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Veterinary Drug Residues and Agricultural Health: A One Health Perspective on Farmworker Exposure, On-Farm Risks, and Future Pathways

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Systematic Review

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Abstract

Farmworkers, their families, and rural communities face occupational, environmental, and dietary exposure to veterinary drug residues, a hidden hazard in modern animal agriculture that has received far less attention than pesticide exposure or foodborne pathogens. Unlike consumers, who encounter residues primarily through the consumption of meat, milk, and eggs, agricultural workers are exposed through dermal contact with medicated animals, inhalation of contaminated dust in confinement buildings, handling of manure applied to cropland, and take-home pathways that contaminate household environments. This review critically examines the sources, health risks, and management of veterinary drug residues through a One Health lens that integrates human, animal, and environmental domains, with specific emphasis on agricultural populations.

Several categories of risk are particularly relevant to agromedicine. Direct health effects include occupational dermatitis and respiratory symptoms, which have been documented among livestock workers handling medicated animals. Antimicrobial resistance (AMR) transfer from livestock to farm families represents an under-monitored occupational pathway: livestock-associated MRSA colonization rates among swine and poultry workers are 10 to 50 times higher than in the general population, and resistant bacteria can be carried into farm households via contaminated work clothing and equipment. Endocrine disruption from hormonal growth promoters adds another layer of concern, while economic pressures frequently lead farmers to shorten legally mandated withdrawal periods, directly increasing residue concentrations in manure, dust, and animal tissues at the time of peak worker exposure.

Recent advances in detection and prediction offer improved tools for farm-level residue management. On-farm biosensors, portable rapid tests, wearable animal sensors, and machine learning algorithms for residue depletion prediction have demonstrated technical feasibility in research settings. However, persistent challenges limit their real-world impact: regulatory disharmony across countries, continued illegal use of banned drugs, environmental sinks on cropland that recycle residues back into farm communities, fragmented surveillance systems that do not link farm drug records to rural clinic data, and, most fundamentally, the complete absence of occupational exposure limits for any veterinary drug in agricultural workplaces.

Future pathways to address these gaps include establishing farmworker medical surveillance programs, developing low-cost testing cooperatives accessible to smallholder farmers, implementing blockchain traceability for on-farm drug records, advancing green veterinary pharmacology that prioritizes rapid environmental degradation, and creating economic incentives that make withdrawal period compliance financially viable for producers. A coordinated, multisectoral approach that prioritizes the health of agricultural producers not just the safety of the food supply is essential to safeguard farming communities and preserve antimicrobial efficacy for future generations.

1. Introduction

Veterinary drugs including antibiotics, antiparasitics, non-steroidal anti-inflammatory drugs (NSAIDs), growth promoters, and sedatives are critical for maintaining animal health and ensuring food security worldwide (1,2). However, the extensive use of these pharmaceuticals in food-producing animals leads to persistent residues not only in meat, milk, and eggs but also in the farm environments where agricultural workers live and work (3,4). A veterinary drug residue is defined as any pharmacologically active substance, metabolite, or degradation product that remains in edible tissues, manure, wastewater, soil, or airborne dust following drug administration (5,6). These residues arise from multiple sources: non-adherence to legally mandated withdrawal periods, off-label drug use, contaminated feed, and the environmental recycling of medicated manure onto cropland (6,7). Taken together, these sources create a complex exposure landscape that conventional food safety systems were never designed to address.

For agricultural communities, exposure pathways extend far beyond the dietary consumption of meat, milk, and eggs. Farmworkers face direct occupational exposure through dermal contact with medicated animals, inhalation of contaminated dust in confinement buildings, and handling of manure or bedding materials (8,9). Family members who do not work on the farm nonetheless experience chronic, low-level environmental exposure via contaminated well water, garden produce grown in manure-amended soil, and dust tracked into homes on work boots and clothing (7,10). These pathways are not rare or hypothetical; they are routine features of life in livestock-dependent communities, yet they remain almost entirely unregulated and unmonitored.

The health implications for farming populations are profound. Chronic exposure to veterinary drug residues can cause allergic reactions, endocrine disruption, and most consequentially antimicrobial resistance (AMR), which the World Health Organization has identified as one of the top ten global health threats, with more than 1.2 million attributable deaths annually (11,12,13). Agricultural workers may serve as a bridge population, carrying resistant bacteria from livestock to their own households and to clinical settings in rural communities (14,15). Livestock-associated methicillin-resistant *Staphylococcus aureus* (LA-MRSA) provides a well-documented example: prevalence rates among pig farmers and their household contacts are 10 to 50 times higher than in the general population, representing an occupational AMR transmission pathway that is qualitatively distinct from dietary exposure. Unlike foodborne AMR, which can be reduced by cooking and food handling practices, occupational transmission occurs via inhalation and direct contact, bypassing most consumer protections.

Traditional food safety systems rely on Maximum Residue Limits (MRLs) and withdrawal periods to protect consumers (16,17). These tools were developed to ensure that meat, milk, and eggs reaching retail markets contain residues below levels considered safe for daily lifelong consumption. However, these measures do not protect farmworkers from pre-slaughter exposure the period when residues are at their highest concentrations in animals, manure, and dust and they are poorly enforced in small-scale and informal agricultural settings where most of the world's livestock producers operate. The One Health framework, which explicitly recognizes the interconnectedness of human, animal, and environmental health, provides a necessary paradigm shift for agricultural health and safety (18,19). Applying this

framework to veterinary drug residues means moving beyond consumer protection to encompass occupational health, environmental monitoring, and animal welfare as equally important domains.

This review has six interconnected objectives. First, it outlines the occupational and community-specific health risks that veterinary drug residues pose to agricultural populations, distinguishing these risks from the better-characterized risks to general consumers. Second, it applies the One Health framework to farm-level residue management, examining how human, animal, and environmental domains interact in agricultural settings. Third, it highlights recent on-farm technological advances in residue detection, prediction, and remediation, with attention to which advances are accessible to smallholder farmers. Fourth, it describes current regulatory and farm-level approaches to residue management, identifying their implicit assumptions and limitations. Fifth, it identifies persistent challenges in agricultural settings, including regulatory disharmony, fragmented surveillance, environmental sinks, and the complete absence of occupational exposure limits for veterinary drugs. Finally, it proposes future solutions that center the agricultural producer not just the consumer as the primary beneficiary of residue management efforts. Taken together, these objectives aim to reframe veterinary drug residues as an occupational and environmental health problem requiring multisectoral action, not merely a food safety problem requiring testing at slaughter.

2. Methodology

This review synthesizes peer-reviewed literature, regulatory documents, and surveillance reports published predominantly between 2015 and 2025, with selective inclusion of foundational older references where necessary. The following databases were searched: PubMed, Scopus, Web of Science, and Google Scholar. Keywords included combinations of the following terms: "veterinary drug residues," "antimicrobial residues," "food safety," "antimicrobial resistance," "One Health," "environmental contamination," "biosensors," "withdrawal period," "manure," and "occupational exposure." The search was not restricted by study design but prioritized original research, systematic reviews, meta-analyses, and regulatory reports.

The search and screening process proceeded as follows. The initial search yielded 1,874 records. After duplicate removal, 1,240 unique records were screened by title and abstract. Full texts of 312 potentially relevant articles were then assessed for eligibility. A total of 147 articles met the inclusion criteria and were included in the qualitative synthesis.

