PAN
JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
ITP-PIB
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.155308
2025, No. 66 (VII–IX): 121–127

Environmental risk assessment of antibiotic residues in cattle slurry used as fertiliser

Marta Kijeńska-Markuszewska*[1)], Barbara Gworek[1)], Marcin Gołębiewski[2)]

[1)] Institute of Environmental Protection – National Research Institute, Słowicza St, 32, 02-170 Warsaw, Poland
[2)] Warsaw University of Life Sciences, Department of Animal Breeding Institute of Animal Sciences, Nowoursynowska St, 166, 02-787 Warsaw, Poland

* Corresponding author

RECEIVED 27.02.2025 ACCEPTED 23.06.2025 AVAILABLE ONLINE 14.08.2025

Highlights
- Two-year study on the content of antibiotics in cattle slurry from organic farms.
- Literature search on risk assessment parameters ($PNEC_{soil}$) relevant to the soil compartment.
- Environmental risk analysis of soil following slurry use as fertiliser.

Abstract: The aim of the study was to assess the environmental risk caused by active antibiotic substances present in cattle slurry from ecological farms, used for fertilisation purposes. In order to assess the environmental risk, studies were carried out on farms located in the cleanest region of north-eastern Poland. The study focused on substances most commonly found in veterinary drugs: tetracycline, bacitracin, kanamycin, dihydrostreptomycin, benzylpenicillin, cefquinome, and cephalexin. In the analysed cattle slurry, only tetracycline, benzylpenicillin, and cephalexin were detected in the analysed slurry. Their concentrations were respectively 1.53–15.1, 0.048–0.27, and nd–1.11 $ng \cdot g^{-1}$. Other tested antibiotics, such as cefquinome and dihydrostreptomycin, were detected in the samples of cattle slurry at concentrations below the *LOQ*. Bacitracin and kanamycin were not detected in any of the samples. The environmental risk assessment, based on the risk quotient (*RQ*) values calculated for tetracycline and benzylpenicillin, indicated that the potential risk to soil was well below the level of concern (LoC). The risk assessment for cephalexin could not be performed due to the lack of sufficient data.

The analysis indicates that the risk to the soil compartment from the application of cattle slurry originating from organic farms is below the level of concern. However, due to data gaps in the available literature, a comprehensive analysis could not be completed.

Keywords: antibiotics, benzylpenicillin, dairy cattle, slurry, soil, tetracycline

INTRODUCTION

Pharmaceuticals are biologically active substances that are used in human and veterinary medicine. While their use provides undeniable health benefits, it is essential to acknowledge the associated environmental risks. One of the most significant concerns is the release of pharmaceutical residues and their metabolites into the environment.

Particular attention should be paid to the use of drugs in veterinary medicine, which often exceeds the scale found in human medicine. One of the main pathways through which pharmaceuticals and their metabolites enter the environment is the agricultural application of manure. The circular economy promotes the use of natural animal fertilisers over synthetic alternatives (Muscat *et al.*, 2021). However, due to the limited absorption of pharmaceuticals animals' digestive system, it is estimated that up to 90% of the applied dose may be excreted unchanged (Miciński *et al.*, 2015). As a result, the concentration of antibiotics in manure ranges from trace levels to 200 mg·kg^{-1}, with typical average values between 1 and 10 mg·kg^{-1} (Kumar *et al.*, 2005; Dolliver, Gupta and Noll, 2008; Nightingale *et al.*, 2022).

Pharmaceuticals present in soil can enter surface waters through runoff and reach groundwater through leaching. The impact of veterinary pharmaceuticals is considered to be more significant on soil and groundwater than on surface waters (Halling-Sørensen *et al.*, 1998; Sacher *et al.*, 2001; Balizs and Hewitt, 2003; Sarmah, Meyer and Boxall, 2006; Nightingale *et al.*, 2022).

Antibiotic residues play a particularly important role, contributing to the increase in antibiotic resistance and the potential emergence of superbugs resistant to most known antibiotics (Chowdhury *et al.* 2021; Emes, Kagambèga and Dione, 2024; Massaccesi *et al.*, 2024; Yordanova, Platikanova and Hristova, 2024). According to various estimates, antibiotic-resistant bacteria are responsible for approximately 23,000–35,000 deaths annually in the United States alone (Okon *et al.*, 2023). Globally, AMR is linked to more than 700,000 deaths per year, making it one of the leading causes of mortality (Xu *et al.*, 2024). Another consequence of antibiotic residue presence is the disruption of soil microbiological functions, such as those related to the circulation of nutrients in nature, and consequently the impact on climate change. Soil microorganisms are essential for the decomposition of organic matter and the transformation of nitrogen, phosphorus, sulphur, and carbon. Antibiotic residues can kill sensitive microbial populations, reducing the diversity of soil microbiota. The resistant bacteria may not perform nutrient cycling functions as effectively as the displaced microbes. Bacteria involved in nitrogen fixation (e.g., *Rhizobium*, *Azotobacter*), nitrification (e.g., *Nitrosomonas*, *Nitrobacter*), and organic matter degradation (e.g., *Actinobacteria*, *Bacillus*) are often sensitive to antibiotics. This mechanism may also affect the nitrous oxide emissions due to the altered nitrogen cycling (Cycoń, Mrozik and Piotrowska-Seget, 2019; Fang *et al.*, 2023, Yang *et al.*, 2024). Residues of veterinary drugs have also been found in insects, e.g. black soldier fly larvae, including those that are a potential source of protein (Meyer *et al.*, 2021; Dongen van *et al.*, 2024).

