

Review

Occurrence, fate, and environmental loss of antiparasitic veterinary drugs in animal waste

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ABSTRACT

Antiparasitic veterinary drugs, specifically anthelmintics, anticoccidials and ectoparasiticides, are increasingly recognised as global environmental contaminants, entering agroecosystems primarily via animal excreta and accumulating in manure and slurry before transfer to soils, water bodies and crops. This review provides a comprehensive synthesis of these drug classes, covering usage patterns, excretion and persistence dynamics, occurrence in manure and slurry, within-manure transformation pathways, environmental fate and transport pathways, ecotoxicological effects on non-target organism, and mitigation strategies. Excretion and transformation behaviour are governed by compound lipophilicity and chemical structure: highly lipophilic macrocyclic lactones and benzimidazoles persist predominantly in faecal matter and undergo class-specific transformation reactions, whereas the transformation pathways of pyrethroids within manure remain almost entirely uncharacterised despite well-documented soil-phase chemistry. Occurrence data are sparse and dominated by isolated farm- or species-specific studies rather than systematic surveys and validated analytical methods for pyrethroids and its transformation products in manure are scarce. Environmental fate is strongly governed by lipophilicity: macrocyclic lactones and pyrethroids move primarily via particle-associated surface run-off, whereas benzimidazoles and ionophores show moderate mobility and can leach into surface waters. Ecotoxicological risks are most critical for dung-colonising invertebrates exposed to macrocyclic lactone residues and for aquatic organism exposed to pyrethroid-contaminated sediments. Mitigation strategies, including composting, storage, bioaugmentation, and source-based interventions, show compound-specific efficacy and are rarely validated at farm scale. The review identifies three primary barriers to robust environmental risk assessment: the scarcity of validated multi-residue analytical methods, particularly for pyrethroids and its transformation products, the lack of systematic occurrence and usage monitoring; and the limited farm-scale evaluation of mitigation technologies.

1. Introduction

Animal excreta are the principal route by which veterinary medicinal products (VMPs) and their metabolites enter the environment. Following administration, a substantial proportion of many drugs is excreted unchanged or as biologically active metabolites in urine and faeces, making manure and slurry major reservoirs of pharmaceutical residues (Koschorreck et al., 2002). Given the scale of livestock production in Europe where the EU-27 and the UK together generate

approximately 1.4 billion tonnes of manure annually (Königer et al., 2021), the release of VMPs from excreta constitutes a critical pathway linking veterinary drug use to soil, water and biota. Globally, between 3000 and 27000 tonnes of VMPs are estimated to be introduced into the environment each year through animal manure (Song and Guo, 2014).

Land spreading remains the dominant and economically-favoured manure management strategy (Zalewska et al., 2023) but repeated applications risk the accumulation of residues across environmental matrices, including soil, plants and water (Kuppusamy et al., 2018).

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Among the drug classes of greatest concern in this context are the anthelmintics, anticoccidials, and ectoparasiticides. Ivermectin, a broad-spectrum anthelmintic widely used against nematodes and arthropods, has been shown to negatively affect the diversity and behaviour of dung beetles when present in cow dung, thereby impeding dung decomposition (Floate, 2006; Steel and Wardhaugh, 2002; Römbke et al., 2010). Anticoccidial ionophores and synthetic anticoccidials are used extensively in poultry and, to a lesser extent, in ruminant and pig production to control coccidiosis, a disease responsible for substantial losses to the global poultry industry (Noack et al., 2019; Kadykalo et al., 2018). Synthetic pyrethroid ectoparasiticides, meanwhile, are of particular environmental concern due to their high toxicity to non-target invertebrates and their potential to act as endocrine disruptors in both vertebrates and invertebrates (Tuck et al., 2018). Veterinary drug residues present in soil can be taken up by crops and ultimately enter the human food chain (Stando et al., 2022), and can also leach into aquifers, as shown by the detection of 17 anthelmintic drugs in Irish groundwater (Mooney et al., 2021).

Existing reviews of VMPs in the environment have been largely confined to individual compound classes or environmental compartments, with antibiotic residues dominating the literature relative to anthelmintics and ectoparasiticides. General assessment of veterinary medicines in the environment (Boxall et al., 2003b, 2003a; Kaczala and Blum, 2016) have established the broad regulatory and contamination context but do not examine animal waste as a distinct environmental pathway. Class-specific reviews have addressed avermectin ecotoxicology (Bai and Ogbourne, 2016; Edwards et al., 2001), anthelmintic fate and effects on non-target organisms (Vokřál et al., 2023; Beynon, 2012a), ectoparasiticides environmental consequences (Beynon, 2012b; Joachim et al., 2025; Haseler et al., 2024a), pyrethroid microbial degradation and toxicity (Singh et al., 2022b; Galadima et al., 2021; Kansal et al., 2023; Katagi, 2012), while the occurrence and transformation of VMPs more broadly in manure and slurry have received limited and fragmented interest (Wohde et al., 2016a). No existing review integrates usage patterns, excretion dynamics, within-manure transformation, environmental fate and transport, ecotoxicological effects, and mitigation strategies for anthelmintics, anticoccidials, and pyrethroid ectoparasiticides within a single synthesis. This fragmentation has produced poorly defined structure–excretion relationships, inconsistent reporting of global usage data, limited characterisation of transformation products across drug classes, and analytical constraints that hinder cross-study comparability in complex waste matrices. The present review addresses these gaps by providing a comprehensive synthesis spanning the full pathway from drug administration through to environmental exposure for these three drug classes.

To address these gaps, this review provides a systematic and integrative assessment of anthelmintic, anticoccidial, and pyrethroid ectoparasiticide residues in animal waste. Specifically, it (1) summarises usage patterns across agricultural production systems; (2) synthesises excretion dynamics and the influence of physicochemical properties on elimination routes; (3) evaluates the occurrence of parent compounds and metabolites in manure and slurry; (4) explores transformation products formed in manure matrix; (5) assesses major environmental pathways including leaching, sorption, and surface run-off; (6) examines analytical challenges associated with detecting these compounds in complex waste matrices; and (7) reviews the ecotoxicological effects on non-target organisms and current and emerging mitigation strategies. Together, these components establish a comprehensive framework for understanding the environmental fate of anthelmintics, anticoccidials, and pyrethroids in livestock waste and for identifying priorities for more sustainable management practices.

2. Methodology

This review focused on peer-reviewed and grey literature addressing the occurrence, excretion, transformation, environmental fate,

ecotoxicological effects, and mitigation of VMPs, specifically anthelmintics, anticoccidials, and pyrethroid ectoparasiticides in animal manure and slurry. Searches were conducted across four databases: Google Scholar, ISI Web of Knowledge (Web of Science Core Collection), Scopus, and PubMed. Search strategies employed Boolean combinations of terms relating to veterinary pharmaceutical compounds, livestock waste matrices, environmental processes, analytical techniques, and risk assessment. Full details of the Boolean search strings are provided in [Supplementary Material S1](#).

Publication years were filtered from 2000 to 2026 to capture recent developments in veterinary drug use, analytical detection methods (e.g., GC-MS, LC-MS/MS, HRMS), and manure treatment technologies (e.g., composting, anaerobic digestion). Studies published prior to 2000 were retained where they provided foundational pharmacokinetic or metabolic insights which are vital to understanding excretion profiles and residue behaviour (e.g., Donoho et al., 1978; Hennessy et al., 1989).

Grey literature and institutional reports were incorporated from the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization/Joint FAO–WHO Expert Committee on Food Additives (JECFA), the European Medicines Agency (EMA), and the World Organisation for Animal Health (WOAH). Cross-references from retained articles were screened for additional relevant sources not captured by database searches.

Records retrieved from Web of Science, Scopus, and PubMed were merged and deduplicated, yielding 674 unique references. Title and abstract screening excluded 545 records that did not meet the inclusion criteria, principally studies confined to non-manure environmental matrices (e.g., aquatic-only studies), human pharmaceutical residues, or investigations outside the scope of the three target drug classes. The remaining 129 publications were retained for full-text evaluation and data synthesis together with 10 additional sources (grey literature, cross-references).

2.1. Use in agricultural production system

Anthelmintics control gastrointestinal helminths, liver fluke, and lungworms in grazing ruminants and are applied via oral drench, topical pour-on, injectable, or intraruminal bolus (Beynon, 2012a). In the United Kingdom and Ireland, pasture-based cattle and sheep systems are associated with high levels of internal parasite exposure, resulting in frequent anthelmintic use, while predominantly indoor production systems generally experience lower infection rates (Kools et al., 2008). Parasite burdens also vary geographically: liver fluke tends to be more prevalent in wetter regions such as lowland areas and the Atlantic zones, whereas other gastrointestinal nematodes are a more uniform concern across temperate grazing systems (Ducheyne et al., 2015; Morgan and Van Dijk, 2012). The macrocyclic lactone, ivermectin, dominates anthelmintic use because of its broad-spectrum activity against both endo- and ectoparasites (Beynon, 2012a; Haseler et al., 2024b).

Anticoccidials are used to control coccidiosis caused by *Eimeria* spp., a disease responsible for estimated annual losses exceeding US \$3 billion to the global poultry industry and that also causes significant losses in cattle and other livestock (Noack et al., 2019; Kadykalo et al., 2018). Prophylactic in-feed administration remains the dominant management strategy because intervention after the appearance of clinical signs is deemed late to prevent productive losses. Two categories are in use: polyether ionophores which include monensin, salinomycin, lasalocid, narasin, maduramicin, and semduramicin, derived from fermentation products of *Streptomyces* spp.; and synthetic anticoccidials including diclazuril, nicarbazin, halofuginone and toltrazuril (Noack et al., 2019). In the European Union (EU), anticoccidials used in poultry are classified as zootechnical feed additives under Regulation (EC) No. 1831/2003 and require no veterinary prescription. Whereas in ruminants and pigs, where coccidiosis is not considered systemic, their use is regulated as a veterinary medicine under Directive 2001/82/EC (European Parliament And Council Of The European Union, 2001). In the UK, anticoccidials

were reported as accounting for over 40% of all antimicrobials sold for use in food and non-food animals in 2011, with ionophores comprising more than 70% of this volume (Noack et al., 2019).

Synthetic pyrethroids are used as ectoparasiticides in livestock to control ticks, lice, keds, blowfly, and scab-mites in sheep and cattle, and are applied topically as dips, pour-ons, sprays or impregnated ear-tags (Beynon, 2012b). Across Europe, ectoparasite control strategies have progressively shifted toward insect growth regulators and pour-on macrocyclic lactones, though dipping and spray-based treatments continue to be employed for both preventive and therapeutic purposes in certain countries (Beynon, 2012b). Pyrethroids are also used in livestock systems as topical fly repellents and for the management of lice and chorioptic mange, frequently off license.

Across all three classes, the lack of systematic-use monitoring remains to be a critical gap: anticoccidials require no prescription in poultry production, anthelmintics consumption remains poorly collated across member states, and ectoparasiticide use is poorly monitored by compound or formulation type. As a result, environmental risk cannot be reliably evaluated at the landscape level.