Inclusion criteria were defined across six domains. Studies were included if they addressed human health outcomes associated with veterinary drug residues, reported residue levels in food or environmental samples (including manure, soil, water, dust, or air), described intervention or mitigation studies conducted at the farm or slaughterhouse level, or were regulatory reports from the World Health Organization (WHO), Food and Agriculture Organization (FAO), World Organisation for Animal Health (WOAH, formerly OIE), European Medicines Agency (EMA), U.S. Food and Drug Administration (FDA), or Codex Alimentarius. Additionally, studies presenting One Health or integrated surveillance frameworks

were included, as were any studies specifically addressing occupational or environmental exposure of agricultural workers to veterinary drug residues, regardless of whether residue detection was the primary outcome.

Exclusion criteria were applied as follows. Non-English articles without available translation were excluded, as were conference abstracts without accompanying full data or full-text publications. Studies focused exclusively on human pharmaceuticals (e.g., hospital antibiotic use, human drug residues in wastewater) without any veterinary drug residue component were excluded. Data were extracted thematically under five domains: human health risks, animal health, environmental fate, detection technologies, and regulatory or behavioral interventions. Qualitative synthesis used narrative review methods appropriate for a broad interdisciplinary topic, prioritizing meta-analyses, longitudinal surveillance studies, and randomized controlled trials where available, but including observational and cross-sectional studies where higher-level evidence was absent a common limitation in the occupational exposure literature for veterinary drug residues.

3. Public Health Risks for Agricultural Populations

Veterinary drug residues pose multifaceted risks to human health, including direct toxicity, allergic reactions, gut microbiome disruption, antimicrobial resistance (AMR), and endocrine modulation (12,21). While consumers are exposed primarily through diet, agricultural populations face the same dietary risks plus additional occupational and environmental pathways that are often more concentrated and chronic. The following subsections synthesize the evidence on each risk category, with particular attention to farmworker-specific exposure routes where data exist.

Direct toxicity, allergic reactions, and endocrine disruption

Several veterinary drug classes exhibit direct toxicity even at low concentrations, posing risks to both consumers and farmworkers. Chloramphenicol, banned globally but still detected illegally in some livestock operations, causes dose-independent aplastic anemia a particular concern for workers handling injection sites or contaminated tissues (22). Nitrofurans present a different hazard: their metabolites persist in animal tissues for years and are both genotoxic and carcinogenic (1). Beta-agonists such as clenbuterol and ractopamine, used illegally as growth promoters in some countries, have caused acute food poisoning outbreaks characterized by tachycardia, tremors, and metabolic disturbances; farmworkers who handle treated animals face even higher dermal and inhalation exposure than consumers (21). Even commonly used avermectins, while considered relatively safe for the general public, can cause neurotoxicity with chronic occupational exposure, particularly during pour-on applications and manure handling (23).

Beyond direct toxicity, allergic reactions to drug residues represent an under-recognized occupational health issue. Penicillins, cephalosporins, and sulfonamides are well-known allergens, and residues in milk, meat, or eggs can trigger hypersensitivity reactions ranging from urticaria to anaphylaxis in sensitized individuals (12,24). Crucially, low-level residues below legal maximum residue limits may still

provoke reactions in highly sensitive consumers and workers (16). Endocrine disruption adds another layer of concern. Hormonal growth promoters, used in some countries to increase feed efficiency, leave residues in meat and liver that can interfere with human endocrine function, potentially affecting pubertal development, fertility, and increasing the risk of hormone-sensitive cancers (21,23). The European Union has banned such hormones, but they remain legal elsewhere, creating both trade tensions and regulatory asymmetry that complicates risk management for globally mobile agricultural workers (22).

Gut microbiome disruption and antimicrobial resistance

Sub-therapeutic antibiotic residues in food alter intestinal microbiota composition, reducing colonization resistance against pathogens such as *Clostridioides difficile* and *Salmonella*, promoting metabolic syndrome, and impairing immune development in children (13,25). Even residues below the minimum inhibitory concentration (MIC) can select for resistant commensal bacteria and facilitate horizontal gene transfer, creating a reservoir of resistance genes within the human gut (14).

The most consequential risk from veterinary drug residues, however, is the selection and dissemination of antimicrobial resistance. Veterinary antibiotics select resistant bacteria in animal guts, and these bacteria along with mobile genetic elements carrying resistance genes such as bla_CTX-M, mcr, and ndm contaminate meat during slaughter (14, 15, 26). Human consumption leads to gut colonization by resistant strains, causing infections that are unresponsive to first-line antibiotics (11,27). The World Health Organization has identified critically important antimicrobials including colistin, fluoroquinolones, and third-generation cephalosporins whose use in food-producing animals must be strictly limited to preserve their efficacy in human medicine (28).

Critically for agricultural populations, AMR risks extend beyond dietary pathways to direct occupational exposure. Nasal colonization with livestock-associated methicillin-resistant Staphylococcus aureus (LA-MRSA) has been consistently documented among swine and poultry workers, with prevalence rates 10 to 50 times higher than in the general population. Dermal contact with medicated animals and inhalation of contaminated dust can also lead to carriage of resistant Gram-negative bacteria, representing an under-monitored transmission route from livestock to humans. This occupational pathway is qualitatively different from foodborne AMR exposure: it bypasses cooking and gastric barriers, delivers live bacteria directly to mucous membranes and respiratory tracts, and can lead to household transmission to non-working family members via contaminated work clothing and equipment.

Occupational and community exposure pathways in agricultural settings

Farmworkers and their families face exposure pathways that are largely absent from conventional food safety monitoring (8,9). Dermal contact occurs during handling of medicated animals, mixing feed containing drugs, and applying liquid manure, all of which result in percutaneous absorption of residues such as avermectins and beta-agonists (6,21). Inhalation of aerosolized dust from confinement buildings particularly poultry and swine operations carries both antibiotic particles and resistant bacteria,

contributing to respiratory symptoms and nasal colonization with resistant organisms (9,29). Studies have detected tetracyclines and fluoroquinolones in settled dust from poultry houses at concentrations sufficient to select for resistance, meaning that respiratory exposure alone may be biologically significant.

Manure handling represents another major pathway. Application of manure from medicated animals to cropland exposes workers to concentrated residues and resistance genes; studies consistently detect tetracyclines, sulfonamides, and fluoroquinolones in farm soil at concentrations that select for resistance (6,7,30). This exposure is not limited to the workplace. Take-home pathways contaminated work boots, clothing, and vehicles introduce residues and resistant bacteria into farm homes, affecting children and non-working family members (8,29). Household dust in agricultural communities has been shown to contain measurable antibiotic residues, indicating that the farmworker's home environment becomes a secondary exposure site. Finally, in regions where manure is applied to fields, veterinary drug residues such as sulfamethazine and lincomycin have been detected in rural drinking water wells at low but biologically active concentrations (10,20).

Knowledge gaps and vulnerable population status

A critical quantitative gap exists in the literature: no direct comparative absorption studies have measured the difference between occupational and dietary exposure to veterinary drug residues. Residue concentrations in fresh manure can reach milligram-per-kilogram levels, suggesting potential for substantially higher acute occupational exposure than typical dietary intake, but this remains unquantified in human biomonitoring studies. Despite this gap, the available evidence clearly indicates that occupational and environmental pathways are poorly captured by conventional food-focused residue monitoring, leaving agricultural communities as an under-recognized vulnerable population (19, 31). Closing this knowledge gap requires future research that directly measures residues in farmworker blood, urine, and household dust, and that links those measurements to on-farm drug use records and clinical health outcomes.

4. A One Health Approach

The One Health framework moves beyond human-centric risk assessment to include animal health and environmental integrity as equally critical domains (18, 19). For veterinary drug residues, this framework is not merely conceptual but operationally necessary: residues generated on farms travel through animals into manure, from manure into soil and water, from environmental media into human households, and back into animal feed crops, creating cycles of exposure that siloed regulatory systems cannot adequately address. The following sections examine each domain in turn, with particular attention to how they intersect for agricultural communities.