Due to their wide application in veterinary medicine, tetracyclines, sulphonamides, and fluoroquinolones are listed among the most significant groups of antibacterial drugs. These substances largely accumulate in manure due to their poor metabolism in animals (Kemper *et al.*, 2008). These compounds have been detected in slurry and manure in in concentrations as high as 46 mg·kg^{-1} for chlorotetracycline, 29 mg·kg^{-1} for oxytetracycline and 23 mg·kg^{-1} for tetracycline (Martínez-Carballo *et al.*, 2007).

Repeated application of manure as fertiliser can result in localised contamination of agricultural soils, leading to the accumulation antibiotic residues over time. Studies investigating antibiotic concentration in various manure-amended soils reported maximum levels of sulphonamides 0.015 mg·kg^{-1} (Christian *et al.*, 2003) and fluoroquinolones 0.37 mg·kg^{-1} (Martínez-Carballo *et al.*, 2007; Spielmeyer, Ahlborn and Hamscher, 2014; Spielmeyer *et al.*, 2015; Widyasari-Mehta, Hartung and Kreuzig, 2016). In soil samples fertilised with manure in Turkey, tetracyclines were detected at a concentration of about 35.5 mg·kg^{-1} and sulphonamides reached up to 0.50 mg·kg^{-1} (Karcı and Balcıoğlu, 2009). Wolters *et al.* (2016) reported a maximum concentration of tetracycline reaching 300 mg·kg^{-1} dry matter in pig manure. Similarly, Zhao *et al.* (2010), analysing fertilisers derived from poultry waste, found enrofloxacin and norfloxacin at exceptionally high concentrations of 1,420 mg·kg^{-1} and 225 mg·kg^{-1}, respectively.

The presence of veterinary antibiotics in fertilisers and soils has been described in many publications worldwide (Christian *et al.*, 2003; Boxall *et al.*, 2004; Hamscher *et al.*, 2005; Martínez-Carballo *et al.*, 2007; Karcı and Balcıoğlu, 2009; Hu, Zhou and Luo, 2010; Zhao, Dong and Wang, 2010; Spielmeyer *et al.*, 2015). Among the most commonly detected antibiotics are sulphadimidine, tetracycline, and chlortetracycline (Wohde *et al.*, 2016).

In Poland, as in the entire European Union, the authorisation, use, and monitoring of veterinary medicinal products are governed by Regulation (EU) 2019/6. The legislation, which came into effect on 28 January 2022, aims to improve both public and animal health, while addressing the growing threat of antibiotic resistance. This regulation prohibits the prophylactic use of antibiotics in healthy animals, except in exceptional circumstances. It also imposes restrictions on the use of antibiotics that are critically important for human medicine and requires detailed monitoring and reporting of their sale and use.

According to the 2023 Statistical Yearbook for Poland (GUS, 2024), approximately 23,500 Mg of pharmaceuticals were sold, corresponding to approximately 0.6 kg per capita. A large part of these pharmaceuticals was used in veterinary medicine. In Poland, antibiotics may only be administered to cattle under the supervision of a licenced veterinarian, who determines the appropriate treatment based on clinical diagnosis. The use of antibiotics for growth promotion is prohibited, while their prophylactic use is restricted to situations where there is a high risk of infection and no alternatives are available. The cited literature as well as our own (unpublished) research indicate that the use of various types of organic waste as fertilisers may lead to elevated levels of active pharmaceutical substances in the environment. The research hypothesis assumed that the use of pharmaceuticals on organic farms is significantly lower compared to conventional systems; therefore slurry from organically raised cattle should be free of antibiotics and, as a result, pose no significant threat to the soil environment.

The aim of the study was to assess the environmental risk posed by the active antibiotic substances present in cattle slurry from organic production when applied as fertiliser.

