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Chapter 3
Challenges of Veterinary Antibiotic Pollution from Swine Farms and Possible Wastewater Treatment Options

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Abstract: The rapid growth of pig farming in Asia has led to increased antibiotic use in swine production, resulting in significant environmental pollution from antibiotic residues in wastewater. These residues pose risks to ecosystems, human health, and agricultural productivity, but research on the extent of contamination and effective mitigation strategies remains limited. Conventional wastewater treatment methods often fall short in eliminating veterinary antibiotics, allowing these contaminants to persist in the environment. This issue is exacerbated by the structure, persistence, resistance, toxicity, and high risks associated with antibiotics, making their treatment particularly challenging. As a result, there is a pressing need for more efficient treatment technologies. Recent studies have explored various methods and optimal conditions for removing antibiotic residues from swine farm effluents. Advanced technologies, such as upflow anaerobic sludge blankets (UASB) and membrane bioreactors, show promise but are costly and difficult to implement on a larger scale. In contrast, more affordable and accessible approaches like adsorption and nature-based solutions, including constructed wetlands (CWs) and phytoremediation, offer significant advantages due to their low cost, simplicity, and minimal energy requirements. One particularly promising approach involves combining biochar with manganese oxides for antibiotic removal. Manganese oxides are abundant, easy

to process, and environmentally friendly, while biochar modified with manganese oxides possesses a high positive surface charge and strong antibiotic immobilization capacity. This combination enhances the removal efficiency of antibiotics and helps reduce the spread of antibiotic-resistant genes, addressing both environmental pollution and public health concerns. This innovative method holds great potential for mitigating the environmental impacts of antibiotic residues in swine wastewater. However, further research is needed to optimize the use of biochar-manganese oxide composites for effective antibiotic removal, ultimately contributing to more sustainable and safer agricultural practices by reducing environmental harm and combating antibiotic resistance.

Keywords: *antibiotic residues, swine wastewater, biochar-manganese oxide composites, antibiotic resistance, constructed wetlands*

1. Introduction

(1) Antibiotic Pollution from Swine Farm

Wastewater pollution from agricultural activities, particularly pig farming, has become a critical environmental challenge. Pig farming produces substantial waste, including both organic and inorganic pollutants, that negatively impact ecosystems. Among these pollutants, antibiotics and antimicrobials, such as fluoroquinolones, are especially concerning due to their extensive use in animal husbandry and their persistence in the environment. The issue of antibiotic pollution from swine farms has garnered significant attention because of its harmful effects on ecosystems and public health.

Antibiotics are essential for maintaining livestock health and improving feed efficiency, facilitating the production of high-quality

meat. In Japan, tetracycline is the most widely used antibiotic in food-producing animals, followed by polyethers, penicillins, sulfonamides (SAs), and macrolides (MLs). Table 1 highlights nine antibiotics commonly employed in Japanese livestock farming.

Table 1. Classification and application of 16 pharmaceuticals and metabolites in Japan

Compound	Classification	Use in
Lincomycin (LCM)	Lincosamides	Livestock
Tylosin (TYL)	Macrolides	Livestock
Tilmicosin (TMC)	Macrolides	Livestock
Tiamulin (TML)	Pleuromutilins	Livestock
Sulfamonomethoxine (SMM)	Sulfonamides	Livestock
Sulfamethazine (SMZ)	Sulfonamides	Livestock
Oxytetracycline (OTC)	Tetracyclines	Livestock
Sulfamethoxazole (SMX)	Sulfonamides	Livestock & human
N-Acetyl sulfamethoxazole (N-SMX)	Metabolite of SMX	Livestock & human
Trimethoprim (TMP)	Synthetic antibiotic	Livestock & human
Carbamazepine (CBZ)	Antiepileptics	Human
Crotamiton (CRT)	Antipruritics	Human
Sulfapyridine (SPD)	Metabolite of sulfasalazine	Human
Diclofenac (DCF)	Non-steroidal anti-inflammatory drugs	Human
Clarithromycin (CAM)	Macrolides	Human
Acetaminophen (ACT)	Antipyretic analgesics	Human