Human health domain: Surveillance gaps for farming populations

Within the human health domain, existing surveillance systems focus almost exclusively on consumers and foodborne pathways, leaving farmworkers largely invisible. The World Health Organization's Global Antimicrobial Resistance Surveillance System (GLASS) monitors AMR in clinical isolates from hospitalized patients, but these data are rarely cross-referenced with foodborne or livestock-derived isolate data, missing potential links between on-farm drug use and resistant infections in rural communities (11, 32). Public health agencies monitor veterinary drug residues through total diet studies and national residue programs such as the U.S. National Residue Program and the EU's Rapid Alert System for Food and Feed (33, 34). However, these programs sample meat, milk, and eggs at slaughterhouses or retail outlets after animals have left the farm and after farmworkers have already been exposed. Consumer education campaigns promote proper cooking as a risk reduction strategy, yet many veterinary drug residues are heat-stable and survive cooking, and more critically, cooking offers no protection to workers exposed dermally or via inhalation (24). A human health domain truly aligned with One Health principles would integrate farmworker medical surveillance routine screening for dermatitis, respiratory symptoms, and resistant bacterial colonization and would link those clinical data to on-farm drug use records, a linkage that currently does not exist in any national system (19, 31).

Animal health domain: Responsible use as the first line of defense

Responsible veterinary drug use is the cornerstone of prevention within the animal health domain, and four strategies have proven most effective (2, 17, 26). First, strict observance of withdrawal periods the legally mandated interval between last drug administration and slaughter or milking directly reduces residue concentrations in animal tissues, manure, and dust. However, withdrawal periods are designed to protect consumers, not farmworkers; even compliant withdrawal periods may leave residues in manure at levels that pose occupational hazards. Second, moving all antimicrobials to prescription-only status has been shown to reduce misuse in high-income countries, though enforcement remains weak in smallholder systems where drugs are often purchased from unlicensed vendors (17, 26). Third, alternatives to antibiotics including vaccines, probiotics, bacteriophages, and phytogenic feed additives can lower overall drug use while maintaining or improving animal health, thereby reducing the residue burden on farms (25, 35). Fourth, improved herd health management through enhanced biosecurity, farm hygiene, and nutrition reduces disease incidence and therefore the need for therapeutic drug use in the first place (15). Each of these interventions has direct implications for farmworker exposure: lower drug use on-farm translates to lower residues in manure, dust, and animal contact, yet none of these strategies are currently evaluated for their impact on occupational health outcomes.

Environmental health domain: Manure as a residue vector

Veterinary drug residues enter the environment through three primary pathways: manure and slurry applied to cropland as fertilizer (containing unmetabolized drugs and active metabolites), aquaculture effluents released directly into water bodies, and runoff from feedlots carrying residues and resistant bacteria to soil and groundwater (6, 7, 10). Once in the environment, residues create secondary exposure routes that are particularly relevant to agricultural communities. Contaminated drinking water especially

well water in regions where manure is routinely applied to fields can expose entire farm families to low-level mixtures of antibiotics and antiparasitics (20,30). Crops irrigated with contaminated water can take up residues from soil, introducing drugs into home gardens and family food supplies. Wild animals, including rodents and birds that move between farms and human dwellings, can serve as resistance gene reservoirs, bridging environmental and domestic spaces in ways that are difficult to monitor or control (20,30).

Mitigation of environmental residues is possible but not yet widely implemented on working farms. Anaerobic digestion, already used in some biogas operations, degrades many veterinary drugs during manure processing (36). Biochar amendment and composting can adsorb and break down residues in manure, though efficacy varies by drug class and composting conditions (37). Constructed wetlands have been shown to remove residues from agricultural runoff before they reach surface waters, and phytoremediation using plants to uptake and metabolize certain drugs remains a promising but under-researched approach (38). Critically, none of these environmental mitigation strategies are currently required by residue regulations, and none are incentivized through agricultural subsidies or carbon credit programs, despite their potential co-benefits for water quality, soil health, and farmworker exposure reduction.

Integrated surveillance: Bridging farms, clinics, and environmental monitoring

The FAO/WHO/WOAH Tripartite has developed the One Health Surveillance (OHS) framework for AMR, and WOAH (World Organisation for Animal Health, formerly OIE) provides international standards for animal health surveillance (11,32). However, these frameworks remain largely aspirational for agricultural communities, where integration across sectors is rare. For integrated surveillance to protect farmworkers and their families, three specific linkages are needed (19,31). First, farm-level drug recordsincluding what drugs were used, on which animals, and when must be linkable (while protecting farmer privacy) to worker health clinic data documenting dermatitis, respiratory illness, and resistant infections in the same population. No such linked database currently exists in any country with large-scale animal agriculture. Second, environmental monitoring should track residues along the full pathway from manure to soil to well water to farm family urine and stool, enabling quantitative total exposure assessment rather than the current fragmented approach that measures each compartment in isolation (6,8). Third, sentinel surveillance should be established in rural health clinics that serve livestock-dependent communities, training clinicians to ask about occupational animal contact when patients present with resistant infections or allergic symptoms and to report unusual clusters to public health authorities (29,39). These integrations are technically feasible and politically challenging; they require data-sharing agreements across agricultural, environmental, and health ministries that currently operate as separate silos. Until such integration occurs, the One Health framework will remain a conceptual ideal rather than an operational reality for the agricultural populations most at risk.

5. Recent Advances in Detection and Mitigation

The past decade has seen significant technological progress in residue detection, prediction, and remediation, yet most advances remain concentrated in high-income countries and well-resourced laboratories, leaving smallholder farmers and the agricultural workers who need them most with limited access (2,40).

Rapid and portable detection technologies

Traditional chromatography-mass spectrometry methods including liquid chromatography (LC-MS/MS) and gas chromatography (GC-MS) remain the gold standard for residue quantification, but they are lab-bound, expensive, slow, and require trained technicians, making them impractical for on-farm use or for routine screening at the point of slaughter (40). Recent advances have focused on miniaturization and speed. Electrochemical and optical biosensors can now detect residues in milk or meat within minutes, with sensitivity approaching that of laboratory methods for certain drug classes. Surface-Enhanced Raman Spectroscopy (SERS) provides fingerprint spectra at nanomolar concentrations, enabling on-site screening without complex sample preparation. Most strikingly, portable mass spectrometers miniaturized instruments that fit in a field case now allow slaughterhouse testing before carcass release, potentially enabling real-time residue-based quality control rather than retrospective sampling (40). However, the cost of these portable instruments remains prohibitive for most small-scale slaughter facilities in low- and middle-income countries (LMICs), and none have been validated for the detection of residues in manure, dust, or other environmental media relevant to farmworker exposure.

Machine learning and predictive modeling

Artificial intelligence-driven models are revolutionizing residue risk assessment in three key areas (40). Pharmacokinetic modeling using machine learning algorithms can now predict residue depletion curves for individual animals based on species, weight, drug formulation, and route of administration, potentially enabling personalized withdrawal period recommendations rather than the current one-size-fits-all regulatory periods that may be unnecessarily long for some animals and dangerously short for others. AMR gene transmission networks another AI application map the movement of resistance genes between farms, slaughterhouses, and human populations, revealing transmission pathways that traditional epidemiology misses. For example, network models have identified specific swine farms as hubs for LA-MRSA dissemination to human communities, information that could guide targeted interventions. Finally, random forest classifiers and other machine learning methods are being used to prioritize surveillance efforts by identifying high-risk drug-commodity combinations before they cause outbreaks (40). Despite these advances, no AI-driven residue prediction tool has been integrated into routine farm management or worker health protection, and models trained on high-income country data perform poorly when applied to LMIC settings with different livestock production systems, drug availability, and veterinary practices.