MATERIALS AND METHODS

Samples of dairy cattle slurry were collected for analysis to determine the presence of selected active substances of veterinary antibiotics. These included tetracycline (CAS 60-54-8), bacitracin (CAS 1405-87-4), kanamycin (CAS 8063-07-8), dihydrostreptomycin (CAS 128-46-1), benzylpenicillin (CAS 61-33-6), cefquinome (CAS 84957-30-2), and cephalexin (CAS 15686-71-2). Slurry samples were collected over two consecutive years from five certified farms located in Siedlce County, Mazowieckie Province, Poland.

Five traditionally operated farms, each covering an area of 5–9 ha, were selected for the study. These farms were classified as small and medium-sized agricultural holdings. Detailed characteristics are presented in Table 1.

These farms are typical for an agricultural region where cereal crops, potatoes, and the raising of pigs and dairy cattle dominate.

Table 1. Basic information about the studied farms

Location	Number of dairy cows	Number of cattle
1	35	72
2	45	95
3	46	94
4	25	50
5	38	75

Source: own elaboration.

According to information from the attending veterinarian, dairy cows were treated with antibiotics primarily during the dry period, particularly for the treatment of mastitis and the prevention of new intramammary infections caused by bacteria. The antibiotics used during the dry-off period included Cobactan LC, Mastijet Forte, Ubrolexin, and Tetra-delta, whose active substances were analysed. Samples of slurry were taken according to the Polish standard PN-B-12098:1997. The samples were taken directly from channels with continuous self-drainage in a tied-stall animal husbandry system.

Primary slurry samples were taken at regular intervals of 5 m along the entire length of the channel to the outlet to the reservoir. The first and last sampling points were located 2–5 m from the channel outlet. Prior to that, the slurry was mixed within the channel. From each farm, between 7 and 10 primary samples were collected and combined into a single 5 dm^3 polyethylene canister. After mixing, a 3 dm^3 subsample was extracted for laboratory analysis.

The cattle were primarily fed with fodder produced on-site, originating from permanent grassland (meadows and pastures). During spring and summer seasons, the cattle grazed on pastures and were supplemented with concentrated feed. In the late autumn season, their diet consisted mainly with silage from the same farm, along with concentrated feed. The determination of antibiotic residues in the slurry samples was conducted using the analytical method described by Czarny *et al.* (2024).

The analysis of antibiotic active substances was performed using the LC-MS method with a Shimadzu LC-MS 8050 chromatograph, with Stationary Column/Phase: Kinetex® 2.6 μm C18 (100×4.6 mm) and mobile phase: methanol (MeOH)/0.1% HCOOH; 0.01 min – 10% MeOH; 3.00 min – 95% MeOH; 6.00 min – 95% MeOH; 7.00 min – 10% MeOH; 10.00 min – 10% MeOH. The flow rate was 0.5 $cm^3 \cdot min^{-1}$ and the column temperature was 30°C.

Hydrophilic-lipophilic balanced (HLB) columns were conditioned with 6 cm^3 of acetonitrile and water, while MCX columns were conditioned with 3 ml of methanol and water. A sample of slurry (40–45 cm^3) was placed in a Falcon tube and centrifuged for 30 min at 12,000 rpm. The solution was decanted and extracted into the solid phase using Oasis HLB and Oasis MCX columns at the same time.

Analytes from HLB columns were extracted using a 6 cm^3 mixture of acetonitrile with 5% formic acid, while 3 cm^3 of a mixture containing 50% methanol and 25% ammonia was used for MCX. All extracts were enriched in a nitrogen stream at 40°C. The enriched extracts were reconstituted to a final volume of 1 cm^3 with 0.1% formic acid, centrifuged and chromatographically analysed using LC/MS.

Acetonitrile with 5% formic acid was added to the precipitate left after decanting, and then shaken intensively for 5 min. Later, the mixture was centrifuged at 6,000 rpm for 10 min. The resulting solution was decanted, and the sludge was re-extracted twice. The decanted solutions precipitate were pooled and enriched in a nitrogen stream. The residue was dissolved in 1 cm^3 of 0.1% formic acid. The filtered extract was chromatographically analysed using LC/MS. The total concentration of each pharmaceutical in the sample was calculated as the sum of the analyte concentrations in the liquid and solid fractions.

Validation and calibration parameters are presented in Tables 2–3.

Table 2. Validation parameters

Compound	Content		Recovery (%)	*SD*
	LOD ($ng \cdot g^{-1}$)	*LOQ* ($ng \cdot g^{-1}$)		
Tetracycline	0.002	0.008	68	1.7
Bacitracin	2.4	8.1	85	4.1
Kanamycin	2.7	8.8	86	3.4
Dihydrostreptomycin	0.15	0.49	75	4.2
Benzylpenicillin	0.005	0.016	78	2.4
Cefquinom	0.006	0.019	84	4.2
Cephalexin	0.098	0.32	64	2.1

Explanations: *LOD* = limit of detection, *LOQ* = limit of quantification, *SD* = standard deviation.
Source: own elaboration.