Source: (Hanamoto et al. 2023)

However, the overuse and improper application of antibiotics have led to the emergence of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs), posing significant risks to both human and environmental health. Globally, annual antibiotic usage is estimated to range between 100,000 and 200,000 tons, with

consumption increasing by 65% between 2000 and 2015. In Japan, large quantities of antibiotics are sold each year, predominantly for veterinary purposes. Alarmingly, 30–90% of administered antibiotics are excreted by animals through urine and feces, eventually entering the environment via livestock manure. In 2017, Japan produced approximately 22 million tons of swine waste, representing nearly 30% of the nation's total livestock waste. Swine waste is typically managed by separating it into solid and liquid fractions. The liquid fraction is treated aerobically using activated sludge systems, while the solid fraction is composted. However, conventional treatment methods are largely ineffective at removing antibiotics, allowing these pollutants to persist in the environment and exacerbate pollution.

The environmental consequences of antibiotic pollution are profound. Residual antibiotics in soil and water disrupt microbial communities that are essential for maintaining ecosystem balance. Of greater concern is the role of antibiotic residues in the proliferation of ARB. These bacteria can transfer resistance genes to other microorganisms, including human pathogens, through horizontal gene transfer. The spread of antibiotic resistance poses a significant global public health threat by diminishing the effectiveness of antibiotics in treating infectious diseases. Addressing this issue requires innovative approaches and sustainable solutions to mitigate antibiotic pollution and its associated risks to ecosystems and human health.

(2) Challenges in Antibiotic Removal from Swine Wastewater

Antibiotic contamination in swine wastewater is a significant and growing environmental issue, with far-reaching impacts on ecosystems and public health. The complex chemical properties of antibiotics, their toxicological effects on aquatic organisms, and their role in fostering

antimicrobial resistance (AMR) present numerous challenges for effective wastewater treatment. This section outlines the major obstacles in addressing the removal of antibiotics from swine wastewater:

1) Persistence and Resistance of Antibiotics

Antibiotics such as sulfonamides and tetracyclines are highly persistent in the environment, making their removal from wastewater difficult. Their microparticle size allows them to bypass conventional treatment systems, such as sedimentation or biological treatments, and persist in treated effluent. For example, high concentrations of sulfonamide antibiotics (560–4660 ng/L) and tetracycline antibiotics (810−2420 ng/L) have been detected in surface waters near livestock farms, such as those in Jiangsu Province, China (Wei et al. 2011). These concentrations illustrate the inefficiency of traditional wastewater treatment systems in fully eliminating these contaminants.

Tetracycline, in particular, poses a significant challenge due to its resistance to degradation. Its continued presence in wastewater creates a cycle of environmental reintroduction, with resistant bacteria and genes re-entering agricultural systems. This feedback loop exacerbates AMR, making disease treatment in livestock and humans increasingly difficult and less effective over time.

2) High Costs of Advanced Treatment Technologies

While advanced technologies, such as membrane filtration, show promise for removing antibiotics from wastewater, their prohibitive costs make them inaccessible for large-scale application, particularly in agriculture. For many livestock operations, especially in developing countries, investing in such technologies is economically unfeasible. This leaves a critical gap in treatment capabilities, allowing antibiotics to persist in wastewater discharged into the environment. Efficient and

cost-effective alternatives are urgently needed. The development of affordable technologies that can effectively remove antibiotics at the source, such as in agricultural wastewater streams, is fundamental to addressing this issue. Without such innovations, the economic burden of advanced treatment technologies will continue to hinder progress in tackling antibiotic contamination.

3) Mixture Toxicity

Antibiotics in wastewater pose significant toxicological risks to aquatic ecosystems. Their presence disrupts microbial communities, affecting processes such as growth, respiration, and enzyme activity in aquatic organisms, including proteobacteria, cyanobacteria, algae, daphnia, and fish. Antibiotics such as sulfonamides and tetracyclines inhibit the replication and metabolic pathways of algae, which are essential for maintaining ecological balance. Moreover, mixtures of antibiotics present in wastewater can have synergistic toxic effects, leading to stronger adverse impacts on aquatic organisms than individual compounds. These disruptions can cascade through the ecosystem, reducing biodiversity and impairing critical ecological functions.

