



Aerobic Composting of Antibiotic-contaminated Manure: Degradation Processes and Their Effects on Greenhouse Gas Emissions

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Authors' contributions

This work was carried out in collaboration among all authors. Author AC wrote the systematic review protocol. Authors WN and SK managed the literature searches and data extraction. Author AC wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Introduction: The widespread use of antibiotics in livestock production results in significant excretion of unmetabolized residues in manure, posing risks such as the emergence of antibiotic-resistant bacteria (ARB), antibiotic resistance genes (ARGs), and elevated greenhouse gas (GHG) emissions. Composting has emerged as a promising strategy to mitigate these risks.

Aims: This review formed a foundation for manure incubation regarding the fate and effects of three antibiotics – Tylosin, Enrofloxacin, and Oxytetracycline on manure GHG ammonia (NH₃)

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emissions, and fertilizer quality. It synthesizes existing evidence on antibiotic degradation during composting, highlighting the influence of composting conditions, additives, and their effects on greenhouse gas emissions.

Methods: A comprehensive literature search was done following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Systematic searches were performed in three databases: Web of Science, PubMed, and Scopus, for original articles using a combination of Query terms and an established inclusion and exclusion criteria.

Results: The 66 studies that met the criteria were from 21 countries. Outcomes show that composting conditions (temperature, aeration, moisture), additive types (e.g., biochar, zeolite), and microbial inoculants play critical roles in antibiotic degradation and GHG emission dynamics. Thermophilic composting promotes degradation of labile antibiotics, while persistent compounds may require extended treatment.

Overall, the review identified that physicochemical and microbial processes drive antibiotic degradation, suggesting that specific additives enhance these pathways, influencing GHG emissions.

Conclusion: Composting is a viable strategy for managing antibiotic-laden manure and calls for further research into advanced treatments, bioaugmentation, and integration with other waste management technologies.

Keywords: Livestock manure; antibiotic-resistant genes; composting additives.

1. INTRODUCTION

Antibiotics are natural compounds derived from living organisms or created synthetically in the laboratory. They can be taken parenterally, orally, or applied topically to eliminate or hinder the growth of microorganisms (Hosain *et al.*, 2021). They are used therapeutically to treat, control, and prevent diseases, while the non-therapeutic use is for growth promotion and feed digestibility enhancers (Bacanli & Başaran, 2019) in other countries, but their use in food animals within the European Union has been banned since the year 2006 (Van Boeckel *et al.*, 2015; Spielmeier, 2018).

A recent survey found that in Africa, 75% of the countries allow antibiotics to be used for growth promotion, with animals accounting for 50–80% of total antibiotic use (Van *et al.*, 2020). Most of the available data on antimicrobial use across the continent has been collected since 2015, showing that tetracyclines, β -lactams, aminoglycosides, lincosamides, quinolones, polypeptides, amphenicols, macrolides, and sulfonamides are among the most widely used antibiotic classes (Van *et al.*, 2020; Hosain *et al.*, 2021).

Animals eliminate a considerable portion of antibiotics through their faeces and urine, posing a significant risk of unchanged or active drug metabolites being present in the environment (Massé *et al.*, 2014) through manure inputs or from the intensified production of livestock (Marutescu *et al.*, 2022), and this leads to the presence of antibiotic-resistant bacteria in

manure (Jadeja & Worrich, 2022). Antimicrobial resistance is a growing problem globally because every year, antibiotic resistance kills 7 million people worldwide, with up to 10 million fatalities anticipated by 2050. If nothing is done to mitigate this threat, AMR could render certain bacterial diseases substantially more lethal than they are now (Murray *et al.*, 2022).

The application of manure with antibiotic residues may impact the soil microbial functions essential for nutrient cycling and climate regulation since greenhouse gas production is microbially mediated (Petersen *et al.*, 2013). Composting has been proposed as an effective method to curb the spread of antimicrobial resistance in the environment. It helps minimize the likelihood of its transmission to crops and the food chain while also supplying essential fertilizer components (Zalewska *et al.*, 2021; Zalewska *et al.*, 2023). Although composting, driven by microbiological activity, is a preferred method for managing manure and biosolids (Wan *et al.*, 2021), how it affects the degradation of antibiotic residues and greenhouse gas emissions is not clearly understood.

