M, Singh DK. Insight into the amoxicillin resistance, ecotoxicity and remediation strategies. *J Water Process Eng.* 2021;39:101858. <https://doi.org/10.1016/j.jwpe.2020.101858>
54. Nybom I, Bucheli TD, Garland G. Antibiotics Uptake from Soil and Translocation in the Plants – Meta-analysis. *Chimia.* 2024;78:209–14. <https://doi.org/10.2533/chimia.2024.209>
55. van Dongen KC, Huang W, Jongedijk E, van de Kooi B, de Lange E, van der Fels-Klerx HJ, et al. Transfer of antibiotic residues from digestate-amended soil to edible crops in a circular food production system. *Environ Pollut.* 2025;384:126915. <https://doi.org/10.1016/j.envpol.2025.126915>
56. Hu JS, Xiao HY, Tang XY, Yan H, Chen Z, Cheng JH, et al. Polarity and fluorescent fractions of manure dissolved organic matter could affect differently the adsorption and desorption of antibiotics in soils. *J Environ Manage.* 2025;378:124767. <https://doi.org/10.1016/j.jenvman.2025.124767>
57. Herrero-Villar M, Taggart MA, Mateo R. Medicated livestock carcasses and landfill sites: Sources of highly toxic veterinary pharmaceuticals and caffeine for avian scavengers. *J Hazard Mater.* 2023;459:132195. <https://doi.org/10.1016/j.jhazmat.2023.132195>
58. Guo X, Xiong J, Liu H, Wang H, Cheng Q, Tang F, et al. Targeted Screening, Distribution and Sources of Antibiotics in Drinking Water Sources and its Risk Assessment in Sichuan Province, China. *Environ Manage.* 2025;75:1168–80. <https://doi.org/10.1007/s00267-025-02120-6>
59. Yang LH, Qiao B, Xu QM, Liu S, Yuan Y, Cheng JS, et al. Biodegradation of sulfonamide antibiotics through the heterologous expression of laccases from bacteria and investigation of their potential degradation pathways. *J Hazard Mater.* 2021;416:125815. <https://doi.org/10.1016/j.jhazmat.2021.125815>
60. Xi F. The enrofloxacin pollution control from fish to environment. *Mar Pollut Bull.* 2024;199:115923. <https://doi.org/10.1016/j.marpolbul.2023.115923>
61. Nguyen MK, Lin C, Bui XT, Rakib MR, Nguyen HL, Truong QM, et al. Occurrence and fate of pharmaceutical pollutants in wastewater: insights on ecotoxicity, health risk and state-of-the-art removal. *Chemosphere* 2024;354:141678. <https://doi.org/10.1016/j.chemosphere.2024.141678>
62. Benarab N, Fangninou FF. The issues of antibiotics: cephalixin antibiotic as emerging environment contaminant. *IJSRP* 2020;10:p9843. <https://doi.org/10.29322/IJSRP.10.02.2020.p9843>
63. Sikorski Ł, Beś A. Effects of two pharmaceuticals: doxycycline and norfloxacin on plant and animal organisms living in the freshwater. *Ecohydrol Hydrobiol* 2024;24:506–15. <https://doi.org/10.1016/j.ecohyd.2024.02.007>
64. Liu Y, Cheng D, Xue J, Feng Y, Wakelin SA, Weaver L, et al. Fate of bacterial community, antibiotic resistance genes and gentamicin residues in soil after three-year amendment using gentamicin fermentation waste. *Chemosphere* 2022;291:132734. <https://doi.org/10.1016/j.chemosphere.2021.132734>
65. Kodešová R, Chroňáková A, Grabicová K, Kočárek M, Schmidtová Z, Frková Z, et al. How microbial community composition, sorption and simultaneous application of six pharmaceuticals affect their dissipation in soils. *Sci Total Environ* 2020;746:141134. <https://doi.org/10.1016/j.scitotenv.2020.141134>
66. World Health Organization, Food and Agriculture Organization of the United Nations, United Nations Environment Programme, World Organisation for Animal Health. A one health priority research agenda for antimicrobial resistance. Geneva: World Health Organization; 2023.
