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META-ANALYSIS

Antibiotics residues in pig slurry and manure and its environmental contamination potential. A meta-analysis

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Abstract

Livestock excrements are used as natural fertilizer, in the form of manure or slurry, to provide nutrients and organic matter to arable soils. However, it is potentially contaminated with antibiotics residues, used in livestock farming to prevent diseases (and thus animal losses), as well as to increase animals' body weight. This poses a contamination risk to surrounding environments. Therefore, we quantitatively evaluated data from 57 peer-reviewed articles published over the past 20 years to generate an overview of antibiotics residues in manure, slurry, soils, plants, and water. Our results revealed that pig manure and slurry, mostly from European countries, contained fluoroquinolones, sulfonamides, and tetracyclines. Furthermore, antibiotics used in animal husbandry are found to contaminate surrounding environments, exceeding the proposed EU threshold value for maximal environmental contamination by veterinary antibiotics in soil in many countries. In soil samples, the highest contents of tetracyclines and sulfonamides were detected in the UK (41 ± 18 μg/kg and 300 ± 10 μg/kg, respectively) and in Austria (370 μg/kg) for fluoroquinolones. In water environments, antibiotics contents were detected in low amounts in most countries (< 2 μg/L), with the highest content of fluoroquinolones and tetracyclines detected in the USA (3 ± 0.7 μg/L and 1.3 ± 0.6 μg/L, respectively) and of sulfonamides in the USA and Germany (0.3 ± 0.8 μg/L and 0.2 ± 2 μg/L, respectively). In plants, an accumulation of tetracyclines and sulfonamides was found in China, Germany, and Spain (> 50 μg/kg). However, no significant specificity of these antibiotics residues to country or continent could be observed. It is urgent that the use of veterinary antibiotics be significantly reduced in order to diminish their residues in slurry, and thus their contamination potential to the surrounding environments.

Keywords Veterinary drug · Environmental contamination · Livestock production

1 Introduction

To maintain proper hygienic conditions of livestock in agriculture, excrements of animals are removed from their housing. The undigested remains, urine, and faeces can subsequently be used as natural fertilizer on arable land in the form of slurry or manure, respectively (Bohrer et al. 2019; Marszałek et al. 2019). To prevent diseases and animal loss during breeding, veterinary antibiotics are frequently used therapeutically in livestock agriculture in many countries (Bohrer et al. 2019; Marszałek et al. 2019). Antibiotics can also be applied sub-therapeutically to increase the animals' body weight or to improve the efficiency of food intake (Bohrer et al. 2019; Chee-Sanford et al. 2009; Marszałek et al. 2019; Rasschaert et al. 2020). However, due to the chemical structure and bio-availability of the antibiotics, the prescribed drugs may not be completely metabolized and thus absorbed by the animals. The remaining parent compounds and their metabolites of up to 60–90 % will be excreted in faeces and urine (Bohrer et al. 2019; Chee-Sanford et al. 2009; Marszałek et al. 2019). As these components can affect the surrounding environment, its storage and application may create a contamination risk to water, plant, and soil environments. Moreover, with the use of antibiotics, antibiotics-resistant bacteria can develop and consequently be found in the gastrointestinal tract of the animals (Rasschaert et al. 2020; Xia et al. 2019), with a subsequent threat of transfer to humans. Therefore, not only the antibiotics residues but also the resulting resistant bacteria may spread and accumulate in other

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ecological niches, such as groundwater, surface water and water courses, and soils and crops, depending on the properties of the antibiotics (Bohrer et al. 2019; Kivits et al. 2018; Rasschaert et al. 2020). The input of those compounds into the soil environment may affect its microorganisms, which are responsible for nutrient cycles and pollutant degradation (Marszałek et al. 2019). This contamination may lead to the accumulation of those compounds in plant tissue of crops growing on fields fertilized with slurry or through irrigation with contaminated water (Kivits et al. 2018; Marszałek et al. 2019). Furthermore, this might have an adverse effect on human and animal health as it can contribute to possible development of allergies and antibiotic resistances (Marszałek et al. 2019). Furthermore, antibiotics may have negative effects to ecosystem services such as biodiversity, which is beyond the scope of our study.

According to the One Health Concept, all ecological niches are connected (Destoumieux-Garzón et al. 2018). Residues of raw manure from animals treated with antibiotics may reach livestock or humans when it is being spread on arable land. Due to antibiotic-resistant bacteria, some diseases may become difficult to treat for both animals and humans (Rasschaert et al. 2020). Nevertheless, no threshold values exist to limit the amount of drug residues reaching soil or water bodies in European countries. However, the EU directive CVMP/VICH/592/98-FINAL from 2000 (Committee for Medicinal Products for Veterinary Use 2016) proposes the predicted environmental concentration (PEC) of veterinary medicinal products to be less than 100 μg/kg in soil, and less than 1 μg/L in groundwater. The maximum amount of veterinary drug residues in livestock food products by EU regulation EG 37/2010 (The European Commission 2010) states that no animal tissue may contain more than 100–600 μg/kg. However, there are no threshold values for vegetable food products growing on agricultural land treated with contaminated manure or slurry.