This review synthesizes existing research to evaluate (i) the impacts of antibiotic residues in cattle manure on greenhouse gas emissions during composting (ii) the processes and factors that affect antibiotic degradation during aerobic composting (iii) what additives are incorporated into the manure during composting. By consolidating current knowledge, this review aims to support informed decision-making for

sustainable manure management and highlight research gaps needing further investigation.

2. MATERIALS AND METHODS

A comprehensive literature search was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, as outlined by Liberati *et al.*, (2009). The systematic searches were performed in three databases: Web of Science, PubMed, and Scopus, for original articles published between 2000 and 2024. The search targeted publications from the year 2000 because this is when the antibiotic debate on policies covering antibiotic use regulation started in Europe (Van Boeckel *et al.*, 2015). A combination of query terms like greenhouse gas*, methane*, nitrous oxide*, carbon dioxide*, composts*, livestock* or cattle* or cow*, and dung* or feces* or slurry* or manure*, and antibiotic* or drug* or antimicrobial* were used. Articles retrieved from the search qualified to be included in the review if they were original articles published in English from studies done on laboratory or at field scale from any location globally describing the effects of antibiotic residues in the cattle manure on greenhouse gas emissions during composting or if they were studies on the effects of aerobic composting on antibiotic residues in the presence of additives. Specifically, the review focused on the impact of antibiotic residues in cattle, pig, and chicken manure on greenhouse gas emissions during aerobic composting; the processes and factors influencing antibiotic degradation; and the types and roles of additives used during composting.

Studies were excluded if they were presented in book chapters or focused on composting manures from camels, ducks, horses, sewage sludge, food wastes, or human excreta. These exclusions were made to ensure consistency and relevance across the reviewed studies, or involved waste types with different chemical compositions, microbial communities, or antibiotic usage patterns that could bias comparisons with cattle, pig, and chicken manure.

3. RESULTS AND DISCUSSION

3.1 The PRISMA Flow Chart Outcomes

A systematic literature search that was conducted using PubMed, Web of Science, and Scopus to identify studies examining the processes by which aerobic composting influences the degradation of antibiotic residues

and its effects on greenhouse gas emissions using a predefined inclusion criterion resulted in 66 publications that were deemed relevant. These studies focused on livestock manure (cattle, pig, and chicken), addressing composting processes, antibiotic residue degradation, GHG emission outcomes, and the role of composting additives. The study selection process is summarized in the PRISMA flow diagram in Fig. 1.

The 66 studies included in the review were from 21 countries. The study locations were distributed across the globe except South America as follows: 5 studies from Canada, 14 studies from the USA, 3 from Africa, 4 from Australia, 3 from Europe, 2 from the Middle East, and 35 from Asia, as shown in Fig. 2.

3.2 The Impacts of Antibiotic Residues in Cattle Manure on Greenhouse Gas Emissions during Composting

It was found that during the composting experiments, the manure was co-composted with four categories of materials. The first category is the plant materials that are found on the farm like wood chips and rice husks (Arikan *et al.*, 2006), wheat, and barley straws (Esperón *et al.*, 2020), sawdust (Chen *et al.*, 2019), rice husks (Wang *et al.*, 2022), corn straws (Staley *et al.*, 2020; Ren *et al.*, 2021; Pei *et al.*, 2021; Staley *et al.*, 2020), tea stalks (Chen *et al.*, 2022) mushroom spent residues, bamboo charcoal, and biochar (Lin *et al.*, 2021). The second category of co-composting materials consisted of chemical amendments like phosphogypsum (Hao *et al.*, 2005), Zeolite, attapulgite activated carbon composite, lime (Lin *et al.*, 2021), and 3-nitrooxypropanol (Owens *et al.*, 2020), which is a pharmaceutical material that has been developed to reduce enteric CH₄ production. The 3-Nitrooxypropanol works by specifically inhibiting the methyl-coenzyme M reductase, an enzyme in methanogenic archaea that catalyzes the CH₄-forming reaction in the rumen.