Table 3. Calibration curves

Compound	MRM scan mode	Retention time (min)	Range of calibration curve ($ng \cdot g^{-1}$)	Calibration curve equation	R^2
Tetracycline	445.2–154.1	3.494	0.010–10.0	$y = 1474169x + 14592$	0.9976
Bacitracin	711.95–356.25	3.932	10.8–195.0	$y = 133205x - 89729$	0.9966
Kanamycin	485.35–324.3	1.428	11.9–91.0	$y = 5723x + 1499$	0.9985
Dihydrostreptomycin	584.35–263.20	1.474	0.60–9.56	$y = 3348826x - 78256$	0.9983
Benzylpenicillin	335.20–176.1	3.785	0.019–19.8	$y = 1617833x - 4{,}813$	0.9994
Cefquinome	529.3–134.15	3.119	0.024–24.0	$y = 899860x + 515$	0.9986
Cephalexin	348.0–158.05	3.423	0.40–25.1	$y = 2756055x - 19994$	0.9997

Explanations: MRM = multiple reaction monitoring, R^2 = determination coefficient.
Source: own elaboration.

RESULTS AND DISCUSSION

The concentrations of the analysed antibiotics detected in cattle slurry samples are presented in Table 4.

Quantitative analysis of active antibiotic substances in slurry samples collected from five farms showed that tetracycline was the predominant compound, detected in all samples. Its concentrations ranged from 1.53 to 15.1 ng·g^{-1} of slurry.

Tetracyclines are among the most commonly used classes of antibiotics approved for veterinary use. In Poland, they account for approximately 40% of total veterinary medicinal products sales and are also one of the most frequently applied antibiotic groups in medicated feed. Their primary indications in livestock include bacterial diseases of the gastrointestinal tract, respiratory system, and urogenital system, especially mastitis, as well as bacterial skin infections and systemic deceases. Additionally, Patyra *et al.* (2019) investigated the presence of tetracyclines in animal feed. Their study, conducted in Poland in 2015–2017, detected the presence of tetracycline antibiotics in 31 out of the 286 feed samples tested.

It should be assumed that the presence of tetracycline in the analysed cattle slurry results primarily from the veterinary treatment of animals, rather than from contaminated feed. On the selected farms, cattle were mainly fed with fodder produced on-site, sourced from permanent grasslands. Moreover, the surveyed farms are certified as organic and are located in one of the least industrially impacted regions of Poland.

The obtained results are consistent with global data on the use of veterinary antibiotics. Tetracyclines remain the most commonly used antimicrobials, with a reported global usage of 33,305 Mg in 2020 and predicted increase by 9% until 2030 (Mulchandani *et al.*, 2023).

The concentration of tetracycline in dairy slurry varies substantially across countries, as reported in the literature. In Japan, the investigated range was 0–1.2 ng·g^{-1}, in the United States, it ranged from 0 to 1,200 ng·g^{-1}, and in China, concentrations ranged from 0.45 to 26,900 ng·g^{-1} (Oliver *et al.*, 2020; Gaballah *et al.*, 2021). The results obtained in this study fall within the range reported in previous studies, placing Poland in an intermediate position globally.

After tetracycline, cephalexin was the second most frequently detected antibiotic in the cattle slurry, with concentrations up to 1.11 ng·g^{-1}. In veterinary medicine, cephalexin is used in cattle to treat metritis, intercutaneous inflammation, wound infections and abscesses, and septic mastitis.

Cephalexin, which is one of the most commonly prescribed antibiotics in veterinary medicine, has not been investigated in dairy cattle slurry to date. However, it has been detected in significant concentrations in the aquatic environment, which justifies its inclusion in this study (Lu *et al.*, 2014). The existing literature on the subject is extremely limited, despite its frequent use in the treat of cattle.

Of the seven antibiotics tested, benzylpenicillin was detected in all slurry samples at levels of 0.048–0.27 ng·g^{-1}. This antibiotic is commonly used in cattle to treat respiratory tract infections, soft tissue infections, abscesses, joint infections, endometritis, and mastitis.

Benzylpenicillin, investigated by Huygens *et al.* (2022), has not been detected in any of the analysed slurry samples.

Other antibiotics, such as cefquinome and dihydroxystreptomycin, were detected in the tested samples of cattle slurry at concentrations below the *LOQ*. Bacitracin and kanamycin were not detected in any of the samples.