Therefore, knowledge on the quantity of antibiotics contained in manure and slurry as well as their contamination potential in different environments such as soil and water bodies will increase our understanding on sources and magnitude of environmental contamination with antibiotics. Our research focuses on the most frequently used antibiotics in livestock agriculture: tetracyclines, sulfonamides, and fluoroquinolones (Bohrer et al. 2019) in different countries and environmental compartements. Therefore, we aimed at generating a systematic and quantitative overview of veterinary antibiotics residues found in livestock excrements and the environment including soil and water. We will test the following hypotheses:

i) Residues of different groups of antibiotics can be found in manure and slurry from agricultural livestock.

ii) Antibiotics residues can be found in the environment including soil, water, and plants directly adjacent to agricultural land fertilized with manure or slurry.

iii) Type of antibiotics residues is country- and / or continent-specific.

2 Material and methods

2.1 Source of data

The peer-reviewed published articles and book chapters used in this study were obtained from ISI Web of Science. Key words used for the search were a) "pig slurry" and "antibiotic" and b) "pig manure" and "antibiotic." The time frame was set for the years between 2000 and 2020. A total of 452 entries matching these search properties were found at ISI Web of Science. Subsequently, studies used for this meta-analysis were selected by the following criteria: i) the literature contained the information on the amount of antibiotics detected in manure and slurry given in μg/kg or in any unit which could be converted to μg/kg; ii) the obtained antibiotics contents are based on field data and were not generated artificially; and iii) the obtained contents were available as means or could be calculated as such. Finally, 12 articles containing the amount of antibiotics in pig slurry, 21 articles containing the amount of antibiotics in pig manure, and 24 articles containing the amount of antibiotics in soil and water environments, and plants were evaluated in this study.

2.2 Data categorization

In this study, antibiotics detected in pig slurry and manure as well as soil, water, and plants were grouped into four groups, including fluoroquinolones, sulfonamides, tetracyclines and all other groups of antibiotics.

2.3 Statistical analysis

The statistical analysis was conducted using RStudio (version 1.4.1106). The boxplots were generated using the package "ggplot2" (Wickham 2009). The statistic test used in this study was performed using the package "car" (Fox and Weisberg 2019). Data were checked for normality and equality of variances using Shapiro-Wilk test and Levene's test, respectively. Since the data are not normal-distributed, a non-parametric Kruskal-Wallis test was used for a comparison of medians between sets of samples. Standard errors were calculated for the median values for each country and antibiotics group.

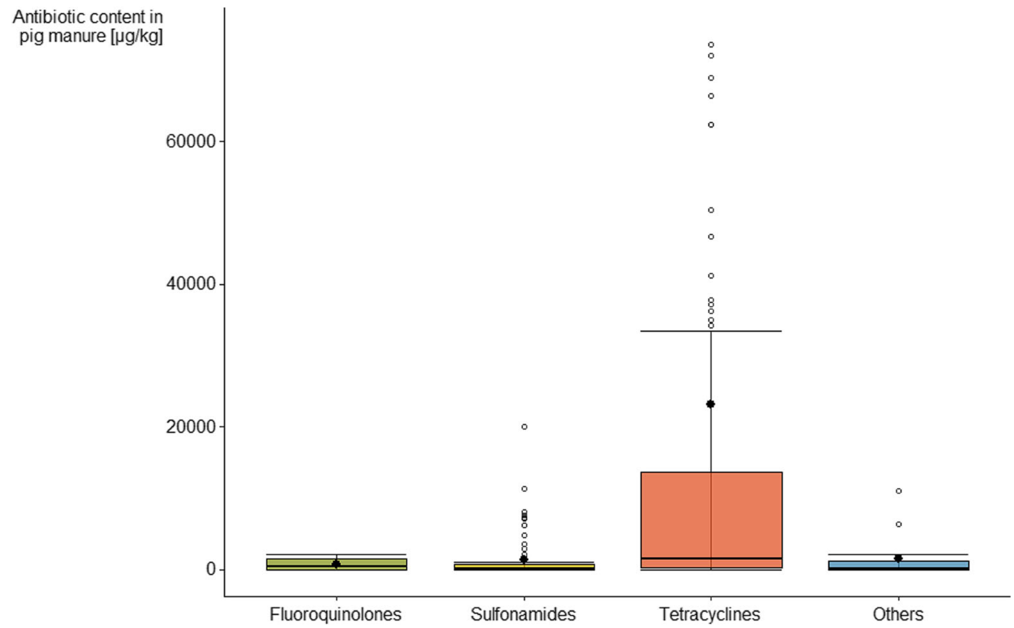

Fig. 1 Box and whisker plots showing the content of each antibiotics group in µg/kg (fluoroquinolones, sulfonamides, tetracyclines, and all other groups of antibiotics) detected in pig manure. Data were obtained from Berendsen et al. (2015), Chen et al. (2012), Cheng et al. (2016), Hamscher et al. (2005), Hanna et al. (2018), Hu et al. (2008), Jacobsen and Halling-Sørensen (2006), Ji et al. (2012), Li et al. (2013), Martínez-Carballo et al. (2007), Qiao et al. (2012), Topi and Spahiu (2020), van den Meersche et al. (2016), Widyasari-Mehta et al. (2016), Xu et al. (2020), Zhang et al. (2015), and Zhao et al. (2010).

3 Results and discussion

3.1 Antibiotics content in pig manure and pig slurry

Overall, we found that pig manure contained antibiotics up to 376,210 µg/kg (tetracyclines group, Fig. 1). The highest median value for antibiotic content in pig manure was detected for the tetracyclines group as well (median ± SE = 1,550 ± 6,209 µg/kg). The lowest median value for antibiotic content in pig manure was detected for the sulfonamides group (median ± SE = 98 ± 485 µg/kg, max 20,000 µg/kg). The average content for the fluoroquinolones and all other antibiotic groups were 465 ± 224 µg/kg, max 2,230 µg/kg, and 185 ± 1,075 µg/kg, max = 11,010 µg/kg, respectively.