The third category consisted of the manure that was co-composted with pharmaceutical fermentation residues like the penicillin (Ren *et al.*, 2021; Zhang *et al.*, 2015) vinegar wastes (Liu *et al.*, 2022) and Chinese herbal medicine (Guo *et al.*, 2022 ; Zhang *et al.*, 2017). Lastly, the fourth category consisted of composting of manure with commercial decomposers like the antibiotic-degrading bacteria and a consortium of cellulolytic fungi (Salma *et al.*, 2021), like the *Aspergillus niger* and *Trichoderma spp.*

The literature search showed that 24% of the included studies mentioned the effects of veterinary antibiotics on greenhouse gas emissions during composting. The studies varied from those that caused an increase, a decrease, and no effect on greenhouse gas and ammonia emissions. A study by Kang *et al.*, (2022) found that aerobic composting in the presence of penicillin G transformed biological nitrogen fixation by reducing the abundance of denitrifying bacteria. This causes a reduction in Nitrous oxide (N₂O) emissions. Penicillin G was beneficial in enhancing manure fertilizer quality due to reduced N losses through gaseous losses. Contrary findings were observed by Sun *et al.*, (2022) who observed an elevated gaseous

loss of NH₃ during aerobic composting of manure in the presence of spiramycin residues. Research by Chen *et al.*, (2019) showed that adding sulfamethoxazole and norfloxacin increased cumulative CO₂ emissions while reducing total NH₃ loss via volatilization. Further, he discovered that sulfamethoxazole alone decreased cumulative CO₂ emissions but significantly ($p < 0.05$) increased N₂O emissions during the initial 7 days. In contrast, the individual addition of norfloxacin inhibited CO₂, CH₄, and N₂O emissions while increasing cumulative NH₃ loss through volatilization. More studies on the effects of composting on greenhouse gas emissions are presented in Table 1.