2.2. Occurrence in manure

Anthelmintic residues show a pronounced contrast between fresh excreta and stored waste. Ivermectin reaches high concentrations in dung deposited directly on pasture, with reported levels of 310 – 810 $\mu\text{g kg}^{-1}$ dry weight in freshly excreted cattle dung (Römbke et al., 2010) and a median concentration of 930 $\mu\text{g kg}^{-1}$ in pig faeces shortly after oral treatment (Carrillo Heredero et al., 2025), as summarised in Table 1. However, once incorporated in slurry, ivermectin is typically diluted below the limit of detection, reflecting both its hydrophobicity and the mixing of treated and untreated animal waste in collection tanks (Carrillo Heredero et al., 2025). This creates a sharp spatial and temporal exposure gradient: dung pats on pasture represent short-term, highly localised “hotspots” for dung fauna, whereas land-applied slurry generally carries much lower ivermectin loads (Vokrál et al., 2019; Römbke et al., 2010; Carrillo Heredero et al., 2025). A broader feedlot survey similarly found macrocyclic lactones (abamectin, doramectin, eprinomectin and ivermectin) at concentrations of 1–36 $\mu\text{g kg}^{-1}$ dry weight in biosolids from some operations, with levels strongly dependent on the waste-management system used (Coleman et al., 2013).

Benzimidazole residues in excreta used for field fertilisation have also been documented, although less consistently than macrocyclic lactones or ionophores. In sheep faeces, albendazole sulphoxide (ABZ-SO) was the dominant residue at $79064 \pm 5081 \mu\text{g kg}^{-1}$ dry weight, reflecting its known predominance as the primary circulating metabolite; the sulphone metabolite (ABZ-SO₂) was approximately 10-fold lower at $7584 \pm 2222 \mu\text{g kg}^{-1}$, while the parent compound was present at considerably lower concentrations ($202 \pm 25 \mu\text{g kg}^{-1}$) (Navrátilová et al., 2021).

Anticoccidial ionophores show a clear species-related distribution pattern in US livestock waste matrices. Monensin occurs at broadly similar background concentrations in both dairy manure storage tanks ($1000 \pm 500 \mu\text{g kg}^{-1}$) and poultry litter storage piles ($900 \pm 100 \mu\text{g kg}^{-1}$), whereas salinomycin reached $5300 \pm 2200 \mu\text{g kg}^{-1}$ in poultry litter but remained below $100 \mu\text{g kg}^{-1}$ in dairy manure, while lasalocid showed the reverse pattern, at $3300 \pm 500 \mu\text{g kg}^{-1}$ in dairy manure but below $100 \mu\text{g kg}^{-1}$ in poultry litter (Arikan et al., 2016). These differences likely reflect which ionophores are licensed and routinely included in feed formulation for each species.

Pyrethroid ectoparasiticides remain rarely reported in manure occurrence surveys, yet the available data point to a strong dichotomy between background and treatment-associated residues. In a controlled dosing trial, deltamethrin in laying hen faeces rose to $13,511 \pm 172 \mu\text{g kg}^{-1}$ by day 14 of continuous administration, with a faecal excretion rate of 68% of the applied dose (Liu et al., 2023). In

contrast, a survey of beef cattle feedlot biosolids found that deltamethrin and cypermethrin were not detected in any sample, despite being both registered for use as cattle ectoparasiticides in Australia, although this comparison is confounded by route of administration, as the cattle products are typically applied dermally rather than dosed orally (Coleman et al., 2013). This suggests that pyrethroid residues in manure are highly dependent on recent treatment history and dosing intensity, and that, unlike macrocyclic lactones detected in the same feedlot samples, pyrethroids may be rapidly degraded, bound to solids below detection limits, or simply absent where treatment timing does not coincide with sampling.

Overall, the dataset for anthelmintics, anticoccidials, and pyrethroids in manure is sparse compared to antimicrobials, and is dominated by a small number of species- and farm-specific studies rather than systematic surveys. Reported concentrations therefore reflect a combination of treatment regimen, time since dosing, and manure handling practices rather than a representative picture of typical residue levels. Poultry litter and fresh pasture dung appear to be the matrices most likely to retain high concentrations of these compound classes, while stored slurry and feedlot biosolids tend to show either strong dilution or non-detection, consistent with the broader pattern of analytical and monitoring gaps.

2.3. Excretion

The excretion of VMP residues following treatment is governed by multiple interacting factors, including the route of administration, physicochemical properties of the active substance, animal species, body condition, and feed intake. Injectable formulations are widely employed to enhance drug stability, improve bioavailability, or extend tissue persistence (Manasa et al., 2024). Although less convenient than oral or typical routes, parenteral administration is preferred for treating individual animals or small groups and is particularly common for targeted therapeutics (Sun et al., 2004; Bishop, 2005). Conversely, oral or in-feed administration is preferred when entire herds or flocks require treatment (Vermeulen et al., 2002). Representative examples include the prophylactic inclusion of anticoccidials in poultry feed and the pour-on administration of endectocides to cattle (Peek and Landman, 2011; Laffont et al., 2001). Pour-on delivery of endectocides results in approximately 2.5 times more active ingredient than injectable formulations, leading to greater amounts of residues being excreted in the environment (Prichard et al., 2012).

The physicochemical properties of VMPs, particularly lipophilicity (expressed as log P), exert a major influence on absorption, distribution, metabolism, and excretion as tabulated in Table 2. Highly lipophilic compounds, including avermectins and benzimidazoles, exhibit poor aqueous solubility and limited gastrointestinal absorption, resulting in predominantly biliary and faecal elimination (Marczak et al., 2015). These compounds bind strongly to organic matter, which reduces their mobility in soil but prolongs their persistence in manure-amended environments (Carrillo Heredero et al., 2025; Kreuzig et al., 2007). In contrast, more polar compounds tend to undergo greater systemic absorption but exhibit higher aqueous mobility following faecal and urinary excretion, facilitating transport to surface waters and groundwater, as observed for multiple compounds in agricultural catchments (Song et al., 2010).

High excretion rates have been observed across multiple VMP classes, and these are summarised in Fig. 1 which presents reported excretion data by drug class, administration route, and livestock species.

Within the avermectin class, ivermectin is excreted largely as the unchanged parent compound. Faecal excretion accounts for 69% of the administered dose in cattle following pour-on application, 30% in pigs after subcutaneous dosing, and 95.5% in sheep after intraruminal delivery, with urinary excretion remaining below 1% across all three species (Laffont et al., 2001; Chiu et al., 1990; Alvinerie et al., 1999). The marked difference between cattle and sheep faecal excretion values

Table 1
Occurrence of VMP residues in different manure and slurry across four species.

Drug Class	Sub-class	Active Ingredient	Bovine		Porcine		Ovine		Poultry		Key notes	References
			Level ($\mu\text{g kg}^{-1}$)	Source	Level ($\mu\text{g kg}^{-1}$)	Source	Level ($\mu\text{g kg}^{-1}$)	Source	Level ($\mu\text{g kg}^{-1}$)	Source		
Anthelmintics	Avermectins	Ivermectin	310–810	Pasture	930	Collected from rectum	930 $\pm$ 0.5	Collected from rectum	–	–	High in freshly excreted dung; largely diluted below LOD in stored slurry	Römbke et al. (2010); Carrillo Heredero et al. (2025); Vokrál et al. (2019) Coleman et al. (2013)
		Abamectin, doramectin, eprinomectin, and ivermectin	< 1–36	Feedlot biosolids (dry. wt.)	–	–	–	–	–	–	Detected in some feedlot waste samples; concentration varied with waste-management practices	
	Benzimidazoles	Albendazole & metabolites	–	–	–	–	202 $\pm$ 25 (ABZ); 79,064 $\pm$ 5081 (ABZ-SO); 7584 $\pm$ 2222 (ABZ-SO ₂)	Faeces used for field fertilisation	–	–	Sulphoxide metabolite dominates total residue load by approximately 400-fold over parent compound	Navrátilová et al. (2021)
		Fenbendazole	–	–	292–460	Solid-phase pig slurry	–	–	–	–	Detected at all four sampled farms	
Coccidiostats and antiprotozoals	Ionophore	Monensin	1000 $\pm$ 500	Storage tank	–	–	–	–	900 $\pm$ 100	Storage pile	High in cattle and poultry	Arikan et al. (2016)
		Salinomycin	< 100	–	–	–	–	–	5300 $\pm$ 2200	–	Very high in poultry litter	
Ectoparasiticides	Pyrethroids	Lasalocid	3300 $\pm$ 500	–	–	–	–	–	< 100	–	High in cattle	Liu et al. (2023)
		Deltamethrin	–	–	–	–	–	–	13,511	Faeces; day 14 of dosing trial	Reached this level after 14 days of continuous dosing; not detected as a background residue in feedlot biosolids	

Table 2

Log P values of selected anthelmintic, anticoccidial, and pyrethroid drugs.

Drug Class	Subclass	Active Ingredient	Log P	Reference
Anthelmintics	Benzimidazoles	Albendazole	2.70	Maqbool et al. (2018)
		Mebendazole	2.83	El Gammal et al. (2022)
		Oxibendazole	2.61	Marczak et al. (2015)
	Avermectins	Doramectin	4.34	
		Eprinomectin	4.33	
		B1A		
		Ivermectin	5.83	Jamlaki et al. (2026)
	Milbemycins	Moxidectin	4.37	Marczak et al. (2015)
	Imidazothiazoles	Levamisole	2.75	
	Salicylanilides	Closantel	7.60	
Coccidiostats and antiprotozoals	Ionophore	Rafoxanide	7.77	
		Lasalocid A	6.62	
	Triazine	Toltrazuril sulfone	4.01	
		Halofuginone	1.31	
	Quinazoline derivative			
Ectoparasiticides	Pyrethroids	Cypermethrin	5.73	
		Deltamethrin	5.96	

partly reflects differences in route of administration, formulation, and species-specific gastrointestinal physiology. In swine, the route of administration strongly influences the excretion profile: oral dosing produces a peak faecal concentration of 930 $\mu\text{g kg}^{-1}$, substantially higher than that following subcutaneous injection (14.8 $\mu\text{g kg}^{-1}$), followed by rapid depletion in both cases. Eprinomectin, a related avermectin applied as a pour-on formulation in cattle, follows a similar elimination pattern: over 28 days, 17–20% of the dose is recovered in

faeces and only 0.35% in urine (Erzen et al., 2007). Biliary excretion is the primary route for ivermectin elimination across species, as demonstrated by high bile radioactivity at all sampling time points in radiolabelled disposition studies (Chiu et al., 1990).

Fenbendazole, a benzimidazole anthelmintic, demonstrates consistently high faecal excretion: 77% in cattle and up to 95% in sheep following oral dosing at 5 mg kg^{-1} bw, with 50–60% faecal recovery in pigs (Food And Agriculture Organization Of The United Nations 1989b). These differences are attributable primarily to interspecies variation in gastrointestinal transit time and hepatic metabolism. Albendazole diverges from this pattern: extensive hepatic oxidation and hydrolysis produce polar metabolites that are preferentially eliminated via urine. In sheep following intraruminal administration at 4.75 mg kg^{-1} bw, urinary excretion accounts for 62.4% of the dose compared with 20.8% in faeces (Hennessy et al., 1989; Food And Agriculture Organization Of The United Nations 1989a).