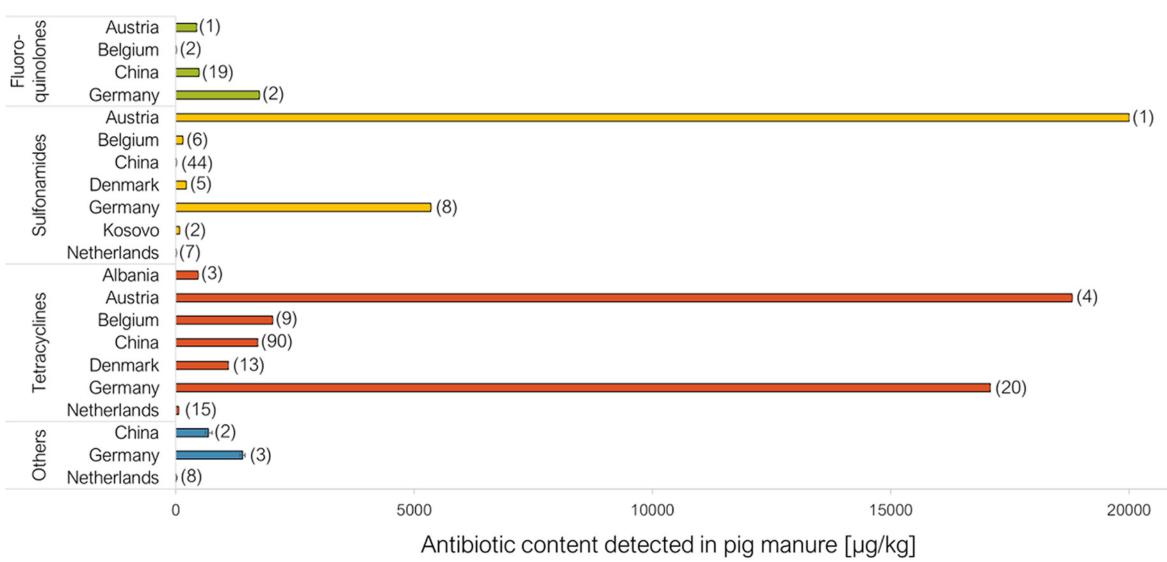

Fig. 2 Bar chart representing the median of antibiotics content and standard error (SE) of each antibiotics group detected in pig manure in different countries. The numbers in parentheses indicate the sample size of data used for the analysis (n). Data were obtained from Berendsen et al. (2015), Chen et al. (2012), Cheng et al. (2016), Hamscher et al. (2005), Hanna et al. (2018), Hu et al. (2008), Jacobsen und Halling-Sørensen (2006), Ji et al. (2012), Li et al. (2013), Martínez-Carballo et al. (2007), Qiao et al. (2012), Topi und Spahiu (2020), van den Meersche et al. (2016), Widyasari-Mehta et al. (2016), Xu et al. (2020), Zhang et al. (2015), and Zhao et al. (2010).

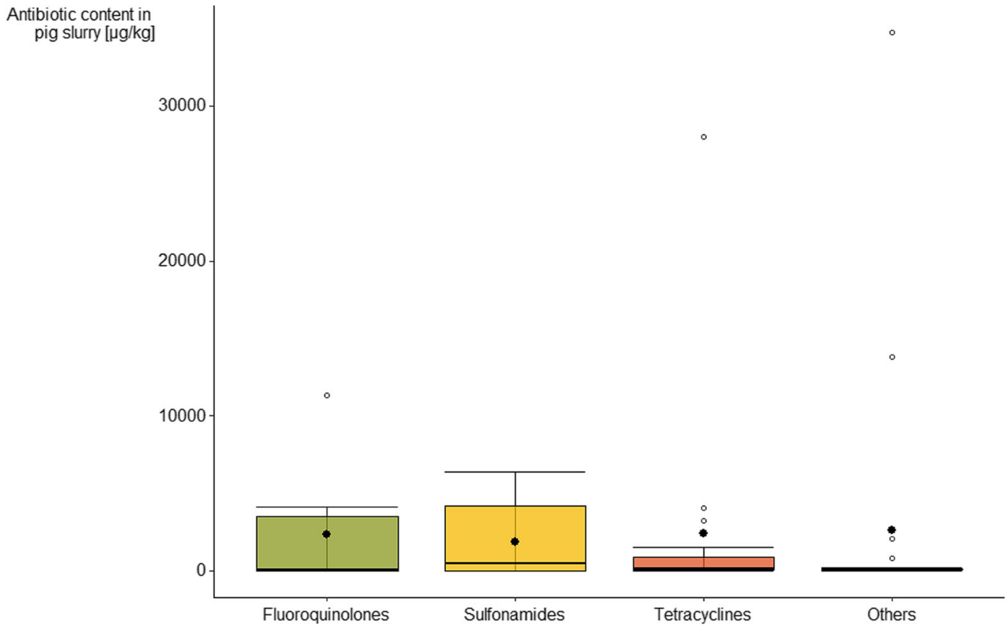

Fig. 3 Box and whisker plots showing the content of each antibiotics group in µg/kg (fluoroquinolones, sulfonamides, tetracyclines, and all other groups of antibiotics) detected in pig slurry. Data were obtained from Blackwell et al. (2009), Bourdat-Deschamps et al. (2014), Brambilla et al. (2007), Dreher et al. (2012), García-Sánchez et al. (2013), Haller et al. (2002), Hamscher et al. (2002), Rasschaert et al. (2020), Reichel et al. (2013), Sengeløv (2003), and Weiss et al. (2008).