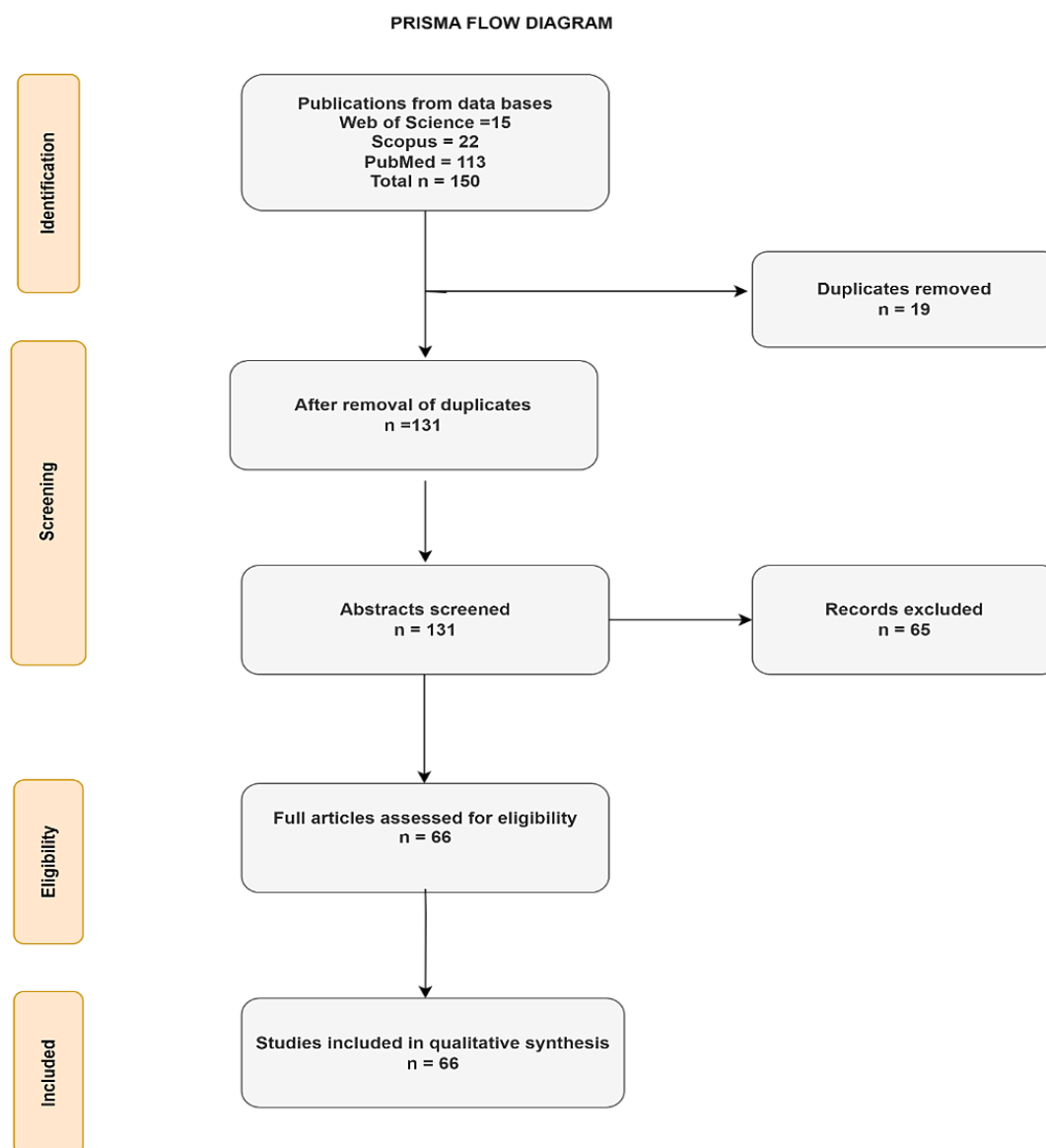


Fig. 1. Flowchart showing the selection process for included studies

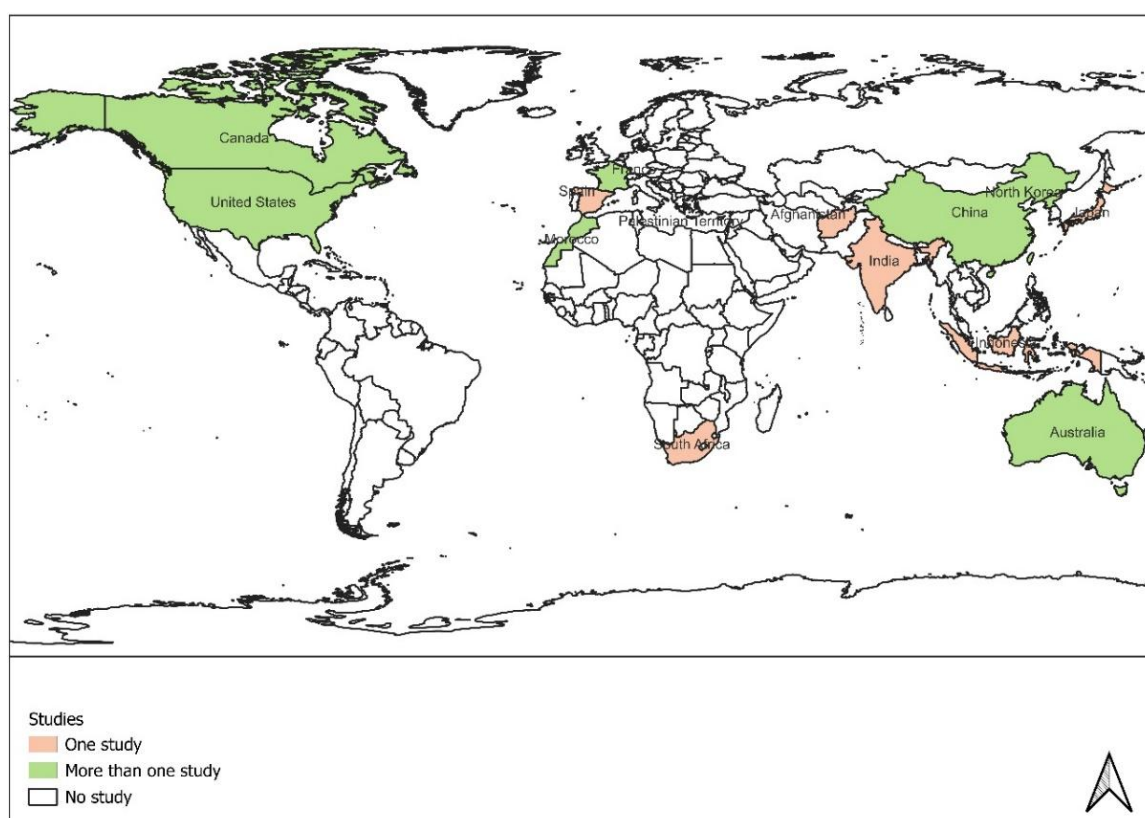


Fig. 2. Global distribution of studies that met inclusion criteria. The shades of different colors represent the number of original article publications from each country