4) Seasonal Variability in Antibiotic Concentrations

Antibiotic concentrations in wastewater vary with seasonal changes, often peaking during the summer months. This seasonal variability complicates the operation and design of treatment systems, which must handle fluctuating levels of contaminants. The higher concentrations observed in warmer months increase the risk of environmental contamination, requiring dynamic and adaptable treatment methods capable of addressing seasonal variations effectively.

5) Need for Source-Level Treatment and Management

The most effective approach to addressing antibiotic contamination in swine wastewater is to prevent its release at the source. Agricultural operations must implement measures to reduce the discharge of antibiotics into water bodies, including better waste management practices and more targeted use of antibiotics in livestock farming. Efforts should also focus on developing innovative, low-cost, and scalable technologies capable of removing antibiotics before they enter surface water or groundwater. By targeting the source of contamination, it is possible to minimize the spread of antibiotics and reduce their environmental and public health impacts.

2. Treatment of Swine Wastewater

(1) Swine Wastewater Treatment Methods in Japan

Various methods have been developed to remove antibiotics from wastewater, with several approaches specifically applied to swine wastewater in Japan, as shown in Table 2. Among these methods, aeration — particularly continuous and intermittent aeration — plays a significant role by providing oxygen, which can facilitate the removal of antibiotics. However, some treatment methods, such as membrane bioreactors, are prohibitively expensive and may not be feasible for widespread application.

More cost-effective alternatives, such as batch reactors, offer practical solutions. These systems utilize specific microbes capable of breaking down certain antibiotics. Nevertheless, not all antibiotics are easily degradable by bacteria, particularly those that are highly concentrated or chemically resistant. For such cases, additional or alternative methods must be employed to ensure the effective removal of these persistent compounds.

Table 2. Swine wastewater treatment methods in various pig farms in Japan

Numbers of Sows	Production and growth stage	Separation process of solid and liquid	Treatment method	Aeration condition
81	Sows - weaning Fattening	Yes, Fermentation bed	Membrane bioreactor	Continuous
610	Sows - weaning, fattening	Yes, partly fermentation bed	Activated sludge process	Continuous
	Fattening	Fermentation bed	–	–
1867	All	No, partly fermentation bed	Activated sludge process	Continuous
523	All	Yes	Activated sludge process	Intermittent
863	All	Yes	Activated sludge process	Intermittent
4934	Sows - lactating	Yes	Aerated lagoon	Intermittent
	Weaning - fattening	Yes	Aerated lagoon	Intermittent
502	Sows-lactating, fattening	Yes	Membrane bioreactor	Continuous
	Weaning - fattening	Yes	Activated sludge process	Continuous
321	Sows - weaning	No	Aerated lagoon	Intermittent
	Fattening	Fermentation bed	–	–
90	All	Yes, partly fermentation bed	Sequencing batch reactor	Intermittent
236	All	Yes	Two-stage activated sludge process	Continuous
n.i.	–	Yes	Two-stage activated sludge process	Continuous

Source: (Watanabe et al. 2023)

(2) A Case Study on Antibiotic Removal in Two Swine Wastewater Treatment Systems in China

China, being the world's largest producer and consumer of pork, uses significantly more antibiotics in its swine industry compared to other countries, such as the United States, to achieve comparable levels of meat production. This heavy reliance on antibiotics has raised significant environmental and public health concerns. In 2013, it was

estimated that the total antibiotic usage in China was approximately 162,000 tons, with around 52% of this amount consumed by animals (Zhang et al. 2018). A large portion of these antibiotics eventually enters the environment through manure and wastewater, posing risks of antibiotic contamination and the development of ARB.

One of the key challenges facing the Chinese swine industry is the inadequate treatment of wastewater from pig farms. Many farms rely on simple and outdated treatment methods, such as lagoons or anaerobic digesters. While these systems are cost-effective, they are largely ineffective at removing antibiotics and their residues from the wastewater. Recently, more advanced treatment systems, such as UASB and anaerobic-aerobic oxidation systems, have been introduced to some farms. However, these systems require further evaluation to determine their efficiency and feasibility for widespread use in mitigating antibiotic contamination.