A strong variation was found within the antibiotics content in pig manure among different countries (Fig. 2). Antibiotics of the fluoroquinolones group were detected in four countries (Austria, Belgium, China, and Germany). The median value of fluoroquinolones in pig manure ranged from 5 ± 0.04 (median ± SE, Belgium, n = 2) to 1,755 ± 1 µg/kg (median ± SE, Germany, n = 2). Sulfonamides were detected in seven countries (Austria, Belgium, China, Denmark, Germany, Kosovo, and the Netherlands). Their content varied from 6 ± 0.2 (mean ± SE, Netherlands, n = 7) to 20,000 µg/kg (Austria, n = 1). Antibiotics of the tetracyclines group were also detected in seven countries Albania, Austria, Belgium, China, Denmark, Germany, and the Netherlands). The tetracyclines content varied from 61 ± 2 (median ± SE, Netherlands, n = 15) to 18,803 ± 2 µg/kg (median ± SE, Austria, n = 4).

We found that pig slurry contained antibiotics up to 34,730 µg/kg (combination of other antibiotic groups, Fig. 3). The highest median value for antibiotic content in pig slurry was conducted for the sulfonamides group (median ± SE = 490 ± 1,018 µg/kg, max = 6,400 µg/kg). The lowest median value was found for fluoroquinolones in pig slurry (median ± SE = 52 ± 1,504 µg/kg, max = 11,300 µg/kg). The median content for the tetracyclines group and combination of other antibiotics were 95 ± 1,018 µg/kg, max 28,000 µg/kg, and 58 ± 2,287 µg/kg, respectively.

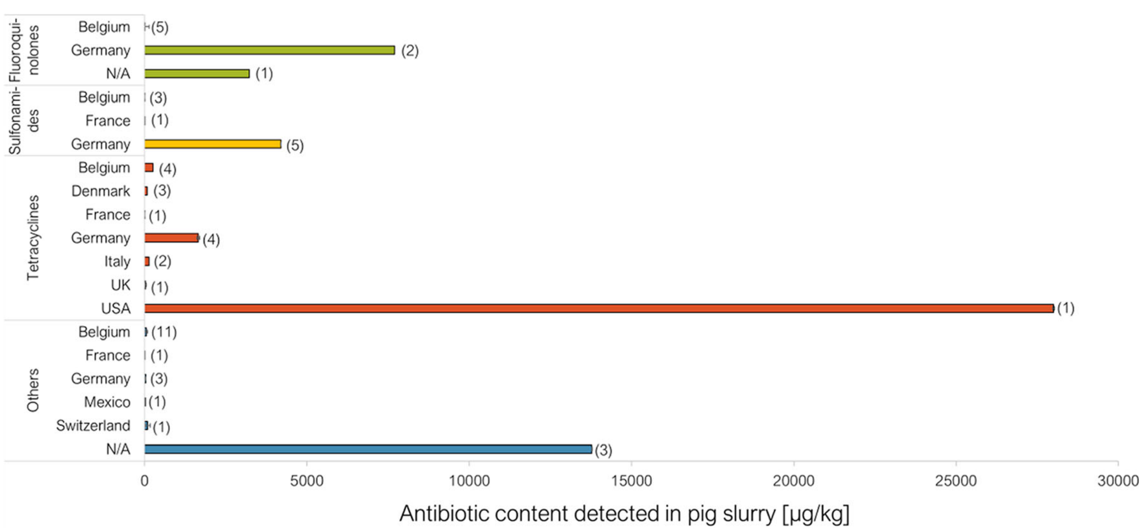

Fig. 4 Bar chart representing the median of antibiotics content and standard error (SE) of each antibiotics group detected in pig slurry in different countries. The numbers in parentheses indicate the sample size of data used for the analysis (n). Data were obtained from Blackwell et al. (2009), Bourdat-Deschamps et al. (2014), Brambilla et al. (2007), Dreher et al. (2012), García-Sánchez et al. (2013), Haller et al. (2002), Hamscher et al. (2002), Rasschaert et al. (2020), Reichel et al. (2013), Sara et al. (2013), Sengeløv (2003), and Weiss et al. (2008).