Table 1. Effects of composting with various additives on greenhouse gas emissions from chicken, pig, and cattle manure over varying durations

No.	Animal waste	Composting additive	Composting duration (days)	Effects on GHG	Reference
1	Cattle manure	Lignite	90	Decreased NH ₃ emissions during composting by 54% while elevating overall greenhouse gas by 2.6 times	(Bai <i>et al.</i> , 2020)
2	Chicken pig and cattle manure	Corn stovers	28	Negligible CH ₄ emissions at the end of composting	(Liu <i>et al.</i> , 2021)
3	Pig manure	wheat straw	24	Reduction of N ₂ O and CH ₄ through effective aeration	(Zeng <i>et al.</i> , 2018)
4	Cattle and swine manure	Wheat straw	33	Reduced 50.8 and 40.9% of N ₂ O and CH ₄ emissions, respectively	(Zeng <i>et al.</i> , 2018)
5	Dairy manure	-	42.	Increased CO ₂ and CH ₄ emissions due to high temperature	(Mulbry & Ahn, 2014)
6	Cattle manure	-	44	NH ₃ volatilization decreased by 52.4%	(Cui <i>et al.</i> , 2019)
7	Cattle manure	Saw dust	22	Denitrification caused rapid N ₂ O emissions when the oxygen content was reduced.	(Ahn <i>et al.</i> , 2011; Tsutsui <i>et al.</i> , 2013)

3.3 The Processes and Factors Influencing Antibiotic Degradation in Livestock Manure during Composting

Composting relies on a succession of microbial communities that thrive in thermophilic and mesophilic conditions. During the thermophilic phase, temperatures can reach 55°C to 70°C, creating an environment conducive to the breakdown of complex organic compounds, including antibiotics (Agga *et al.*, 2022). Elevated temperatures enhance the degradation of thermolabile antibiotics, such as tetracyclines and macrolides, by denaturing their chemical structures as observed by Yu *et al.*, (2019). In addition, composting fosters enzymatic activity that can further catalyze the breakdown of antibiotic molecules.

According to Cycoń *et al.*, (2019) microbial activity is crucial for degrading antibiotics, with bacteria and fungi metabolizing them as carbon sources. Enzymes like beta-lactamases hydrolyze antibiotic compounds, influenced by temperature, aeration, moisture, and the compost's carbon-to-nitrogen ratio.

At a temperature of 55 °C, the degradation of chlortetracycline was rapid, reaching up to 99% in 30 days in a study by Arikan *et al.*, (2006). Thermophilic conditions are critical for the degradation of heat-sensitive antibiotics, whereas mesophilic conditions may facilitate the breakdown of more persistent compounds, as observed by Mitchell *et al.*, (2015).

Aerobic composting (Gou *et al.*, 2018) enhances microbial activity and enzymatic degradation by providing optimal oxygen levels for aerobic microorganisms. Proper aeration is essential for maintaining these conditions, as it supports the growth of aerobic and facultative anaerobic microbes, which play a key role in organic matter decomposition. While some strict anaerobes may decline due to increased oxygen availability, composting promotes microbial succession, favouring groups such as *Actinobacteria* and *Proteobacteria*. Gou *et al.* (2018) observed significant shifts in microbial community composition after composting, including reductions in the abundance of certain *Chloroflexi*, *Firmicutes*, and *Bacteroidetes* phyla, depending on the composting stage and environmental conditions.

Moisture levels of 50-60% are ideal for microbial activity (Kim *et al.*, 2016). Excessive moisture

can lead to anaerobic conditions, slowing degradation, while low moisture levels can inhibit microbial processes. However, for some antibiotics like tylosin, breakdown occurs rapidly through hydrolysis (Zhang *et al.*, 2019). The presence of hydroxyl ions also makes it form strong ionic bonds with the organic component, ensuring that the antibiotic is not detectable after a short period (Loke *et al.*, 2002). A balanced C:N ratio (typically between 25:1 and 30:1) supports microbial growth and activity, promoting efficient decomposition of organic matter and associated contaminants. Bulking agents like rice straw, maize straw, and biochar promote antibiotic degradation, as most antibiotics are unstable in thermophilic conditions (Lin *et al.*, 2021). Additionally, they absorb nutrients, binding them and preventing access to microbial degradation (Kim *et al.*, 2012). Sorption plays a key role in this removal, driven by the abundance of divalent cations in organic matrices and their ability to form chelate complexes with organic substances (Ezzariai *et al.*, 2018).