Levamisole, an imidazothiazole anthelmintic, is predominantly excreted in the urine of both cattle and pigs, consistent with its low molecular weight, weakly basic character, and the high polarity of its metabolites, which favour renal clearance over biliary elimination. Urinary excretion accounts for 80–85% of the dose in pigs and 83% in cattle following oral administration, with only 5–11% appearing in faeces (Paulson and Feil, 1996; Food And Agriculture Organization Of The United Nations and World Health Organization, 1994). Monepantel, an amino-acetonitrile derivative, exhibits a distinct excretion profile following intravenous administration in sheep (1 mg kg^{-1} bw): only 4% of the dose is recovered in faeces, reflecting the drug's rapid oxidation to the sulfone metabolite, which undergoes extended systemic circulation due to its large volume of distribution and prolonged mean residence time (111 h) (Karadzovska et al., 2009). Oral administration of monepantel to cattle at 3.75 mg kg^{-1} bw yields 36% faecal and 21% urinary

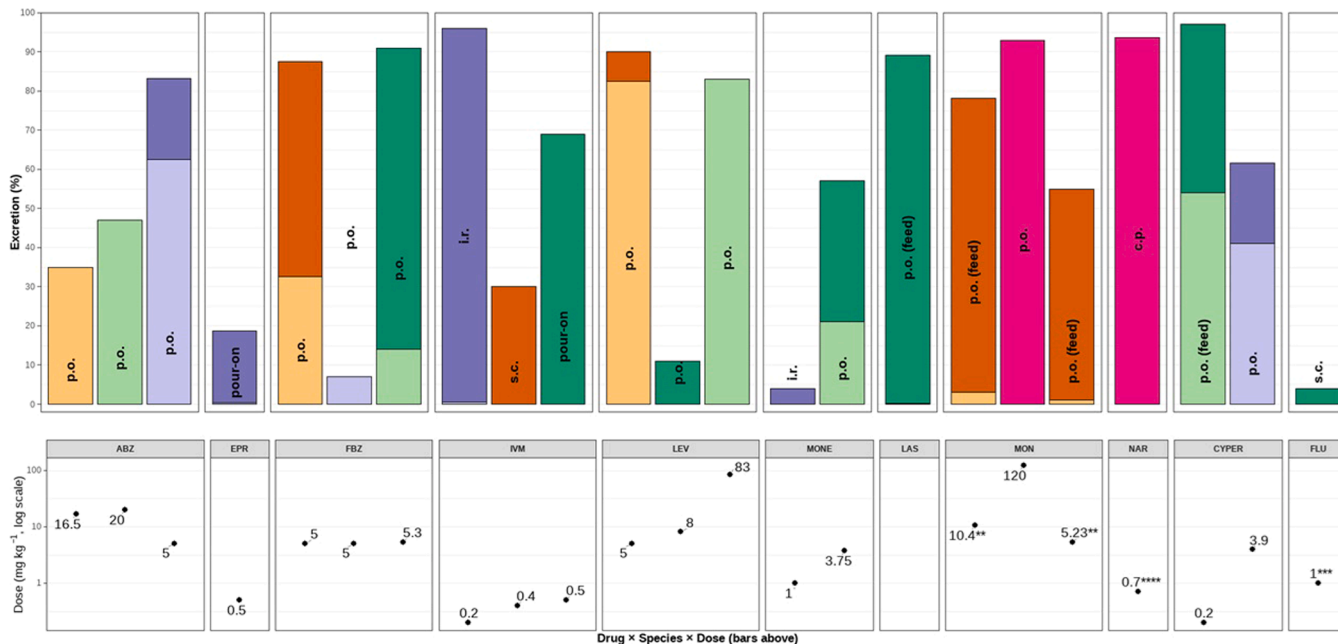


Fig. 1. The excretion rate vs. dosage of different VMPs in different elimination routes across four species. Drugs: ABZ – albendazole; EPR – eprinomectin; FBZ – fenbendazole; IVM – ivermectin; LEV – levamisole; MONE – monepantel; LAS – lasalocid; MON – monensin; NAR – narasin; CYPER – cypermethrin; FLU – flumethrin. Mode of administration: p.o. – oral, i.r. – intraruminal, s.c. – subcutaneous, i.m. – intramuscular, i.v. – intravenous, c.p. – cardiac puncture. (dosage is 12/mg day over 135 days of Ivmec sustained release bolus device,** drug amount administered was in terms of milligrams and administered after feeding them with 50 mg monensin/kg feed, ***drug amount administered was in terms of milligrams and **** 0.7 μCi in 100 μL of 85% DMSO and 15% saline as a vehicle). (Kozuh Erzen et al., 2007; Ali and Hennessy, 1996; Catherman et al., 1991; Chiu et al., 1990; Committee For Veterinary Medicinal Products, 1998, 2001; Donoho et al., 1978; Elanco Us Inc, 2018; European Medicines Agency and Committee for Medicinal Products for Veterinary Use, 2012; Food And Agriculture Organization Of The United Nations 1989a; Food And Agriculture Organization Of The United Nations 1989b; Food And Agriculture Organization Of The United Nations, 2009; Food And Agriculture Organization Of The United Nations and World Health Organization, 1994; Hennessy et al., 1993; Karadzovska et al., 2009; Laffont et al., 2001; Paulson and Feil, 1996; World Health Organization, 1996).

excretion (Elanco Us Inc, (2018)).

Among ionophore coccidiostats, monensin is excreted almost exclusively via faeces across all species studied. In cattle receiving 330 mg day⁻¹ orally, 40–50% of the dose is recovered in faeces (Donoho et al., 1978). In poultry fed 120 mg kg⁻¹, faecal excretion accounts for 85–101% of the dose (Food And Agriculture Organization Of The United Nations, 2009). Lasalocid shows a similar elimination pattern in cattle, with 89% of the dose recovered in faeces and only 0.18% in urine (European Medicines Agency and Committee for Medicinal Products for Veterinary Use, 2012). Narasin, administered to poultry by cardiac puncture at 0.7 µCi, is excreted predominantly in excreta, with 93.6% of the dose recovered in chickens and 76.7% in Japanese quail within 28 days; biliary and gastrointestinal excretion represents the principal elimination route in both species (Catherman et al., 1991).

Pyrethroids are synthetic ectoparasiticides characterised by high lipophilicity and extensive hepatic metabolism. Despite this lipophilicity, excretion patterns differ considerably between compounds within this class, reflecting differences in route of administration, metabolic fate, and species physiology. Cypermethrin demonstrates relatively high total recovery across both major elimination routes. In cattle administered 0.2 mg kg⁻¹ bw orally via feed, 54% of the dose is recovered in urine and 43% in faeces, indicating predominantly renal elimination of polar metabolites following hepatic ester hydrolysis and oxidation (World Health Organization, 1996). In sheep receiving a higher oral dose of 3.9 mg kg⁻¹ bw, urinary excretion accounts for 41% and faecal excretion for 20.5% of the administered dose, with lower total recovery suggesting greater tissue retention or dose-dependent metabolic saturation at the higher dose level (Committee For Veterinary Medicinal Products, 2001). In contrast, flumethrin administered subcutaneously to cattle at 1 mg kg⁻¹ bw is excreted at only 0.03% in faeces and 4% in urine, indicating that the vast majority of the absorbed dose is eliminated via routes not captured in mass-balance studies or is retained in tissues below analytical detection limits (Committee For Veterinary Medicinal Products, 1998). This difference between cypermethrin and flumethrin likely reflects the greater susceptibility of cypermethrin to ester hydrolysis, generating water-soluble metabolites amenable to urinary excretion, whereas flumethrin metabolism may proceed via pathways producing conjugates eliminated in bile at sub-quantifiable concentrations (World Health Organization, 1996; Committee For Veterinary Medicinal Products, 1998).

Collectively, these data demonstrate that a substantial proportion of administered VMPs is excreted largely unmetabolised or as biologically active metabolites, with the dominant elimination route determined primarily by lipophilicity and metabolic fate. Highly lipophilic compounds, such as avermectins and ionophore coccidiostats, are predominantly eliminated via faeces through biliary excretion, contributing directly to manure-associated environmental burdens. More polar compounds, including levamisole and albendazole metabolites, favour urinary excretion, increasing the potential for aquatic contamination via run-off from manure-amended land. Pyrethroids present a distinct profile: despite high lipophilicity, rapid ester hydrolysis in some compounds yields polar urinary metabolites that are consequently excreted into the environment, whereas others exhibit negligible total recovery, implying extensive tissue sequestration. Across all drug classes, route of administration and animal species exert additional, independent effects on excretion magnitude, underscoring the complexity of predicting environmental exposure from VMP use in livestock production.

2.4. Transformation once in manure

VMPs excreted by treated livestock enter manure as the parent compound or as primary metabolites formed during hepatic biotransformation. Within the manure matrix, these residues undergo a further chemical transformation governed by the anaerobic conditions, elevated organic carbon, microbial enzymatic activity and periodic exposure to light and oxygen. The nature of the transformation differs markedly

between drug classes and is determined by the reactive functional groups on each module.

2.5. Macrocyclic lactones

Macrocyclic lactones are excreted predominantly as the intact parent compound, binding tightly to dung organic matter due to their high lipophilicity. The chemistry, pharmacokinetics and metabolism of this drug class are reviewed in detail elsewhere (Campbell, 1989; Vercruysse and Rew, 2002). Within the manure matrix, transformation proceeds along two main pathways. The first is the photolytic isomerisation at the dung surface, where UV exposure converts the C-8/C-9 double bond to yield the 8,9-Z geometric isomer (Wohde et al., 2016a). The second pathway is microbial glycosidase-mediated hydrolysis of the bis-oleandrose disaccharide at C-13, which proceeds stepwise to produce the monosaccharide intermediate and then the fully deglycosylated aglycone. Both the ivermectin monosaccharide and aglycone have been detected directly in fresh cattle dung by desorption electrospray ionisation – high-resolution mass spectrometry (DESI-HRMS), confirming that glycosidic cleavage begins within the faecal matrix itself (Wohde et al., 2016b). Accompanying these hydrolytic changes, cytochrome P450-type oxidative reactions generate a suite of hydroxymethyl products alongside the dihydroxymethyl derivative 4,26-dihydroxymethyl-H2B1a, all of which were identified in dung from treated cattle (Wohde et al., 2016b).

2.6. Benzimidazole anthelmintics

The chemistry, pharmacokinetics, and metabolic pathways of this drug class have been comprehensively reviewed elsewhere (Tuck et al., 2016). Within-manure transformation therefore begins from an already-oxidised precursor. Continued microbially-mediated oxidation converts ABZ-SO to the sulphone ABZ-SO₂, completing the two-step sequential thioether oxidation characteristic of this class. Additionally, residual ABZ undergoes spontaneous abiotic oxidation ABZ-SO on exposure to air at the dung surface, a process Navrátilová et al. (2021) observed to be substantially complete within 24 h of faecal deposition.