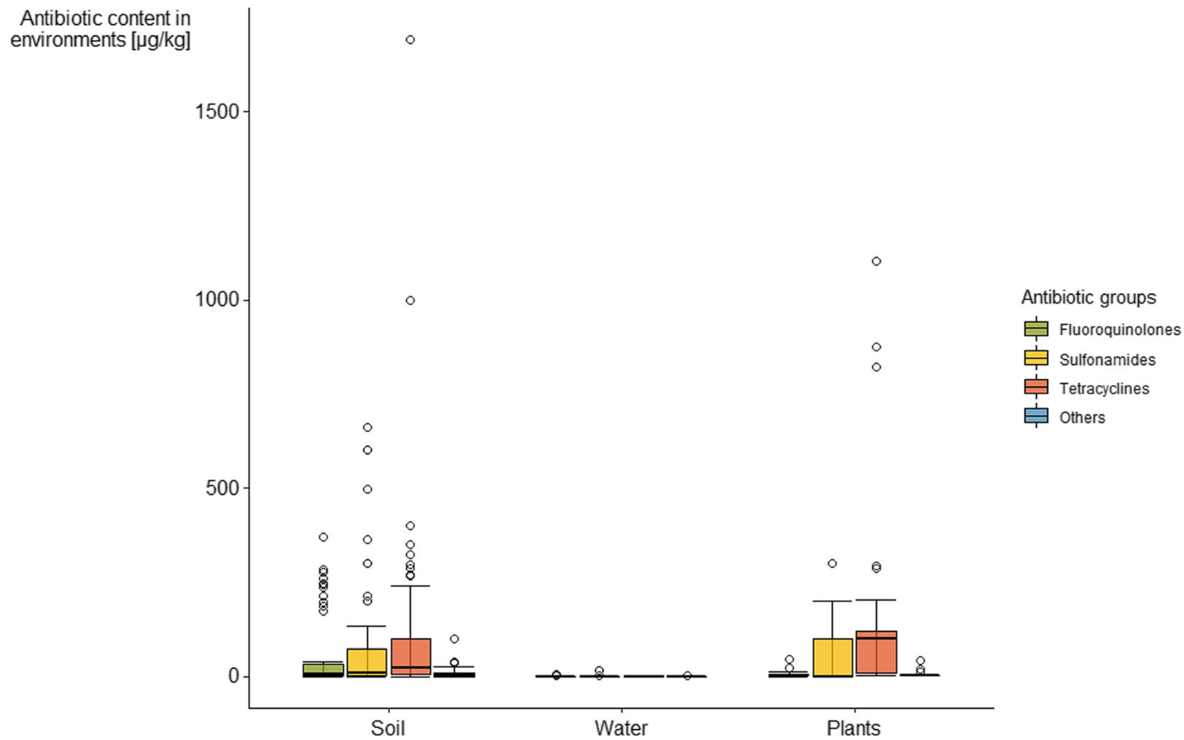

Fig. 5 Box and whisker plots showing the content of each antibiotics group (fluoroquinolones, sulfonamides, tetracyclines, and all other groups of antibiotics) in μg/kg for soil and plants, and in μg/L for water. Data were obtained from Blackwell et al. (2009), Camotti Bastos et al. (2018), Campagnolo et al. (2002), Chen et al. (2012), Cheng et al. (2016), Conde-Cid et al. (2018), Hamscher et al. (2005), Hamscher et al. (2002), Hamscher and Mohring (2012), Hanna et al. (2018), Hu et al. (2010), Jacobsen et al. (2004), Kay et al. (2005), Martínez-Carballo et al. (2007), Marszałek et al. (2019), Qiao et al. (2012), Raich-Montiu et al. (2007), Rasschaert et al. (2020), Reichel et al. (2013), Sengeløv (2003), Shelver et al. (2010), Weiss et al. (2008) and Zhang et al. (2015).

Within antibiotic groups detected in pig slurry, a strong variation was found (Fig. 4). The content of fluoroquinolones group ranged from 14.2 ± 13.8 (median ± SE, Belgium, n = 5) to 7,700 ± 0.1 μg/kg (median ± SE, Germany, n = 2). Sulfonamides were detected in three countries in Europe (Belgium, France, and Germany). The contents of sulfonamides

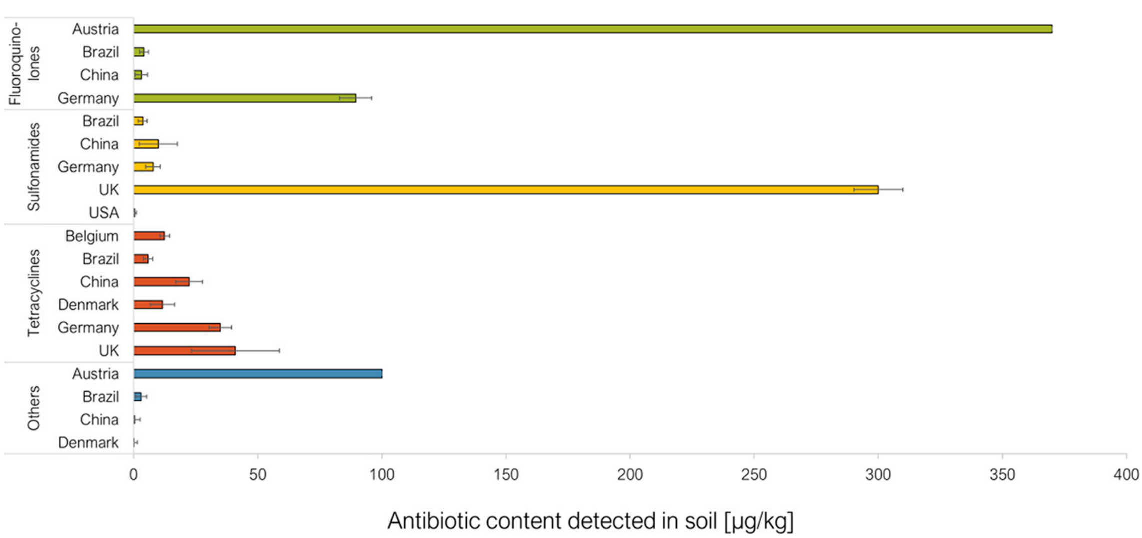

Fig. 6 Bar chart representing the median content and standard error (SE) of each antibiotics group detected in soil in different countries. The numbers in parentheses indicate the sample size of data used for the analysis (n). Data were obtained from Blackwell et al. (2009), Camotti Bastos et al. (2018), Chen et al. (2012), Cheng et al. (2016), Hamscher et al. (2002), Hamscher et al. (2005), Hanna et al. (2018), Hu et al. (2010), Kay et al. (2005), Marszałek et al. (2019), Martínez-Carballo et al. (2007), Rasschaert et al. (2020), Reichel et al. (2013), Sengeløv (2003), Shelver et al. (2010), and Zhang et al. (2015).