The time taken or duration to compost manure plays a key role. Time mainly affects the degradation of sulfamethazine during composting. In a study by (Dolliver *et al.*, 2008), extractable sulfamethazine levels remained unchanged after 35 days, and no additional analyses were done. Similarly, (Kim *et al.*, 2012) reported that extractable sulfamethazine in swine manure showed no change after 35 days of commercial composting, but significant reductions were observed in 80 days. In another study, Cessna *et al.*, (2011) noted minimal degradation of sulfamethazine in composted manure from feedlots after 36 days; however, reductions of approximately 88% and 93% were achieved after 63 and 126 days, respectively. A related study on sulfamethazine dissipation in stockpiled feedlot manure indicated that degradation rates were slow during the first 28 days, but extractable sulfamethazine levels decreased by 98% after 77 days as observed by Sura *et al.*, (2014).

Oxidation-reduction (redox) reactions are important mechanisms for degrading antibiotic residues in the environment (Dolliver *et al.*, 2008). These reactions involve the transfer of electrons, resulting in bond cleavage, functional group transformation, or ring structure disruption, which ultimately reduces the antibiotic's activity (Wang *et al.*, 2024). For instance, tetracyclines and sulfonamides are known to undergo oxidative degradation under aerobic conditions,

leading to the breakdown of their aromatic rings and active functional groups (Arikan *et al.*, 2006). Similarly, quinolones such as Ciprofloxacin and Enrofloxacin can be transformed under redox conditions, particularly during composting or advanced oxidation processes, resulting in decreased antimicrobial potency (Guo *et al.*, 2022). These redox-driven alterations enhance the environmental detoxification of antibiotic residues in manure and other organic waste streams

3.4 The Types of Additives used during Composting

Additives are materials incorporated into composting systems to enhance the composting process's efficiency, quality, and environmental performance. The review showed that the manure was co-composted with four categories of materials. The first category is the plant materials that are found on the farm like wood chips and rice husks (Arikan *et al.*, 2006), wheat, and barley straws (Esperón *et al.*, 2020), sawdust (Chen *et al.*, 2019), rice husks (Wang, Chu, *et al.*, 2022), corn straws (Staley *et al.*, 2020; Ren *et al.*, 2021; Pei *et al.*, 2021; Staley *et al.*, 2020), tea stalks (Chen *et al.*, 2022) mushroom spent residues, bamboo charcoal, and biochar (Lin *et al.*, 2021).

The second category of co-composting materials consisted of chemical amendments like phosphogypsum (Hao *et al.*, 2005), Zeolite, attapulgite, activated carbon composite, lime (Lin *et al.*, 2021) and 3-nitrooxypropanol (Owens *et al.*, 2020) which is a pharmaceutical material that has been developed to reduce enteric CH₄ production. The 3-Nitrooxypropanol works by specifically inhibiting the methyl-coenzyme M reductase, an enzyme in methanogenic archaea that catalyses the CH₄-forming reaction in the rumen.

The third category, the manure was co-composted with pharmaceutical fermentation residues, like the penicillin (Ren *et al.*, 2021; Zhang *et al.*, 2015), vinegar wastes (Liu *et al.*, 2022), and Chinese herbal medicine (Guo *et al.*, 2022; Zhang *et al.*, 2017).

Lastly, the fourth category consisted of composting of manure with commercial decomposers like the antibiotic-degrading bacteria and a consortium of cellulolytic fungi (Salma *et al.*, 2021) like *Aspergillus niger* and *Trichoderma spp.*

3.5 The Role of Additives Used during Composting

The use of conditioning agents in composting has been shown to improve the degradation rates of antibiotic residues significantly by Chen *et al.*, (2022). Research indicates that mixing biochar with zeolite during composting enhances the degradation rates of tetracycline antibiotics (Lin *et al.*, 2021). This combination not only increases adsorption but also provides additional nutrients that support microbial growth as observed by Marutescu *et al.*, (2022). The microbial inoculants of specific microbial strains like *Aspergillus niger* and *Trichoderma spp.* known for their antibiotic-degrading capabilities can further enhance the degradation process. Studies by Dela Cruz *et al.*, (2022) have demonstrated that inoculating compost with these strains leads to higher removal efficiencies for various antibiotics. The regulation or maintenance of optimal temperature through active management can also promote more effective degradation. Thermophilic composting processes have been shown to reduce heat-sensitive antibiotic residues more effectively than mesophilic conditions, which degrade persistent antibiotics (Chen *et al.*, 2022).

