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Review

An Integrated Review of Pesticides and Antibiotics in Agricultural Environments: Occurrence, Cross-Media Transport, and Plant Uptake

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Abstract

With the continuing intensification of modern agriculture, pesticides and antibiotics are extensively used to control pests and diseases, but their improper use and indirect inputs have resulted in widespread contamination of agricultural environments and food products. This review synthesizes how these contaminants enter agroecosystems, their occurrence across soils, waters and agricultural products, and the processes that redistribute residues across air–water–soil interfaces and into the soil–plant continuum. We summarize cross-media transport pathways (e.g., runoff/leaching, volatilization–deposition and irrigation-driven redistribution) and relate environmental exposure to plant uptake using a harmonized indicator set, including the bioconcentration factor (BCF), translocation factor (TF), octanol–water partition coefficient (log Kow) and soil organic carbon–water partition coefficient (Koc). We further discuss key determinants of crop accumulation, including compound-specific properties, soil characteristics and plant physiological traits, and highlight how these factors jointly shape residue profiles in edible tissues. Finally, we outline research priorities for source reduction, standardized multi-matrix surveillance, fate-to-uptake modeling, and microbiome-enabled remediation strategies to support pollution control, food safety and public health.

Keywords: agroecosystems; environmental monitoring; soil–crop transfer; cross-media transport; emerging contaminants

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1. Introduction

Pesticides and antibiotics are widely used in agricultural practice to control weeds, insect pests, and diseases to safeguard crop yields [1,2] and to maintain livestock health [3]. Compared with no control, the judicious application of pesticides can substantially increase crop yields: insecticides by approximately 36%, herbicides by about 50%, and fungicides by around 6% [4]. The use of antibiotics reduces the burden of livestock diseases and plays a major role in global animal production [5]. In addition, antibiotics such as streptomycin and oxytetracycline are important tools for suppressing bacterial epiphytotics in crops [6]. To meet rising food demand, global pesticide consumption has continued to increase; according to FAO, total pesticide use reached about 4.10 million tonnes in 2019, reflecting steady growth over time. For antibiotics, one study projects that global livestock antibiotic use (AMUQ) will increase by approximately 29.5% by 2040 relative to 2019 [7].

However, the excessive and improper use of pesticides and antibiotics in real-world agricultural production has resulted in continual inputs of diverse compounds into the environment and their subsequent transport, leading to widespread residues across agricultural ecosystems [8–11]. Recent studies have shown that approximately 64% of global agricultural land is at risk of pesticide pollution, with 31% classified as high-risk areas [12]. In addition, monitoring surveys of rivers worldwide have revealed that antibiotic concentrations at more than 25% of sampling sites exceed ecological risk thresholds [13].

Due to their high environmental persistence and bioaccumulation potential, these widely distributed contaminants can be absorbed and accumulated by crops [14], thereby entering the human body through the food chain and posing potential health risks. Studies have confirmed that vegetables, soybeans, and maize are capable of accumulating antibiotics from contaminated irrigation water [15,16], while crops such as cucumber and cowpea have been shown to take up and retain pesticide residues [17].

Accumulation of pesticides and antibiotics in crops introduces these chemicals into the food chain, creating an important human exposure route that poses potential health risks. Dietary exposure to pesticides has been associated with multiple adverse outcomes, including non-Hodgkin lymphoma, multiple myeloma, prostate cancer, Parkinson disease, as well as cognitive and respiratory disorders [18]. In recent years, exposure to low doses of antibiotics has been linked to numerous human health concerns, including obesity, carcinogenicity, reproductive effects, and teratogenicity [19], and residues in food have been implicated in these toxic effects [20,21]. Recent food-monitoring studies further indicate that pesticide residues remain frequently detectable in commonly consumed fruits and vegetables. A 17-year survey of 1223 apple samples detected 57 active substances in 64.2% of samples and identified compound-specific acute dietary risks for both children and adults, with children showing greater vulnerability; similarly, a large-scale study of 590 minor vegetable samples detected pesticide residues in 39.8% of samples and reported unacceptable acute risk in some child-consumption scenarios. Recent monitoring studies on commercially relevant fruits and vegetables further show that pesticide residues remain common in food matrices and may translate into differentiated dietary risks across consumer groups. Multi-year surveillance of apples [22] and a large-scale survey of minor vegetables [23] both reported frequent residue detection and identified higher concern in some child-exposure scenarios. In addition, contaminated foods can introduce antibiotic resistance genes (ARGs) into the human gastrointestinal tract [24], potentially undermining the effectiveness of antibiotics against common infections [25].

Beyond direct exposure concerns, this issue is also embedded in formal regulatory and governance systems. For pesticides, residue oversight is typically based on MRLs; Codex defines a pesticide MRL as the legally permitted maximum residue concentration in food or feed under good agricultural practice [26]. In the European Union, coordinated control programmes are implemented to verify compliance with MRLs and assess consumer exposure [27], whereas in the United States, analogous surveillance is conducted through the USDA Pesticide Data Program [28]. By contrast, the governance of antibiotic-related risks, particularly AMR, is increasingly framed within a One Health approach linking human, animal, plant, and environmental health [29]. Nevertheless, recent reviews suggest that integrated AMR surveillance remains insufficiently operationalized [30] and still requires stronger intersectoral coordination and governance capacity [31,32].

However, extant studies are still scattered, often concentrating on isolated aspects of the problem, such as contamination in a single environmental matrix, transport between compartments, or transfer from soil to plants, without integrating these elements into a comprehensive analysis. Consequently, there is a need for a clear framework that links environmental occurrences across various matrices with cross-media transport and the ac-

cumulation of residues in edible plant tissues. The development of standardized indicators and predictive models that connect environmental exposure to crop residues is limited, hindering effective monitoring and food-safety management.

Against this backdrop, this review summarizes the current status of pesticide and antibiotic contamination, examines environmental migration processes in plant–soil systems as well as the mechanisms of plant uptake and accumulation, and discusses the implications for food safety management and multi-matrix monitoring. This review aims to integrate occurrence, migration, and uptake into a unified analytical framework that links environmental distribution with the transfer of residues to edible crops. Finally, this paper outlines potential control strategies, including source reduction, microbiologically mediated remediation, and regional monitoring, with the aim of providing a more systematic scientific basis for contaminant management and food safety protection in agricultural environments.

To facilitate readers in reproducing the literature screening process described in this review, the detailed search strategy, inclusion criteria, and screening procedures are presented in Figure S1.