This study aimed to investigate the effectiveness of two different treatment technologies employed at two separate swine farms, referred to as Farm A and Farm B, in reducing antibiotic contamination in wastewater. Figure 1 illustrates the technical flowcharts of the swine wastewater treatment systems implemented in Farm A and Farm B. The study provided insights into the performance of these treatment systems and the challenges they faced in removing various antibiotics.

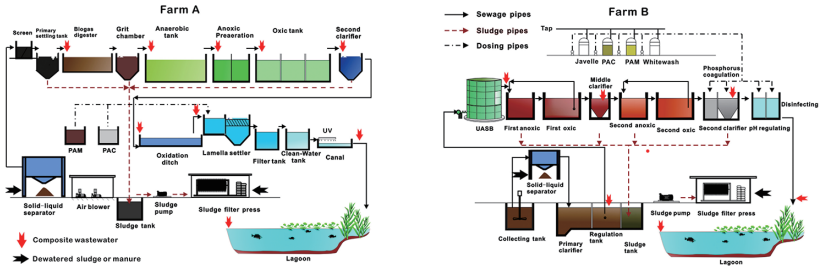


Figure 1. Diagram of wastewater treatment systems in Farm A and Farm B. Source: (Zhang et al. 2018)

Farm A employed a combination of an anaerobic digester, an A^2/O system (anaerobic-anoxic-oxic), and a lagoon system, with the anaerobic digester serving as the primary treatment component. The wastewater underwent successive treatment stages, including anaerobic, anoxic, and aerobic processes, before being discharged into the lagoon. Despite these efforts, the system demonstrated limited effectiveness in removing certain antibiotics. Among the 21 targeted antibiotics detected in wastewater samples from Farm A (Figure 2), the predominant compounds in the influent included sulfachloropyridazine, sulfamonomethoxine, oxytetracycline, and lincomycin. In the effluent, the dominant antibiotics were sulfamonomethoxine, chlortetracycline, tetracycline, oxytetracycline, and lincomycin. Tetracycline and its related compounds proved particularly difficult to remove, persisting throughout the treatment process. The highest concentrations detected in Farm A's effluent were 166 ± 3.64 μg/L for lincomycin and 1.40 ± 1.00 μg/L for oxytetracycline.

