Environmental Contamination: Causes and Solutions
https://www.sciltp.com/journals/eccs

Article

Concentrations of Anthelmintics in Irish Sediments and Wastewater Treatment Plant Derived Biosolids from Ireland

Ann Marie Coggins [1,*], Martin Sharkey [1], Stuart Harrad [2], Mark G. Healy [3] and Shijie Wang [2,*]

[1] Physics, School of Natural Sciences, University of Galway, H91 CF50 Galway City, Ireland
[2] School of Geography, Earth, and Environmental Sciences, University of Birmingham, Birmingham B15 2TT, UK
[3] Civil Engineering, College of Science and Engineering, University of Galway, H91 HX31 Galway City, Ireland
* Correspondence: Marie.coggins@universityofgalway.ie (A.M.C.); sxw597@student.bham.ac.uk (S.W.)

How To Cite: Coggins, A.M.; Sharkey, M.; Harrad, S.; et al. Concentrations of Anthelmintics in Irish Sediments and Wastewater Treatment Plant Derived Biosolids from Ireland. *Environmental Contamination: Causes and Solutions* **2026**, *2*(2), 6. https://doi.org/10.53941/eccs.2026.100006

Received: 8 April 2026
Revised: 27 May 2026
Accepted: 4 June 2026
Published: 29 July 2026

Abstract: Pharmaceutical residues, particularly anthelmintics (AHs), are increasingly detected in water, sediments, soils, and wastewater biosolids due to high usage, poor removal in treatment plants, and extensive use in both humans and animals. Many AHs are persistent, lipophilic, and toxic to non-target organisms. Environmental monitoring of AHs in sediments and wastewater-derived biosolids is essential to manage ecological and human health risks. This study reports the concentration of four AHs, albendazole (ABZ), emamectin benzoate (EMB), fenbendazole (FEN), and ivermectin (IVE) in n = 81 inland and transitional/coastal sediment samples in Ireland. Additionally, concentrations in n = 21 wastewater treatment plant-derived biosolid samples collected from seven wastewater treatment plants in Ireland are reported. FEN was the most frequently detected (DF, 86%) AH in sediment and also had the highest reported median concentration (0.103 µg/kg dw). Sediment concentrations were at the low end of those reported internationally. Comparison with Norman $PNEC_{sed}$ values suggest that sediment ABZ concentrations present a low ecotoxicological risk, while concentrations of FEN present a moderate ecotoxicological risk. This study reports new data on sediment concentrations of EMB sampled at locations remote from aquacultural activities, with a small number of sample concentrations (n = 8) greater than concentrations suggested to present an ecological risk (0.2 ng/g). Both ABZ and IVE were frequently detected (100% DF) in biosolids. IVE had the highest median concentration (0.57 µg/kg dw) most likely due to higher $logK_{ow}$ values promoting strong adsorption to the organic rich matrix. Biosolid concentrations were within the range of the limited previous reports for biosolids internationally. In light of the EU Soil Strategy and the ongoing review of the EU Sewage Sludge Directive (86/278/EEC), further studies on the concentrations of pharmaceutical residues, including AHs, are required to fully understand the impact of their reuse as agricultural fertilizers.

Keywords: anthelmintics; sediments; river; transitional; albendazole; emamectin benzoate; ivermectin; fendendazole

1. Introduction

The growing detection of hazardous chemicals, including pharmaceutical residues, across environmental compartments remains a critical environment concern [1]. In recent decades, the number and concentration of

pharmaceuticals entering the environment, particularly in developing countries [2], have risen due to higher consumption, improper disposal, and inadequate wastewater treatment.

Pharmaceuticals are designed to have biological effects at low concentrations, which makes their presence in the environment concerning. As a result, when present in the environment they are referred to as emerging *chemicals of concern* due to their potential effects on non-target organisms [3]. Among the many drugs used in human and veterinary medicine, anthelmintics (AHs) represent a significant proportion of total pharmaceutical consumption across the European Union (EU) [4].

AHs are used in both human and veterinary medicine to treat infections caused by ecto- and endoparasites [5]. First introduced in the 1960s, compounds such as fenbendazole (FEN), levamisole, and albendazole (ABZ) are among the most commonly used. These drugs belong to the benzimidazole class and are primarily effective against nematodes, although ABZ also exhibits activity against trematodes and cestodes.

A second major group of AHs, the macrocyclic lactones, include the avermectins—such as ivermectin (IVE) and emamectin benzoate (EMB). These compounds are active against nematodes and certain ectoparasites and represent the most widely used class of anthelmintic drugs used in veterinary medicine [5]. EMB is a broad spectrum avermectin used across agriculture, forestry and aquaculture. It is commonly used to treat sea lice on farmed salmon where it is administered via feed [6,7].

Many AHs such as FEN and ABZ and IVE are lipophilic and display high sorption efficiency to organic-rich materials such as sewage sludge [8–10] sediments, and soils [11], resulting in concentrations which are toxic to non-target organisms living in these microenvironments [12]. The impact of the presence of macrocyclic lactone residues in the environment, such as IVE, which can remain active for up to four months in stored manure, have been well documented [13]. IVE is harmful to both plants and non-target organisms such as the dung-beetle and earth worm [14–16]. Within the EU, abamectin, comprising a mixture of avermectin B1a and B1b, is classified as very toxic to aquatic life and is a suspected reproductive toxin [17]. It is no longer approved for use as a biocide [18] and is subject to Prior Informed Consent requirements for export. In 2025, abamectin was added to the Water Framework Directive (WFD) Watch List as an emerging pollutant of concern [19]. Since 2023 the Scottish EPA have implemented a new Environmental Quality Standard for the use of EMB in fish farming [7].

Direct discharges from pharmaceutical manufacturing (e.g., direct disposal on agricultural land or discharge to sewage treatment plants [4] are considered a negligible source of environmental contamination compared to emissions resulting from human and animal use. Intensive livestock and aquaculture systems are particularly vulnerable to parasitic infections and therefore rely heavily on AHs for treatment. However, up to 90% of orally administered AHs can be excreted as the parent compound or as active metabolites, which may enter the environment either directly following application or indirectly via agricultural runoff [20].