2. Pollution Status of Pesticides and Antibiotics

2.1. Common Contaminant Types and Sources

Pesticides are widely applied for the control of crop pests and diseases, while antibiotics are frequently used in livestock production and, to a lesser extent, in plant disease management. Based on their intended use, pesticides can be categorized into insecticides, fungicides, and herbicides [6]. Representative insecticide groups include organophosphates (e.g., chlorpyrifos, malathion), pyrethroids (e.g., cypermethrin), and neonicotinoids (e.g., imidacloprid), which are primarily used for insect control. Fungicides such as triazoles (e.g., tebuconazole) and benzimidazoles (e.g., carbendazim) target fungal pathogens, whereas herbicides like triazines (e.g., atrazine) and acetanilides (e.g., acetochlor) are widely applied to suppress weed growth in fields. Pesticides can also be classified according to their chemical structure [6], with major examples including organophosphates, organochlorines, carbamates, pyrethroids, neonicotinoids, and triazoles. Among them, organochlorine pesticides (e.g., DDT) have garnered global attention due to their environmental persistence and potential for biomagnification [33].

In terms of antibiotics, commonly used classes in agricultural production include tetracyclines, sulfonamides, fluoroquinolones, macrolides, aminoglycosides, and lincosamides [34]. For instance, oxytetracycline (a tetracycline) and sulfamethoxazole (a sulfonamide) are widely employed for disease prevention in livestock and poultry [35], and can persist in the environment long after excretion. Fluoroquinolones such as enrofloxacin and ciprofloxacin are extensively used in both livestock and aquaculture due to their broad-spectrum activity, yet they exhibit high ecological toxicity and poor degradability [36]. Aminoglycosides like streptomycin and kasugamycin are among the few antibiotics officially approved for use in plant disease management [37]. Antibiotics can enter soil and aquatic environments through direct application, animal excreta, or irrigation with contaminated wastewater, leading to the accumulation of multiple antimicrobial resistance risks in the environment. Figure 1 summarizes the common contaminant types and major input sources of pesticides and antibiotics in agricultural environments.

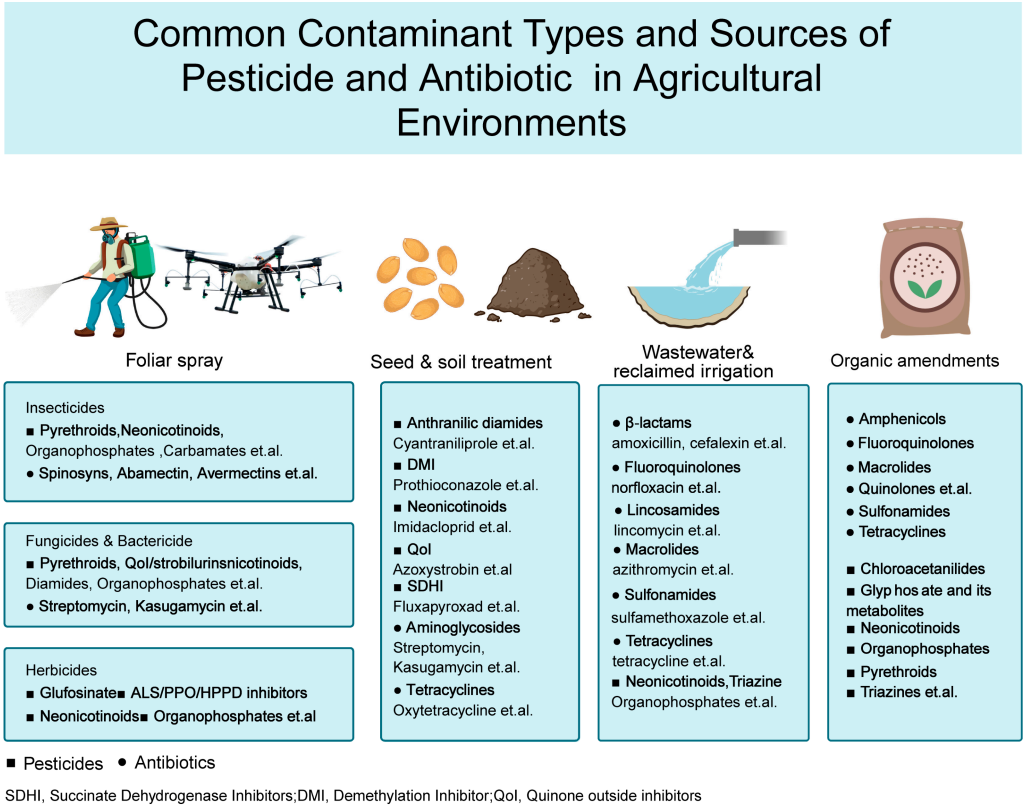

Figure 1. Common Contaminant Types and Sources of Pesticide and Antibiotic in Agricultural Environments.

The primary source of pesticide contamination is the direct application during crop cultivation, including foliar spraying [38], seed treatment [39], and other field practices. These applications lead to the accumulation of pesticide residues in soils, water bodies, and on or within crop tissues. In contrast, antibiotics typically enter the environment through indirect pathways. They are extensively used in livestock and poultry farming, but are often not fully metabolized within the animals. As a result, antibiotics are excreted in their parent or partially active forms and subsequently applied to agricultural fields through manure or organic fertilizer derived from animal waste [40]. This practice represents a major environmental dissemination route for both antibiotics and antibiotic resistance genes. In contemporary crop protection, direct application is the principal route by which pesticides enter agroecosystems. The most common practice is foliar spraying, which underpins the management of major diseases, insect pests, and weeds across staple and cash crops. Multiple studies have reported that appropriately designed spray programs can deliver effective field control of targets such as rice neck blast, cotton thrips, and lepidopteran pests of maize [41–44].

Soil application is likewise widely employed to manage subterranean insect pests, soil-borne diseases, and weeds, including pre-emergence control. Representative practices include soil incorporation of pesticides and in-furrow or band application to improve within-soil distribution and reduce phytotoxicity; the use of blended fumigants to suppress soil-borne pathogens; and pre-emergence herbicide treatments to lower early-season weed pressure [45–47].

Seed treatment is a common strategy within integrated pest management (IPM), conferring prophylactic protection before sowing to reduce disease and pest risks during the seedling stage; for example, SDHI-class treatments are used to manage seedling diseases in cereals and oilseed crops, anthranilic diamides (e.g., chlorantraniliprole) are employed

for early-season insect control in maize, and benzimidazoles are applied to target specific seedling diseases in rice [48–52].

Antibiotics enter agricultural environments through three main pathways: (1) direct agricultural application for crop protection, (2) indirect introduction through reclaimed-water irrigation and the land application of sludge or biosolids, and (3) veterinary use followed by manure application.