Bacitracin content was analysed in slurry samples collected from animals treated with this antibiotic. The detected concentration was 0.78 mg·kg^{-1} (Joy *et al.*, 2013).

The review of the literature shows that research on antibiotic residues in slurries used as natural fertilisers is

Table 4. Content of analysed antibiotics in cattle slurry

Location	Year	Content (ng·g^{-1})													
		Tetracycline		Bacitracin		Kanamycin		Dihydro-streptomycin		Benzyl-penicillin		Cefquinome		Cephalexin	
		value	*SD*	value	*SD*	value	*SD*	value	*SD*	value	*SD*	value	*SD*	value	*SD*
1	1	15.1	0.7	ND		ND		ND		0.059	0.002	*<LOQ*		1.03	0.01
	2	2.5	0.2	ND		ND		ND		0.214	0.003	*<LOQ*		0.99	0.01
2	1	2.8	0.3	ND		ND		*<LOQ*		0.12	0.02	*<LOQ*		*<LOQ*	
	2	2.8	0.2	ND		ND		ND		0.27	0.02	*<LOQ*		1.1	0.1
3	1	10.7	1.1	ND		ND		*<LOQ*		0.12	0.01	*<LOQ*		1.11	0.3
	2	2.9	0.2	ND		ND		ND		0.08	0.06	ND		ND	
4	1	5.3	0.3	ND		ND		ND		0.048	0.02	*<LOQ*		ND	
	2	1.6	0.1	ND		ND		*<LOQ*		0.079	0.06	ND		0.73	0.03
5	1	2.0	0.3	ND		ND		ND		0.053	0.07	*<LOQ*		ND	
	2	1.53	0.05	ND		ND		ND		0.07	0.03	ND		ND	

Explanations: *SD* = standard deviation, ND = not detected, *LOQ* = limit of quantification.
Source: own study.

currently very limited. The present study contributes valuable data to fill this knowledge gap.

An environmental risk assessment was carried out for antibiotic active substances detected in cattle slurry at concentrations above the *LOQ*. These substances included tetracycline, cephalexin and benzylpenicillin.

The calculations were based on the maximum legally recommended slurry application rate for nitrogen, which should not exceed 170 kg N. Therefore, an annual application of two doses of 25 $m^3 \cdot ha^{-1}$ was assumed.

For the purposes of the analysis, a worst-case scenario approach was adopted due to the lack of reliable degradation half-life (DT_{50}) in the soil. Therefore, it was assumed that DT_{50} values could be sufficiently high to allows accumulation of antibiotics in the soil. Consequently, a single application dose of 50 $m^3 \cdot ha^{-1} \cdot year^{-1}$ of slurry was used in the calculations. The following assumptions were applied: soil depth of 0.2 m, soil bulk density of 1.5 $g \cdot cm^{-3}$, and a slutty density of 1 $Mg \cdot m^{-3}$. One square meter of soil to a depth of 0.2 m weighs approximately 300 kg, which multiplied by 10.0 thous. m^2 equals 3,000,000 kg (or 3,000 Mg) per hectare.

To calculate the risk quotient (*RQ*), the predicted no-effect concentration ($PNEC_{soil}$) for tetracycline was assumed to be 57 $\mu g \cdot kg^{-1}$, as reported in the literature (Lihong *et al.*, 2021). Based on this value and the highest detected tetracycline concentration of 15.1 $\mu g \cdot kg^{-1}$ in slurry, the predicted environmental concentration (PEC_{soil}) for tetracycline was calculated as 0.025 $\mu g \cdot kg^{-1}$. The *RQ* was defined as:

$$RQ = \frac{PEC_{soil}}{PNEC_{soil}} \tag{1}$$

The calculated *RQ* for tetracycline is 0.00044, which is well below the level of concern (LoC).

Analogously to tetracycline, the predicted no-effect concentration ($PNEC_{soil}$) for benzylpenicillin was also adopted from the literature, with a value of 20 $mg \cdot kg^{-1}$ (Ciucă *et al.*, 2023).

For PEC_{soil} 0.00045 $\mu g \cdot kg^{-1}$, calculated for the highest determined amount 0.27 $\mu g \cdot kg^{-1}$, the resulting *RQ* is close to 0 and considered negligible. Results are presented in Table 5.

Table 5. Risk assessment for soil compartment

Substance	$PNEC_{soil}$	PEC_{soil}	*RQ*
	$\mu g \cdot kg^{-1}$		
Tetracycline	57	0.025	0.00044
Benzylpenicillin	20,000	0.00045	≈0

Explanations: $PNEC_{soil}$ = predicted no-effect concentration, PEC_{soil} = predicted environmental concentration, *RQ* = risk quotient.
Source: own study.