67. El-Sharkawy H, Tahoun A, Rizk AM, Suzuki T, Elmonir W, Nassef E, et al. Evaluation of *Bifidobacteria* and *Lactobacillus* probiotics as alternative therapy for *Salmonella typhimurium* infection in broiler chickens. *Animals* 2020;10:1023. <https://doi.org/10.3390/ani10061023>



68. Lenkova T, Nikonov I, Kuznetsov Y, Karpenko L, Balykina A. Development of the probiotic feed supplement based on *Lactobacillus plantarum* to increase the broiler productivity. *Int J Innov Technol Explor Eng* 2019;9:2492–7. <https://doi.org/10.35940/ijtee.A4582.119119>
69. Iscaro C, Cambiotti V, Petrini S, Feliziani F. Control programs for infectious bovine rhinotracheitis (IBR) in European countries: an overview. *Anim Health Res Rev* 2021;22:136–46. <https://doi.org/10.1017/S1466252321000116>
70. Seidavi A, Tavakoli M, Asroosh F, Scanes CG, Abd El-Hack ME, Naiel MA, et al. Antioxidant and antimicrobial activities of phytonutrients as antibiotic substitutes in poultry feed. *Environ Sci Pollut Res* 2022;29:5006–31. <https://doi.org/10.1007/s11356-021-17401-w>
71. Baraitareanu S, Vidu L. Dairy farms biosecurity to protect against infectious diseases and antibiotics overuse. In: Mareş M, Hua Erin Lim S, Lai K-S, et al., editors. *Antimicrobial resistance-a one health perspective*. IntechOpen; 2021. <https://doi.org/10.5772/intechopen.93200>
72. Seo S. Precision feeding, precision livestock farming, SMART farming: are these our prospective livestock farming? *Anim Ind Technol* 2025;12:1–19. <https://doi.org/10.5187/ait.2025.12.1.1>
73. Amangelsin Y, Semenova Y, Dadar M, Aljofan M, Bjørklund G. The impact of tetracycline pollution on the aquatic environment and removal strategies. *Antibiotics* 2023;12:440. <https://doi.org/10.3390/antibiotics12030440>
74. Apreja M, Sharma A, Balda S, Kataria K, Capalash N, Sharma P, et al. Antibiotic residues in environment: antimicrobial resistance development, ecological risks and bioremediation. *Environ Sci Pollut Res* 2022;29:3355–71. <https://doi.org/10.1007/s11356-021-17374-w>
75. Ben Ayed A, Akrouf I, Albert Q, Greff S, Simmler C, Armengaud J, et al. Biotransformation of the fluoroquinolone, levofloxacin, by the white-rot fungus *Coriopholis gallica*. *JoF* 2022;8:965. <https://doi.org/10.3390/jof8090965>
76. Çakar ŞN, Göçenoğlu Sarıkaya A, Osman B. Biosorption of Congo red from aqueous solutions by *Craterellus cornucopioides* biosorbent: kinetic, isothermal and thermodynamic studies. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi* 2024;28(3):325–34. <https://doi.org/10.19113/sdufenbed.1454469>
77. Kochi LY, Kitamura RS, Rocha CS, Brito JC, Juneau P, Gomes MP, et al. Synergistic removal of ciprofloxacin and sulfamethoxazole by *Lemna minor* and *Salvinia molesta* in mixed culture: implications for phytoremediation of antibiotic-contaminated water. *Water* 2023;15:1899. <https://doi.org/10.3390/w15101899>
78. Panja S, Sarkar D, Datta R. Removal of tetracycline and ciprofloxacin from wastewater by vetiver grass (*Chrysopogon zizanioides* (L.) Roberty) as a function of nutrient concentrations. *Environ Sci Pollut Res* 2020;27:34951–65. <https://doi.org/10.1007/s11356-020-09762-5>
79. Lu X-M, Liu Y-X. Effects and mechanisms of aquatic landscape plants on the removal of veterinary antibiotics from hydroponic solutions. *Int J Phytoremediation* 2025;27:117–27. <https://doi.org/10.1080/15226514.2024.2402877>
80. Zhao R, Ma J, Shen S, Wang M, Sun Y. Deciphering the effects of *Paracoccus denitrificans* on florfenicol degradation and microbial community in sediments. *Aquaculture* 2025;596:741662. <https://doi.org/10.1016/j.aquaculture.2024.741662>
81. Wolff Leal T, Tochetto G, Lima SV, de Oliveira PV, Schossler HJ, de Oliveira CR, et al. Nanoplastics and Microplastics in Agricultural Systems: Effects on Plants and Implications for Human Consumption. *Microplastics*. 2025;4:16. <https://doi.org/10.3390/microplastics4020016>
82. Bocktor J, Hoyle FC, Farag MA, Ebaid M, Walsh T, Whiteley AS, et al. Microplastics and nanoplastics: fate, transport and governance from agricultural soil to food webs and humans. *Environ Sci Eur*. 2025;37:68. <https://doi.org/10.1186/s12302-025-01104-x>