(1) Crop protection is a critical pathway for antibiotic entry into agriculture. In some systems, antibiotics are deliberately administered to manage plant diseases. Representative examples include streptomycin for fire blight in apples, jinggangmycin for rice sheath blight, and tetracyclines for citrus huanglongbing [53–59]. (2) Following crop protection, another significant pathway is the reuse of wastewater, sludge, and reclaimed water. A wide variety of antibiotic classes have been identified in hospital, pharmaceutical, and municipal wastewater streams. The reintroduction of these contaminants into agroecosystems can occur through the use of reclaimed water for irrigation and the land application of sludge or biosolids. Incomplete removal of antibiotics during treatment results in variable effluent concentrations [60–69]. (3) Veterinary use and manure amendment represent another major pathway for antibiotics entering agricultural soils. Veterinary use of antibiotics in livestock production is substantial, and incomplete metabolism leads to residues in manure. Consequently, the application of manure and slurry to farmland represents a significant pathway by which antibiotics enter agricultural soils [7,70–76].

These pathways, which refer to the routes through which contaminants enter agricultural systems, are not always discrete in practice, because agricultural inputs themselves may already carry contaminant residues. A study of 15 bio-based fertilisers found pesticide or pharmaceutical compounds in most samples, with concentrations ranging from 4.1 to 181 μg/kg [77]. This finding indicates that agricultural amendments may inadvertently carry pesticides, antibiotics, and other contaminants, thereby contributing a hidden and persistent pollutant load to soils. Notably, the reported concentrations (4.1–181 μg/kg) approach levels shown in other studies to affect soil microbial communities and facilitate bioaccumulation. Furthermore, in certain regions, wastewater irrigation [78] and the reuse of treated effluent [79] remain important supplements to agricultural water supplies. In instances where treatment is deemed incomplete, municipal or livestock-derived wastewaters have the potential to introduce a mixture of pesticide and antibiotic residues into farmland systems, thereby establishing a persistent source of contamination.

2.2. Pollution Status in Soils and Water Bodies

Agricultural soils and irrigation-related water bodies serve as the primary environmental sinks for pesticides and antibiotics. Due to their persistence (long environmental half-lives) and strong sorption to soils (high Koc), these contaminants remain in agroecosystems over extend periods. To facilitate comparison, the key physicochemical properties and policy restrictions of the selected compounds are summarized in Tables S1 and S2.

2.2.1. Pesticide Residues in Soils and Water Bodies

Driven by the rapid intensification of modern agriculture, global pesticide consumption has continued to rise in efforts to secure crop yields. In practice, overuse and misuse are common, leaving agricultural soils widely contaminated with residues of diverse pesticides at varying concentrations. As a national-scale example, a survey of 154 surface soil samples across China revealed that more than 76% of the samples contained 21–30 pesticide residues, indicating the widespread and complex nature of pesticide contamination in Chinese soils [80]. In long-term monitoring of wheat fields near Beijing, commonly detected compounds included carbendazim and imidacloprid, with tri

fungicides (e.g., hexaconazole) occasionally reaching >1000 μg/kg (dry weight) [81]. Legacy organochlorines remain detectable in specific settings such as karst soils in Hubei (organochlorine pesticides, OCPs 0.16–43.10 μg/kg; dominated by DDTs and mirex) [82]. Across Europe, large-scale surveys reported pesticide residues in 97% of agricultural soils, with ≥2 substances in 88% of samples and a substantial fraction of high-risk fields under conventional management [83–85].

Beyond soils, pesticide residues are widely detected in surface and groundwater associated with agricultural activities such as irrigation and aquaculture. These residues comprise diverse compounds, with concentrations varying across a broad range.

Irrigation canals and agricultural catchments typically exhibit ng/L to low-μg/L levels of total pesticide concentrations, with multi-compound detections common. Across 64 monitored water bodies spanning 10 European countries and Argentina, total pesticide concentrations ranged 6.89–5860 ng/L [86]. By comparison, a basin-scale survey in Spain detected 35 actives, with bentazone peaking at 18,000 ng/L [87]. Near-coastal systems show broader chemical coverage: a Chinese aquaculture area reported up to 296 pesticide compounds with a small subset driving ecological risk [88], and the eastern Shandong coast documented concurrent legacy OCPs in seawater, sediments, and biota [89]. In the Beijing region, 10 pesticide compounds were identified in rivers, with concentrations from below detection to 323.44 ng/L [90]. Following direct application in agricultural fields, a substantial portion of pesticides can adsorb onto soil particles or migrate through leaching and surface runoff during rainfall or irrigation events, thereby contaminating surface and groundwater systems [91].

Shallow and hydrogeologically vulnerable aquifers are especially susceptible to pesticide contamination, with residues often detected at ng/L levels in agricultural settings. In a representative irrigated agricultural region of the North China Plain, groundwater contamination is dominated by atrazine and its transformation products desethylatrazine (DEA) and desisopropylatrazine (DIA), with high detection frequencies and pronounced spatial heterogeneity [92]. In southern Netherlands farmlands, transformation products such as BAM (2,6-dichlorobenzamide), DMS (N, N-dimethylsulfamide), and desphenylchloridazon were persistently and widely detected from 1980 to 2020, indicating high mobility and environmental persistence in groundwater [93]. Regarding legacy OCPs, shallow groundwater in Shouguang, Shandong Province, commonly contained OCP residues, with most samples below drinking-water standards but localized hotspots of elevated concentrations [94]; across multiple regions of India, OCPs were widespread in groundwater and frequently exceeded standards, reaching up to 890 ng/L in some areas, underscoring persistence, regional disparities, and strong links to contaminated soils [95]. By comparison, currently used pesticides such as neonicotinoids and fipronil-class compounds are widely detected in groundwater. In Minnesota (USA), clothianidin occurred in 41% of springs at up to 200 ng/L, with contamination concentrated in shallow (<40 m), oxic aquifers and spatial patterns strongly modulated by geology, land use, and groundwater age [96]. In agricultural areas of Korea, 26 pesticides were detected in shallow groundwater; metolachlor showed the highest detection frequency (10.13%) with a mean concentration of 12.30 ng/L. Detection frequencies in agricultural settings were significantly higher than in background areas, indicating widespread ng/L-level contamination and pronounced regional heterogeneity in shallow aquifer systems [97].

Overall, the available evidence indicates that both legacy and currently used pesticides are widely present in agricultural environmental compartments, particularly in soils and groundwater, although their detection frequencies and concentration ranges vary substantially among compounds and regions. Such variation likely reflects differences in historical usage, ongoing inputs, and local hydrogeological settings.