Fenbendazole (FBZ) undergoes analogous oxidation to its sulphoxide and sulphone metabolite. Kreuzig et al. (2007) used ¹⁴C-radiotracers to show that the sulphoxidation of the phenylthiogroup at C-5 yields FBZ-SO as the primary manure-phase transformation product, detectable from 14 days of anaerobic pig manure incubation onward. Under strictly anaerobic conditions, representative of slurry storage, conversion proceeds only to the sulphoxide. The same study demonstrated that FBZ-SO₂ forms as a secondary oxidation product when manure-borne residues are incorporated into aerobic soil where strong oxidising conditions and a more active microbial community drive the second oxidation step, and sulphoxide/sulphone formation proceeds further and faster than when the parent compound is applied to soil without the manure thus confirming that the manure matrix itself actively promotes transformation. Kreuzig et al. (2007) found that flubendazole remained predominantly as the unchanged parent compound throughout a 102-day anaerobic incubation in pig manure, with no metabolite detected.

2.7. Ionophore antibiotics

The chemistry, pharmacokinetics, and metabolic fate of this drug class have been extensively reviewed elsewhere (Tuck et al., 2016). Ionophore antibiotics are polyether carboxylic acids excreted as mixtures of the parent compound and metabolites generated by O-demethylation, hydroxylation, and oxidation. Donoho et al. (1978) documented more than 50 chromatographically distinct metabolites in the faeces of ¹⁴C-monensin-dose animals, with O-desmethyl monensin (metabolite M-1) being one of the few characterised in detail; this metabolite retains ionophore activity, confirming that primary

transformation products of monensin are not pharmacologically inert. Within a manure pile, additional microbially-driven transformation occurs, with monensin concentrations declining under the influence of the resident bacterial community rather than simply reflecting dilution of pre-formed excreted metabolites (Donoho et al., 1978).

Sun et al. (2014) characterised the specific biotransformation products formed during incubation of monensin and salinomycin in broiler litter microcosms. For monensin, a transformation product designated as TP-MON (Fig. 2) was identified with a mass-to-charge ratio (m/z) of 707, an increase of 14 mass units relative to the parent, consistent with a single hydroxylation of the polyether backbone. TP-MON formation was absent in autoclaved controls, indicating biological mediation. For salinomycin, a transformation product TP-SAL (m/z = 531) was generated in broiler litter via ring A cleavage which is a structurally distinct mechanism from the hydroxylation producing TP-MON and, once formed, showed no further degradation over a 10-day soil incubation, indicating that this transformation product is more persistent than its parent ionophore (Sun et al., 2014). Lasalocid is excreted mainly as parent (74–83%) and metabolites in broiler excreta but more extensive in vivo metabolism is observed in turkey (Zizek et al., 2015). Within manure transformation of lasalocid is predominantly biotic, as no significant transformation is observed in sterilised matrices (Zizek et al., 2015).

2.8. Synthetic pyrethroids

Despite this established soil-phase chemistry, the available literature addresses pyrethroid transformation almost exclusively in soil (Xu et al., 2015, 2018; Xie and Zhou, 2008; Shen et al., 2015; Yao et al., 2015; Kurnia, 2019; Muñoz-Leoz et al., 2009; Mantzos et al., 2016; Rafique and Tariq, 2015; Raikwar and Nag, 2006), aqueous and sediment phases (Lee et al., 2004; Adelsbach and Tjeerdema, 2003; Gosetti et al., 2018), or broad environmental reviews (He et al., 2008; Tang et al., 2018; Galadima et al., 2021; Kansal et al., 2023; Naeem et al., 2023; Aiello et al., 2021). In the single study conducted in a manure matrix, Ong et al. (2016) determined the half-life and degradation of cypermethrin in poultry manure in the context of house fly control but measured only the degradation of the parent compound and did not profile transformation products, with the authors themselves noting the characterisation of insecticide metabolites in poultry manure as a direction for future work. No study specifically characterising the transformation products of synthetic pyrethroids within the manure matrix or following manure amendment to soil could be identified, representing a clear gap in literature.

The primary transformation pathway of pyrethroids is well characterised in soil systems: microbially-mediated hydrolysis of the central ester bond, catalysed by carboxylesterases that release an alcohol moiety and a carboxylate. This reaction yields 3-phenoxybenzaldehyde as an early intermediate, which is subsequently oxidised to 3-phenoxybenzoic acid (3-PBA) via microbial dioxygenase activity; further ring cleavage produces 3-hydroxybenzoate, catechol and protocatechuate, which enter central metabolic pathways and can be mineralised to CO₂ and H₂O (Singh et al., 2022a). The 3-PBA metabolite is consistently produced across a wide range of pyrethroid-degrading bacterial genera and has been proposed as a fingerprint product of microbial pyrethroid hydrolysis (Singh et al., 2022a).

2.9. Pathways of loss to the environment

VMPs can enter the environment directly or indirectly (Fig. 3). Land application of manure from treated animals is the predominant indirect route by which veterinary medicinal products enter the terrestrial environment (Kemper, 2008; bártíková et al., 2016). Once manure is applied to agricultural land, residues are subject to physical, chemical, and biological processes that govern their partitioning between soil, water, and plant compartments. The pathways through which

anthelmintics, anticoccidials, and pyrethroid ectoparasiticides move from the manure matrix into the surrounding environmental compartments differ markedly according to their physicochemical properties.

2.10. Macrocyclic lactones

Following the application of manure containing ivermectin onto land, the compound partitions rapidly and strongly into the organic fraction of the soil, with carbon-normalised sorption coefficients (K_{oc}) reaching 3550 L kg⁻¹ (Prasse et al., 2009) and soil-water distribution coefficients (K_d , the ratio of compound concentration in the solid phase to that in solution) values of up to 160 L kg⁻¹ across a range of soils (Krogh et al., 2008b, 2008a). This affinity for organic matter effectively immobilises dissolved ivermectin, rendering leaching to groundwater negligible under normal conditions.

Because dissolved transport is negligible, the primary pathway by which macrocyclic lactones residues move from manure-amended soils into surface waters is via particle-associated surface run-off. Residues sorbed to fine soil particles and organic colloids can be physically mobilised during rainfall events and transported off-site with eroded sediment. Fernández et al. (2011) confirmed this in a semi-field study under Mediterranean conditions, detecting ivermectin in run-off and drainage waters only during the first rainfall event following treatment, and primarily in the particle-bound rather than dissolved fraction: run-off particle concentrations reached 1.66 µg kg⁻¹ dry weight under the pasture scenario and 5.89 µg kg⁻¹ under the arable land (manure-amended) scenario, whilst dissolved concentrations remained below 6–88 ng/L and were undetectable in all subsequent events. In contrast, Bair et al. (2017) found that less than 0.1% of applied ivermectin was transported in surface run-off from irrigated Californian pasture plots, with the majority retained in the manure or upper 5 cm of soil beneath the application sites, suggesting that transport risk under flood-irrigated conditions is low despite high drug residue loading. Together, these studies illustrate that ivermectin transport via run-off is highly event-dependent, governed by the timing of the first significant rainfall or irrigation relative to manure application, and that the ecological risk to aquatic systems is associated with the sediment-bound fraction rather than the dissolved phase.

2.11. Benzimidazoles

Benzimidazole anthelmintics, including albendazole, fenbendazole, and oxfendazole, are excreted in faeces as mixtures of the parent compound and oxidised metabolites. Unlike the macrocyclic lactones, benzimidazoles are considered slightly-to-moderately mobile in soil. Porto et al. (2021) investigated leaching of this drug class in soil column, reaching depths of up to 25 cm in a 30-cm column. Although the mobilised fraction is small, this is sufficient for residues to reach the rhizosphere, and under repeated manure applications, accumulation in surface soils is expected.

Under field conditions, Navrátilová et al. (2023) applied sheep excrement from ABZ-treated animals to plots of clover (*Trifolium pratense*) and alfalfa (*Medicago sativa*) and monitored the distribution of ABZ and its metabolites in soil and plant tissues over three months. ABZ-SO and ABZ-SO₂ were detected in soil at depths 0–5 cm and 5–25 cm from the point of faecal disposition and in plant tissues at distances up to 60 cm from the excrement which is considered beyond the zone of detectable soil contamination. This spatial spread indicates active root uptake and translocation within the plant, extending the contamination footprint well beyond the area of direct manure contact. Contaminated fodder plants subsequently transferred ABZ metabolites to a second cohort of native sheep fed with the harvested plants, demonstrating a complete excrement-soil-plant-animal circulation loop under realistic agricultural conditions. The concentration of ABZ-SO detected in the plasma of these secondarily exposed animals was approximately 1000-fold lower than that achieved by direct therapeutic

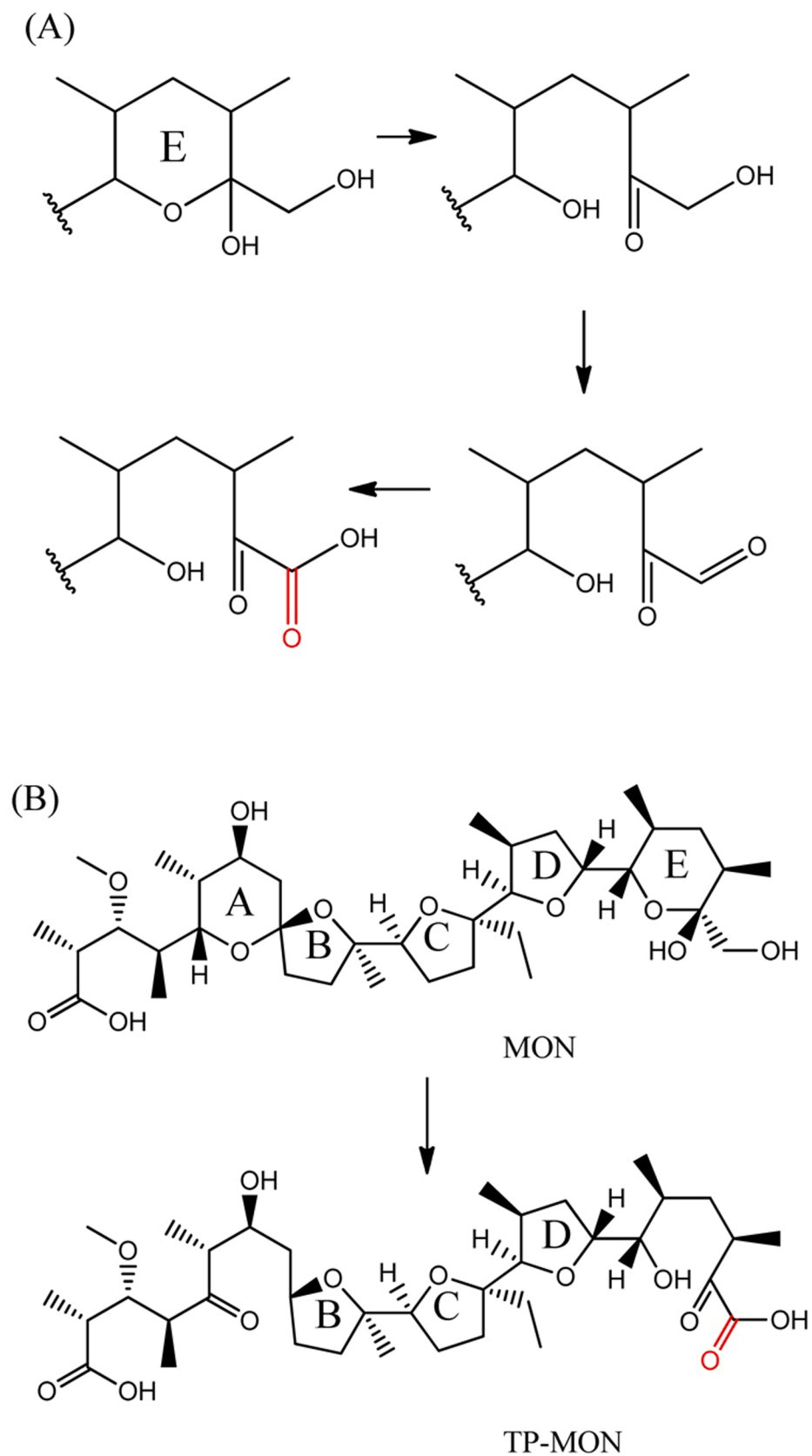


Fig. 2. (A) Predicted initial biotransformation pathways of MON based on UM-BBD modelling. (B) Proposed molecular structure of the MON transformation product, TPMON. Source: [Sun et al., 2014](#). Reproduced with permission from American Chemical Society.