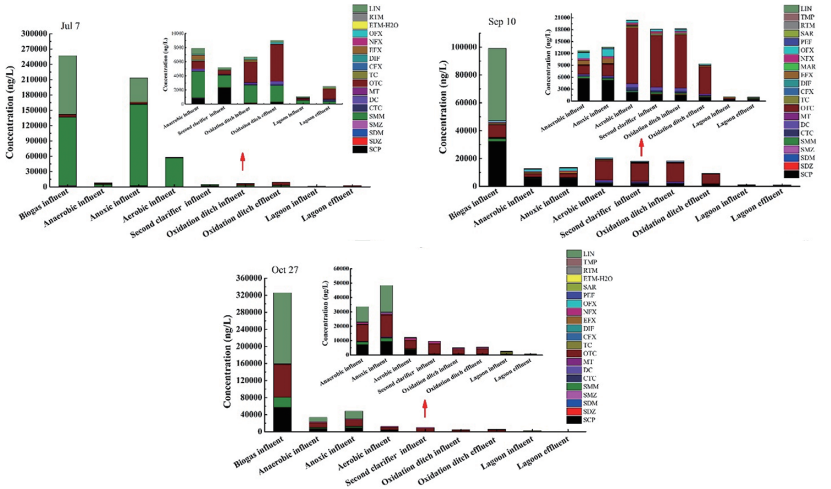


Figure 2. Antibiotic concentrations in the liquid phase of each treatment unit at Farm A during three sampling times (July 7, September 10, and October 27, 2016). Abbreviations: SCP (sulfachlorpyridazine), SDZ (sulfadiazine), SDM (sulfadimethoxine), SMZ (sulfamethazine), SMM (sulfamonomethoxine), CTC (chlortetracycline), DC (doxycycline), MT (methacycline), OTC (oxytetracycline), TC (tetracycline), CFX (ciprofloxacin), DIF (difloxacin), EFX (enrofloxacin), MAR (marbofloxacin), NFX (norfloxacin), OFX (ofloxacin), PEF (pefloxacin), SAR (sarafloxacin), ETM-H2O (erythromycin-H2O), RTM (roxithromycin), TMP (trimethoprim), and LIN (lincomycin). Source: (Zhang et al. 2018)

Farm B, on the other hand, used a combination of a UASB system, an $(A/O)^2$ system (anoxic/oxic-anoxic/oxic), and a lagoon system for wastewater treatment. The UASB system is considered an advanced anaerobic treatment method that enhances the degradation of organic matter. The study targeted 22 antibiotics in the wastewater samples from Farm B, including 5 sulfonamides, 5 tetracyclines, 7 fluoroquinolones,

3 macrolides, lincomycin, and trimethoprim. In the influent of Farm B's treatment system, sulfachloropyridazine and oxytetracycline were the most predominant antibiotics. After treatment, the effluent still contained significant concentrations of sulfachloropyridazine, sulfamonomethoxine, oxytetracycline, trimethoprim, and lincomycin (Figure 3). Similar to Farm A, tetracycline and its related compounds remained persistent and were detected in all samples, indicating the difficulty of removing these antibiotics even with advanced treatment technologies.

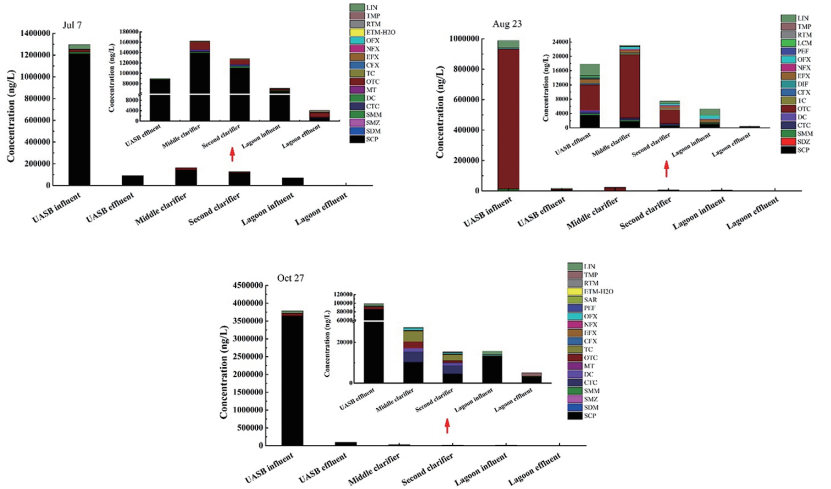


Figure 3. Antibiotic concentrations in the liquid phase of each treatment unit at Farm B during three sampling times (July 7, August 23, and October 27, 2016). Source: (Zhang et al. 2018).

The study revealed that both wastewater treatment systems demonstrated some degree of effectiveness in reducing the total concentration of antibiotics in swine wastewater. The anaerobic digester from Farm A and the UASB system from Farm B, each made significant

contributions to antibiotic reduction. However, neither technology was fully capable of eliminating antibiotics from the wastewater. Overall, the findings highlight the challenges of treating antibiotic-laden wastewater from swine farms, even with the use of advanced technologies. Both Farm A and Farm B faced notable limitations in removing certain antibiotics, particularly tetracycline and its derivatives, which remained prevalent in the treated effluents. These results emphasize the need for additional or alternative treatment methods to achieve higher removal efficiencies and prevent the release of antibiotic residues into the environment.

Future research should focus on exploring and optimizing advanced treatment technologies. Possible solutions include integrating CWs, membrane bioreactors, or other nature-based approaches to enhance antibiotic removal from swine farm wastewater. Furthermore, the implementation of stricter regulations on antibiotic usage in livestock farming, coupled with improved waste management practices, could play a crucial role in mitigating the environmental impact of antibiotic contamination.