Once released, their mobility and persistence depend on several factors, including their chemical structure (e.g., the presence of functional groups susceptible to oxidation, reduction, or hydrolysis) which can result in the production of more reactive or mobile metabolites. Their octanol–water partition coefficient (Log Kow), which is typically high for many AHs and promotes strong adsorption to soil or sediment; as well as soil characteristics such as organic matter content, pH, and metal concentration [11], and the local hydrogeological conditions [21,22].

Previous studies have detected AHs in groundwater [22], surface waters [23–25], and coastal waters [26], linking their presence primarily to agricultural and aquacultural activities. Evidence of AH circulation from treated animals to their faeces, to fodder plants, and subsequently to untreated animals feeding on these plants illustrates potential environmental contamination pathways to the human food chain but also the risk of developing drug resistance. These findings underscore the importance of monitoring AHs and their residues in the environment [27].

Due to the high excretion rates of AHs in both humans and animals, wastewater also represents a significant source of these compounds in the environment. Elevated concentrations of AHs have been reported in both wastewater influents and effluents [28–30]. Zhao et al. [28] calculated removal efficiencies for 19 AHs in wastewater treatment plants (WWTPs) ranging from −425% to 100%, highlighting the potential risk posed by the more water-soluble AHs such as ricobendazole—a metabolite of ABZ to aquatic ecosystems.

In some EU countries, such as Ireland and Spain, large quantities (>80%) of WWTP-derived biosolids are applied directly to agricultural land. AHs present in these biosolids, when used as soil fertilisers, could pose a threat to soil organisms as well as to surface and groundwater. Many anthelmintics are lipophilic, making it important to quantify their concentrations not only in WWTP-derived biosolids but also in sediments and soils. Currently, European data on AH concentrations in soils and sediments are limited [23,24], as are data for WWTP-derived biosolids [31]. Therefore, obtaining this information is critical for assessing the environmental risks associated with the use of biosolids as agricultural fertilizers [32].

Moreno-González et al. [24] analysed 40 pharmaceuticals, including three AHs, in water and coastal sediment samples from a Mediterranean lagoon. Thiabendazole was detected in 83% of sediment samples, with agricultural

activity near the lagoon identified as the likely source of contamination. Similarly, Wagil et al. [23] reported concentrations of FEN and flubendazole in a limited number of water, sediment, and fish tissue samples collected near an animal breeding facility in Poland. Detection frequencies were highest in water samples compared to the other matrices.

A study of human and veterinary pharmaceuticals in the marine environment in Korea [26] found that the four AHs tested in seawater accounted for only 3–5% of the total concentrations of target pharmaceuticals, compared to 50–60% in marine sediments. Thiabendazole (THI) was the most prominent AH, with sediment concentrations near fish farms two to three times higher than those in coastal sediments, and up to 4–1400 times higher than antibiotic concentrations in river sediments. Chen et al. [8] measured concentrations of 19 AHs in water and sediment samples collected along the Tujiang River in China. Benzimidazoles dominated both sediment and water samples, reflecting their widespread use, with ABZ and ricobendazole showing 100% detection frequencies. Concentrations of macrocyclic lactones were lower, likely due to their more limited use and higher pseudo-partitioning coefficients beween water and sediment (Kp,s). Elevated water concentrations were observed downstream of industrial and residential wastewater discharges. High Kp,s values calculated for AHs such as ABZ, levamisole (LEV) and THI indicate a strong tendency for these compounds to accumulate in sediments, with the highest concentrations detected near a large fish farm. In terms of ecotoxicological risk, macrolactones—including ivermectin (IVE) and eprinomectin (EPR) exhibited higher toxicity compared to benzimidazoles.

AHs are increasingly detected in water, sediments, and wastewater-derived biosolids, with sediments often acting as environmental sinks. Climate change-related events, such as increased incidence of infectious diseases and higher demand for AH treatments, combined with altered precipitation and runoff patterns, could further exacerbate environmental contamination from domestic and agricultural sources [33]. Their persistence, bioaccumulation, and ecotoxicological risks to non-target organisms highlight the potential for environmental harm and the spread of drug resistance [5]. In response to growing concerns regarding drug resistance, since December 2025, in Ireland new rules on the use of antiparasitic medicines for animal healthcare were introduced, veterinary prescriptions are now required for all medicines [34]. Environmental monitoring of AHs in sediments and WWTP sludges is therefore essential to assess contamination pathways and manage ecological and human health risks.

The aim of this paper is to present, for the first time, a baseline assessment of the concentration of four anthelmintics (IVE, EMB, ABZ and FEN) in inland and coastal/transitional sediment and WWTP-derived biosolids samples collected from around Ireland. To the authors' knowledge, this study is the first report of background sediment concentrations of EMB remote from aquaculture activities. Biosolid concentrations are analysed alongside available metadata on population equivalent (PE), WWTP treatment type. Sediment concentrations are analysed using data on sediment type and water flow (sediment). An assessment of the ecotoxicology risk at the concentrations determined in sediment are performed using a risk quotient (RQ) approach and comparisons made with similar previous reported studies.

2. Methods

2.1. Sample Collection and Pre-Treatment

The project sampling campaign involved the collection of transitional/estuarine and freshwater sediment samples and samples of wastewater treatment plant derived biosolids. A total of n = 81 sediment samples, both transitional/estuarine (n = 19) and fresh water (n = 62) were collected from sites across the Republic of Ireland in 2023 (Figure 1). In addition, in collaboration with Uisce Éireann (www.water.ie (accessed on 20 May 2026)) a total of n = 21 samples of biosolids, destined to be used as agricultural fertilisers, were collected from seven WWTPs located across Ireland in 2023. Each of the WWTPs served different population equivalents (PEs) and had different sludge treatment processes (Table S1). Further details regarding the sampling methods employed for both sediment and biosolids sampling are reported previously [35]. All samples were analysed for four anthelmintics, namely ivermectin, emamectin benzoate, albendazole, and fenbendazole (Table 1). Ivermectin and emamectin benzoate were purchased from Chiron AS (Trondheim, Norway), while albendazole and fenbendazole were obtained from Merck KGaA (Darmstadt, Germany).