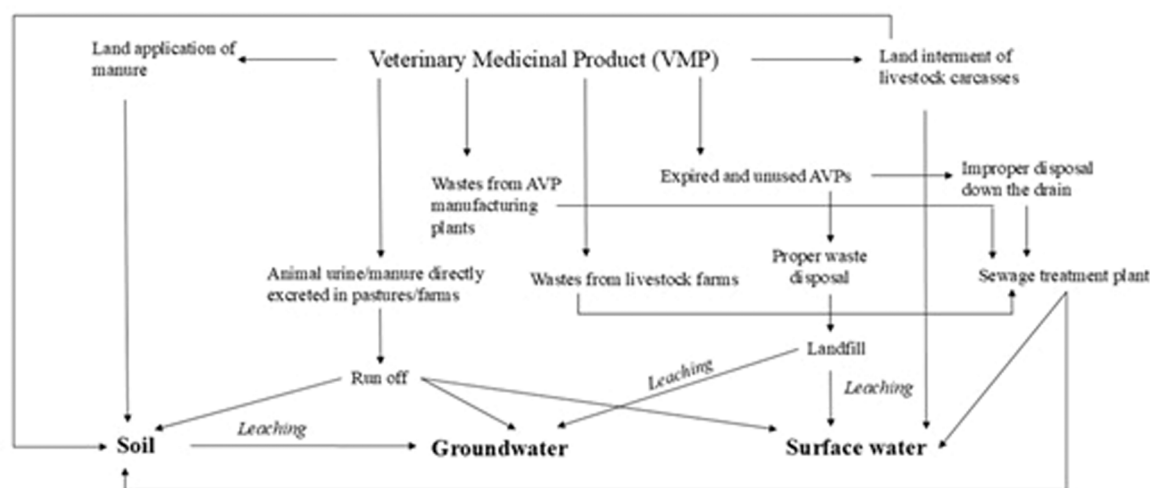


Fig. 3. The different points of entry of VMPs into the environment.

dosing ($1.90 \pm 0.11 \mu\text{g mL}^{-1}$), yet sufficient to raise concern regarding sub-therapeutic helminth exposure and resistance selection (Navrátilová et al., 2021; Kellerová et al., 2020; Lanusse et al., 1995).

2.12. Anticoccidials

Ionophore anticoccidials, specifically monensin, lasalocid and salinomycin, are excreted in faeces and enter the soil when manure is land-applied. Their movement from the manure matrix into soil and water is governed by moderate, pH-dependent sorption. Sassman and Lee (2007) measured organic carbon-normalised sorption coefficients ($\log K_{oc}$) of 2.1–3.8 for monensin and 2.9–4.2 for lasalocid across eight contrasting agricultural soils, with sorption inversely related to soil-solution pH for both compounds. Lasalocid exhibited consistently stronger sorption than monensin. Analysis of beef waste lagoon effluent used for field irrigation confirmed that monensin was present at $40 \mu\text{g L}^{-1}$ in the aqueous fraction and $2000 \mu\text{g kg}^{-1}$ in the suspended solids, corresponding to a field K_d of approximately 50 L kg^{-1} , within the laboratory-derived range (Sassman and Lee, 2007). Nevertheless, subsequent analysis of drainage water in a ditch receiving water from the irrigated fields showed concentrations at or below the detection limit, indicating substantial soil attenuation of dissolved ionophores under the conditions studied.

Surface run-off is the primary route for ionophore transport to nearby water bodies. Navarro et al. (2022) conducted simulated rainfall experiments on agricultural soils amended with poultry litter containing monensin and salinomycin, and measured surface run-off losses of 0.8–31% of the applied ionophore mass, with leaching losses of 0.4–38%. Monensin consistently showed the greatest run-off losses of the two compounds. A notable finding was that the poultry litter amendment itself altered the physicochemical properties of the soil surface in ways that enhanced ionophore mobility in run-off and leachate relative to unamended controls, showing that the amendment acts as an active mobilising agent rather than a simple carrier. Song et al. (2010) confirmed the field relevance of these findings, detecting monensin and amprolium in surface waters adjacent to a Michigan farm receiving routine manure applications, with soil concentrations positively correlated with surface water concentrations at the same sites. VMPs applied in post-harvest (autumn/winter) applications were found at higher concentrations in soil and drainage than those applied in spring, reflecting the reduced biological activity and greater hydrological connectivity of soils during colder and wetter months.

2.13. Pyrethroids

Synthetic pyrethroids used as veterinary ectoparasiticides, including cypermethrin, permethrin, lambda-cyhalothrin and deltamethrin, enter the soil environment through a different primary route. Applied topically as pour-on or dips rather than administered systematically, pyrethroids reach the soil primarily via direct contact between treated animals and the ground surface, transfer to pasture through skin residues and deposition of pyrethroid-contaminated dung following partial dermal absorption and faecal elimination. Wash-off during rainfall represents an additional entry pathway specific to topical pour-on formulations, where residues remaining on the hide are mobilised directly into the surrounding soil and runoff. Once in soil, their movement is governed by extreme hydrophobicity: $\log K_{ow}$ values range from 6.10 for permethrin to 7.0 for lambda-cyhalothrin (He et al., 2008; Laskowski, 2002) and soil organic carbon partition coefficients that are exceptionally high ranging up to $247,000\text{--}330,000 \text{ cm}^3 \text{ g}^{-1}$ (He et al., 2008). As a result, dissolved transport through the soil profile is effectively absent, and groundwater contamination via leaching is negligible. Despite their immobility in solution, pyrethroids are readily transported off-site via surface run-off in association with suspended solid particles and organic colloids. Mantzos et al. (2016) demonstrated both processes clearly in a 193-day field study of cypermethrin in sunflower cultivation plots: the insecticide was detected below 10 cm depth in only a handful of samples and at concentration below $20 \mu\text{g kg}^{-1}$, confirming minimal downward mobility; in run-off water the microgranular formulation was detected on only one occasion at trace levels; however, run-off sediment contained cypermethrin at detectable concentrations across seven sampling events, with peak values of $97\text{--}500 \mu\text{g kg}^{-1}$ recorded 7 days after foliar application depending on slope and tillage treatment. Once pyrethroid-containing sediment reaches aquatic systems, the compound rapidly partitions from the water column to bed sediment. He et al. (2008) reported that only 30% of applied lambda-cyhalothrin remained in the water phase after one day in ditch mesocosm experiments, concentrating in the benthic compartment where it poses the greatest risk to sediment-dwelling invertebrates.

2.14. Analytical challenges

Measurement of anthelmintic, anticoccidial, and pyrethroid residues in animal waste is analytically challenging due to both the physicochemical properties of the target compounds and the complexity of the matrices in which they occur. All three groups are characterised by high lipophilicity which drives strong partitioning into the organic and particulate fractions of manure and faeces and promotes irreversible

binding to soil organic matter (Carrillo Heredero et al., 2024; Litskas et al., 2010; Wohde et al., 2016b). While high-affinity binding facilitates analyte retention in the solid fraction during centrifugation, it simultaneously promotes co-extraction of lipids, pigments, and other interferences. These co-extractants contribute to ion suppression or enhancement in electrospray ionisation and increase background noise in chromatographic analysis (Biswas et al., 2012). Optimising sample preparation requires balancing extraction efficiency with matrix clean-up, as insufficient extraction reduces recovery, while excessive clean-up may cause analyte loss, particularly for strongly bound residues.

Methanol and acetonitrile are solvents of choice for analyte extraction of macrocyclic lactone residues from solid matrices. Carrillo Heredero et al. (2024) developed and validated an LC-MS/MS method using ultrasonication with methanol for both faeces and soil, yielding recoveries of $92.3 \pm 12.0\%$ and $96.2 \pm 13.8\%$, respectively, with limits of detection (LOD) of $0.66 \mu\text{g kg}^{-1}$ (faeces) and $0.54 \mu\text{g kg}^{-1}$ (soil). Matrix-matched calibration was required for soil due to pronounced matrix effects, while faecal extracts were adequately quantified using solvent standards. Litskas et al. (2010) extracted eprinomectin from faeces using acetonitrile and from soil using acetone, both extract subsequently were subjected to C_{18} SPE clean-up. The method demonstrated the same LOD and limit of quantification (LOQ) for each matrix, with values $2.5 \mu\text{g kg}^{-1}$ (wet weight) for faeces and $1 \mu\text{g kg}^{-1}$ for soil (wet weight). Recovery during the C_{18} SPE step was sensitive to flow rate, with losses exceeding 40% when sample loading exceeded 6 mL min^{-1} . Complete drying of the eluate under nitrogen also removed the need for the hexane back-extraction step used in earlier protocols. Following clean-up, fluorescence detection was performed by pre-column derivatisation with N-methylimidazole and trifluoroacetic anhydride (TFAA), which was necessary because avermectins lack strong UV chromophores. Wohde et al. (2016b) likewise used acetonitrile extraction with HPLC-FLD but showed that the SPE clean-up step could be eliminated for field-exposed dung and soil samples (aged >1 month in the field), with no loss of chromatographic selectivity. For freshly collected dung, however, SPE remained necessary, as unresolved matrix co-extractants caused peak interferences; matrix complexity was also found to be species- and diet-dependent, with sheep dung presenting greater challenges than cattle dung. Wohde et al. (2016b) also found that the water content of dung samples is a critical pre-extraction variable; adjusting dry field-exposed samples to 85% moisture content before acetonitrile extraction substantially improved recovery of residues particularly in samples held in the field for nine months. HPLC-FLD methods remain in use due to their lower cost and good sensitivity. Wohde et al. (2016b) also used desorption electrospray ionisation-high resolution mass spectrometry (DESI-HRMS) to detect metabolite residues in dung for the first time, illustrating the potential of non-target HRMS approaches to extend beyond the parent compound in the environmental monitoring of MLs.