2.2.2. Antibiotic Residues in Soils and Water Bodies

Antibiotics primarily enter agricultural environments through the application of livestock manure, sludge-based fertilizers, and irrigation with reclaimed water. While these materials are commonly regarded as valuable sources of nutrients in agriculture, they also represent significant sources of antibiotic contamination.

Antibiotics are widespread across agricultural environments, yet their distributions exhibit pronounced spatial heterogeneity. Concentrations and forms of occurrence (speciation and phase partitioning) are governed by multiple factors, including source inputs, intrinsic physicochemical properties, characteristics of the receiving media, and agricultural management practices.

Soils are the principal sink for antibiotics in agricultural environments, especially in fields amended with livestock manure. Evidence from across the globe indicates that agricultural soils are contaminated to varying degrees, with tetracyclines, sulfonamides, fluoroquinolones, and macrolides most frequently detected [98]. For example, in multiple vegetable soils across the Pearl River Delta (South China), tetracyclines (TCs) were widespread: more than 85% of samples contained three or more TCs, with a mean concentration of 78.05 μg/kg [99]. Tetracyclines and fluoroquinolones are largely concentrated in surface horizons and decline with depth, whereas sulfonamides often show the opposite pattern [100,101].

A survey of 24 representative antibiotics in Hong Kong rivers and coastal waters showed ubiquitous occurrence of tetracyclines (TCs; detection frequency 100%), while sulfonamides (SAs), fluoroquinolones (FQs; 78.60–100%), roxithromycin (RTM; 50%), and novobiocin (NOV; 50%) each exhibited detection frequencies $\geq$50%. Compared with river water, concentrations of most antibiotics were lower in seawater [102]. A survey in Xinjiang, China, reported total antibiotic concentrations of 17.37–84.09 ng/L in surface waters and 16.38–277.41 ng/L in groundwater. Norfloxacin was the most abundant compound in surface waters, whereas pefloxacin predominated in groundwater. These contrasting distributions were attributed to differences in antibiotic physicochemical properties and soil characteristics [103].

Residual antibiotics impose sustained selective pressure in the environment, promoting the selection and enrichment of antibiotic-resistant bacteria (ARB) carrying ARGs [104]. Importantly, ARG persistence does not necessarily decline in parallel with measurable antibiotic residues, because co-selection by non-antibiotic stressors and the genetic linkage of ARGs on mobile elements can maintain resistance even when direct antibiotic selection is weak or absent [105]. Accordingly, agricultural environments should be viewed not only as sinks of antibiotic residues, but also as reservoirs in which ARGs may be maintained and disseminated through mobile genetic elements and horizontal gene transfer [106].

Accordingly, a systematic synthesis of the occurrence and distribution of antibiotics and ARGs in soils and waters (surface water, groundwater, and irrigation water) is essential to delineate the full scope of antibiotic pollution in agroecosystems.

ARGs are now globally pervasive [72,107]. Accordingly, several studies have interrogated the global biogeography of ARGs to discern macro-scale regularities in their occurrence and distribution. A survey of 226 activated-sludge samples from 142 wastewater treatment plants (WWTPs) across six continents identified 179 ARGs spanning 15 antibiotic classes and defined 20 “core ARGs” detected in all samples, together accounting for 83.80% of total ARG abundance; β-lactam, glycopeptide, and tetracycline classes predominated [108]. While total ARG abundance did not differ significantly among continents, diversity was higher in Asia and community composition showed pronounced intercontinental differentiation. ARG abundance correlated positively with mobile genetic elements (MGEs), and more than half of the 1112 high-quality genomes recovered harbored

mobilizable ARGs, underscoring WWTP activated sludge as a critical global reservoir and exchange hub for environmental ARGs [108]. Another study focused on the distribution of soil ARGs. Drawing on 1088 soil metagenomes worldwide, it identified 558 ARG subtypes across 23 classes, with a mean abundance of 121 ppm; abundances were significantly higher in agricultural than in non-agricultural habitats. A global map of ARG abundance revealed hotspots in East and South Asia, Western Europe, and the eastern United States, with elevated levels also observed at high latitudes, including New Zealand and Northern Europe [109].

Overall, the available evidence points to widespread but spatially heterogeneous occurrence of antibiotics and ARGs, shaped by anthropogenic inputs, host microbial communities, and mobile genetic elements. These patterns suggest that agricultural environments can serve not only as contaminant sinks, but also as reservoirs for resistance dissemination. Cross-study comparisons should nevertheless be interpreted cautiously, because reported occurrence patterns are strongly influenced by sampling design, analytical coverage, extraction efficiency, matrix effects, and method detection limits. Moreover, many monitoring studies focus primarily on parent compounds, whereas transformation products and other derived residues are much less consistently captured. Such methodological differences may partly contribute to the substantial variability in reported detection frequencies and concentration ranges across regions and studies.

2.2.3. Co-Occurrence and Mixture

Pesticide and antibiotic residues are ecotoxic environmental pollutants with implications for human health; their pervasive co-occurrence undoubtedly poses a major challenge to the ecological integrity of agroecosystems and to food safety.

Moreover, pesticides and antibiotics frequently co-occur in real agricultural environments, resulting in complex patterns of co-contamination. For example, in China's Haihe River System (HRS)—a representative agricultural irrigation region—researchers employed high-resolution mass spectrometry to screen 268 contaminants and identified 62 priority compounds for spatiotemporal tracking, encompassing both pesticides and antibiotics [110].

In midstream Ganges water samples, a total of 51 emerging organic contaminants (EOCs) and their metabolites were concurrently detected, including pharmaceuticals such as sulfamethoxazole (detection frequency 73%, maximum 63 ng/L) and pesticides such as diuron (detection frequency 100%, maximum 95 ng/L) and atrazine (detection frequency 82%, maximum 12 ng/L) [111]. These riverine examples underline a seasonal inversion: pharmaceutical-dominant mixtures during high-flow periods and pesticide-dominant mixtures in dry seasons. Notably, in a set of samples from the Niyang River on the Qinghai–Tibet Plateau, 33 antibiotics and six pesticides from the triazine and benzimidazole classes were co-detected; representative concentrations included erythromycin (median 5.20 ng/L) among antibiotics and carbendazim (median 66 ng/L) and thiabendazole (median 88 ng/L) among pesticides. Antibiotics predominated during the high-flow season, whereas pesticides predominated during the dry season [112].