Figure 1. Locations sampled in 2023: red pins indicate inland sediment sites; blue pins indicate transitional/coastal sites (map adapted from https://irish.gridreferencefinder.com). The same map can also be found in our report entitled Assessment of the Environmental Contamination of Irish Soils and Sediments with Hazardous Chemicals (TERRAChem), available at: https://www.epa.ie/publications/research/environment--health/research-516-assessment-of-the-environmental-contamination-of-irish-soils-and-sediments-with-hazardous-chemicals-terrachem.php (accessed on 20 May 2026).

Table 1. Overview of the anthelmintics measured in this study.

Chemical	Chemical Class	Approved Uses in Ireland
Ivermectin *	Macrocyclic lactone	Broad spectrum wormer, approved for use in humans and animals, used to treat for parasitic infections (round, eye & lung worm, warbles, lice and mites).
Emamectin benzoate	Macrocyclic lactone	Approved for infestations of parasitic sea lice in Atlantic salmon.
Albendazole	Benzimidazole	Approved for treatment of parasites (round, lung & tape worm and adult fluke) in cattle and sheep.
Fenbendazole *	Benzimidazole	Approved for use in animals, used for the treatment of parasitic (round, lung and tape worm) in cattle, sheep pigs and companion pets such as dogs and cats.

* Also available as a combination product.

2.2. Laboratory Processing of Sediment and WWTP-Derived Biosolids Samples

Surficial sediment samples (0–5 cm depth) were collected from river sites using grab sampling. Approximately 1 kg of sediment was obtained from sites dominated by coarse (>2 mm) grain sizes, while ~0.5 kg was collected from sites with finer sediments (e.g., coastal sites). Sampling was conducted using either stainless-steel digging tools or a Van Veen grab sampler, pre-cleaned prior to each use with a detergent wash followed by triple rinses in acetone, cyclohexane, methanol, and distilled water. Samples were placed into high density poly ethylene (HDPE) containers and transported to the laboratory, where they were homogenised and wet-sieved to 2 mm before being transferred into 50 mL centrifuge tubes. Samples were then sealed and stored at −80 °C until freeze-drying which was performed using a Labconco FreeZone freezer at maximum vacuum of 0.133 mbar and a temperature of −40 °C for approximately six days, dried sediments were then stored for at 4 °C until analysis. Biosolid samples were prepared for analysis in line with the procedures outlined above. A summary of the characteristics of the WWTPs sampled in the study are provided in Section S1 of the SM. Three biosolids samples were collected from each site at four-month intervals, January, May and September 2023.

2.3. Sample Preparation Protocols

A 1 g aliquot of sediment (0.1 g for biosolid) was placed into an ASE extraction cell. To this was added 50 ng of mixed internal standard (IS) solutions containing anthelmintics (d_2-ivermectin, d_3-albendazole; Greyhound Chromatography, Birkenhead, UK), followed by 30 min equilibration before extraction using an ASE 350 system with MeOH/H_2O (optima grade 1:1, *v*/*v*) as the extraction solvent [29], with three static extraction cycles of 5 min each at 70 °C, followed by a 3 min purge. Following extraction, the extract was concentrated incipient dryness to remove methanol. After this, the concentrated extract was diluted to approximately 60 mL with H_2O. SPE cartridges (Waters PRiME HLB, 3 cc, 60 mg) were preconditioned with 12 mL H_2O containing 5% MeOH, before loading the 60 mL aqueous extract onto the SPE cartridge. After loading, the cartridge was dried under vacuum for approximately 5 min to remove residual water, before analytes were eluted with 8 mL methanol, followed by 2 mL acetone, under light vacuum. The combined eluate (~10 mL) was evaporated to incipient dryness under a gentle stream of nitrogen at 40 °C, before the residue was diluted in 0.25 mL H_2O and 0.25 mL MeOH, vortexed briefly, and syringe-filtered (0.22 μm) into an autosampler vial. Following this, the 0.5 mL final extract was transferred to an LC vial and spiked with 10 ng recovery determination standard (RDS) (d_3-FEN; also referred to as syringe standard or internal standard).

2.4. Instrumental Analysis

Determination of anthelmintic concentrations was performed using a Sciex Exion UPLC coupled to a Sciex 5600+ TripleTOF MS. Chromatographic separation was achieved with an Acquity UPLC BEH C18 column (100 × 2.1 cm, 1.7 μm, Waters, Milford, CT, USA) using a mobile phase of high purity water with 0.05% formic acid and 5 mM ammonium formate (Optima grade, Fisher Scientific (Pittsburgh, PA, USA) (mobile phase A)) and methanol (Optima grade, Fisher Scientific (mobile phase B)). The LC program commenced with 10% B and was increased linearly to 100% over 3.5 min and held for a further 4 min. The mobile phase composition was returned to 10% B over 0.5 min and held for 2.5 min to equilibrate for the next sample. The overall method duration was 10 min with a flow rate of 0.4 mL/min. The injection volume was 10 μL and the column oven was maintained at 45 °C throughout.

The TripleTOF MS was equipped with a Turbo V ion source, which was operated in positive ion mode using electrospray ionisation (ESI+) at 5000 V. Curtain gas was set to 25 psi, nebuliser gas (GS1) to 65 psi, and drying gas (GS2) to 35 psi. The CAD gas was set to medium, and the source temperature was maintained at 250 °C. The instrument was operated in high-resolution mode and scanned between 100 and 1000 Da. A SCIEX automated calibrant delivery system was used to maintain mass accuracy. A manual mass calibration was performed prior to each batch of samples, and an automatic mass calibration was performed after every five injections. Identification and quantification of target analytes were performed using Multiquant 2.0 software. Target analytes were identified using a combination of correct retention time and *m*/*z* transition values. Native anthelmintics were quantified with: Ivermectin *m*/*z* 892.5 > 569.3; Emamectin benzoate *m*/*z* 886.8 > 158.0; Albendazole *m*/*z* 266.1 > 232.1; FEN *m*/*z* 300.1 > 268.0. For IS and RDS were: d_2-ivermectin *m*/*z* 894.5 > 571.3; d_3-Albendazole *m*/*z* 269.1 > 234.1; d_3-FEN *m*/*z* 303.1 > 268.1.