3. Removal of Veterinary Antibiotics from Swine Wastewater

(1) Phytoremediation

The treatment of swine wastewater, particularly with a focus on the removal of veterinary antibiotics, remains a significant challenge in environmental engineering. Among the various potential approaches, the utilization of algae has emerged as a promising solution. Algae, with their inherent ability to remove antibiotics, represent a sustainable and nature-based method for wastewater treatment. Through the

process of phytoremediation, both microalgae (unicellular organisms) and macroalgae (multicellular organisms) can play a critical role in addressing this issue.

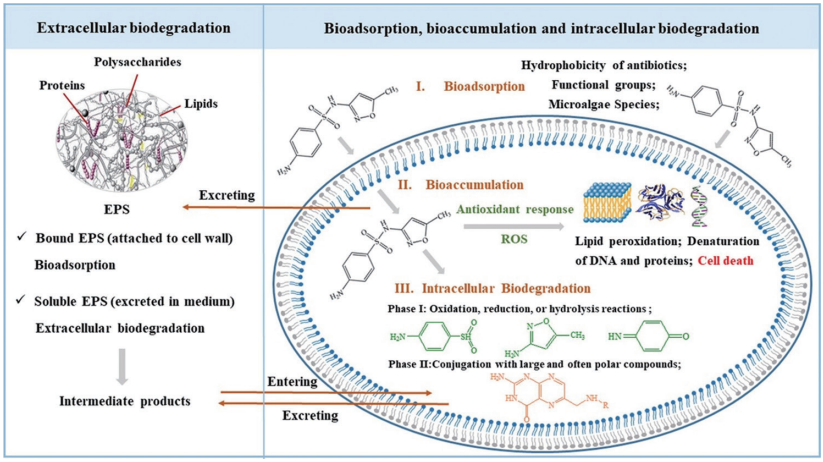


Figure 4. Mechanisms underlying antibiotic removal by microalgae. Source: (Xiong et al. 2021)

One of the notable pathways through which algae contribute to the degradation of antibiotics is biodegradation, which includes indirect photodegradation. Since algae require light and carbon dioxide to grow, their exposure to sunlight plays a vital role in facilitating this process. Studies have demonstrated that when algae, particularly microalgae, are present in an aqueous solution containing tetracycline (a commonly used veterinary antibiotic), the rates of bio-adsorption and bioaccumulation of tetracycline are significantly reduced. In fact, it has been observed that these rates can decrease by as much as 50% when the solution is exposed to sunlight in the presence of algae. Furthermore, microalgae exhibit an additional advantage by influencing the pH levels of their environment. As these organisms grow, they naturally regulate

the pH, particularly within reactor systems designed for wastewater treatment (Ding et al. 2015; Wu et al. 2019). The photosynthetic activity of algae not only promotes their growth but also leads to an increase in pH levels. This rise in pH is a crucial factor in the effective removal of certain ionic antibiotics, including tetracycline. The hydrolysis of tetracycline and similar compounds is strongly pH-dependent, and the pH adjustments facilitated by algae create an environment conducive to breaking down these antibiotics.

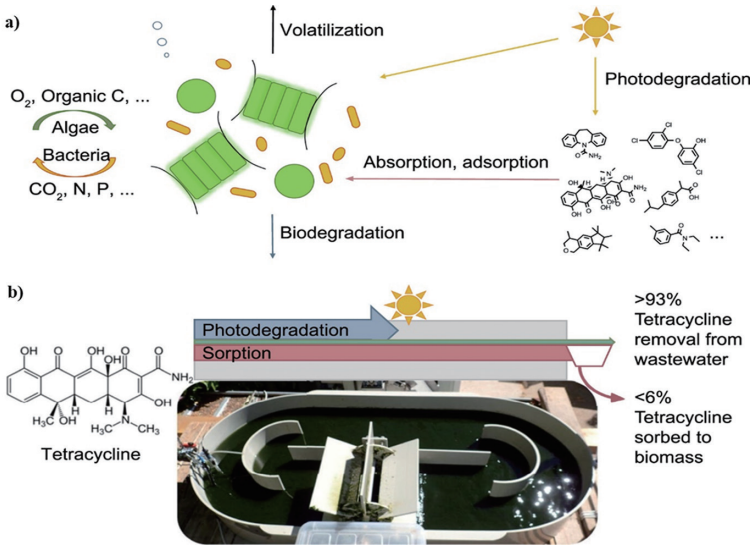


Figure 5. a) Removal of antibiotics using algae-bacteria method, b) Tetracycline removal through algal pond system. Source: (Li et al. 2022)