Co-occurrence of pesticides and antibiotics is also evident in groundwater. In a typical irrigated agricultural region, four antibiotics (mean detection frequencies 37–100%) and five pesticides (27.50–88.30%) were simultaneously detected, with the highest summed concentration reaching 538 ng/L [92]. In a survey across the North China region, co-occurrence was widespread in farmland soils: pesticides ranged from non-detect to 3800 μg kg^{-1} and antibiotics from non-detect to 951 μg kg^{-1} across 530 samples [113]. In subsurface and soils, co-detection persists but is filtered by hydrogeology and sorption, yielding mixtures with fewer classes yet longer residence.

These co-occurrence patterns indicate that ecological risk in agricultural waters cannot be inferred solely from single-compound occurrence data [114,115]. In mixture toxicology, concentration addition (CA) and independent action (IA) are commonly used as reference models for estimating combined effects [114,116]. CA is generally applied as the default or conservative baseline for chemicals with similar or insufficiently resolved modes of action, whereas IA is more appropriate when components act through dissimilar pathways or target sites [116,117]. However, environmentally realistic mixtures do not always conform neatly to these idealized assumptions, and deviations such as synergistic or antagonistic effects may occur depending on mixture composition, concentration range, and biological endpoint [118,119]. Therefore, co-occurrence data are more appropriately interpreted in combination with mixture-oriented risk screening rather than on a compound-by-compound basis alone [115,120].

3. Environmental Migration of Pesticides and Antibiotics

3.1. Environmental Migration of Pesticides

Following direct application in agricultural settings, pesticides are not only retained within environmental matrices such as soil but are also transported beyond target areas via air masses and hydrological flows. As shown in Figure 2, pesticides and antibiotics can migrate across soil, water, air, and crop compartments through multiple transport pathways. When pesticides are applied using sprayers or unmanned aerial vehicles, a fraction fails to deposit on the intended crop and is carried by wind to non-target areas; this process is termed spray drift [121,122]. Drift from aerial application is substantially greater than that from ground-based spraying [123,124]. Pesticides that have drifted into surrounding environments may further volatilize or adsorb to particulate matter and be entrained by wind erosion into the atmosphere, thereby facilitating transport to even more distant non-target regions [124,125]. Such airborne pesticides have been detected not only over agricultural landscapes but also in remote mountain regions, coastal zones, and even the Arctic; notably, concentrations of atrazine in agricultural areas and in the Arctic differ by less than one order of magnitude, indicating long-range atmospheric transport, recirculation, and persistence in distant environments [126].

In contrast to legacy OCPs, which are mainly detected as persistent residues from historical use, many pesticides still used in modern agriculture continue to enter the atmosphere through ongoing application and are subsequently returned to crop and soil surfaces by dry and wet deposition. A survey from Turkey showed that pesticides in air deposit either directly via dry deposition—where benomyl exhibited the highest dry-deposition velocity—or via precipitation, with the highest concentrations in rainfall reported for benomyl and pymetrozine ranging from 4–31.73 ng/L [127]. In a separate monitoring campaign across three land-use categories in São Paulo State, Brazil, pesticides were detected in all rainwater samples (0.10–596 ng/L). In predominantly agricultural areas, both the detection frequency of 19 compounds and the total wet-deposition flux were significantly higher than in the metropolitan zone, indicating that rainfall is an important pathway for returning atmospheric pesticide residues to environmental surfaces, especially in agricultural settings [128].

After deposition, these residues may follow several major environmental fates. First, they may be adsorbed and retained in soils. For example, neonicotinoids such as imidacloprid and thiamethoxam are readily adsorbed by soils, with the process largely governed by clay minerals and associated with a risk of partly irreversible retention [129]. Higher soil organic matter also strengthens atrazine sorption by promoting hydrogen bonding and hydrophobic interactions [130]. Second, deposited residues may be washed into the surface mixed layer during rainfall or irrigation and subsequently leach into shallow groundwa-

ter [96,131,132]. Third, they may be exported in dissolved or particulate forms via runoff and erosion to field ditches and fluvial networks, while excessive irrigation can further accelerate their downward migration into subsurface aquifers [133]. A smaller fraction may also re-enter the atmosphere through re-volatilization or resuspension. Overall, these processes show that soils act as a major reservoir and redistribution hub for pesticide residues after application.

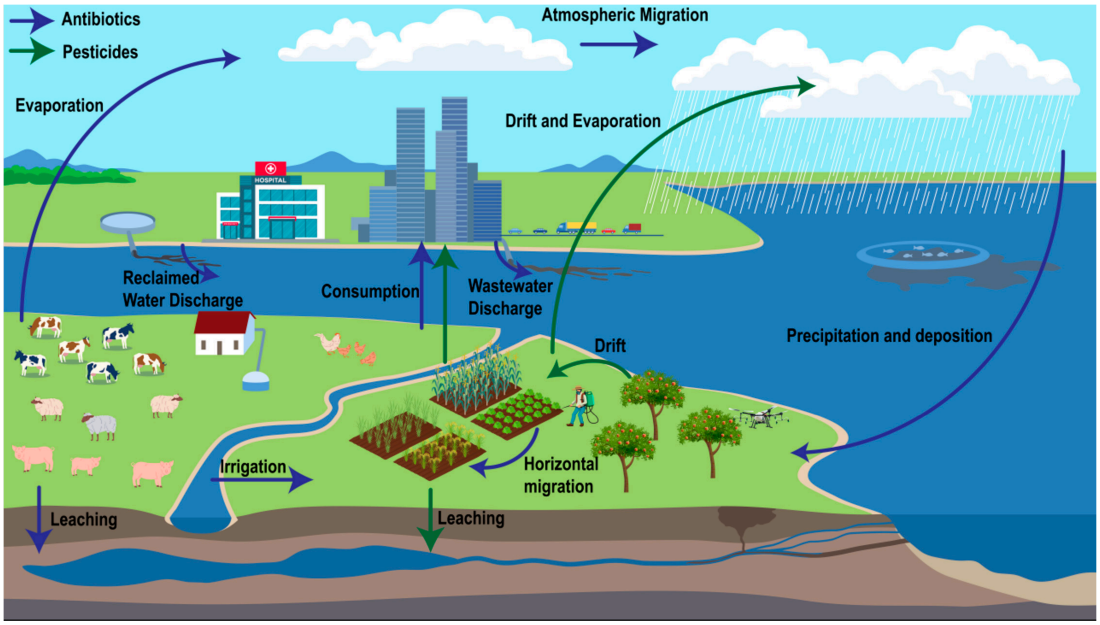

Figure 2. Cross-media transport pathways of pesticides and antibiotics in agroecosystems. This schematic summarizes the major sources and environmental processes governing the fate of pesticides (green arrows) and antibiotics (blue arrows) across the air–water–soil–crop continuum. Key pathways include inputs via wastewater/reclaimed-water discharge and irrigation, spray drift and volatilization during field application, long-range atmospheric transport followed by precipitation-driven deposition, surface runoff and horizontal migration, and downward leaching to deeper soil layers and groundwater.