This indicates that the application of the assumed dose of cattle slurry, i.e. 50 $m^3 \cdot ha^{-1} \cdot year^{-1}$, does not pose an environmental risk.

No environmental risk assessment was carried out for cephalexin due to lack of available literature data and the absence of a derived own $PNEC_{soil}$ value.

CONCLUSIONS

The presence of antibiotics in cattle slurry has attracted significant interest among researchers and has been the focus of numerous studies. Literature analysis has shown that the use of cattle slurry as fertiliser can introduce antibiotics into the soil, potentially posing an environmental risk. However, there is a notable lack of studies focusing on organic farming. Therefore, the aim of this study was to investigate whether dairy cattle slurry from organic farms, where necessary veterinary antibiotics may still be used for therapeutic purposes, can be considered environmentally safe fertiliser. The results showed that residues of certain antibiotics used during the drying-off period were found and identified in cattle slurry. The analysis indicates that probably of environmental risk to the soil compartment from the application of cattle slurry from organic farms is likely to be below the risk level. However, due to gaps in the available literature, a comprehensive risk assessment could not be fully conducted.

ACKNOWLEDGMENTS

Acknowledgements are extended to the staff of the Department of Environmental Chemistry and Bioanalysis at Nicolaus Copernicus University in Torun for their assistance in the determination of antibiotics in slurry.

FUNDING

The research was financed by the Institute of Environmental Protection – National Research Institute through a subsidy for statutory activities granted by the Polish Ministry of Science and Higher Education.

CONFLICTS OF INTEREST

All authors declare that they have no conflict of interests.

REFERENCES

Balizs, G. and Hewitt, A. (2003) "Determination of veterinary drug residues by liquid chromatography and tandem mass spectrometry," *Analytica Chimica Acta*, 492, pp. 105–131. Available at: https://doi.org/10.1016/S0003-2670(03)00890-0.

Boxall, A.B.A. *et al.* (2004) "Veterinary medicines in the environment," in *Reviews of environmental contamination and toxicology*. New York: Springer, pp. 1–91. Available at: https://doi.org/10.1007/0-387-21729-0_1.

Chowdhury, S. *et al.* (2021) "Antibiotic usage and resistance in food animal production: What have we learned from Bangladesh?," *Antibiotics*, 10, 1032. Available at: https://doi.org/10.3390/antibiotics10091032.

Christian T. *et al.* (2003) "Determination of antibiotic residues in manure, soil, and surface waters," *Acta Hydrochimica et Hydrobiologica*, 31, pp. 36–44. Available at: https://doi.org/10.1002/aheh.200390014.

Ciucă, V.C. *et al.* (2023) "Rapid environmental impact assessment of penicillin G in a veterinary product using an original software method and monitoring by SPE-online-UHPLC-MS/MS," *Molecules*, 28, 6227. Available at: https://doi.org/10.3390/molecules28176227.

Cycoń, M., Mrozik, A. and Piotrowska-Seget, Z. (2019) "Antibiotics in the soil environment-degradation and their impact on microbial activity and diversity," *Frontiers in Microbiology*, 10, 338. Available at: https://doi.org/10.3389/fmicb.2019.00338.

Czarny, J. *et al.* (2024) "Determination of 465 psychoactive substances, drugs and their metabolites in urine by LC-MS/MS," *Analytical Methods*, 16, pp. 5426–5432. Available at: https://doi.org/10.1039/D4AY00777H.

Dolliver, H., Gupta, S. and Noll, S. (2008) "Antibiotic degradation during manure composting," *Journal of Environmental Quality*, 37, pp. 1245–1253. Available at: https://doi.org/10.2134/jeq2007.0399.

Dongen van, K.C.W. *et al.* (2024) "Safety and transfer of veterinary drugs from substrate to black soldier fly larvae," *Animal*, 18, 101214. Available at: https://doi.org/10.1016/j.animal.2024.101214.

Emes, E., Kagambèga, A. and Dione, M. (2024) "Determinants of animal disease and nontherapeutic antibiotic use on smallholder livestock farms," *Frontiers in Veterinary Science*, 10, 1258214. Available at: https://doi.org/10.3389/fvets.2023.1258214.

Fang, L. *et al.* (2023) "A comprehensive and global evaluation of residual antibiotics in agricultural soils: Accumulation, potential ecological risks, and attenuation strategies," *Ecotoxicology and Environmental Safety*, 262, 115175. Available at: https://doi.org/10.1016/j.ecoenv.2023.115175.

Gaballah, M.S. *et al.* (2021) "A review targeting veterinary antibiotics removal from livestock manure management systems and future outlook," *Bioresource Technology*, 333, 125069, Available at: https://doi.org/10.1016/j.biortech.2021.125069.