2.5. Data Analysis and Risk Assessment

Non-parametric statistical tests were used to make comparisons of mean concentration of target chemical and the various metadata recorded for the sample or sample location (population density, sediment type, river flow speed (FARL Index), and year of collection for sediments; PE, treatment type, and month of collection for biosolids). For two sample means, Mann-Whitney U tests were used, and for more than two sample sets, Kruskal-Wallis H tests were used (confidence interval of 95%, Significance level (p) of 0.05). Where data were recorded to be below the limits of quantification (LoQ), proxy values were determined using {LOQ × Detection Frequency} according to [36]. Using predicted no effect concentration values for sediments ($PNEC_{sed}$), published by the NORMAN network www.norman-network.com/nds/ecotox (accessed on 23 May 2026) [37], available for two of the target anthelmintics (ABZ and FEN), RQs were calculated to evaluate ecotoxicological risks using the following equation:

$$RQ = \frac{MEC_{95}}{\text{Lowest PNEC}}$$

where MEC_{95} is the 95th percentile concentration in sediment samples and $PNEC_{sed}$ is the PNEC for sediment values.

3. Results and Discussion

3.1. Concentrations of Anthelmintics in Irish Fresh Water and Transitional/Coastal Sediments

Table 2 presents the descriptive statistics of the concentrations of target anthelmintics in Irish inland and coastal/transitional sediments collected in 2023. Concentrations reported for inland sediments were not significantly different to those reported in coastal/transitional sediments ($p > 0.05$). The most frequently detected anthelmintic was FEN (DF 86%), followed by EMB (69.1%), IVE (66%) and ABZ (38%). As shown in Figure 2, the target chemical with the highest median concentration was FEN (median; 0.103 mg/g dw), followed by IVE (median; 0.059 mg/g dw).

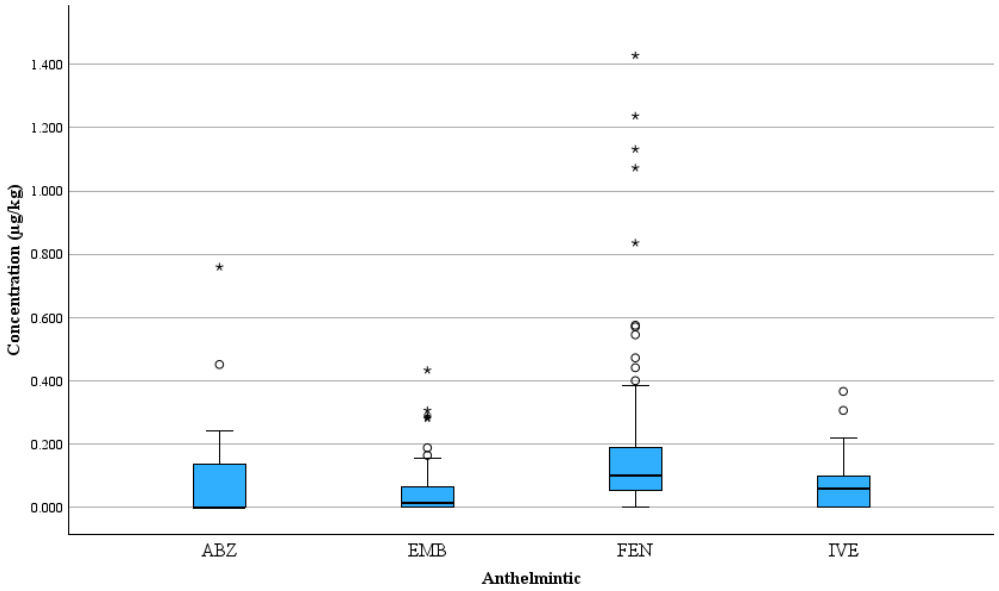

Figure 2. Graphical overview of concentrations of anthelmintics in transitional/coastal and inland sediment samples collected around Ireland in 2023. Legend: Blue box denotes interquartile range (IQR) & median; bars denote non-outlier maxima and minima (<1.5 × IQR); circles denote mild outliers (1.5–3.0 × IQR); stars denote major outliers (>3.0 × IQR).

Table 2. Statistical summary of concentrations, (µg/kg dry weight) of target anthelmintics in Irish inland and transitional/coastal sediments (sieved to 2 mm), samples were collected in 2023.

Anthelmintic /Statistical Parameter	DF (%)	Range	Median	Arithmetic Mean	SD	$PNEC_{sed}$ [a]	RQ [b]	LOQ
Albendazole (ABZ)	38.3	<0.002–0.760	<0.002	0.072	0.119	7.65	0.035	0.002
Emamectin Benzoate (EMB)	69.1	<0.001–0.434	0.016	0.051	0.082	n/a	n/a	0.001
Fenbendazole (FEN)	86.4	<0.007–1.428	0.103	0.198	0.281	8.41	0.130	0.007
Ivermectin (IVE)	65.4	<0.003–0.367	0.059	0.066	0.070	n/a	n/a	0.003

[a] predicted no effect concentration values for sediment from NORMAN database, 2024 [b] Risk Quotient.

3.2. Concentrations of Anthelmintics in Irish Sediments Compared to Previous International Data

In comparison to previous studies (Table 3), data concentrations reported for Irish sediment are low and consistent with previous reports, and usage patterns in Ireland [22] which have shown benzimidazoles (BZD) to have highest detection frequencies. In this current study, FEN is detected more frequently than other target chemicals [8,38]. Although ABZ also a BZD had a DF of 38%, both BZDs are among the more commonly used BZDs in veterinary medicine in Ireland, collectively both active ingredients are approved for use in 51 products. FEN is more commonly used in lactating cows, whereas ADZ is more commonly used in housed animals [22]. Although the highest concentration of FEN (1.24 mg/g) was detected in a river situated in a rural area nearby agricultural activities, the sample size was insufficient to draw definitive conclusions regarding potential pathways of contamination. In addition, one limitation of this current study is that samples were only monitored for the parent drug and not metabolites. Both ABZ and FEN are sensitive to oxidation, ABZ is metabolised in mammals; however, its primary metabolite (ABZ-SO) is more soluble and mobile and perhaps less likely to be detected in sediment [21,22]. Similarly, FEN is transformed into FEN-SO or oxfendazole.