3.2. Environmental Migration of Antibiotics

The transport of antibiotics in the environment is a complex, multi-scale, and multi-medium process. Although antibiotics share many physicochemical transport pathways with other pesticides, including sorption, runoff, leaching, and deposition, their environmental migration also involves biologically mediated processes associated with ARGs, MGEs, and microbial hosts.

After release into agroecosystems, antibiotics partition among soil [134–136], water and air compartments, but are typically retained in soils and surface waters as long-term sinks. Key redistribution pathways include sorption–desorption, downward movement through the soil profile, and hydrologic transport via runoff and groundwater [137,138], with episodic atmospheric transport and deposition also reported [139–141]. In paddy red soils, colloidal mineral/organic particles (e.g., clay minerals, iron oxides and humic substances) can facilitate vertical and interfacial transport by forming reversible complexes with antibiotics and by modifying local adsorption capacity and microbial habitats [142].

ARGs are increasingly recognized as important environmental contaminants whose risks may, in some contexts, exceed those of the antibiotics themselves, because they can be exchanged among microorganisms and thereby promote the spread and persistence of resistance in environmental reservoirs [143]. The core mechanism of this dissemination is horizontal gene transfer (HGT)—that is, bacteria acquire genetic material from the

surrounding environment via conjugation, transformation, or transduction rather than solely through vertical inheritance [144,145]. During HGT, MGEs—including plasmids, transposons, and integrons—serve as vectors or "shuttles" for ARGs, markedly accelerating their dissemination across bacterial species and lineages [146]. Consequently, elucidating the transport and fate of ARGs and MGEs across complex environmental matrices is crucial for assessing and managing ecological risks in agricultural systems, safeguarding food safety, and protecting human health.

Repeated, long-term application of animal manures laden with high concentrations of antibiotic residues, ARB, and ARGs markedly promotes the vertical migration of ARGs and MGEs within agricultural soils [147–149]. For example, ARGs have been detected throughout manure-amended soil profiles from 0 to 100 cm depth, demonstrating their movement into deeper horizons [150]. Soil properties are key regulators of this process: structural equation modeling (SEM) indicates that soil pH, organic carbon content, and soil texture, particularly sand fraction, are primary drivers of ARG vertical transport [151]. Beyond abiotic controls, the bacterial community itself is considered a principal determinant; certain ARGs are conveyed to deeper layers by their host bacteria rather than being governed solely by physicochemical factors [150]. Rainfall events significantly enhance ARG vertical migration and leaching [151], heightening the risk of groundwater contamination, while irrigation can mobilize ARGs, MGEs, and related contaminants in overland runoff, facilitating pollution of rivers, lakes, and other surface waters. Notably, wastewater discharged from hospitals and pharmaceutical plants carries ARGs that can disperse directly into surrounding aquatic environments via exchange within surface waters and through subsurface groundwater pathways [152,153]. ARB and their associated ARGs can be aerosolized, and airborne ARB/ARGs have been persistently detected in locally collected air samples across diverse settings—including wastewater treatment plants, composting facilities, intensive livestock operations, and industrial, urban, and rural environments [154–158]. Suspension of ARGs in the atmosphere is of particular concern because it can facilitate long-range transport and promote dissemination across environmental compartments and ecosystems. For example, a four-year monitoring campaign at a high-mountain observatory in the free troposphere analyzed rain and snow by qPCR and 16S rRNA gene sequencing, demonstrating intercontinental-scale atmospheric transport and deposition of ARGs and MGEs [159].

The environmental dissemination of ARGs is shaped by multiple factors. Integrating global soil metagenomes, a study employing structural equation modeling with 169 spatial covariates coupled with random forest prediction identified anthropogenic activities (livestock production, manure or reclaimed-water irrigation, and pesticide application) as the dominant drivers of ARG enrichment, whereas climate and soil nutrients act indirectly by modulating host communities [109]. Studies have shown that the spatial distribution of ARGs is influenced by climatic factors such as precipitation and temperature, while MGEs and heavy metals are the primary driving forces for their dissemination, contributing approximately 19% and 29%, respectively. These factors can facilitate the horizontal transfer of ARGs through co-selection mechanisms [160].

Taken together, pesticides and antibiotics are redistributed repeatedly among air, water, and soils, with soils acting as a major reservoir as well as a secondary source. Their environmental movement is driven by direct inputs, atmospheric deposition, leaching, runoff, erosion, and, in some cases, re-volatilization. For antibiotics, dissemination is further shaped by biological carriers and genetic elements, including ARB, ARGs, and MGEs, which can facilitate persistence and spread across environmental compartments. These coupled physicochemical and biological processes determine contaminant availability at the plant–air and plant–soil interfaces. Therefore, it is important to investigate how

pesticides and antibiotics cross these interfaces, enter above- and below-ground tissues, and are transported within plants.

4. Soil-Mediated Plant Uptake, In-Plant Translocation and Metabolism

In agroecosystems, xenobiotics can reach edible tissues through both belowground and aboveground pathways. Soil-mediated exposure represents the dominant and best-characterized pathway in many agricultural settings. For soil-mediated exposure, the process generally involves three coupled steps: (i) vertical transport in soil, (ii) root uptake, and (iii) in-plant translocation and storage. Direct uptake through leaves and stems may also occur after deposition or surface exposure. For consistency, we refer to key physicochemical descriptors (log Kow, water solubility, Koc, molecular weight) and use standard metrics: the bioconcentration factor (BCF, typically C_{plant}/C_{medium}) for overall enrichment from the exposure medium, and the translocation factor (TF = C_{shoot}/C_{root}, unitless) for in-plant mobility. These metrics help distinguish controls on entry into plants from controls on redistribution among tissues. Figure 3 summarizes the major uptake, translocation, accumulation, and metabolism mechanisms of pesticides and antibiotics in plants under agricultural exposure scenarios. Moreover, prior to root uptake, only the dissolved and desorbable fractions in the soil pore water are directly available to plants. It can thus be concluded that physicochemical properties exert a significant influence on the retention of contaminants in the soil, in addition to regulating the actual amount of contaminants that reach the root surface. This distinction is significant because the total amount retained in the soil does not necessarily correspond to the concentration available to plants or the amount accumulated in the final edible tissues. The concentration in soil pore water is often a better indicator of plant exposure than the total residue in bulk soil [161]. This is because pH, organic matter, clay minerals, and coexisting ions jointly control sorption, desorption, and resupply to the root interface [162]. Recent work also showed that dynamic bioavailability measured by DGT can correlate well with antibiotic concentrations in roots and shoots [161].