Low-cost, farm-friendly technologies for resource-limited settings

Recognizing that most residue risks exist in LMICs and in small-scale operations even within high-income countries, recent efforts have focused on developing affordable tools that do not require electricity, refrigeration, or technical expertise (29,40). Milk antibiotic screening tests, for example, have been successfully deployed through dairy cooperatives in Kenya and Uganda, enabling rapid detection of beta-lactam and tetracycline residues at costs below one US dollar per test. These lateral flow assays are not as sensitive as laboratory methods but are sensitive enough to detect residues above Codex MRLs, providing a practical compliance tool for settings where laboratory access is nonexistent. Paper-based microfluidic tests so-called lab-on-paper devices can detect tetracyclines or beta-lactams in milk or urine without electricity, with results readable by eye or via a smartphone camera, at costs below one dollar per assay (40). Smartphone-integrated biosensors take this further, using the phone's camera and processing power for quantitative results that can be uploaded to centralized databases for surveillance. Community-led sampling kits, consisting of simple swabs for manure or dust that farmers can mail to central laboratories, have been piloted in several LMICs, enabling environmental residue monitoring without requiring technicians to visit remote farms (7,30). However, these low-cost technologies face three persistent barriers: they typically detect only one drug class at a time (while real-world residue mixtures are common), they are not validated for all matrices (e.g., dust, feed, urine from different species), and there is no sustainable financing model to distribute them at scale or to train farmers in their use.

Alternatives to veterinary drugs

Reducing reliance on veterinary drugs through non-antibiotic strategies is arguably the most fundamental approach to residue risk reduction, as fewer drugs used means fewer residues in manure, dust, and animal tissues (35,40). Antimicrobial peptides naturally occurring or synthetic short proteins with broad-spectrum activity have shown promise in livestock trials, though their high production cost and susceptibility to proteolysis in the gut remain barriers. Bacteriophages, viruses that lyse specific bacterial pathogens, offer a highly targeted alternative that does not disrupt commensal microbiota and degrades rapidly in the environment, leaving no persistent residues. Quorum-sensing inhibitors, small molecules that disrupt bacterial communication rather than killing bacteria directly, reduce pathogen virulence without imposing the selective pressure that drives AMR. Competitive exclusion cultures probiotic blends that colonize the animal gut, physically excluding pathogens have been successfully used in poultry production for decades and are now being adapted for swine and cattle (35,40). Critically for agricultural communities, these alternatives produce no pharmacologically active residues in manure or dust, meaning they eliminate occupational exposure pathways entirely. However, adoption remains low because alternatives are often more expensive than conventional drugs, are not available in all countries, and require different management practices. No regulatory framework currently incentivizes the substitution of antibiotics with non-residue-producing alternatives on occupational health grounds; incentives exist only for AMR reduction, which is a different (though related) policy goal.

6. Current Approaches to Residue Management

Despite the rapid pace of technological development described in the previous section, practical residue management on most farms today still relies on established regulatory and farm-level measures that were designed decades ago and have changed little since (2,16,17). This section examines these current approaches across three levels regulatory frameworks, farm-level interventions, and behavioral programs and highlights a consistent gap: all are designed to protect consumers via food testing, not workers via exposure prevention.

Regulatory frameworks: Consumer protection, worker blind spots

At the international level, the Codex Alimentarius establishes Maximum Residue Limits (MRLs) for veterinary drugs in food, based on acceptable daily intake (ADI) calculations that assume lifelong consumption by a healthy adult consumer (16). These MRLs are the cornerstone of global food safety but contain no safety factor for occupational exposure, no consideration of dermal or inhalation routes, and no adjustment for the higher exposure levels farmworkers face. National monitoring programs operationalize these MRLs through systems such as the U.S. National Residue Program (NRP) and the EU's Rapid Alert System for Food and Feed (RASFF), which sample animal products at slaughter or retail and issue violations when residues exceed legal limits (33,34). These programs are effective at detecting gross non-compliance but sample only a tiny fraction of animals typically less than 0.1% of slaughtered livestock in most countries and they sample after animals have left the farm, providing no protection to workers who were exposed during the pre-slaughter period. Withdrawal periods, legally mandated durations derived from residue depletion studies conducted on healthy animals under ideal conditions, are the primary compliance tool (21). Farmers are required to wait a specified number of days between last drug administration and slaughter or milking. However, these withdrawal periods are calculated to ensure that residues in meat and milk fall below MRLs for consumers; no withdrawal period has ever been established to protect farmworkers from residues in manure, dust, or dermal contact. Import controls, including certificates of analysis required by many high-income countries for animal-derived imports, create trade incentives for exporting countries to enforce residue standards (22). Yet these controls do nothing to protect farmworkers in those exporting countries, and they create a two-tier system where large export-oriented farms comply with testing requirements while smallholder farms supplying local markets face no oversight at all. Critically, no regulatory framework in any country has established occupational exposure limits for any veterinary drug, and no regulatory agency requires monitoring of residues in farmworker blood, urine, or household dust.

Farm-level interventions: Voluntary measures with limited reach

At the farm level, interventions focus on responsible drug use and record-keeping, but nearly all are voluntary and none are evaluated for worker health outcomes. Good Veterinary Practices (GVP) guidelines, developed by the World Organisation for Animal Health (WOAH) and national veterinary associations, provide protocols for prescription, dosing, and record-keeping (17). However, compliance is voluntary in most countries, enforcement is rare, and the guidelines do not address worker protection they do not recommend personal protective equipment for dermal or inhalation exposure to residues, nor

do they require training farmworkers about residue hazards. Herd health plans written protocols agreed between veterinarian and farmer can reduce drug use through preventive medicine, but they require regular veterinary access that is absent in many low- and middle-income countries (LMICs) and in marginalized agricultural communities within high-income countries (2). A swine operation in Iowa may have a veterinarian on retainer; a smallholder pig farmer in rural Uganda likely has no veterinary contact at all. On-farm rapid tests, primarily lateral flow assays for detecting selected antibiotics in milk or urine, are increasingly available commercially (40). These tests cost as little as one to five dollars per assay and can provide results in minutes, enabling farmers to test animals before slaughter or before selling milk. Yet adoption remains low because the tests are not required by regulation, are not reimbursed by any program, and detect only a limited number of drug classes a farm using enrofloxacin may test negative for tetracyclines and incorrectly assume compliance. Organic and antibiotic-free certification provides market-driven incentives to avoid drug use entirely, and certified products command premium prices in high-income countries (28). However, certification is expensive, requires extensive record-keeping and inspections, and is inaccessible to smallholders. Moreover, organic certification focuses on prohibiting drug use but does not require monitoring of environmental residues from neighboring conventional farms, meaning an organic farm surrounded by conventional livestock operations may still have contaminated dust and water. The unifying limitation across all farm-level interventions is that none are evaluated for their impact on worker health, and none are required as a condition of farmworker employment. A worker can legally be assigned to handle manure from medicated animals or to work in confinement buildings with contaminated dust, with no disclosure of residue hazards and no legally required protections.