83. Kumar M, Xiong X, He M, Tsang DC, Gupta J, Khan E, et al. Microplastics as pollutants in agricultural soils. *Environ Pollut*. 2020;265:114980. <https://doi.org/10.1016/j.envpol.2020.114980>
84. Sattar B, Liu G, Yousaf B, Arif M, Gulzar MZ, Haider MI, et al. Microplastic contamination in agricultural soils from mulch films and organic amendments: Transformation mechanism, soil-Biota toxicity and future perspectives. *Waste Manag*. 2025;205:115032. <https://doi.org/10.1016/j.wasman.2025.115032>
85. Okeke ES, Chukwudozie KI, Addey CI, Okoro JO, Ezeorba TP, Atakpa EO, et al. Micro and nanoplastics ravaging our agroecosystem: A review of occurrence, fate, ecological impacts, detection, remediation and prospects. *Heliyon*. 2023;9:e13296. <https://doi.org/10.1016/j.heliyon.2023.e13296>
86. Hoang VH, Nguyen MK, Hoang TD, Ha MC, Huyen NT, Bui VK, et al. Sources, environmental fate and impacts of microplastic contamination in agricultural soils: A comprehensive review. *Sci Total Environ*. 2024;950:175276. <https://doi.org/10.1016/j.scitotenv.2024.175276>
87. Tian L, Jinjin C, Ji R, Ma Y, Yu X. Microplastics in agricultural soils: sources, effects and their fate. *Curr Opin Environ Sci Health*. 2022;25:100311. <https://doi.org/10.1016/j.coesh.2021.100311>
88. Xiaoxiao F, Yuanyuan S, Chen S, Xu J. Trends and mechanisms in agricultural mulch film microplastic pollution: a critical review. *Green Sciences*. 2025;27:33–51. <https://doi.org/10.2478/pjct-2025-0015>
89. Guo S, Mu L, Sun S, Hou X, Yao M, Hu X, et al. Concurrence of microplastics and heat waves reduces rice yields and disturbs the agroecosystem nitrogen cycle. *J Hazard Mater*. 2023;452:131340. <https://doi.org/10.1016/j.jhazmat.2023.131340>
90. Eelager MP, Masti SP, Dalbanjan NP, Madihalli S, Gunaki MN, Kurbetta LK, et al. Atrazine integrated biodegradable poly(vinyl alcohol)/xanthan gum active films for mulching applications: An alternative to microplastic generation plastic mulch. *Prog Org Coat*. 2024;192:108510. <https://doi.org/10.1016/j.porgcoat.2024.108510>
91. Gambo AB. Engineering Solutions for the Detection and Remediation of Emerging Microplastic Pollutants in Agricultural Soils and Water Supplies: A Systematic Review. *IJRASET*. 2026;14:1665–73. <https://doi.org/10.22214/ijraset.2026.77195>
92. Mohajerani A, Karabatak B. Microplastics and pollutants in biosolids have contaminated agricultural soils: An analytical study and a proposal to cease the use of biosolids in farmlands and utilise them in sustainable bricks. *Waste Manag*. 2020;107:252–65. <https://doi.org/10.1016/j.wasman.2020.04.021>
93. Ji H, Zhou C, Li P. Applications of biochar in the remediation of soil microplastic pollution: A review. *Soil Sci Soc Am J*. 2025;89:e70078. <https://doi.org/10.1002/saj2.70078>

94. Dang TM, Huynh TT, Chang-Chien GP, Bui HM, et al. The role of biochar in combating microplastic pollution: a bibliometric analysis in environmental contexts. *Beilstein J Nanotechnol.* 2025;16:1401–16. <https://doi.org/10.3762/bjnano.16.102>
95. Kongkham B, Duraivadivel P, Gupta N, Shrabana N, Kumar P, et al. Mechanisms, prospects and limitations of vetiver-based green technology for remediation of environmental contaminants of emerging concern. *Discov Geosci.* 2026;4:160. <https://doi.org/10.1007/s44288-026-00532-3>
96. Chakraborty S, Talukdar A, Dey S. Role of fungi, bacteria and microalgae in bioremediation of emerging pollutants with special reference to pesticides, heavy metals and pharmaceuticals. *Discov Environ.* 2025;3:91. <https://doi.org/10.1007/s44274-025-00217-7>
97. Gondek K, Mierzwa-Hersztek M, Jarosz R. Effect of willow biochar and fly ash-derived zeolite in immobilizing heavy metals and promoting enzymatic activity in a contaminated sandy soil. *CATENA.* 2023;232:107429. <https://doi.org/10.1016/j.catena.2023.107429>
98. Dianatdar F, Etemadifar Z, Momenbeik F. Removal of amoxicillin and co-amoxiclav by newly isolated *Stenotrophomonas maltophilia* DF1. *Int J Environ Sci Technol.* 2024;21:9377–90. <https://doi.org/10.1007/s13762-024-05709-2>

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