Polyether ionophore anticoccidials (monensin, salinomycin, narasin, and lasalocid) present distinct analytical challenges related to their large molecular masses, the absence of strong chromophores, and their tendency to form sodium or ammonium adducts rather than protonated species under electrospray ionisation. Early analytical methods therefore relied on post-column derivatisation for UV or fluorescence detection; LC-MS/MS is now the preferred approach, enabling multi-residue quantification without derivatisation. Biswas et al. (2012) developed an LC-MS/MS method for four ionophores in aged poultry litter, achieving method detection limits (MDL) of $0.67\text{--}2.02 \mu\text{g kg}^{-1}$ and recoveries of 92–104% from their own spiked litter experiments. A critical finding was that without phosphoric acid pre-wash prior to SPE, salinomycin and narasin exhibited pronounced retention time shifts and split chromatographic peaks in poultry litter extracts which are attributed to matrix protein raising pH and competing with analyte binding on the SPE sorbent. Phosphoric acid treatment denatured these proteins and improved chromatographic behaviour comparable to that of standard

solutions. The choice of internal standard was also identified as a methodological concern as earlier studies had used simatone, a pesticide despite its low molecular weight and lack of structural resemblance to ionophore.

Teglia et al. (2017) adopted an alternative approach for the analysis of 21 different residues in poultry litter which included anthelmintics such as albendazole and fenbendazole, together with antimicrobials, non-steroidal anti-inflammatory drugs (NSAIDs), and hormones. Instead of using mass spectrometric detection, the method employed HPLC coupled with fluorescence and diode array detection. Peak co-elution was addressed using multivariate curve resolution-alternating least squares (MCR-ALS) chemometric modelling, no SPE step was included. The method achieved recoveries ranging from 91% to 106% across the analytes, demonstrating that broad multi-class determination can be achieved without MS-based detection, provided that chromatographic overlap is adequately resolved through mathematical modelling.

Nebot et al. (2023) validated an HPLC-ESI-MS/MS for the determination of 29 analytes in lyophilised swine manure, covering antibiotics, anti-inflammatory drugs, and corticosteroids; however, anthelmintics were not included in the final validated method. Although eight coccidiostats and ionophores were initially considered, seven compounds, namely decoquinat, maduramicin, monensin, narasin, nicarbazin, robenidine, and salinomycin, were excluded during MS optimisation because of inadequate ionisation response. This highlights the persistent analytical difficulty associated with this compound class, even when MS-based detection is used instead of UV or fluorescence detection. Lyophilisation prior to extraction reduced sample water content and contributed to improved method sensitivity, with the validated method achieving trueness values of 63–128% over a linear range of 100–1500 $\mu\text{g kg}^{-1}$.

Pyrethroids are predominantly determined using gas chromatographic techniques. Most validated methods have been developed for matrices other than livestock manure and faeces. Applications have largely focused on agricultural and environmental matrices, including agricultural and playground soils, surface water, ground water, paddy-field water and sediments (Esteve-Turrillas et al., 2004; Bragança et al., 2019; Lyytikäinen et al., 2003; Serôdio and Nogueira, 2005; Aznar et al., 2017). Other reported applications include sewage sludge, animal feed, and food of animal origin (Rede et al., 2024; Feo et al., 2011; Fernandez-Alvarez et al., 2010).

Despite the extensive application of these techniques across environmental and food matrices, relatively few studies have investigated pyrethroids in animal waste. Aznar et al. (2014) reported a validated isotope-dilution GC-MS method for 41 organic contaminants including 8 pyrethroids. The method adapted the QuEChERS approach, previously applied mainly to food (Anastassiades et al., 2003). Analytes were extracted from lyophilised manure using acetonitrile. Magnesium sulphate and sodium acetate was used to promote phase separation. Dispersive-solid phase extraction (d-SPE) using magnesium sulphate, primary-secondary amine (PSA) and C_{18} was used for clean-up. Application to manure obtained from four Spanish farms identified pyrethroids and PAHs as the predominant contaminants. The study also highlighted the need to account for pyrethroid stereoisomers and reported the first concentration data for these contaminants in poultry manure.

Coleman et al. (2013) developed a method for the simultaneous determination of two ectoparasiticides classes which includes two synthetic pyrethroids (deltamethrin and cypermethrin) and four macrocyclic lactones (abamectin, doramectin, ivermectin, and eprinomectin) in beef cattle feedlot waste. To address the heterogeneous solid matrix, samples were freeze-dried and ground, followed by extraction via ultrasonication with methanol and acetone, diluted with water, and subjected to solid phase extraction (SPE) using Oasis HLB cartridges. Signal enhancement due to matrix was observed for the macrocyclic lactones, resulting in higher absolute method recoveries from real waste (63–101%) than SPE absolute recoveries from spiked ultrapure water

(46–61%). Pyrethroid SPE absolute recoveries were 79–85%, although absolute method recoveries were lower (53–74%). Neither pyrethroid was detected in feedlot waste, including at the facility where deltamethrin was used, likely because of rapid photochemical and microbial degradation.

Overall, the selection of an analytical method for multi-residue analysis requires balancing selectivity, sensitivity, and sample throughput. For panels comprising more than ten analytes, LC–MS/MS is generally the most suitable platform because it can provide the required sensitivity and selectivity within a single method. However, reliable quantification is more challenging in complex matrices and ideally requires isotope-labelled internal standards to compensate for matrix effects, including ion suppression or enhancement. Fluorescence detection remains highly sensitive and accurate for macrocyclic lactones but requires pre-column derivatisation. Ionophores similarly require derivatisation to enable sensitive UV detection but can be more sensitively analysed using MS. Pyrethroids are most sensitively determined by GC–MS/MS as reflected in the markedly higher detection limits reported for them on LC–MS/MS. Despite the greater calibration demands associated with LC–MS/MS, it remains the more practical choice for broad multi-residue analysis, offering shorter run times, typically below 15 min, reduced solvent consumption, simplified sample preparation, higher throughput, and less labour-intensive data processing compared with conventional HPLC–UV or HPLC–fluorescence methods. The analytical methods discussed above, together with their key performance characteristics, are summarised in Table 3.

2.15. Ecotoxicological effects and mitigation

Ivermectin, doramectin, and eprinomectin are excreted largely unchanged in faeces of treated livestock, where residues can reach concentrations harmful to dung-colonising invertebrates during the period following treatment. Pour-on and sustained-release formulations prolong faecal excretion profiles, with eprinomectin delivered via sustained-release bolus, a mode of administration with limited commercial availability, shown to suppress dung-breeding insect emergence for up to 140 days post-treatment (Nieman et al., 2018). Across multiple comparative field studies, the relative harm to dung fauna was ranked as doramectin > ivermectin > eprinomectin > moxidectin (Floate et al., 2002). Moxidectin consistently exerts a lower adverse effect than the avermectins, a difference attributable to its lower faecal excretion and distinct pharmacokinetic profile however it remains classified as a substance of environmental concern (Suárez et al., 2009).

These residues affect both the abundance and diversity of coprophilous fauna. Dung flies (*Scathophaga stercoraria*, *Musca autumnalis*) and dung beetles (*Aphodiuss* spp., *Onthophagus* spp.) are particularly affected. For abamectin and doramectin, LC_{50} values in sheep faeces for springtails (*Folsomia candida*) and enchytraeids (*Enchytraeus crypticus*) were in the range of 1.0–2.4 mg kg⁻¹ dry faeces, indicating that realistic field exposures may approach or exceed toxic thresholds (Kolar et al., 2008). Ivermectin exerted greater toxic effects on the springtail in a two-species test system with the predatory mite *Hypoaspis aculeifer* (LC_{50} of 0.14 mg kg⁻¹) than in single-species assays (LC_{50} of 50 mg kg⁻¹), suggesting that predator-prey interactions may enhance ivermectin toxicity (Jensen et al., 2009). Effects extend beyond mortality, with trans-generational studies documenting reduced horn size in male dung beetle offspring when only their fathers was exposed to ivermectin, highlighting its sublethal and cross-generational consequences (baena-Díaz et al., 2018). Earthworms are highly sensitive to macrocyclic lactones, and the disruption of dung-colonising communities can indirectly delay dung degradation, reduce soil fertility, and diminish the ecosystem activities that coprophagous insects provide.

Anticoccidials, principally the ionophores (monensin, salinomycin, lasalocid) and triazines (toltrazuril), also pose risks to soil invertebrates, though generally at higher concentrations than macrocyclic lactones. Monensin affects earthworm reproduction with an EC_{50} of

12.7 mg kg⁻¹ dry soil and a NOEC of 3.5 mg kg⁻¹ (Zizek et al., 2011), while springtails and enchytraeids are far more tolerant, with EC_{50} values exceeding 350–600 mg kg⁻¹ (Jensen et al., 2009). If fresh poultry manure is applied without prior treatment, the predicted environmental concentration of monensin may exceed the predicted no-effect concentration, constituting a credible ecological risk under certain conditions. Toltrazuril and its stable metabolite ponazuril are poorly degraded during aerobic composting and can migrate from compost to soil and into vegetables, negatively affecting seed germination and root elongation and disrupting soil enzyme activities (Huo et al., 2022).

Pyrethroids are highly toxic to invertebrates and aquatic organisms. Their excretion in sheep faeces following dipping or pour-on treatments, combined with the disposal of spent dip, can expose dung, soil, and aquatic communities to ecotoxicologically relevant concentrations (Beynon, 2012b). Dung-fauna sensitivity also differs markedly between individual SP compounds. Deltamethrin residues have been associated with the highest and most prolonged toxic effects on coprophagous insects, with insecticidal activity in cattle dung persisting for 7–14 days post-treatment, whereas flumethrin is generally regarded as less toxic to dung beetles, with several studies finding little or no measurable impact on adult beetle populations or on the rate of dung decomposition. Repeated treatment may intensify this risk. When deltamethrin application coincides with peak beetle emergence, activity in the following generation can be reduced by up to 75%; therefore, the two or three consecutive treatments commonly used in some production systems could plausibly contribute to local population decline, or even field-scale extinction (Beynon, 2012b).

2.16. Mitigation strategies

Mitigation of anthelmintic, anticoccidial, and pyrethroid residues in animal waste can be approached at both the source (reducing the amount of drug administered) and the treatment stage (reducing concentrations in excreta prior to environmental release). At the source, targeted selective treatment reduces anthelmintic use by treating only animals with a clinical need, potentially reducing drug input by up to 84% without compromising productivity. Rotational and follow-on grazing regimes reduce pasture larval burdens and the frequency of treatment. Housing animals during and after treatment reduces direct faecal deposition onto pasture and allows for manure to be collected and treated before land application. For residues already present in the collected manure and slurry, the principal technological approaches are composting, storage, bioaugmentation, and adsorption.