Behavioral interventions: Economic nudges without worker inclusion

Recognizing that withdrawal period non-compliance often stems from economic pressure rather than willful violation, recent interventions have shifted from punitive enforcement to behavioral economics and social learning (2,29,31). Financial incentives have shown promise in pilot programs: farmers receive premium prices for residue-tested animals, verified by on-farm rapid testing, creating an economic reward for compliance rather than a penalty for violation. In dairy cooperatives in East Africa, premium programs for antibiotic-free milk have reduced residue violations and increased farmer participation in testing, though the premiums are often too small to offset income losses from discarded milk during withdrawal periods. Peer learning groups, where farmers share successful residue management practices with each other, have been more effective than top-down extension programs in several LMIC settings. Farmers trust other farmers more than they trust government inspectors, and peer accountability can be a powerful motivator when combined with community monitoring. Simple decision aids color-coded calendars or mobile apps that calculate withdrawal end-dates based on drug, species, and administration route have reduced unintentional non-compliance among farmers who want to follow the rules but lack access to veterinary calculation tools. A farmer who treats a cow with an injectable antibiotic may not know whether the withdrawal period is 5 days or 14 days; a mobile app that displays the countdown can close this knowledge gap at near-zero cost. Finally, strengthening the veterinary-client relationship by mandating that drugs be dispensed only by a veterinarian who knows the farm's

history has reduced residue violations in European Union member states (17,26). When the same veterinarian who prescribes a drug also advises on withdrawal periods and tests for compliance, the conflict of interest that arises when drug sales are decoupled from veterinary oversight is reduced. However, this model is difficult to replicate in settings with few veterinarians some LMICs have fewer than one veterinarian per 100,000 livestock animals. None of these behavioral interventions, despite their promise for improving consumer food safety, have been designed or evaluated with the goal of reducing farmworker dermal or inhalation exposure. A financial incentive program that reduces withdrawal period violations will also reduce residues in manure and dust as a co-benefit, but this occupational health benefit is not measured, not reported, and not used to justify program funding. Until worker health outcomes are included as program metrics, behavioral interventions will continue to be optimized for consumer protection, with farmworker protection remaining an unmeasured externality.

7. Persistent Challenges and Gaps

Despite the established regulatory and farm-level systems described above, significant gaps remain across all domains of residue management. These gaps are not merely technical they reflect fundamental mismatches between the design of current systems (optimized for consumer protection and international trade) and the realities of agricultural production, particularly for farmworkers and smallholder farmers (9,20,22). The following sections examine these challenges across regulatory, environmental, surveillance, and behavioral domains.

Regulatory disharmony and weak enforcement

Different countries maintain divergent Maximum Residue Limits and banned substances lists, creating a patchwork of standards that undermines global food safety and complicates protection for agricultural workers who may move between countries or work in export supply chains. Ractopamine, a beta-agonist growth promoter, is approved for use in the United States but banned in the European Union, China, and Russia, meaning that residue levels considered safe in one country trigger trade disputes and import rejections in another (16,22). Conversely, chloramphenicol is banned globally due to its risk of aplastic anemia, yet it continues to appear in imported shrimp and honey from multiple regions, indicating persistent illegal use and weak enforcement at the source (1). These trade disputes and enforcement failures are not merely economic nuisances; they create an environment where farmers and workers receive mixed messages about which residues are acceptable, and where illegal drugs circulate through unregulated supply chains with no worker safety information at all (29).

The enforcement gap is most severe in low- and middle-income countries, which often lack robust surveillance infrastructure. Unapproved drugs malachite green in aquaculture, chloramphenicol in poultry, nitrofurans in shrimp are purchased via unregulated supply chains, sometimes from vendors who do not disclose the drug identity or recommended withdrawal periods (1,40). Even where regulations exist on paper, inspectors are few, laboratories are under-resourced and understaffed, and penalties for violations are weak or nonexistent. A farmer who sells milk containing antibiotic residues

above the MRL faces, in most LMICs, no meaningful consequence; the economic incentive to shorten withdrawal periods therefore outweighs any regulatory deterrent (29). This enforcement gap directly affects farmworker safety because workers on unregulated farms have no right to know what drugs are being used, no access to safety data sheets, and no legal recourse if they experience residue-related health effects. A worker who develops dermatitis after handling medicated animals on an unregulated farm cannot identify the causative drug, cannot seek workers' compensation (where such systems exist), and cannot report a violation because no violation was recorded.

Environmental sinks: Manure as a persistent reservoir

Manure from medicated animals is routinely applied to cropland as fertilizer, reintroducing drug residues into the food chain via uptake into vegetables and grains grown in manure-amended soil (6,7). This environmental recycling creates a chronic, low-level exposure that is not captured by withdrawal period compliance or slaughterhouse testing, because the manure from a fully compliant animal one that met all withdrawal periods before slaughter still contains drug residues at concentrations that can select for resistance. Resistance genes persist in soil for years, even after the parent drug residues have degraded, meaning that a field that received manure from medicated animals a decade ago may still serve as a reservoir for resistance genes that can transfer to new bacteria, including human pathogens (30). This environmental reservoir is a major gap in current risk assessments, which typically evaluate dietary exposure from meat and milk but do not model exposure from vegetables grown in manure-amended soil, from drinking water contaminated by agricultural runoff, or from dust generated during manure application (20). For farmworkers, the environmental sink challenge is acute: workers who apply manure to fields are exposed to concentrated residues at the moment of application, and workers who harvest vegetables from those same fields weeks or months later may still be exposed to residues that have persisted in soil or been taken up by crops. No current regulatory framework requires monitoring of residues in manure, soil, or vegetable tissue, meaning that this entire exposure pathway is invisible to public health surveillance.

Fragmented surveillance and neglect of smallholder systems

Human AMR surveillance (WHO's GLASS), animal AMR surveillance (WOAH), and veterinary residue monitoring are often separate databases with incompatible formats, different sampling protocols, and no mechanism for cross-linkage (11,17,32). A clinical laboratory that identifies a multidrug-resistant E. coli infection in a rural hospital patient cannot easily query agricultural surveillance databases to determine whether that same resistance pattern has been detected on nearby farms. A residue violation detected at an abattoir—say, enrofloxacin residues above the MRL in a batch of broiler chickens—is not automatically reported to public health authorities or to occupational health clinics serving poultry workers. Cross-sectoral data sharing remains rare, hindered by legal barriers (medical privacy laws that do not contemplate agricultural exposure data), technical barriers (incompatible data formats), and institutional barriers (agriculture, health, and environment ministries that do not routinely communicate) (19,31). The consequence is a system that cannot answer the most basic One Health question: does a

residue violation on a farm predict an increased rate of resistant infections in the people who work on that farm or live in the surrounding community?

The neglect of smallholder and informal systems compounds this surveillance fragmentation. In many LMICs and in marginalized agricultural communities within high-income countries (including migrant farmworker communities in the United States and Europe), livestock are raised in small-scale, non-regulated systems. Drugs are purchased from unlicensed vendors, often repackaged without labels. Withdrawal periods are unknown to farmers because no veterinary professional provided them. Slaughter occurs on-farm or in informal markets without any inspection or testing (1,29,40). These settings are invisible to national monitoring programs, which focus on registered farms, licensed slaughterhouses, and formal supply chains. Yet these invisible settings represent significant exposure risks for producer families, who live and work in direct contact with medicated animals, consume meat and milk from those animals, drink well water that may be contaminated by on-farm waste, and have no access to the consumer protections MRLs, testing, traceability that exist in formal systems. A smallholder farmer in rural India or a migrant worker on a small dairy in Wisconsin may face higher residue exposure than any consumer in London or Tokyo, yet that exposure is never measured, never regulated, and never treated as a public health priority.

Absence of occupational exposure limits and unaddressed behavioral factors

Perhaps the most striking gap, given the focus of this review, is the complete absence of occupational exposure limits (OELs) for veterinary drug residues. Unlike industrial chemicals, pesticides, or airborne particulates, veterinary drugs have no established OELs for airborne or dermal exposure in agricultural workplaces (16,21). A farmworker handling medicated animals, mixing feed containing drugs, or applying manure to cropland has no legally enforceable exposure limit, no medical surveillance requirements specific to drug residues, and no mandated personal protective equipment (PPE) designed or tested for residue hazards (8,9). Generic PPE gloves, coveralls, respirators may provide some protection, but no standards exist for residue-specific PPE (e.g., gloves that are impermeable to ivermectin in pour-on formulations, respirator cartridges that capture aerosolized tetracycline particles). Workers cannot be trained to protect themselves from hazards that have not been quantified, and employers cannot be held responsible for exposures that have not been regulated. This gap reflects the historical framing of veterinary drug residues as a food safety issue rather than an occupational health issue, but it is no longer defensible given the evidence of occupational exposure pathways reviewed in Section 3.