Both FEN and ABZ sediment concentrations (µg/kg) are on the lower end (median; 0.103, <LoQ–1.43, median; 0.001, < LoQ–0.76 respectively) of the range of concentrations recently reported by Lei et al. [38] for sediment of the Lhasa River (in the dry season) (FEN; 0.36–12.60 mg/g, ABZ; ND-13.6 mg/g), and significantly lower than sediment concentrations reported for the Tuojiang river, China (median FEN; 2.69 mg/g, ABZ; 2.02 mg/g) [8] and Jiangan river and Ming Yuan lake in China (FEN; 2.8–9.9 mg/g, ABZ 1.9–5.1 mg/g) [29]. ABZ and its metabolites were the most frequently detected anthelmintic in ground water and surface water sampling campaign in Ireland in 2017 [22]. At the time of that study, higher frequencies of detection and higher concentrations coincided with periods of increased usage and intensive meteorological events. Over 80% of samples collection in the current study took place between May and July 2023, and so the impact of seasonality on concentrations could not be examined. River FARL data (Available online: https://gis.epa.ie (accessed on 26 April 2026) was obtained for 70% of the 2023 sampling locations, however no correlation was observed with sample concentrations.

Table 3. Concentrations of target anthelmintics, (µg/kg dry wgt. range and median *(italics*) values are reported, unless indicated otherwise) in Irish sediment and WWTP-derived biosolids and previous reported data internationally. (* mean values).

Reference	Location	ABZ	EMB	FEN	IVE
Sediment data					
This study (2023) µg/kg	Ireland	<0.0023–0.760, *0.001*	<0.0014–0.434, *0.016*	<LoQ0.0065–1.428, *0.103*	<0.0031–0.367, *0.059*
Lei et al., [38] µg/kg	Lhasa River, Xizang China	ND-13.6, 3.7 * (dry season) 4.07–146.0, 34.16 * (wet season)		0.36–12.60, 1.67 * (dry season) 6.70–99.40, 35.82 * (wet season)	ND-3.78, 0.84 (Dry season) ND-23.80, 7.2 * (wet season)
Chen et al., [8] µg/kg	Tuojiang River, China	ND-596.6 *2.02*		2.26–6.27 *2.69*	ND-13.5 ND
Li et al., [29] µg/kg	Chengdu, China	1.9–5.1		2.8–9.9	ND < 0.11
Moreno-González et al., [24] µg/kg	Spain	ND, <0.1			
Kim et al., [26] µg/kg	Southern sea of Korea	(ND-14.8) 11.9 *		(1.57–28.0) 10.5 *	
Wagil et al., [23] µg/kg	River Gościcina Poland			ND (<0.3)	
Lalonde et al., [39] mg/kg	Atlantic Canada, downstream from a fish farm		<0.01–2.5 mg/Kg		
Tucca et al., [40] µg/kg	Chile (at a maximum of 100 m from aquaculture)		2.2–14.6		
Wastewater treatment plant-derived biosolids					
This study (2023) µg/kg	Ireland	0.201–0.938	<LoQ-0.037	<LoQ-5.868	0.240–2.266
Zhao et al., [28] µg/kg	Chengdu, China	2.87–5.11		3.46–5.23	0.61–3.16

Similarly, IVE was detected in low concentrations, and on the low end of those reported by [38] and also [29]. Ivermectin is very commonly used in Ireland, typically on housed animals, and is an active ingredient in eighty approved products. Lower concentrations relative to other target chemicals maybe due to the comparative lower therapeutic doses used. In addition, Ivermectin is tightly bound to organic matter, but is transformed into several transformation products, not analysed in this study [21].

Concentrations reported in this study are significantly lower than those reported by [40] for sediment near salmon cages in Chile and are orders of magnitude lower than those reported by [39] near an outflow from a salmon farm in Canada. The Scottish EPA (SEPA) have set a sediment environmental quality standard (EQS) of 0.272 ng/g to regulate the quantity of EMB used on fish farms in Scotland. Recent research [41] suggests sediment concentrations as low as 0.2 ng/g (slightly lower than the SEPA EQS of 0.272 ng/g [42]) can result in reduced species diversity and disrupted community structure with crustaceans most at risk. Concentrations ≥ 0.2 ng/g were detected in this study at eight sites, many of which were remote from aquaculture activities.

3.3. Ecological Risk Assessment of Anthelmintic Concentrations in Irish Sediments

Table 2 presents the RQ values for ABZ and FEN. No $PNEC_{sed}$ values are available for the other target chemicals included in the study. Calculated RQs suggest ABZ presents a low ecotoxicological risk and concentrations of FEN presents a moderate ecotoxicological risk. Previous studies have examined the ecological risks posed by anthelmintic concentrations to aquatic life by comparing concentrations in water with relevant PNECs [8,38]. Lei et al. [38] found that water fleas were the most sensitive species to antiparasitic compounds in river water, followed by fish and algae. Among the compounds studied, abamectin and ivermectin posed the highest ecological risk. In contrast to the current study, Lei et al. [38] performed the ecological risk assessments on water concentrations, however warned that the accumulation of these compounds in sediment may further increase ecological risk to invertebrates in water bodies. The ecological risk associated with FEN was found to be season-dependent, while ABZ was classified as presenting a medium risk in certain sections of the river.

Chen et al., [8] concluded that IVE and eprinomectin posed high ecotoxicological risk to invertebrates in the aquatic environment at many sites along the Tuojiang River. The anthelmintics, FEN and ABZ and abamectin presented medium risk. Similar to Lei et al. [38] invertebrates such as water flea were the most sensitive to the presence of anthelmintics. Another ecotoxicological assessment of anthelmintic concentrations in soil highlighted abamectin and ivermectin as the two anthelmintics presenting highest risk to terrestrial organisms such as spring tails [43].