2.16.1. Composting

Composting can substantially reduce ionophore anticoccidial residues from poultry litter, though its efficacy is highly compound- and matrix-specific. Ramaswamy et al. (2010) demonstrated a near-complete reduction of salinomycin (22 mg kg⁻¹ to effectively non-detectable levels over 38 days) in composted poultry manure, compared with only a modest decline in open-heap control material. The thermophilic temperatures (45–65 °C) achieved during active composting promote both microbial degradation and abiotic transformation. However, monensin is notably resistant, as composting temperatures are generally no more effective than ambient conditions for monensin removal in either poultry litter or dairy manure (Arikan et al., 2016). Pilot-scale composting of poultry litter over 150 days under aerated, turned, and combined conditions achieved variable reductions in ionophore anticoccidial concentrations depending on the aeration regime. Monensin declined by 16–40%, salinomycin by 16–68%, and narasin by 13–40% (with turning alone driving reductions outside this range), and transformation products of salinomycin and narasin were identified in composted material (Munaretto et al., 2016). Sun et al. (2014) confirmed that monensin is stable in broiler litter microcosm across a wide range of temperatures and water contents, whereas salinomycin and narasin degrade under high moisture and temperature conditions.

Table 3

Analytical methods for anthelmintic, anticoccidial, and pyrethroid analysis in manure and faecal samples.

Method	Analyte Class	Matrix	Extraction and Clean-up	LOD/LOQ (faeces/manure)	Key Notes	Reference
LC-MS/MS	Anthelmintic (ivermectin)	Faeces, soil, sewage	Ultrasonication with methanol; C18 SPE for faeces; no SPE for soil	LOD: 0.66 $\mu\text{g kg}^{-1}$ (faeces); 0.54 $\mu\text{g kg}^{-1}$ (soil); LOQ: 1.5 $\mu\text{g kg}^{-1}$ (both)	High recovery in faeces (92.3%) and soil (96.2%); matrix effect in soil required matrix-matched calibration; low sewage recovery (33%) due to poor IVM affinity for aqueous phase	Carrillo Heredero et al. (2024)
HPLC-FLD	Anthelmintic (eprinomectin; avermectins)	Cattle faeces and soil	Acetonitrile (faeces) or acetone (soil) extraction + C18 SPE + pre-column TFAA/N-methylimidazole derivatisation	LOD = LOQ: $\mu\text{g kg}^{-1}$ wet wt (soil); 2.5 $\mu\text{g kg}^{-1}$ wet wt (faeces)	Pre-column derivatisation mandatory for fluorescence detection; recovery problems at SPE flow > 6 mL min ⁻¹ ; N ₂ -drying step eliminates need for hexane back-extraction; multiresidue potential demonstrated for five avermectins	Litskas et al. (2010)
HPLC-FLD	Anthelmintic (ivermectin)	Cattle dung (field-exposed) and soil	Acetonitrile extraction; C18 SPE omitted for field-exposed samples (>1 month); water content adjusted to 85% (dung) or 50% (soil) prior to extraction; doramectin as internal standard	LOD: 7.0 $\mu\text{g kg}^{-1}$ dry wt (dung); 0.9 $\mu\text{g kg}^{-1}$ dry wt (soil); LOQ: 17.2 / 2.3 $\mu\text{g kg}^{-1}$ dry wt	SPE omission feasible for aged/field-exposed matrices but caused unresolved interferences in fresh dung; water content of dry samples is a critical extraction variable; DESI-HRMS applied for first time to detect metabolite residues in dung	Wohde et al. (2016b)
LC-MS/MS	Anticoccidials – ionophores (monensin, lasalocid, salinomycin, narasin)	Aged poultry litter	Phosphoric acid pre-wash + methanol extraction + HLB SPE	MDL: 0.67–2.02 $\mu\text{g kg}^{-1}$	Phosphoric acid pre-wash resolved retention time shifts and split peaks caused by matrix proteins and pH; nigericin recommended as surrogate standard (chemically similar to ionophores; not used as feed additive); own recoveries 92–104%; ionophores detected after > 3 years of litter storage	Biswas et al. (2012)
HPLC-FSFD/DAD	Multi-class (21 analytes incl. 2 anthelmintics: albendazole, fenbendazole)	Poultry litter	Simplex-lattice design optimised MeOH: 10 mM phosphate buffer pH 3.5 (33:67 v/v); sonication, shaking, centrifugation; no SPE clean-up	LOD: 6–200 $\mu\text{g kg}^{-1}$; LOQ: 20–610 $\mu\text{g kg}^{-1}$	Fluorescence/UV multi-residue method resolved via MCR-ALS chemometrics rather than mass spectrometry; recoveries 90.3–105.6%; demonstrates that multi-class panels > 10 analytes are achievable without MS, though peak overlap required chemometric modelling to resolve	Teglia et al. (2017)
HPLC-ESI-MS/MS	Multi-class (29 validated analytes: antibiotics, anti-inflammatories, and corticosteroids; no anthelmintics in the final panel — most targeted coccidiostats/ionophores discarded due to poor MS response (see Key Notes))	Lyophilised swine manure	Lyophilisation + MeOH: McIlvaine–EDTA buffer (70:30 v/v); vortex, shaking, centrifugation, filtration; no SPE	Linearity 100–1500 $\mu\text{g kg}^{-1}$; trueness 63–128%	Lyophilisation step reduces water content and lowers LOD; MRM (2 transitions/analyte) gives high selectivity; 7 of 8 targeted coccidiostats (decoquinate, maduramicin, monensin, narasin, nicarbazin, robenidine, salinomycin) excluded at MS-optimisation stage due to poor ionisation response, illustrating the difficulty this class poses even on LC-MS/MS platforms	Nebot et al. (2023)
GC-MS	Multi-class (41 analytes incl. 8 pyrethroids)	Poultry manure	Modified QuEChERS: acetonitrile extraction, MgSO ₄ + NaOAc for phase separation, dispersive-SPE clean-up (MgSO ₄ + PSA + C18)	For pyrethroids: LOD: 2.9–9.6 $\mu\text{g kg}^{-1}$ LOQ: 9.7–21.1 $\mu\text{g kg}^{-1}$	First validated multiresidue method to include pyrethroids in poultry manure; isotope-dilution GC-MS quantification; pyrethroids and polyaromatic hydrocarbons	Aznar et al. (2014)

(continued on next page)

Table 3 (continued)

Method	Analyte Class	Matrix	Extraction and Clean-up	LOD/LOQ (faeces/manure)	Key Notes	Reference
LC-MS/MS	Pyrethroids (deltamethrin, cypermethrin) + 4 macrocyclic lactones	Beef cattle feedlot waste	Ultrasonic solvent extraction + Oasis HLB SPE; d6-cypermethrin internal standard	For pyrethroids: MDL:15–19 µgkg ⁻¹	(PAHs) were the main contaminants detected in real farm samples Pyrethroid absolute method recoveries 53–74%; neither pyrethroids detected in any feedlot sample	Coleman et al. (2013)

For anticoccidial toltrazuril, aerobic composting of chicken manure over 80 days was largely ineffective. Toltrazuril and its major metabolite ponazuril showed no significant degradation while only the transient intermediate toltrazuril sulphoxide broke down significantly (Huo et al., 2022). Ponazuril's (toltrazuril sulphone) persistence extended beyond composting itself. When the finished compost was subsequently used to fertilise soil, ponazuril again degraded far more slowly than the parent compound, with a half-life of up to 347 days in radish-growing soil, and it was the only one of the three compounds shown to migrate from soil into edible plant tissue with residues detected in both lettuce and radish (Huo et al., 2022).

2.16.2. Chemical treatment

The addition of a peroxide mixture containing calcium peroxide to reduce albendazole and levamisole in chicken manure has also been investigated (Turek-Szytów et al., 2020). The study showed higher drug bioavailability when the peroxide mixture is added to the manure. The calcium ions from the mixture saturate the manure sorption complex which causes albendazole and levamisole to have higher bioavailability. The increased bioavailability was accompanied by compound-specific differences in degradation during manure stabilization. The presence of the mixture caused a 92% loss of albendazole during the 35-day manure stabilization process compared to pure manure at 61%. During the stabilisation period, the peroxide mixture did not significantly improve the elimination of levamisole. The removal efficiency remained high and comparable, whether the mixture was present or not, with a reduction of 97% in the presence of the mixture versus 98% in its absence.

2.16.3. Storage

Manure storage under anaerobic conditions at ambient temperatures can degrade certain compounds but is generally less effective than active composting. Salinomycin in liquid pig manure had a half-life of approximately 6 days during anaerobic storage, whereas macrolide antibiotics degraded considerably more slowly (half-lives of 41–130 days), and tiamulin showed no measurable degradation over 180 days (Schlüsener et al., 2006). These results highlight that storage effectiveness is highly drug specific. Regarding ionophores, monensin does not degrade appreciably during open-air storage of broiler litter, consistent with reports that monensin remains stable in stacked litter under typical farm storage conditions (Sun et al., 2014). Active composting, however, appears more effective. Zizek et al. (2011) modelled that composting chicken manure for several months prior to land application, assuming a half-life of approximately six weeks, could reduce the predicted environmental concentration of monensin sufficiently to bring the risk quotient below 1.

2.16.4. Bioaugmentation

Bioaugmentation where drug-degrading microbial consortia are introduced into contaminated faeces or manure offers a promising biological approach to anthelmintic degradation. Lagos et al. (2021) demonstrated that a thiabendazole-degrading bacterial consortium, when applied to sheep faeces spiked with benzimidazole anthelmintics at 5 and 50 mg kg⁻¹, significantly enhanced degradation of thiabendazole, albendazole and ricobendazole relative to uninoculated controls.

Degradation was less effective against benzimidazoles possessing phenyl functional groups (fenbendazole, flubendazole, mebendazole). Fumigation of faeces prior to inoculation accelerated degradation, suggesting that the indigenous microbial community suppresses the introduced consortium. While bioaugmentation holds considerable promise for reducing the environmental burden of recalcitrant anthelmintics from livestock faeces, its practical application is currently constrained by the need to isolate and maintain consortia that are often specific to individual drug classes or compound families.

Overall, no single mitigation strategy is universally effective across anthelmintics, anticoccidials, and pyrethroids. Macrocyclic lactone anthelmintics are generally not well addressed by composting or storage but can be mitigated at source through targeted treatment and delayed turn out to pasture following treatment. Benzimidazole anthelmintics are persistent in faeces and respond to bioaugmentation and chemical oxidation. Ionophore anticoccidials require extended thermophilic composting for partial removal, or storage of several months before land application to allow natural degradation, particularly for monensin. Toltrazuril and ponazuril require particular attention given their persistence through composting and potential for plant uptake. Pyrethroids entering the environment via dip disposal or faecal excretion are best managed by minimising the volume of spent dip, restricting land application of pyrethroid-contaminated waste, and selecting lower-persistence formulations where available. An integrated approach combining source reduction with appropriate pre-treatment of collected waste will be necessary to meaningfully reduce the ecological exposure of non-target organisms to these veterinary drug residues.

2.17. Knowledge gaps and conceptual frameworks

Anthelmintics, anticoccidials, and pyrethroid ectoparasiticides occupy markedly different positions on the spectrum of environmental characterisation, despite sharing a common entry point into the environment through animal excreta. Three priority gaps recur across the literature and constitute the principal barriers to robust environmental risk assessment of these drug classes in animal waste.