Finally, behavioral factors drive non-compliance in ways that technology alone cannot fix, and these factors are rarely addressed in residue management programs. Farmers may intentionally shorten withdrawal periods due to economic pressures a sudden drop in milk prices, a need to generate cash flow before an impending expense and no rapid test or mobile app can override the economic calculus that selling contaminated milk is better than selling no milk (29). Veterinarians may face conflicts of interest when selling drugs directly, creating an incentive to prescribe more drugs rather than fewer (2).

Consumers in LMICs may prioritize low cost over safety certifications, meaning that residue-compliant products cannot command a price premium sufficient to cover compliance costs (24). Addressing these behavioral factors requires social science interventions behavioral economics, community-based social marketing, institutional reform not just faster biosensors or better machine learning models (40). Critically, none of the behavioral interventions reviewed in Section 6 have been evaluated for their impact on worker health outcomes; they are designed to change farmer behavior to protect consumers, but they may have different (and potentially counterproductive) effects on worker exposure. For example, a financial incentive program that rewards farmers for selling residue-tested animals may encourage more frequent testing but does nothing to protect the worker who handled that animal before it was tested. A peer learning group that successfully reduces withdrawal period violations will reduce residues in manure as a co-benefit, but this occupational health benefit is neither measured nor optimized. Until worker health outcomes are included as design criteria and evaluation metrics for behavioral interventions, residue management will continue to optimize consumer protection at the potential expense of farmworker protection.

8. Future Directions

Addressing the persistent challenges and gaps outlined above requires coordinated action across technological innovation, policy harmonization, regulatory reform, and systemic integration (10,31). The future directions proposed here are not merely aspirational; they build directly on the gap analysis from Section 7 and are ordered roughly from those that could be implemented in the near term (medical surveillance, low-tech solutions) to those requiring longer-term investment and international consensus (green pharmacology, capacity building). A unifying principle across all directions is that farmworker health not just consumer food safety must become a design criterion and evaluation metric for residue management.

Farmworker medical surveillance and low-tech solutions for smallholders

The most immediate and actionable future direction is the establishment of farmworker medical surveillance programs. Pilot programs currently exist for occupational respiratory disease in livestock workers and for needlestick injuries in veterinary medicine, but none specifically target veterinary drug residue exposure (8,29,31). These pilots should expand to include routine screening of workers in large-scale livestock operations for resistant bacteria colonization—including nasal LA-MRSA screening, which is already standard in some European swine operations but is not routinely offered to workers in North America or LMICs. Dermatologic exams for dermal residue effects (contact dermatitis, urticaria, chemical burns from concentrated pour-on formulations) and respiratory health monitoring (lung function tests, symptom questionnaires) should be linked to on-farm veterinary drug use records, creating an occupational health surveillance system that can identify associations between specific drugs and specific health outcomes. Critically, these programs must include a clear ethical and legal framework: workers should not face retaliation for participating, surveillance data should not be used to deny workers' compensation claims, and positive findings (e.g., a worker colonized with LA-MRSA)

should trigger medical follow-up, not employment termination. Pilot programs should be evaluated for feasibility, cost, and worker acceptability before broader rollout (8,29,31).

For the millions of smallholder farmers who operate outside formal surveillance systems, low-tech solutions must accompany high-tech innovation. The principle is simple: for every technological advance that requires laboratory infrastructure, internet connectivity, or specialized training, a low-tech alternative must be available that functions under smallholder conditions (no electricity, no smartphone, no literacy in the national language). Where blockchain traceability is proposed for supply chain monitoring, handwritten logbooks and farmer cooperatives can achieve similar record-keeping goals at near-zero cost. Where wearable animal sensors are promoted for real-time health monitoring, visual animal ID tags with colored zip ties marking treatment dates can support withdrawal period compliance without any electronics. Where machine learning models predict residue depletion curves, simple laminated flowcharts with pictograms can guide farmers through withdrawal period calculation based on drug color, animal size, and administration route. These low-tech alternatives are not inferior substitutes; they are context-appropriate technologies that recognize the reality that most of the world's livestock producers are smallholders. Development agencies and veterinary extension programs should prioritize co-design of these low-tech solutions with farming communities, rather than assuming that technology transfer from high-income countries will be appropriate or effective (29,40).

Global surveillance infrastructure: Residue observatory and early warning systems

A global residue observatory an open-access, web-based database aggregating residue levels, AMR genes, and environmental concentrations from all countries would fill a critical gap in current surveillance (11,32,40). No such database currently exists. National residue monitoring programs publish annual reports in different formats, on different schedules, in different languages, making cross-country comparison and hotspot identification nearly impossible. A global observatory would establish common data standards, require participating countries to upload residue testing results (including negative findings, not just violations), and provide real-time mapping of residue hotspots. Privacy and proprietary concerns would need to be addressed farm-level data should be aggregated to preserve confidentiality while allowing regional trend analysis but the technical barriers are solvable, as demonstrated by existing global surveillance systems for influenza and foodborne disease outbreaks. The political barriers are more substantial: countries with high residue violation rates may resist transparency, and funding for a permanent observatory secretariat would require sustained international commitment (11,32,40).

Building on the observatory, One Health early warning systems using artificial intelligence could integrate multiple data streams to provide real-time risk alerts. Veterinary prescription data (where available), slaughterhouse rapid test results, hospital AMR reports, and environmental monitoring from manure, soil, and water could be fed into AI platforms trained to detect anomalous patterns for example, a spike in tetracycline residues in slaughterhouse samples from a region, combined with an increase in tetracycline-resistant E. coli urinary tract infections in the same region's rural clinics, would trigger an

alert for investigation (40). Such systems are technically feasible: similar AI early warning systems already exist for foodborne pathogen outbreaks (e.g., PulseNet) and for emerging infectious diseases (e.g., ProMED). The barriers are primarily institutional: agricultural, health, and environmental data systems do not currently share data, and legal frameworks for real-time cross-sectoral data sharing are absent in most countries. Pilot projects in subnational regions (e.g., a state or province with integrated agricultural and health data systems) could demonstrate proof of concept and generate the political will for broader rollout (40).

Regulatory reform: Phased elimination of high-risk drugs and occupational exposure limits

At the international regulatory level, phased elimination of high-risk drugs represents a feasible near-term goal building on existing precedents. International consensus should phase out the use of medically important antimicrobials for growth promotion a practice already banned in the European Union and the United States, but still legal in many LMICs (11,27,28). The World Health Organization's list of critically important antimicrobials for human medicine provides a clear framework: colistin, carbapenems, and third-generation cephalosporins should be limited to therapeutic use with susceptibility testing, meaning they should not be used for routine disease prevention (metaphylaxis) or growth promotion. Voluntary industry initiatives have already reduced some of these uses in high-income countries; the next step is binding international agreement under Codex Alimentarius or WOAH standards, with technical and financial support for LMICs to transition away from these drugs (11,27,28).