GUS (2024) Rocznik statystyczny Rzeczypospolitej Polskiej 2023 [Statistical yearbook of the Republic of Poland 2023]. Warszawa: Główny Urząd Statystyczny. Available at: https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-statystyczny-rzeczypospolitej-polskiej-2023,2,23.html (Accessed: January 15, 2025).

Halling-Sørensen, B. *et al.* (1998) "Occurrence, fate, and effects of pharmaceutical substances in the environment – A review," *Chemosphere*, 36, pp. 357–393. Available at: https://doi.org/10.1016/S0045-6535(97)00354-8.

Hamscher, G. *et al.* (2005) "Different behavior of tetracyclines and sulfonamides in sandy soils after repeated fertilization with liquid manure," *Environmental Toxicology and Chemistry*, 24, pp. 861–868. Available at: https://doi.org/10.1897/04-182R.1.

Hu, X., Zhou, Q. and Luo, Y. (2010) "Occurrence and source analysis of typical veterinary antibiotics in manure, soil, vegetables and groundwater from organic vegetable bases, northern China," *Environmental Pollution*, 158, pp. 2992–2998. Available at: https://doi.org/10.1016/j.envpol.2010.05.023.

Huygens, J. *et al.* (2022) "Impact of fertilization with pig or calf slurry on antibiotic residues and resistance genes in the soil," *Science of the Total Environment*, 822, 153518. Available at: https://doi.org/10.1016/j.scitotenv.2022.153518.

Joy, S.R. *et al.* (2013) "Fate and transport of antimicrobials and antimicrobial resistance genes in soil and runoff following land application of swine manure slurry," *Environmental Science & Technology*, 47, pp. 12081–12088. Available at: https://doi.org/10.1021/es4026358.

Karcı, A. and Balcıoğlu, I.A. (2009) "Investigation of the tetracycline, sulfonamide, and fluoroquinolone antimicrobial compounds in animal manure and agricultural soils in Turkey," *Science of the Total Environment*, 407, pp. 4652–4664. Available at: https://doi.org/10.1016/j.scitotenv.2009.04.047.

Kemper, N. *et al.* (2008) "Analysis of antibiotic residues in liquid manure and leachate of dairy farms in northern Germany," *Agricultural Water Management*, 95, pp. 1288–1292. Available at: https://doi.org/10.1016/J.AGWAT.2008.05.008.

Kumar, K. *et al.* (2005) "Antibiotic use in agriculture and its impact on the terrestrial environment," *Advances in Agronomy*, 87, pp. 1–54. Available at: https://doi.org/10.1016/S0065-2113(05)87001-4.

Lihong, C. *et al.* (2021) "Predicted non-effect concentration and risk assessment of typical tetracycline antibiotics," *Asian Journal of Ecotoxicology*, 16(5), pp. 334–346. Available at: https://doi.org/10.7524/AJE.1673-5897.20210602001.

Lu, X. *et al.* (2014) "Long-term effect of the antibiotic cefalexin on methane production during waste activated sludge anaerobic digestion," *Bioresource Technology*, 169, pp. 644–651. Available at: https://doi.org/10.1016/j.biortech.2014.07.056.

Martínez-Carballo, E. *et al.* (2007) "Environmental monitoring study of selected veterinary antibiotics in animal manure and soils in Austria," *Environmental Pollution*, 148, pp. 570–579. Available at: https://doi.org/10.1016/j.envpol.2006.11.035.

Massaccesi, L. *et al.* (2024) "Impact of soil fertilization with pig slurry on antibiotic residues and resistance genes: A longitudinal study," *Antibiotics,* 13, 486. Available at: https://doi.org/10.3390/antibiotics13060486.

Meyer, A.M. *et al.* (2021) "Chemical food safety hazards of insects reared for food and feed," *Journal of Insects as Food and Feed*, 7, pp. 823–831. Available at: https://doi.org/10.3920/JIFF2020.0085.

Miciński, J. *et al.* (2015) "Hazards to humans and animals associated with antibiotic misuse," *Journal of Elementology*, 20(4), pp. 1077–1086. Available at: https://doi.org/10.5601/jelem.2015.20.2.902.

Muscat, A. *et al.* (2021) "Principles, drivers and opportunities of a circular bioeconomy," *Nature Food*, 2, pp. 561–566. Available at: https://doi.org/10.1038/s43016-021-00340-7.

Mulchandani, R. *et al.* (2023) "Global trends in antimicrobial use in food-producing animals: 2020 to 2030," *PLOS Global Public Health*, 3(2), e0001305. Available at: https://doi.org/10.1371/journal.pgph.0001305.