3.4. Concentrations of Anthelmintics in Irish WWTP-Derived Biosolids

Table 4 and Figure 3 presents a summary of the concentrations of the target anthelmintics in biosolids. Albendazole and Ivermectin had a 100% DFs, followed by fenbendazole and EMB (86% and 67% respectively). While influent or effluent concentrations were not measured in this study, the higher biosolid concentrations compared to sediment data is most likely due to the concentration of contaminants in waste influents following sludge treatment processes. While mean concentrations of FEN and IVE are comparable, FEN concentrations are skewed by an unexplained outlier (5.9 µg/kg). Both ABZ and IVE have higher $LogK_{ow}$ values (3.07 and 3.22) compared to FEN (1.95) [38], therefore these AHs are more likely to be strongly absorbed to the rich organic matrix and are less mobile. Zhao et al. [28] has previously shown the concentrations of anthelmintics in WWTP sludge to be significantly correlated with $LogK_{ow}$. Concentrations of FEN and IVE in the current study are within the range of the concentrations reported by Zhao et al. [28] for WWTP sludges. Results from the statistical analysis did not highlight any statistically significant association between biosolid concentrations for target chemicals and sludge treatment process or PE. Higher concentrations of the three target AHs were generally observed during the second sampling period in May. Elevated levels were recorded at three sites for FEN and at four sites for both ABZ and IVE. This period coincided with lower rainfall (47.4 mm) compared to January (79 mm) and September (121.5 mm). Biosolid concentrations showed a borderline significant relationship with rainfall ($p = 0.06$).

Table 4. Statistical summary of concentrations (µg/kg dry weight) of target anthelmintics in wastewater treatment plant (WWTP)-derived biosolids (n = 21) from Ireland collected from 7 WWTPs in 2023.

Anthelmintic /Statistical Parameter	DF (%)	Range	Median	Arithmetic Mean	SD	95% Percentile	LoQ
Albendazole (ABZ)	100	0.201–0.938	0.302	0.360	0.201	0.895	0.023
Emamectin Benzoate (EMB)	66.7	<0.014–0.037	0.022	0.021	0.010	0.035	0.014
Fenbendazole (FEN)	85.7	<0.065–5.868	0.560	0.906	1.311	2.631	0.065
Ivermectin (IVE)	100	0.240–2.266	0.570	0.604	0.421	0.096	0.031

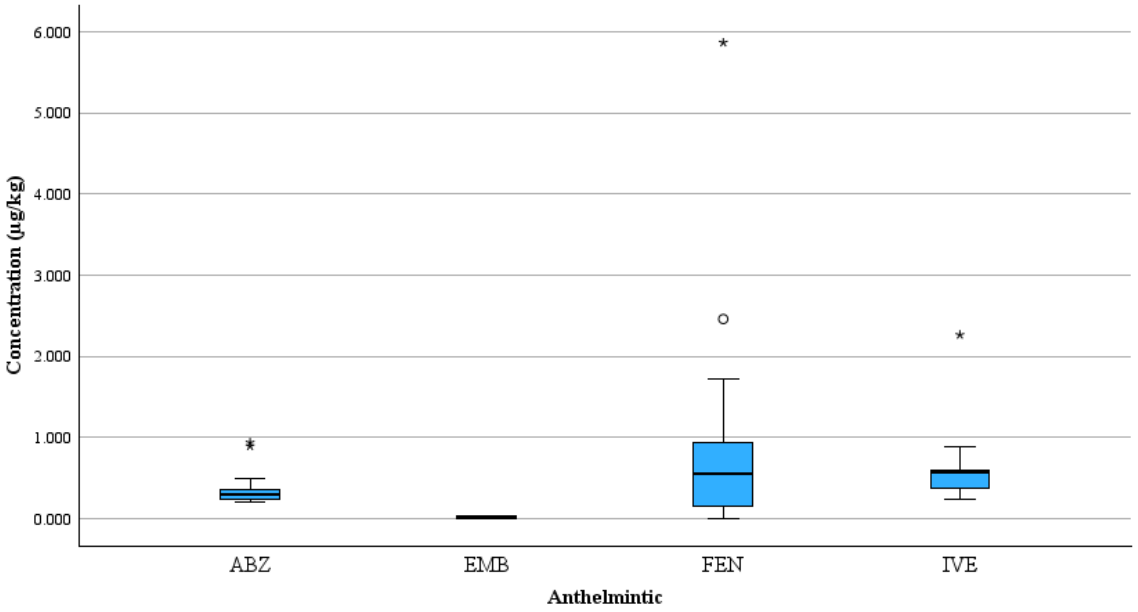

Figure 3. Graphical overview of concentrations of anthelmintics in wastewater treatment plant derived biosolids collected around Ireland in 2023. Legend: Blue box denotes interquartile range (IQR) & median; bars denote non-outlier maxima and minima (<1.5 × IQR); circles denote mild outliers (1.5–3.0 × IQR); stars denote major outliers (>3.0 × IQR).

4. Conclusions

Concentrations of all target anthelmintics (AHs) are at the low end of previous reported concentrations, however high detection frequencies in both sediment and biosolid samples suggest ubiquitous spread of contamination. Fenbendazole, followed by ivermectin were present in highest sediment and biosolid concentrations. Higher detection frequencies for ABZ and IVE in the organic rich biosolids reflect the high $LogK_{ow}$ values for both. Concentrations of ABZ present a low, and FEN a moderate ecotoxicological risk when compared to $PNEC_{sed}$ values promogulated by the NORMAN network. New data on EMB sediment concentrations remote from aquaculture farming is presented. Biosolid AH concentrations are within the range of those reported in the literature, of which there have been only a few previous reports. Further studies are required to investigate potential sources and likely determinants of sediment and biosolid concentrations, as well as the impact of the new veterinary prescription rules in Ireland since December 2025.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2607291450172468/ECCS-26040065-SM.docx.

Author Contributions

A.M.C.: conceptualization, methodology, writing and editing; M.S.: conceptualization, methodology, data curation; S.H.: conceptualization, methodology, editing; M.G.H.: methodology, editing; S.W.: methodology, data curation reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This project is funded under the EPA Research Programme 2021-2030 (2021-HE-1056) and co-funded by the Department of Agriculture, Food and the Marine. The EPA Research Programme is a Government of Ireland Initiative funded by the Department of Communications, Climate Action, and Environment.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available on request.