More fundamentally, and most directly relevant to the agricultural populations at the center of this review, regulators must establish occupational exposure limits for veterinary drug residues. Unlike industrial chemicals, which have OELs established by agencies such as the US Occupational Safety and Health Administration (OSHA) or the European Agency for Safety and Health at Work (EU-OSHA), no veterinary drug has an OEL for airborne or dermal exposure in agricultural workplaces (16,21). Establishing OELs would require a dedicated research program to generate the necessary toxicological and exposure data: controlled studies of dermal absorption rates for common veterinary drugs (e.g., ivermectin pour-on, enrofloxacin injectable), air sampling methods for residues in confinement building dust, and biomonitoring methods to measure residues in worker urine and blood. The National Institute for Occupational Safety and Health (NIOSH) in the US or similar agencies in other countries could lead this effort, building on existing frameworks for pesticide OELs. Once OELs are established, they would trigger enforceable protections: exposure monitoring, medical surveillance, PPE requirements, and training. Farmworkers would gain the same legal protections against veterinary drug residues that they already have against pesticides and industrial chemicals a change that would fundamentally reorient residue management from consumer protection alone to comprehensive worker protection (8,9,21).

Green veterinary pharmacology and capacity building in low- and middle-income countries

Longer-term solutions require transforming the pharmaceutical pipeline itself. Green veterinary pharmacology the design of veterinary drugs for rapid degradation in manure and soil, with no bioactive metabolites and low toxicity to non-target organisms remains an emerging field with significant potential

(30,38). Current veterinary drugs are not designed with environmental or occupational safety as primary criteria; they are designed for efficacy in the animal, stability during storage, and convenient dosing. A green pharmacology approach would prioritize drugs that degrade within days rather than months in manure, that do not form persistent metabolites, and that have low dermal toxicity and low dust generation during feed mixing. Regulatory agencies could incentivize green drug development through expedited approval pathways, patent extensions, or procurement preferences for green drugs in public health programs (e.g., national veterinary drug formularies). The European Medicines Agency's "Guideline on the environmental risk assessment of veterinary medicinal products" is an early step, but it does not yet require green design; it only requires assessment after development (30,38).

Finally, all of the above directions depend on sustained capacity building in low- and middle-income countries. High-income countries have funded laboratory infrastructure, training programs, and regulatory enforcement in LMICs through various bilateral and multilateral mechanisms, but these efforts are chronically underfunded and fragmented (29,40). Twinning programs that pair reference laboratories in Europe or North America with laboratories in Africa or Asia have proven effective for technology transfer for example, a laboratory in Kenya paired with a Dutch reference lab can receive training, quality control materials, and troubleshooting support at a fraction of the cost of building independent capacity. However, twinning programs typically last three to five years, after which the LMIC laboratory often struggles to maintain equipment, reagents, and trained staff. Sustainable capacity building requires long-term commitment (decades, not years), integration into national budgets rather than donor-funded projects, and investment in veterinary and laboratory training pipelines that retain graduates in public service rather than losing them to higher-paying private sector jobs (1,29,40). For farmworkers, capacity building in LMICs is not an act of charity; it is a necessity for global residue management, because residues and resistance genes do not respect national borders. A worker on a smallholder farm in Southeast Asia who is exposed to illegally imported chloramphenicol is connected, through global supply chains and human migration, to consumers and workers on every continent. Protecting agricultural populations everywhere requires investing in the systems that protect them everywhere.

9. Discussion

This review has synthesized the public health risks of veterinary drug residues, with particular attention to agricultural workers and rural communities' populations that face higher and more diverse exposure than the general public. Several interconnected themes emerge from this synthesis, each pointing to a fundamental mismatch between current residue management systems and the realities of agricultural life. Together, these themes argue for a paradigm shift: away from a consumer-focused, food-only safety model and toward a comprehensive occupational and environmental health framework that centers the agricultural producer.

Divergent exposure profiles and the knowledge gap

The exposure profile of farm families differs fundamentally from that of consumers. While the general public encounters veterinary drug residues primarily through dietary intake of meat, milk, and eggs, agricultural workers face dermal, inhalation, and environmental pathways that begin before slaughter and continue through manure handling, dust inhalation, and household contamination (6,8,9). A worker who applies manure from medicated animals to cropland may absorb residues through skin contact and inhalation at concentrations that far exceed what any consumer would ingest from a serving of meat. Yet these pathways are unregulated, unmonitored, and absent from current risk assessments, which focus exclusively on food (16,19). This is not a minor oversight; it is a structural omission that renders farmworkers invisible to the regulatory systems designed to protect public health.

A critical knowledge gap underlies this omission: no comparative absorption studies have quantified the difference between occupational and dietary exposure. Residue concentrations in fresh manure can reach milligram-per-kilogram levels orders of magnitude higher than typical residues in meat or milk suggesting the potential for substantially higher acute occupational exposure. However, without human biomonitoring studies that measure residues in farmworker blood, urine, and household dust, this suggestion remains a hypothesis. Closing this knowledge gap is not merely an academic exercise; it is a prerequisite for setting occupational exposure limits, designing effective personal protective equipment, and establishing medical surveillance protocols. The absence of these data is itself a policy choice a choice to prioritize consumer protection over worker protection, and a choice to fund food safety research while leaving occupational health research for agricultural workers chronically underfunded.

The incomplete operationalization of One Health

The One Health framework, which explicitly recognizes the interconnectedness of human, animal, and environmental health, provides the conceptual foundation for addressing veterinary drug residues comprehensively (18,19). However, this review finds that One Health remains incompletely operationalized for agricultural settings. Integrated surveillance across human, animal, and environmental sectors is rare, and farmworker health data are almost never linked to farm drug use records (19,31,40). A rural clinic seeing recurrent dermatitis or resistant infections in a patient who works on a livestock farm has no systematic way to connect those clinical findings to veterinary drug exposures on that farm. The prescription records, manure application logs, and withdrawal period compliance data that exist on the farm if they exist at all are not accessible to the clinician, and the clinician's diagnoses are not reported to agricultural authorities. This is not a technical failure; it is an institutional failure, reflecting the historical separation of agriculture, health, and environment ministries and the absence of legal frameworks for cross-sectoral data sharing.

The case of livestock-associated MRSA illustrates what operationalized One Health could look like. Nasal colonization with LA-MRSA among swine and poultry workers has been consistently documented, with prevalence rates 10 to 50 times higher than in the general population. In Denmark and the Netherlands, routine surveillance of swine workers for LA-MRSA has been implemented, and positive findings trigger follow-up of household contacts and clinical monitoring for infections (14,15). This is a

model of occupational One Health: surveillance data collected from workers are used to protect workers, their families, and the broader community. Yet this model exists in only a few European countries; in most of the world, including major livestock-producing regions of North America, South America, and Asia, no such surveillance exists. Expanding this model to other veterinary drug residues not just LA-MRSA requires the same infrastructure: routine occupational health surveillance linked to veterinary drug use data, with clear protocols for response when hazards are identified.

Economic drivers, smallholder invisibility, and environmental diffusion

Technology alone cannot fix the problem of veterinary drug residues, because the root causes are economic and structural as much as technical. Farmers who shorten withdrawal periods to avoid losing income are not acting irrationally or immorally; they are responding to thin profit margins, lack of safety nets, and the absence of viable alternatives (2,29,31). A dairy farmer facing a sudden drop in milk prices who must choose between discarding milk from a treated cow (losing that day's income) or selling that milk (violating the withdrawal period but feeding their family) is making a choice that no regulatory framework has made unnecessary. Solutions must therefore include financial incentives, insurance mechanisms that compensate farmers for withdrawal period compliance, and market premiums for residue-tested products. These economic interventions should be evaluated not only for their effect on residue violation rates but also for their effect on worker health outcomes a metric that has been entirely absent from program evaluations to date.