varied from 0.7 (France, $n = 1$) to 4,200 ± 0.1 μg/kg (median ± SE, Germany, $n = 5$). Tetracyclines were detected in seven countries (Belgium, Denmark, France, Germany, Italy, UK, and USA). The highest content of tetracyclines was found in the USA with 28,000 μg/kg ($n = 1$), while the lowest content was found in the UK (30 μg/kg, $n = 1$).

3.2 Antibiotics content in soil, water, and plants

In the environment, we observed the highest amount of antibiotics in soil for tetracyclines with up to 1,691 μg/kg, in water for sulfonamides with up to 16 μg/L, and in plants for tetracyclines with up to 1,104 μg/kg (Fig. 5). The highest median value for antibiotic content was found for tetracyclines in soil and plants (median ± SE = 21.2 ± 26.8 μg/kg, and 100 ± 59.4 μg/kg, respectively), and for sulfonamides in soil as well (median ± SE = 9.5 ± 17.8 μg/kg). The lowest median content was found for the fluoroquinolones group in water (median ± SE = 0.004 ± 0.5 μg/L respectively).

In soil, the highest content of fluoroquinolones was detected in Austria (370 μg/kg, $n = 1$, Fig. 6), followed by Germany (median ± SE = 90 ± 7 μg/kg, $n = 20$). Sulfonamides were detected in high content in agricultural soils in the UK (median ± SE = 300 ± 10 μg/kg, $n = 9$), followed by China (median ± SE = 10 ± 7.7 μg/kg, $n = 21$). The highest content of tetracyclines was detected in the UK (median ± SE = 41 ± 18 μg/kg, $n = 9$), followed by Germany (median ± SE = 35 ± 5 μg/kg, $n = 43$) and China (median ± SE = 22 ± 5 μg/kg, $n = 35$). Trimethoprim was detected in Austria (median = 100 μg/kg, $n = 1$) and a combination of other antibiotics were found in Brazil (median ± SE = 3.1 ± 2.2), whereas in other countries, the contents of other antibiotic groups were low (median < 1 μg/kg).

In water, high fluoroquinolones content was detected in water from field streams in the USA (median ± SE = 3 ± 0.7 μg/L, $n = 3$, Fig. 7) followed by China (median ± SE = 0.002 ± 0.3 μg/L, $n = 12$), including wastewater (max = 0.7 μg/L), drinking water (max = 0.01 μg/L), and river water (max = 0.004 μg/L). High contents of sulfonamides were detected in surface and groundwater in the USA (median ± SE = 0.3 ± 0.8 μg/L, max = 3 μg/L, $n = 7$) and Germany (median ± SE = 0.23 ± 1.98 μg/L, max = 15 μg/L, $n = 8$). Contents of tetracyclines in surface water were under 2 μg/L, with the highest content detected in farm springs, field wells or tile lines in the USA (median ± SE = 1.3 ± 0.6 μg/L, $n = 6$), followed by Germany (median ± SE = 0.1 ± 0.6 μg/L, $n = 7$) and China (median ± SE = 0.1 ± 0.5 μg/L, $n = 10$). The highest amount for other antibiotics was detected for lincomycin in surface water in Germany (max = 0.7 μg/L), and groundwater in USA (max = 1.4 μg/L).

In plants, fluoroquinolones were detected in China (median ± SE = 1.4 ± 2.6 μg/kg, $n = 11$, Fig. 8), wherein the highest content was found in vegetables (max = 45 μg/kg). The highest content of sulfonamides was found in grass and corn in Spain (median ± SE = 100 ± 6 μg/kg, $n = 9$, max = 200 μg/kg), whereas the leaves, roots, and stalk of radish, rape, celery, and coriander in China contained a maximum of 0.8 μg/kg (median ± SE = 0.3 ± 0.4 μg/kg, $n = 15$). The highest tetracyclines contents were detected in wheat roots, stems and leaves, and grain in Germany (median ± SE = 822 ± 18 μg/kg, $n = 5$, max = 1,104 μg/kg), followed by grass and corn in Spain (median ± SE = 100 ± 4 μg/kg, $n = 9$, max = 200 μg/kg) and leaves, roots, and stalk of radish, rape, celery,