Acknowledgments

The authors would like to thank the Marine Institute for access to samples required for the completion of this project. The authors would also like to thank Liam Morrison at the University of Galway's School of Natural Sciences, as well as Ronnie Snijder and Tim Mackie of the Department of Agriculture, Environment, and Rural Affairs' Marine and Fisheries Division, for their assistance in processing samples. Thank you also to the EPA research project Steering Committee for helpful comments on the final draft.

Conflicts of Interest

The EPA had involvement in the project Steering Committee. The authors take full responsibility for the content of the published article. The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. European Commission. Chemicals Strategy for Sustainability Towards a Toxic-Free Environment. 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0667 (accessed on 1 February 2026).
2. Belew, S.; Suleman, S.; Wynendaele, E.; et al. Environmental risk assessment of the anthelmintic albendazole in Eastern Africa, based on a systematic review. *Environ. Pollut.* **2021**, *269*, 116106. https://doi.org/10.1016/j.envpol.2020.116106.
3. Lagos, S.; Tsetsekos, G.; Mastrogianopoulos, S.; et al. Interactions of anthelmintic veterinary drugs with the soil microbiota: Toxicity or enhanced biodegradation? *Environ. Pollut.* **2023**, *334*, 122135. https://doi.org/10.1016/j.envpol.2023.122135.
4. Bio Intelligence Service. Study on the Environmental Risks of Medicinal Products. Final Report; Prepared for Executive Agency for Health and Consumers. 2013. Available online: https://health.ec.europa.eu/system/files/2016-11/study_environment_0.pdf (accessed on 1 February 2026).
5. Vokřál, I.; Podlipná, R.; Matoušková, P.; et al. Anthelmintics in the environment: Their occurrence, fate and toxicity to non-target organisms. *Chemosphere* **2023**, *345*, 140446. https://doi.org/10.1016/j.chemosphere.2023.140446.
6. Hamoutene, D.; Kingsbury, M.; Davies, J.; et al. The persistence of emamectin benzoate in marine sediments with different organic matter regimes, temperatures conditions and antibiotic presence. *Mar. Pollut. Bull.* **2023**, *197*, 115714. https://doi.org/10.1016/j.marpolbul.2023.115714.
7. Water Framework Directive-United Kingdom Advisory Group (WFD-UKTAG). UKTAG Environmental Quality Standards Recommendation for Emamectin Benzoate. Available online: https://www.wfduk.org/sites/default/files/EMB%20EQS%20report%20-%20June%202022%20-%20UKTAG%20signed%20off%20-%20revised%2020230224.pdf (accessed on 1 May 2026).
8. Chen, S.; Gan, Z.; Li, Z.; et al. Occurrence and risk assessment of anthelmintics in Tuojiang River in Sichuan, China. *Ecotoxicol. Environ. Saf.* **2021**, *220*, 112360. https://doi.org/10.1016/j.ecoenv.2021.112360.
9. Kim, H.J.; Lee, D.S.; Kwon, J.H. Sorption of benzimidazole anthelmintics to dissolved organic matter surrogates and sewage sludge. *Chemosphere* **2010**, *80*, 256–262. https://doi.org/10.1016/j.chemosphere.2010.04.029.
10. Kreuzig, R.; Blümlein, K.; Höltge, S. Fate of the benzimidazole antiparasitics flubendazole and FBZ in manure and manured soils. *CLEAN–Soil Air Water* **2007**, *35*, 488–494. https://doi.org/10.1002/clen.200720023.
11. Pavlović, D.M.; Glavač, A.; Gluhak, M.; et al. Sorption of albendazole in sediments and soils: Isotherms and kinetics. *Chemosphere* **2018**, *193*, 635–644.
12. Souza, R.B.; Guimarães, J.R. Effects of avermectins on the environment based on its toxicity to plants and soil invertebrates—A review. *Water Air Soil Pollut.* **2022**, *233*, 259. https://doi.org/10.1007/s11270-022-05744-0.
13. Sands, B.; Noll, M. Toxicity of ivermectin residues in aged farmyard manure to terrestrial and freshwater invertebrates. *Insect Conserv. Divers.* **2022**, *15*, 9–18. https://doi.org/10.1111/icad.12526.
14. Wall, R.; Strong, L. Environmental consequences of treating cattle with the antiparasitic drug ivermectin. *Nature* **1987**, *327*, 418–421. https://doi.org/10.1038/327418a0.