(2) Constructed Wetlands

CWs have proven to be highly effective in removing antibiotics from wastewater, which is one of the key advantages they offer.

However, it is essential to consider not only the presence of suitable substrates and plants but also the characteristics of the materials used in the system. In particular, the addition of biochar has been found to significantly enhance or modify the treatment mechanisms in CWs.

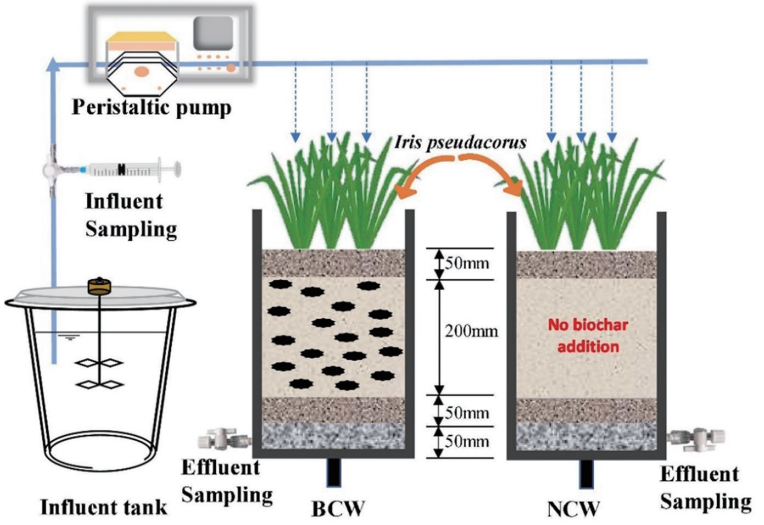


Figure 6. Experimental diagram of biochar-based CWs for antibiotic removal. Source: (Ajibade et al. 2023)

Biochar, known for its nearly neutral pH and predominantly negative surface charge, plays a critical role in the efficiency of antibiotic removal. When incorporated into CWs, biochar's surface properties enable it to attract and retain positively charged antibiotics through adsorption or absorption. This process helps to sequester the antibiotics within the system, where they can be accessed by plants for uptake. Additionally, biochar acts as a physical medium that can hold the antibiotics within the CWs, reducing the likelihood of their release back into the environment. Over time, biochar's capacity to

adsorb or absorb contaminants can be enhanced by the presence of microorganisms within the system. Though the degradation of biochar can be a complex process, the likelihood of biodegradation increases significantly in the long term. Microbial activity can gradually break down biochar and further contribute to the removal of antibiotics, though this depends on the specific microorganisms available in the system.

From a broader perspective, the use of biochar in CWs has the potential to reduce the proliferation of ARGs that can accumulate in wastewater. These ARGs pose a serious risk, particularly in agricultural systems where pigs or livestock may ingest antibiotic-laden waste. By sequestering antibiotics in the biochar, the spread and uptake of ARGs can be mitigated, preventing further contamination of the food chain. Biochar's properties, including its ability to adsorb and retain contaminants, play a key role in this process.

Additionally, biochar's surface chemistry, which includes hydroxyl (-OH) and carboxyl (-COOH) functional groups, allows it to engage in various interactions, such as hydrogen bonding and hydrophobic exchange. These interactions contribute to its ability to trap contaminants and facilitate their removal from wastewater. The biochar surface can also provide a habitat for microorganisms, which can further enhance the removal of nutrients and contaminants, as noted by other researchers.