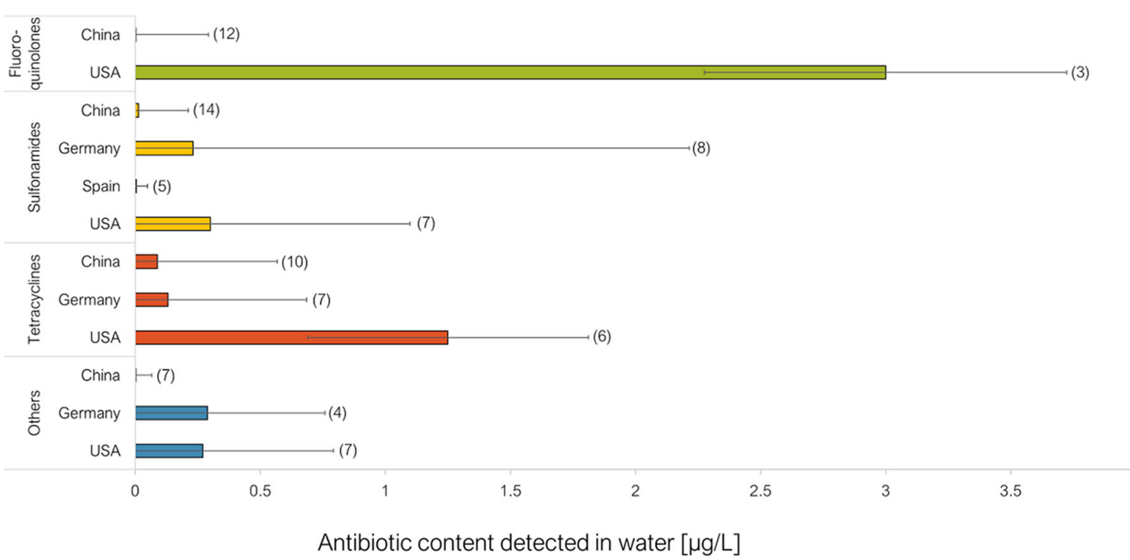

Fig. 7 Bar chart representing the median content and standard error (SE) of each antibiotics group detected in water in different countries. The numbers in parentheses indicate the sample size of data used for the analysis (n). Data were obtained from Campagnolo et al. (2002), Cheng et al. (2016), Hamscher und Mohring (2012), Hanna et al. (2018), Hu et al. (2010), Marszałek et al. (2019), Raich-Montiu et al. (2007), Shelver et al. (2010), and Weiss et al. (2008).

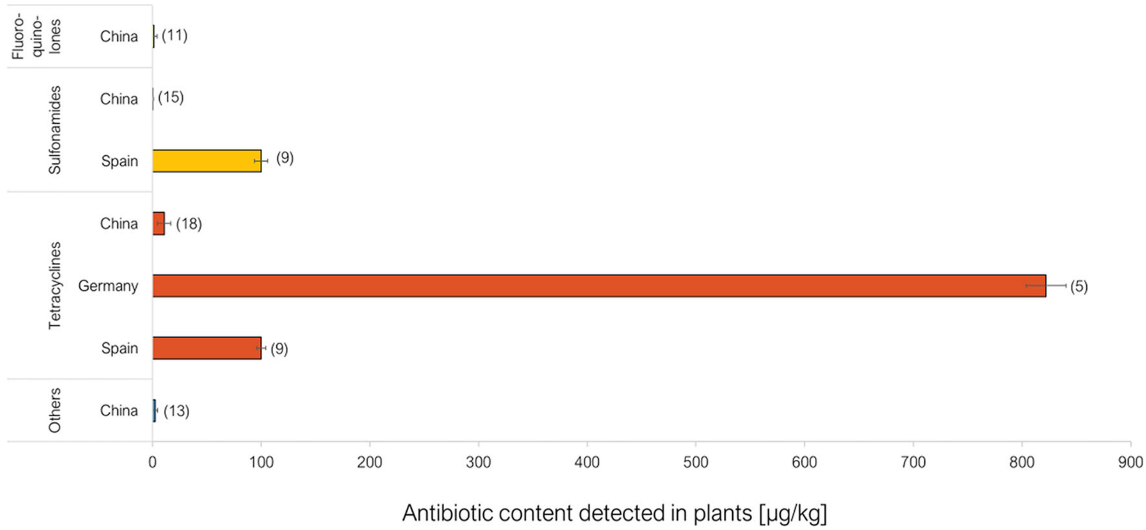

Fig. 8 Bar chart representing the median content and standard error (SE) of each antibiotics group detected in plants in different countries. The numbers in parentheses indicates the sample size of data used for the analysis (*n*). Data were obtained from Conde-Cid et al. (2018), Grote et al. (2007), Hanna et al. (2018), and Hu et al. (2010).

and coriander in China (median ± SE = 10.7 ± 6.1 µg/kg, *n* = 9, max = 200 µg/kg). The highest content among other antibiotics was detected for chloramphenicol in vegetables in China (max = 41 µg/kg).

3.3 Discussion

Veterinary antibiotics in pig manure and slurry were detected in 11 European countries (Albania, Austria, Belgium, Denmark, France, Germany, Italy, Kosovo, Netherlands, Switzerland, and the UK), two countries in America (Mexico and the USA), and one in Asia (China). Among different veterinary antibiotics, especially fluoroquinolones, sulfonamides, and tetracyclines were detected in pig manure and pig slurry. The content of each group of veterinary antibiotics varied greatly in different locations in which they were detected. Pig manure from Austria and Germany (sulfonamides, tetracyclines), Belgium and China (tetracyclines) as well as slurry from the USA (tetracyclines) and Germany (fluoroquinolones, sulfonamides, and tetracyclines) contained high amounts of different antibiotics groups. The variation of detected antibiotics is due to the allowed application amount of veterinary antibiotics in different countries (Marszałek et al. 2019). Furthermore, different antibiotics may have different degradation mechanisms and thus different half-life times (Blackwell et al. 2004). The selected studies also have different sampling times (most are not given in the study). Thus, some antibiotics, which further degraded over time, can potentially be detected in low amounts.