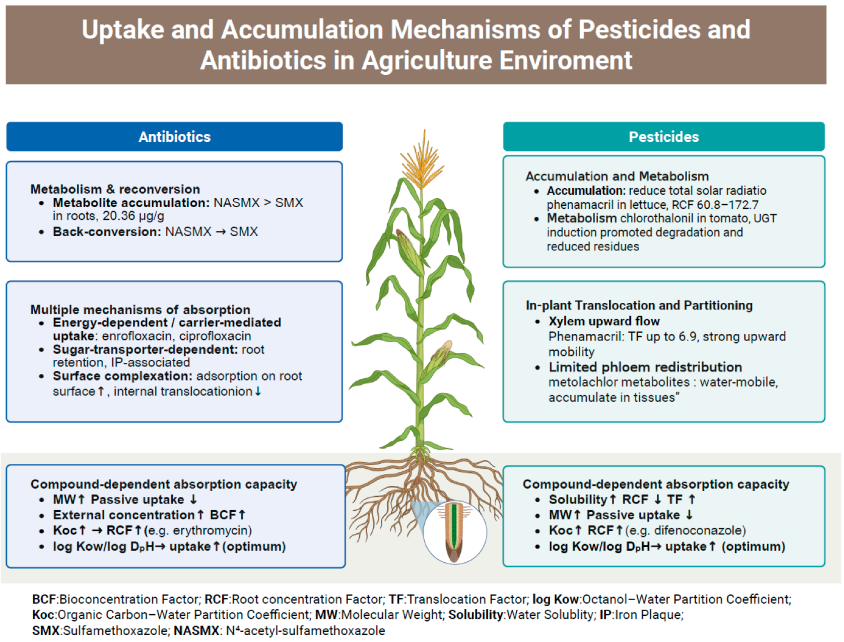

Figure 3. Uptake and Accumulation Mechanisms of Pesticides and Antibiotics in Agriculture Enviroment. Upward and downward arrows indicate an increase or decrease in the corresponding parameter or process, whereas rightward arrows indicate a promoting or causal relationship between factors (e.g., higher Koc leading to higher RCF).

4.1. Migration and Accumulation Mechanisms of Pesticides

The migration and accumulation of pesticides from soil into crops involve vertical transport in soil, root uptake, and subsequent in-plant translocation and sequestration [163]. This trajectory is governed by pesticide physicochemical properties (log Kow, water solubility, Koc, molecular weight) [164], plant anatomical and transpiration traits, and cultivation and water-management practices [165]. Field and laboratory studies now delineate stage-specific controls along this pathway, informing assessments of pesticide fate and food-contamination risks.

To illustrate stage specificity, several studies conceptualize pesticide behavior as three sequential phases: downward movement in soil, root uptake, and in-plant translocation. Representative compounds show contrasting behaviors. Chlorantraniliprole exhibits moderate sorption and can reach stems via both water-driven and sorption-mediated transport, whereas its metabolite IN-EQW78 binds strongly to soil and is far less mobile. By contrast, metolachlor rapidly forms highly soluble metabolites (OA and ESA) that are readily transported with water and accumulate within plant tissues [166]. Crop-specific evidence supports distinct controls on uptake versus redistribution. In maize exposed to imidacloprid, acetamiprid, tricyclazole, azoxystrobin, tebuconazole, and difenoconazole, tissue accumulation was negatively related to Koc and positively related to pore-water concentrations, log Kow, and molecular weight, but negatively related to water solubility. Notably, these relationships reversed when considering TFs, indicating that physicochemical properties can promote entry into roots while simultaneously constraining or facilitating subsequent translocation within plants [167]. Pesticide uptake by roots is not only a passive diffusion process. Recent evidence showed that neonicotinoids mainly enter plant cells through the transmembrane symplastic pathway [168]. The aquaporins PIP1;1 and PIP2;1 can further promote their uptake and accumulation in plant tissues [168].

Compounds also differ in the directionality and magnitude of translocation. Phenamacril in rice and wheat showed strong upward mobility, with TF values up to 6.9, and preferential accumulation in shoots. A small fraction underwent phloem-mediated reverse transport to roots and was exuded to the rhizosphere, where multiple metabolites were detected, indicating that plants can also release transformed residues back to the environment [169]. In-plant redistribution should be evaluated together with biotransformation [R4, R5]. In tomato, cyantraniliprole remained the main residue, but the metabolite profile differed among leaves, flowers, and fruits [170]. Phenamacril can also move through the phloem and then undergo extensive transformation in plant tissues [169].

Across diverse crops including rice [171], wheat [172], cowpea [173], chili pepper [174] pepper, and cucumber, Chinese chive [175] and lettuce [176], pesticide compounds with intermediate log Kow generally show a higher likelihood of both uptake and in-plant redistribution, whereas very hydrophilic or very hydrophobic compounds are more often retained in soil or encounter anatomical barriers to movement. Crop species, growth stage, irrigation regimes, and application methods further modulate net migration.

Notably, some studies have developed dynamic simulation models to characterize the migration of pesticides within plant systems. One such model incorporated key parameters such as the “fruit development window” and “phloem flow dynamics” to successfully simulate the temporal variations in pesticide concentrations in chili pepper and tomato fruits [177]. This modeling approach not only enhances our understanding of pesticide fate and transport mechanisms but also provides a theoretical foundation for designing more targeted and environmentally friendly pesticide application strategies.

4.2. Migration and Accumulation Mechanisms of Antibiotics

The uptake of antibiotics by vegetable crops through wastewater irrigation or manure application represents a significant pathway for antibiotic exposure in the food chain, posing potential threats to human health. Therefore, elucidating the mechanisms underlying their migration and accumulation in plants is of critical importance. For antibiotics, total soil concentration is also an incomplete predictor of plant uptake [161,162]. Their uptake is highly sensitive to soil–solution chemistry because most antibiotics are ionizable under environmental conditions [162]. As a result, soils with similar total residues may still differ in plant exposure potential [162].

When antibiotics such as oxytetracycline are introduced into the soil through irrigation or fertilization at environmentally relevant concentrations, they undergo migration and degradation within the soil profile. While soil processes can transiently elevate ARGs and reshape microbiomes [178], their role here is to modulate the antibiotic concentration and speciation at the plant interface, which in turn constrains uptake and translocation.