3.6 Implications for Greenhouse Gas Emissions

Composting has the potential to mitigate greenhouse gas emissions associated with organic waste management: traditional waste management practices, such as landfilling or lagoon storage, can lead to significant methane emissions due to anaerobic decomposition. According to Nordahl *et al.*, (2023), composting, being an aerobic process, minimizes CH₄ production by promoting aerobic microbial activity and stabilizing organic matter.

By effectively degrading antibiotic residues and converting organic waste into compost (Marutescu *et al.*, 2022), this process contributes to nutrient recycling in agriculture. Healthy soils enriched with compost can enhance carbon sequestration (Lhaj *et al.*, 2024; Schueler *et al.*, 2021) and reduce the need for synthetic fertilizers, which are often associated with higher greenhouse gas emissions during production and application (Sun *et al.*, 2022).

Properly managed compost can improve soil health (Sarwari *et al.*, 2024) by fostering a

diverse microbial community that enhances soil resilience against pathogens and reduces reliance on chemical inputs. This shift can contribute to sustainable agricultural practices that further lower greenhouse gas emissions (Yasmin *et al.*, 2022).

3.7 Environmental and Agricultural Implications

Effective composting of antibiotic-contaminated manure reduces the risk of introducing residual antibiotics into soil and water systems (Xu *et al.*, 2016). By minimizing antibiotic residues, composting also helps mitigate the proliferation of antibiotic-resistant bacteria (ARB) and resistance genes (ARGs). Furthermore, the resulting compost is safer for agricultural use, improving soil fertility without posing significant ecological or public health risks. In a related study, a substantial portion of organic degradation is aerobic, inhibiting methanogenesis and leading to lower emission factors (EFs) values (Moller *et al.*, 2004) compared to Intergovernmental Panel on Climate Change (IPCC) estimates for closed systems (IPCC, 2021).

While composting shows promise in degrading antibiotic residues, challenges remain. Some antibiotics, such as fluoroquinolones and sulfonamides, exhibit high persistence and may require advanced treatments for complete degradation. Additionally, the effectiveness of composting varies depending on the initial concentration of antibiotics and the specific composting conditions (Ray *et al.*, 2017).

3.8 Limitations of this Study

This study on composting antibiotic-contaminated manure has several limitations. First, composting conditions vary significantly, affecting the degradation of antibiotics and the persistence of antibiotic resistance genes (ARGs). While high temperatures can reduce ARGs and antibiotic-resistant bacteria (ARBs), thermophilic microbes that harbour ARGs may still thrive, potentially leading to unintended resistance gene proliferation.

Additionally, certain antibiotics, such as fluoroquinolones and sulfonamides, are highly persistent and may not fully degrade during

composting. This required comparative studies to assess the risks associated with their continued presence in manure.

Another limitation is the variable effectiveness of composting additives, such as biochar, zeolite, and microbial inoculants, which depend on composting conditions and manure composition. This raises concerns about scalability and cost. Finally, even when antibiotic residues are reduced, residual ARGs may persist in compost, posing potential long-term environmental and agricultural risks.

4. CONCLUSION

Composting is a viable and effective strategy for degrading antibiotic residues in livestock manure while simultaneously addressing greenhouse gas emissions. The effectiveness of this process is enhanced by using conditioning agents and optimizing microbial communities within the compost matrix. As agricultural practices evolve towards sustainability, integrating efficient composting techniques will be essential in managing antibiotic residues and promoting environmental health. Further research is needed to optimize composting parameters for effective antibiotic degradation while maximizing ecological and agricultural benefits. Studies should explore bioaugmentation with specialized microbial consortia, assess the long-term environmental impact of residual antibiotics in compost-amended soils, and integrate composting with other waste treatment technologies like anaerobic digestion or biochar application. Advancing these strategies will enhance antibiotic residue management in agriculture, reducing environmental and public health risks associated with antibiotic use.

SUPPLEMENTARY MATERIALS

Supplementary materials available in this link:

<https://www.journalijpss.com/index.php/IJPSS/libraryFiles/downloadPublic/38>

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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