15. Finch, D.; Schofield, H.; Floate, K.D.; et al. Implications of endectocide residues on the survival of aphodiine dung beetles: A meta-analysis. *Environ. Toxicol. Chem.* **2020**, *39*, 863–872. https://doi.org/10.1002/etc.4671.
16. Gao, Y.; Li, X.; Guo, J.; et al. Reproductive responses of the earthworm (*Eisenia fetida*) to antiparasitic albendazole exposure. *Chemosphere* **2015**, *120*, 1–7. https://doi.org/10.1016/j.chemosphere.2014.05.030.
17. ECHACHEM. Abamectin EC Number 615-339-5. 2026. Available online: https://chem.echa.europa.eu/100.113.437/harmonised/83146?searchText=abamectin (accessed on 1 May 2026).
18. European Chemicals Agency. The ECHA Chemicals Database. Substance Info Card, Abamectin. 2025. Available online: https://chem.echa.europa.eu/100.113.437/overview (accessed on 1 May 2026).
19. EU. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:02000L0060-20141120 (accessed on 13 January 2025).
20. Alvinerie, M.; Sutra, J.F.; Galtier, P.; et al. Persistence of ivermectin in plasma and faeces following administration of a sustained-release bolus to cattle. *Res. Vet. Sci.* **1999**, *66*, 57–61.
21. Horvat, A.J.M.; Petrović, M.; Babic, S.; et al. Analysis, occurrence and fate of anthelmintics and their transformation products in the environment. *Trends Anal. Chem.* **2012**, *31*, 61–84. https://doi.org/10.1016/j.trac.2011.06.023.
22. Mooney, D.; Richards, K.G.; Danaher, M.; et al. An analysis of the spatio-temporal occurrence of anthelmintic veterinary drug residues in groundwater. *Sci. Total Environ.* **2021**, *769*, 144804. https://doi.org/10.1016/j.scitotenv.2020.144804.
23. Wagil., M.; Maszkowska, J.; Białk-Bielińska, A.; et al. A comprehensive approach to the determination of two benzimidazoles in environmental samples. *Chemosphere* **2015**, *119*, 535–541. https://doi.org/10.1016/j.chemosphere.2014.04.106.
24. Moreno-González, R.M.; Gros., M.; Barceló, D.; et al. Seasonal distribution of pharmaceuticals in marine water and sediment from a mediterranean coastal lagoon (SE Spain). *Environ. Res.* **2015**, *138*, 326–344. https://doi.org/10.1016/j.envres.2015.02.016.
25. Zrnčić, M.; Gros., M.; Babić, S.; et al. Analysis of anthelmintics in surface water by ultra-high performance liquid chromatography coupled to quadrupole linear ion trap tandem mass spectrometry. *Chemosphere* **2014**, *99*, 224–232.
26. Kim, H.Y.; Lee, I.S.; Oh, J.E. Human and veterinary pharmaceuticals in the marine environment including fish farms in Korea. *Sci. Total Environ.* **2017**, *579*, 940–949.
27. Navrátilová, M.; Raisová Stuchlíková, L.; Matoušková, P.; et al. Proof of the environmental circulation of veterinary drug albendazole in real farm conditions. *Environ. Pollut.* **2021**, *286*, 117590.
28. Zhao., L.; Li, Y.; Gan, Z.; et al. Distribution, fate and removal efficiency of anthelmintic drugs in wastewater treatment plants. *Sci. Total Environ.* **2024**, *908*, 168240. https://doi.org/10.1016/j.scitotenv.2023.168240.
29. Li, Y.; Gan, Z.; Liu, Y.; et al. Determination of 19 anthelmintics in environmental water and sediment using an optimised PLE and SPE method coupled with UHPLC-MS/MS. *Sci. Total Environ.* **2020**, *719*, 137516. https://doi.org/10.1016/j.scitotenv.2020.137516.
30. Sim, W.J.; Kim, H.Y.; Choi, S.D.; et al. Evaluation of pharmaceuticals and personal care products with emphasis on anthelmintics in human sanitary waste, sewage, hospital wastewater, livestock wastewater and receiving water. *J. Hazard. Mater.* **2013**, *248–249*, 219–227. https://doi.org/10.1016/j.jhazmat.2013.01.007.
31. Kinney, C.A; Furlong, E.T; Burkhardt., M.R; et al. Bioaccumulation of Pharmaceuticals and other anthropogenic waste indicators in earthworms from agricultural soil amended with biosolid or swine manure. *Environ. Sci. Technol.* **2008**, *42*, 1863–1870. https://doi.org/10.1021/es702304c.
32. Huygens, D.; Garcia-Gutierrez, P.; Orveillon, G.; et al. *Screening Risk Assessment of Organic Pollutants and Environmental Impacts from Sewage Sludge Management*; JRC Science Policy Report; Publications Office of the European Union: Luxembourg, 2022.
33. Sauermann, C.W.; Leathwick, D.M.; Lieffering, M.; et al. Climate change is likely to increase the development rate of anthelmintic resistance in equine cyanthostomins in New Zealand. *Int. J. Parasitol. Drugs Drug Resist.* **2020**, *14*, 73–79. https://doi.org/10.1016/j.ijpddr.2020.09.001.
34. Animal Health Ireland. Parasite Control. 2026. Available online: https://animalhealthireland.ie/programmes/parasite-control/ (accessed on 1 March 2026).
35. Sharkey, M.; Wang, S.; Harrad, S.; et al. Halogenated and non-halogenated flame retardants in Irish sediments and wastewater treatment plant-derived biosolids. *Sci. Total Environ.* **2024**, *954*, 176582. https://doi.org/10.1016/j.scitotenv.2024.176582.
36. Ali, N.; Dirtu, A.C.; Van den Eede, N.; et al. Occurrence of Alternative Flame Retardants in Indoor Dust from New Zealand: Indoor Sources and Human Exposure Assessment. *Chemosphere* **2012**, *88*, 1276–1282.
37. Norman Substance Database. Available online: https://www.norman-network.com/nds/susdat/ (accessed on 5 October 2022).
38. Lei, M.M.; Gu, X.Y.; Gan, Z.Y.; et al. Occurrence and ecological risk of antiparasitic drugs in the Lhasa River on Qinghai-Xizang Plateau. *Emerg. Contam.* **2026**, *12*, 100613. https://doi.org/10.1016/j.emcon.2025.100613.
39. Lalonde, B.A.; Ernst, W.; Greenwood, L. Measurement of oxytetracycline and Emamectin Benzoate in Freshwater sediments downstream of land-based aquaculture facilities in the Atlantic Region of Canada. *Bull. Environ. Contam. Toxicol.* **2012**, *89*, 547–550. https://doi.org/10.1007/s00128-012-0724-6.

40. Tucca, F.; Moya, H.; Pozo, K.; et al. Occurrence of antiparasitic pesticides in sediments near salmon farms in the northern Chilean Patagonia. *Mar. Pollut. Bull.* **2017**, *115*, 465–468. https://doi.org/10.1016/j.marpolbul.2016.11.041.
41. Arnberg, M.; Drivdal., M.; Evenset, A.; et al. Ecological impacts of Emamectin Benzoate, a Sea Lice Therapeutant, on Benthic Communities in the Vicinity of Norwegian Aquaculture Facilities. *Environ. Sci. Technol.* **2026**, *60*, 3459–3474.
42. SEPA (Scottish Environment Protection Agency), Fish Farm Advisory Group. *Emamectin Benzoate Use in Marine Fish Farms: An Environmental Risk Assessment*; SEPA: Stirling, UK, 1999. Available online: https://www.sepa.org.uk/media/299675/wrc-uc12191-03-review-of-environmental-quality-standard-for-emamectin-benzoate.pdf (accessed on 14 February 2026).
43. Lan, T.; Chen, S.; Zhang, Y.; et al. Occurrence, ecology risk assessment and exposure evaluation of 19 anthelmintics in dust and soil from China. *Chemosphere* **2023**, *334*, 138971.