Studies have demonstrated that different classes of antibiotics exhibit significantly varying accumulation capacities in crops, largely influenced by their physicochemical properties. For instance, in a hydroponic experiment using pak choi, fluoroquinolones showed a markedly higher bioaccumulation potential compared to tetracyclines and sulfonamides. The highest observed bioconcentration factor (BCF) for fluoroquinolones reached up to 0.078, and the accumulation capacity increased with rising antibiotic concentrations in the solution [179,180]. In studies on erythromycin (ERY), the compound exhibited preferential retention in roots, with translocation factors (TFs) less than 1 in both pak choi and water spinach, indicating limited upward mobility [180]. In contrast, fluoroquinolones such as enrofloxacin have been found to accumulate in the leaves and seeds of crops like soybean, common bean, and maize, suggesting a strong capacity for rhizosphere uptake and internal translocation [16]. Antibiotic accumulation is strongly class-dependent [181]. A recent meta-analysis found higher transfer of tetracyclines to leaves than sulfonamides [181]. It also showed that translocation patterns within plants differed among antibiotic classes [181]. Some antibiotics are not only passively absorbed by plants [R8]. Kasugamycin showed transporter-related uptake and phloem redistribution in castor bean, and this process was affected by pH, temperature, and metabolic inhibitors [182].

Antibiotic uptake is compound- and plant-dependent, involving distinct entry routes and vascular transport modes. For example, fluoroquinolones in leafy vegetables have been linked to energy-dependent and/or aquaporin-associated uptake with predominantly xylem-driven translocation [179], whereas kasugamycin shows transporter involvement consistent with active uptake and phloem-associated redistribution that is sensitive to temperature, pH and metabolic inhibitors [182].

Plant surface traits and in planta biotransformation can decouple external retention from internal redistribution of antibiotics. Evidence suggests that root-surface mineral/plaque layers may enhance retention of tetracycline-class compounds while restricting translocation [183], while sulfonamide-class antibiotics can undergo rapid uptake followed by reversible conjugation/deconjugation and detoxification-associated transformations (e.g., CYP450s and glycosyltransferases), with potential downstream effects on primary metabolism [184]. Plant metabolism can further reshape antibiotic residues after uptake [184]. In rice, sulfamethoxazole and N4-acetyl-sulfamethoxazole were rapidly taken up by roots and transported upward [184]. Multiple transformation products were also detected during this process [184].

Overall, antibiotic accumulation in crops is highly context dependent, reflecting chemical properties, plant traits, exposure pathways and metabolic capacity. Integrating these

dimensions is necessary to interpret residue patterns and to inform food-safety management and pollution-control strategies.

5. Conclusions and Outlook

This review integrates current knowledge on the sources, cross-media transport, and plant uptake of pesticides, antibiotics, and antibiotic resistance genes (ARGs) in agricultural systems. Overall, the available evidence indicates that environmental occurrence alone is not sufficient to predict crop contamination. Rather, the transfer of contaminants from soils, irrigation water, wastewater inputs, and atmospheric deposition into plant tissues is jointly regulated by compound-specific physicochemical properties, environmental conditions, rhizosphere processes, and crop traits. Therefore, cross-media transport and plant uptake should be understood not as isolated topics, but as mechanistically connected stages along a source-to-plant continuum.

Current studies have clearly demonstrated that the environmental sources of these contaminants are diverse, yet their dominant entry pathways differ. For pesticides, direct application, misuse, and overuse remain primary drivers of environmental loading. For antibiotics and ARGs, manure amendment, wastewater discharge, reclaimed-water irrigation, and biosolid application represent major introduction routes. Once released, these contaminants may persist in soils and aquatic systems, undergo redistribution during irrigation and precipitation events, and move across environmental compartments including soil, water, sediment, air, and biota. However, the presence of residues in environmental matrices does not necessarily translate directly into accumulation in edible tissues, because actual plant exposure and uptake depend strongly on bioavailability, speciation, transformation, and plant-specific barriers to entry and translocation.

Despite substantial progress, several important knowledge gaps remain. First, existing studies are much stronger in documenting occurrence patterns than in resolving the mechanistic links between environmental exposure and crop accumulation. Second, current research has focused predominantly on root-mediated uptake, whereas direct foliar deposition, surficial retention, penetration through aboveground tissues, and their relative contributions to internal accumulation remain insufficiently addressed. Third, most monitoring programs emphasize parent compounds, while transformation products and metabolites are still underrepresented, even though they may differ markedly in persistence, mobility, and biological effects. Fourth, ARG dynamics cannot always be inferred directly from measurable antibiotic residues, because ARG persistence may be maintained by microbial hosts, mobile genetic elements, and co-selection pressures even in the absence of detectable antibiotic concentrations. In addition, differences in sampling design, analytical methodology, target compounds, plant species, environmental matrices, and reporting metrics continue to limit cross-study comparability and quantitative synthesis.

Future research should therefore prioritize several directions. First, standardized multi-matrix monitoring frameworks are needed to connect source inputs, environmental transport, and edible-tissue residues across soils, irrigation waters, atmospheric deposition, and crop compartments. Second, more mechanism-oriented studies are required to clarify how root exudates, rhizosphere microbial degradation, sorption–desorption dynamics, plant physiology, and species-specific traits shape contaminant bioavailability, uptake, and translocation. Third, future assessments should move beyond parent compounds to explicitly include transformation products, mixture effects, and plant detoxification pathways. Fourth, predictive models should be developed to link environmental exposure, contaminant fate, plant accumulation, and context-dependent food-safety implications under realistic agricultural scenarios. Climate change should also be considered in future assessments, as shifts in temperature, precipitation, and hydrological extremes may alter

contaminant mobility, redistribution, and transformation in agricultural environments. These changes may in turn modify runoff, leaching, and plant exposure patterns under realistic field conditions. Finally, effective mitigation will require not only source control and improved chemical management, but also more specific agricultural measures targeting the environmental dissemination of antibiotic resistance. From a management perspective, reducing dissemination at the source remains critical, and manure pretreatment—especially well-managed composting—has been repeatedly highlighted as a practical route for lowering ARG burdens before land application. Where reclaimed or wastewater-derived irrigation sources are used, mitigation should further rely on fit-for-purpose water treatment and multi-barrier management, rather than on irrigation reuse alone. More broadly, on-farm monitoring, tighter veterinary-drug regulation, and clearer standards for organic fertilizers may serve as complementary measures to reduce environmental ARG spread in agricultural systems. Advancing this field will depend on closer integration of environmental chemistry, plant physiology, agronomy, and microbial ecology, so that contaminant monitoring can be translated into more robust management and regulatory practices.

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Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/foods15081436/s1, Table S1: Key physicochemical properties and policy-related information of the major pesticides discussed in this review, Table S2: Key physicochemical properties and policy-related information of the major antibiotics discussed in this review, Figure S1: Flow diagram of the literature search and selection process.

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