The first is the scarcity of validated multi-residue analytical methods capable of detecting parent compounds and transformation products across these drug classes in complex manure matrices, a deficiency that is most important for pyrethroids. This gap is compounded by the fact that current regulatory frameworks do not mandate manure monitoring. The second is the lack of systematic, broad-spectrum occurrence and usage monitoring across livestock sectors and regions, which means that the existing dataset is dominated by isolated, farm- or species-specific studies rather than representative surveys. The third is the limited farm-scale evaluation of mitigation technologies: composting, storage, and bioaugmentation have each demonstrated compound-specific efficacy under laboratory or pilot conditions, but rarely under realistic operational conditions. Table 4 summarises these gaps, the drug classes most affected, and their consequences for risk assessment.

Across the three drug classes reviewed, environmental fate is best understood as a downstream consequence of two interacting compound properties: lipophilicity and chemical structure. These properties determine the dominant excretion route, the nature of within-manure transformation, soil sorption and mobility, the principal pathway by

Table 4

Key knowledge gaps identified in the occurrence, transformation, and mitigation of VMP residues in animal waste.

Knowledge gap	Specific deficiency	Most affected drug class(es)	Consequence
Analytical methods	Scarcity of validated multi-residue method for pyrethroids and its transformation products in manure or faecal matrices	Pyrethroids	Cannot quantify occurrence or risk associated with transformation products of manure-borne pyrethroid loads
Transformation products	No studies have characterised pyrethroid transformation products within the manure matrix or following manure amendment to soil	Pyrethroids	Well-established soil-phase chemistry cannot be extrapolated to the manure matrix
Occurrence monitoring	Sparse, farm- and species-specific datasets rather than systematic surveys; pyrethroids almost entirely unreported in manure	All three classes, most severe for pyrethroids	Reported concentrations reflect treatment timing and handling practices rather than representative residue levels
Usage monitoring	Anticoccidials require no prescription in EU poultry production; anthelmintic and ectoparasiticide use is poorly collated by compound and formulation across member states	All three classes	Usage intensity cannot be linked to environmental loading at the landscape scale
Mitigation validation	Composting, storage, and bioaugmentation strategies tested mainly at laboratory or pilot scale and rarely validated on farm; no single strategy is universally effective	All three classes	Real-world efficacy and compound-specific recalcitrance (e.g. monensin, toltrazuril/ ponazuril) remain uncertain
Structure-excretion relationships	Relationships between physicochemical properties and elimination routes remain poorly defined in prior reviews and unevenly characterised across drug classes	Anthelmintics, anticoccidials	Limits the ability to predict excretion route and load from compound properties alone
Sublethal and trans-generational ecotoxicology	Evidence largely confined to macrocyclic lactones (e.g. effects on dung beetle offspring); comparable data are lacking for pyrethroids and anticoccidials	Pyrethroids, anticoccidials	Risk assessments may underestimate chronic and indirect ecological effects

which residues are transported off-site, and ultimately the ecotoxicological concern that residues pose to non-target organisms. Fig. 4 presents this framework, tracing each drug class from its defining physicochemical properties through to its dominant environmental pathway and the mitigation approaches to which it responds.

Macrocyclic lactones and pyrethroids are known for its high

lipophilicity. Both are excreted predominantly as the parent compound, bind strongly to organic matter, and are effectively immobile in the dissolved phase, so that particle-bound surface run-off becomes the dominant, and often only meaningful, transport pathway to surface water. Despite this shared physical behaviour, the two classes diverge sharply in how well their manure-phase chemistry is understood: macrocyclic lactones undergo well-documented photolytic isomerisation and microbial deglycosylation within dung, whereas no equivalent transformation pathway has been described for pyrethroids in any manure matrix, even though the analogous soil-phase chemistry is well characterised.

Benzimidazoles occupy a distinct position because hepatic first-pass metabolism means that oxidised metabolites, rather than the parent drug, dominate the faecal residue pool. The resulting metabolites are slightly to moderately mobile in soil, enabling root uptake and, under field conditions, a complete excrement-soil-plant-animal circulation loop that re-exposes grazing livestock.

Ionophore anticoccidials present an intermediate case governed by moderate, pH-dependent sorption rather than extreme hydrophobicity. Their environmental behaviour is strongly species- and compound-specific: monensin and lasalocid show contrasting distributions between dairy manure and poultry litter, and surface run-off following land application of amended litter represents their principal route to nearby water bodies. This intermediate mobility is mirrored in their ecotoxicological profile, with monensin capable of exceeding predicted no-effect concentrations for earthworm reproduction under certain manure-handling scenarios.

The framework also extends to mitigation. Because macrocyclic lactones partition so strongly into organic matter, source-based interventions, such as targeted selective treatment and delayed pasture access, are more tractable than post-excretion treatment, as composting and storage have limited effect on this class. Benzimidazoles, by contrast, respond to bioaugmentation with drug-degrading consortia and to chemical oxidation, both of which act on the oxidised metabolites that dominate the excreted residue pool. Ionophore mitigation is compound-specific and depends on extended thermophilic composting or prolonged storage, particularly for the more recalcitrant monensin. Pyrethroid mitigation remains the least developed, limited to source reduction such as minimising spent-dip volumes, since no manure-specific treatment data exist. Read together, the framework indicates that a compound's position on the lipophilicity-structure axis is not merely descriptive but predictive: it anticipates which environmental compartment will accumulate residues, which transport pathway will dominate, and which mitigation strategy is mechanistically plausible.

3. Conclusion

Anthelmintics, anticoccidials, and pyrethroid ectoparasitides follow markedly different environmental trajectories once excreted into animal waste, governed by their physicochemical properties and the chemistry of the manure matrix itself. Macrocyclic lactones bind strongly to organic matter and create sharp exposure gradients between fresh pasture deposits and stored slurry; benzimidazoles undergo class-specific sulphur oxidation and can circulate through a complete excrement-soil-plant-animal loop; ionophore anticoccidials reach surface waters primarily via run-off, with species-dependent occurrence; and pyrethroids remain the least characterised class, lacking validated analytical methods for manure matrices and transformation product data. Across all three classes, ecotoxicological evidence points to risks ranging from acute toxicity to sublethal trans-generational effects on dung-colonising invertebrates, with potential consequences for dung decomposition, nutrient cycling, and soil fertility. Mitigation strategies demonstrate variable, compound-specific efficacy and have rarely been validated beyond laboratory or pilot scale. Three priority gaps impede robust environmental risk assessment: the scarcity of validated multi-residue methods for parent compounds and transformation products in

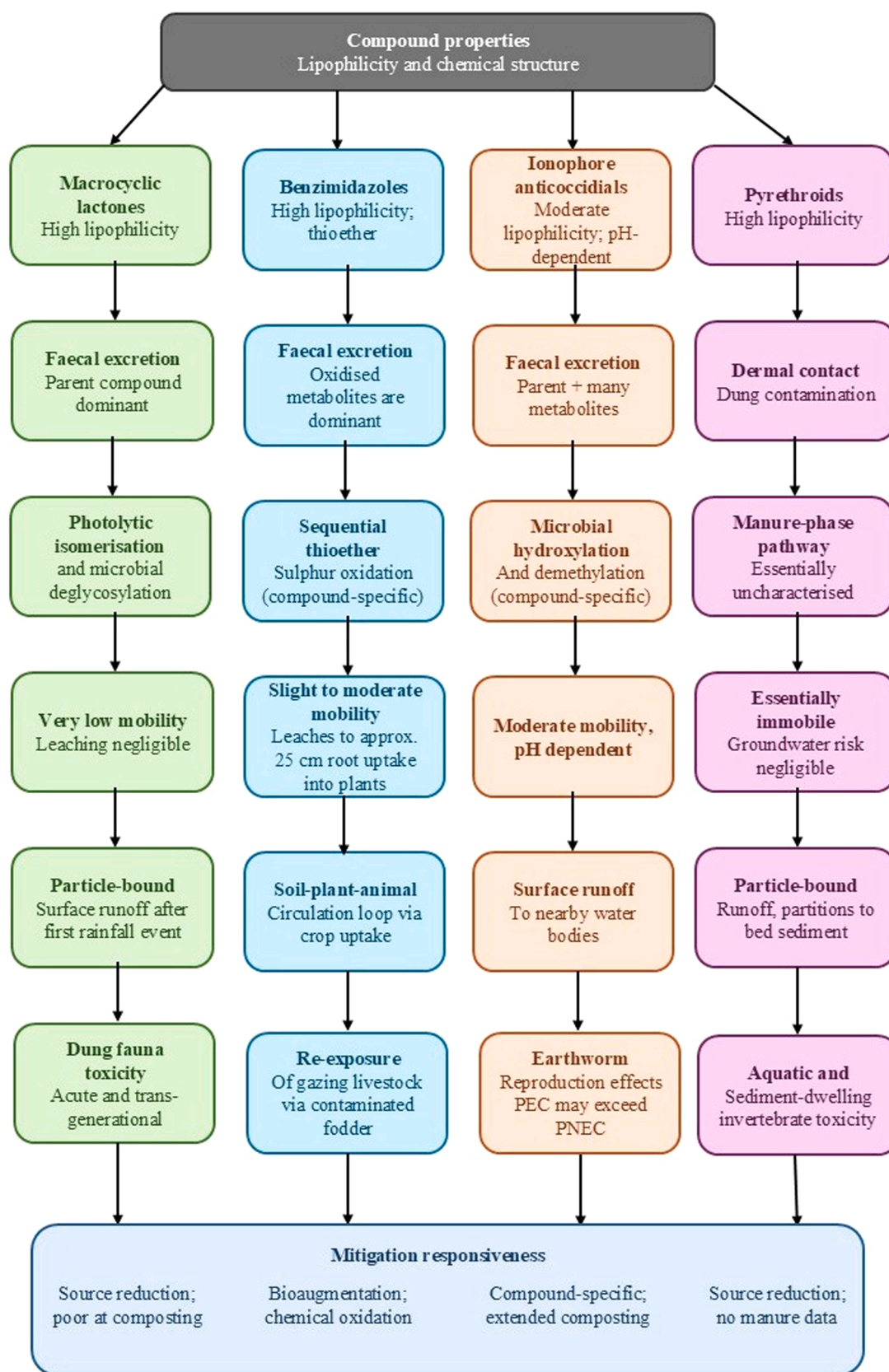


Fig. 4. Conceptual framework.

manure, particularly for pyrethroids; the lack of systematic occurrence and usage monitoring across livestock sectors and regions; and the limited farm-scale evaluation of mitigation technologies under realistic operational conditions. Resolving these gaps is essential to developing evidence-based, sustainable strategies for managing VMP residues in livestock waste and reducing their transfer to soil, water, and the wider environment.

CRedit authorship contribution statement

Vera Capistrano Virtudes: Writing – original draft, Visualization. **Melissa Di Rocco:** Writing – review & editing, Supervision. **Martin Danaher:** Writing – review & editing, Supervision, Conceptualization. **Liam Morrison:** Writing – review & editing, Supervision. **Mark Gerard Healy:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ecoenv.2026.120857](https://doi.org/10.1016/j.ecoenv.2026.120857).

Data availability

Data will be made available on request.

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