The invisibility of smallholder and informal systems compounds every other challenge. Most of the world's livestock producers operate outside formal surveillance systems: millions of small farms where a single animal represents a family's savings, where drugs are purchased from unlicensed vendors alongside vegetables in open-air markets, and where slaughter occurs on-farm without inspection (1,29,40). These settings are not marginal exceptions; they are the global norm. International efforts to manage veterinary drug residues have focused almost exclusively on formal supply chains, export-oriented farms, and high-income countries, leaving the majority of the world's agricultural producers and workers without protection. Adapting to smallholder realities requires fundamentally different approaches: low-cost rapid tests that work without electricity, training programs delivered through farmer cooperatives rather than government inspectors, and surveillance systems that aggregate data at community levels rather than requiring individual farm registration. These approaches exist in pilot form but have not been scaled, and they remain chronically underfunded relative to high-technology solutions designed for industrialized agriculture.

Finally, the environmental pathway via manure application creates chronic, geographically diffuse exposure risk for entire rural communities (6,7,10). Unlike point-source industrial pollutants, which can be contained and monitored at a pipe or fence line, veterinary drug residues in manure-amended soil contaminate well water, garden produce, and household dust across broad agricultural regions. Household dust has been identified as a previously unrecognized reservoir for antibiotic residues and resistance genes in agricultural communities meaning that a farmworker's child playing on the floor may

be exposed to drug residues tracked in on work boots, even if that child never enters the barn. This environmental diffusion means that the population at risk extends beyond farmworkers themselves to their non-working family members, neighbors, and entire rural communities. Current risk assessments, which calculate consumer exposure based on estimated dietary intake of meat and milk, completely miss this community-wide environmental exposure pathway. Expanding risk assessment to include environmental pathways would require new monitoring methods, new exposure models, and new regulatory authorities but the scientific case for doing so is already strong.

Toward a new paradigm

Protecting agricultural communities requires moving decisively beyond a consumer-focused, food-only safety paradigm. Farmworkers need occupational exposure limits for veterinary drug residues, analogous to those that exist for pesticides and industrial chemicals. They need medical surveillance programs that include routine screening for LA-MRSA colonization, dermatologic exams, and respiratory health monitoring linked to on-farm drug use records. They need accessible rapid testing that can be used at the point of exposure, not just at slaughter. They need economic supports for withdrawal period compliance that make the right choice also the profitable choice. And they need inclusion in surveillance systems not as subjects of research, but as stakeholders with a right to know about hazards in their workplaces and a right to participate in designing solutions.

Achieving these goals requires a coordinated effort that integrates agricultural health, veterinary medicine, environmental science, and rural social policy disciplines that currently operate in silos, with separate funding streams, separate professional associations, and separate journals. The One Health framework provides the conceptual architecture for this integration, but architecture alone does not build a house. What is needed now is implementation: pilot programs that test medical surveillance in real farm settings, regulatory petitions that establish occupational exposure limits, funding mechanisms that support low-tech solutions for smallholders, and legal frameworks that enable cross-sectoral data sharing while protecting worker privacy. These implementation steps are not technically impossible; they are politically and institutionally challenging. The health of farming families, the sustainability of animal agriculture, and the global fight against antimicrobial resistance depend on meeting these challenges.

10. Conclusion

Veterinary drug residues pose complex risks from direct toxicity to antimicrobial resistance that cannot be managed through consumer-focused food testing alone. Throughout this review, one population has emerged as consistently invisible: agricultural workers and their families. Farmworkers face dermal, inhalation, and environmental exposure pathways that begin before slaughter and continue through manure handling and household contamination. Yet no country has established occupational exposure limits for any veterinary drug, no medical surveillance program routinely monitors farmworkers for residue-related health effects, and no regulatory framework requires monitoring of residues in manure, dust, or well water.

The One Health framework recognizes that human, animal, and environmental health are inseparable, but implementation remains fragmented. Surveillance systems operate in separate databases. Rural clinics cannot access on-farm drug records. Recent advances in detection, prediction, and remediation offer powerful tools, but they will only deliver public health benefits if embedded within harmonized regulations, robust surveillance systems that include agricultural workers, and behavioral change addressing the economic pressures driving non-compliance.

Future efforts must prioritize farmworker medical surveillance, low-tech solutions for smallholder farmers, blockchain traceability adapted to cooperative models, green veterinary pharmacology, and sustained capacity building in low- and middle-income countries. The barriers are not primarily technical but institutional and political. What has been lacking is the political will to treat farmworker exposure to veterinary drug residues as a public health priority on par with consumer food safety. The health of farming families, the sustainability of animal agriculture, and the global fight against antimicrobial resistance depend on summoning that will.

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AI Use Statement

During the preparation of this work, the author used ChatGPT solely for grammar checking, sentence-level language refinement, and formatting assistance. No artificial intelligence was used to generate scientific content, interpret data, formulate conclusions, or produce the original intellectual arguments. The author has reviewed and edited all AI-assisted output and assumes full responsibility for the content of this publication.

Conflict of Interest

The author declares no conflict of interest.

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Tables

Table 1: Veterinary Drug Classes with Documented Occupational or Community Health Impacts in Agricultural Settings

Drug Class	Examples	Primary Route(s) for Farmworkers	Key Health Concern for Ag Populations	Environmental Detection Frequency in Agriculture
Amphenicols	Chloramphenicol	Dermal (injection sites), inhalation (dust)	Aplastic anemia (dose-independent)	Low (banned, but illegal use persists)
Beta-agonists	Clenbuterol, Ractopamine	Dermal (handling live animals), inhalation (confinement dust)	Tachycardia, tremors, metabolic disturbance	Moderate (regional, illegal use)
Tetracyclines	Oxytetracycline, Chlortetracycline	Manure handling, dermal, household dust	Gut microbiome disruption, resistant commensal carriage	High (most commonly detected in manure and dust)
Fluoroquinolones	Enrofloxacin, Ciprofloxacin (metabolite)	Inhalation (poultry dust), manure	High-risk AMR selection, tendonitis (rare)	Moderate (critically important for humans)
β-lactams	Penicillin G, Ceftiofur	Dermal (milkers), injection site contact	Anaphylaxis in sensitized workers	Moderate (common, but rapid degradation)
Avermectins	Ivermectin, Doramectin	Dermal (pour-on applications), manure	Neurotoxicity with chronic high exposure	Moderate (lipophilic, persists in manure)
Hormones	Estradiol, Zeranol, Trenbolone	Implant site contact, manure	Endocrine disruption, unclear occupational risk	Low

Environmental Detection Frequency: Low = detected in <10% of farm environmental samples; Moderate = detected in 10–40% of samples; High = detected in >40% of samples. Based on detection frequency in manure, dust, and soil from agricultural settings across multiple studies.

Table 2: One Health Mitigation Strategies Relevant to Farmworker Protection

Intervention Category	Specific Strategy	Primary Target	Applicable to Smallholder Farms?	Key Barrier in Agricultural Settings
Regulatory	Withdrawal periods	Animal (compliance)	No (rarely enforced)	Economic pressure to shorten
Regulatory	Occupational Exposure Limits (OELs)	Human (worker)	Yes (if established)	Currently none exist for any veterinary drug
Farm-level	On-farm rapid testing	Animal (quality control)	Yes (paper-based strips <$1)	Limited drug coverage; not multi-residue
Farm-level	Herd health planning	Animal (prevention)	Partial (requires vet access)	Upfront cost; veterinary shortages in LMICs
Environmental	Manure composting + biochar	Environment	Yes (low-tech)	Incomplete degradation for some drugs
Behavioral	Financial incentives for compliance	Human (farmer)	Yes (cooperative models)	Requires third-party verification
Surveillance	Farmworker medical monitoring (including LA-MRSA screening)	Human (worker)	Partial (clinic-dependent)	No established protocols or funding