Moreover, antibiotics used in animal husbandry are found to contaminate surrounding environments. This includes soil and water bodies as well as the accumulation in plants. Although antibiotics become much less stable after being applied onto agricultural land (Marszałek et al. 2019; Venglovsky et al. 2009), soil fertilized with contaminated animal excreta in form of manure or slurry was found to contain up to ten times (tetracyclines in the UK, max = 1000 µg/L, Kay et al. (2005)) the proposed EU threshold value of the PEC of veterinary antibiotics in soil (PEC_{soil} = 100 µg/kg, Committee for Medicinal Products for Veterinary Use (2016)). Soils in Austria, China, Germany, and the UK contained highest amounts of different antibiotic groups among other countries. Due to surface runoff or infiltration, water bodies showed concentrations of antibiotic substances with more than 30 times the amount of the PEC for surface water (tetracyclines in the UK, max = 36 µg/L, Blackwell et al. (2005)) and three times the amount of the PEC for groundwater (sulfonamides in Germany, max = 0.4 µg/L, Hamscher and Mohring (2012)) according to the EU directive ($PEC_{groundwater}$ = 0.1 µg/L, $PEC_{surfacewater}$ = 1 µg/L, Committee for Medicinal Products for Veterinary Use (2016)). However, antibiotics can degrade very quickly when they are distributed into the environment or have a high affinity for adsorption onto soil organic matter (Kemper et al. 2008). Hereby tetracyclines, which are the most commonly used veterinary antibiotic in the EU, bind strongly onto soil organic matter due to complexes with double-charged ions. Consequently, low concentrations of this antibiotic group can be found in water which coincides with the results of our analysis (Kay et al. 2004; Kemper et al. 2008). For other groups, it can be assumed that the concentration in the environment varies depending on the amount of time manure and slurry were stored before their contribution on agricultural lands (Kemper et al. 2008). Additionally, these substances can eventually reach the food chain due to root uptake and thus be detected in crops and vegetables growing directly adjacent to the fertilized soil (Hamscher and Mohring 2012; Marszałek et al. 2019). This report detected antibiotics concentrations in plants ranging from 0.1 μg/kg (Hu et al. 2008) up to 1,104 μg/kg (Grote et al. 2007). And the maximum amount of antibiotics residues allowed in animal products is 100–600 μg/kg (The European Commission 2010). Therefore, the detected content of antibiotics in plants exceeds the EU regulations for animal food products by up to ten-fold. Moreover, as slurry contains more water than manure, its mobility after application leads to the spreading of contained pathogens, such as bacteria or viruses, into soil. Through transportation of these pathogens deeper into soil and water bodies they can survive over a long period of time (up to 119 days in soil (*Brachyspira pilosicoli*), Marszałek et al. (2019)). This creates the risk of animal pathogens, including antibiotic-resistant bacteria, reaching the groundwater (Marszałek et al. 2019; Venglovsky et al. 2009).

In this study, literature reporting antibiotics in manure and slurry were selected. Different types of antibiotics were found mainly in the European countries. To identify the specificity of antibiotics residues to country or continent, the information of antibiotics detected in slurry and manure from many more countries should be included. Antibiotics residues in the environments were detected in Asia (China), Europe (Austria, Belgium, Denmark, Germany, Spain, and the UK) and America (Brazil and the USA). In soils, fluoroquinolones, sulfonamides, and tetracyclines were measured in certain amounts in many countries across all three continents and thus no specificity of antibiotic residues to country or continent can be observed. Nevertheless, sulfonamides and tetracyclines in Germany were detected in high content in plants and water, and fluoroquinolones in the USA in water whereas their concentrations are much lower in other countries.

4 Conclusion

We conclude that residues of antibiotics used in agricultural livestock can be found in manure and slurry which is used as a natural fertilizer. We also confirm that these antibiotics residues contaminated the environment (including soil, water, and plants) directly adjacent to agricultural land fertilized with slurry. However, since only little data is available from non-European countries, we were not able to test or observe a significant specificity of these antibiotic residues to country or continent.

The large amounts of organic matter and nutrients in livestock manure and slurry has brought many positive effects as a natural fertilizer, such as improving soil as well as enhancing crop yield and quality. However, the intensive and excessive use of veterinary antibiotics in livestock agriculture has led to several environmental problems due to the absence of application limits and hygienization processes (Hamscher and Mohring 2012; Marszałek et al. 2019). To avoid these substances as well as the resulting drug-resistant bacteria to reach groundwater or crops, it is necessary to minimize environmental contamination. The overall use of veterinary antibiotics needs to be reduced in order to diminish the amount of drugs in manure and slurry which is eventually used as fertilizer. There are different treatment techniques which can reduce the concentration of antibiotics in animal excrements (see Marszałek et al. (2019) and the references therein): anaerobic digestion, aeration, electron beam irradiation, and sorption. Consequently, the proven partial or almost complete elimination of antibiotics in slurry shows the need for a wider contribution of these techniques on a commercial scale.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13593-022-00762-y.

Code availability Available upon request to the corresponding author

Authors' contributions LF and BT conducted the study including literature search, data evaluation, and manuscript writing, BG improved the manuscript and had the idea for the study.

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Data availability Available upon request to the corresponding author

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

Consent for publication Not applicable

Conflict of interests The authors declare no competing interests.

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