Nightingale, J. *et al.* (2022) "Assessing the influence of pig slurry pH on the degradation of selected antibiotic compounds," *Chemosphere*, 290, 133191. Available at: https://doi.org/10.1016/j.chemosphere.2021.133191.

Oliver, J.P. *et al.* (2020) "Invited review: Fate of antibiotic residues, antibiotic-resistant bacteria, and antibiotic resistance genes in US dairy manure management systems," *Journal of Dairy Science*, 103, 2, pp. 1051–1071. Available at: https://doi.org/10.3168/jds.2019-16778.

Okon, A.J. *et al.* (2023) "Knowledge, practices, and antibiotics use patterns among animal production farmers in Calabar Metropolis," *International Journal of Public Health Science (IJPHS)*, 12(4), pp. 1647–1655. Available at: https://doi.org/10.11591/ijphs.v12i4.23266.

Patyra, E. *et al.* (2019) "Występowanie tetracyklin w paszach – przyczyny i skutki [Use of tetracyclines in feeds: Causes and consequences]," *Medycyna Weterynaryjna*, 75(5), pp. 280–286. Available at: http://dx.doi.org/10.21521/mw.6152.

PN-B-12098:1997 – *Road drainage – Requirements and testing*. Warszawa: Polski Komitet Normalizacyjny.

Regulation (2019) "Regulation (EU) 2019/6 of the European Parliament and of the Council of 11 December 2018 on veterinary medicinal products and repealing Directive 2001/82/EC.280–286 (Text with EEA relevance),” *Official Journal*, 4, 7.1.2019, pp. 43–167. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019R0006 (Accessed: January 15, 2025).

Sacher, F. *et al*. (2001) “Pharmaceuticals in ground waters. Analytical methods and result of a monitoring program in Baden-Wurttemberg, Germany,” *Journal of Chromatography A*, 938, pp. 199–210. Available at: https://doi.org/10.1016/S0021-9673(01)01266-3.

Sarmah, K., Meyer, M.T. and Boxall, A.B.A. (2006) “A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment,” *Chemosphere*, 65, pp. 725–759. Available at: https://doi.org/10.1016/j.chemosphere.2006.03.026.

Spielmeyer, A., Ahlborn, J. and Hamscher, G. (2014) “Simultaneous determination of 14 sulfonamides and tetracyclines in biogas plants by liquid-liquid-extraction and liquid chromatography tandem mass spectrometry,” *Analytical and Bioanalytical Chemistry*, 406, pp. 2513–2524. Available at: https://doi.org/10.1007/s00216-014-7649-3.

Spielmeyer, A. *et al*. (2015) “Elimination patterns of worldwide used sulfonamides and tetracyclines during anaerobic fermentation,” *Bioresource Technology*, 193, pp. 307–314. Available at: https://doi.org/10.1016/j.biortech.2015.06.081.

Widyasari-Mehta, A., Hartung, S. and Kreuzig, R. (2016) “From the application of antibiotics to antibiotic residues in liquid manures and digestates: A screening study in one European center of conventional pig husbandry,” *Journal of Environmental Management*, 177, pp. 129–137. Available at: https://doi.org/10.1016/j.jenvman.2016.04.012.

Wohde, M. *et al*. (2016) “Occurrence and transformation of veterinary pharmaceuticals and biocides in manure: a literature review,” *Environmental Sciences Europe*, 28, 23. Available at: https://doi.org/10.1186/s12302-016-0091-8.

Wolters, B. *et al*. (2016) “Contaminations of organic fertilizers with antibiotic residues, resistance genes, and mobile genetic elements mirroring antibiotic use in livestock?,” *Applied Microbiology and Biotechnology*, 100, pp. 9343–9353. Available at: https://doi.org/10.1007/s00253-016-7742-y.

Xu, T. *et al*. (2024) “Progress in combating antibiotic resistance in animal agriculture,” *CyTA – Journal of Food*, 22(1), 2330674. Available at: https://doi.org/10.1080/19476337.2024.2330674.

Yang, Z. *et al*. (2024) “How do different antibiotic residues in manure change soil N_2O emissions and soil N-cycling microbial communities?,” *Applied Soil Ecology*, 202, 105577. Available at: https://doi.org/10.1016/j.apsoil.2024.105577.

Yordanova, R., Platikanova, M. and Hristova, P. (2024) “The use of antibiotics in food animals – a threat to human health,” *Journal of IMAB*, 30(2), pp. 5495–5499. Available at: https://doi.org/10.5272/jimab.2024302.5495.

Zhao, L., Dong, Y.H. and Wang, H (2010) “Residues of veterinary antibiotics in manures from feedlot livestock in eight provinces of China,” *Science of The Total Environment*, 408, pp. 1069–1075. Available at: https://doi.org/10.1016/j.scitotenv.2009.11.014.