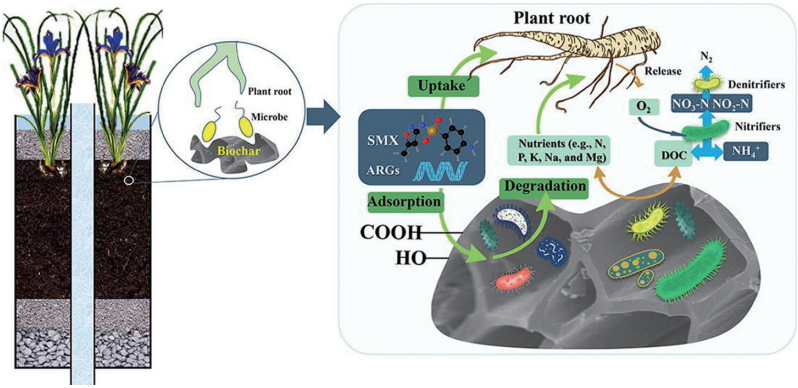


Figure 7. Processes involved in the removal of antibiotics using biochar-based CWs. Source: (Ajibade et al. 2023)

Figure 7 illustrates some of the functional groups present on the surface of biochar, including hydroxyl and carboxyl groups, which contribute to its adsorption capacity. These functional groups also help support the colonization of microorganisms, enabling them to thrive on the biochar surface. In turn, this microbial activity accelerates the removal of antibiotics and other nutrients, improving the overall treatment efficiency of the CWs.

(3) Enhancing Anaerobic Processes with Biochar Derived from Swine Manure

Another important consideration involves the treatment of solid waste, such as manure, through a process known as pyrolysis. By pyrolyzing swine manure, it is possible to repurpose the resulting biochar as an additive to enhance the anaerobic digestion (AD) of swine wastewater. This approach not only facilitates the recovery of energy but also contributes to the attenuation of ARGs.

This process creates a beneficial cycle, where waste is effectively managed by first undergoing pyrolysis to produce carbon-rich biochar. The biochar can then be utilized to adsorb and remove antibiotics and other contaminants from the wastewater, leveraging its adsorption properties. This dual function of waste conversion — generating energy while reducing contamination — presents a sustainable solution for managing swine wastewater.

Wang et al. (2022) demonstrated that the use of dewatered swine manure-derived biochar (DSMB) in AD systems enhances microbial activity and promotes energy recovery. DSMB also plays a key role in limiting the spread of ARGs by preventing their re-ingestion by pigs. Additionally, the study found that DSMB positively influences CH_4 production during the digestion of swine wastewater (Figure 8a), making it a promising additive for in situ biogas production during AD.

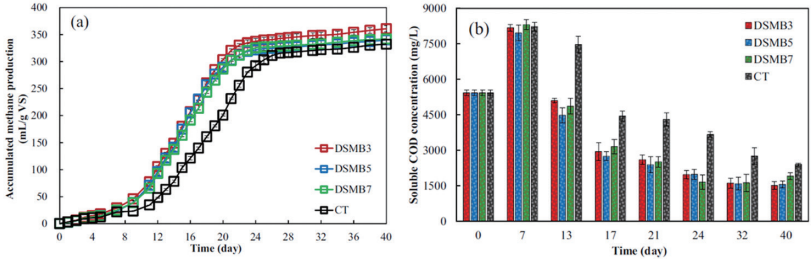


Figure 8. a) Methane production, b) COD removal. Source: (Wang et al. 2022)

Microbial community analysis revealed that dominant microorganisms at the genus level, such as Clostridium sensu stricto, Defluviitoga, Terrisporobacter, and Syntrophomonas, are crucial in the AD process. These microorganisms not only aid in digesting the wastewater but also contribute to the degradation of antibiotics, further

improving process efficiency.

The results show a clear distinction from the control group, with a significant decrease in chemical oxygen demand (COD) concentration (Figure 8b). This demonstrates the effectiveness of biochar-enhanced AD in reducing both organic matter and antibiotic contamination.

(4) Combined Effects of Active Manganese Species and Biochar

Developing efficient catalysts for antibiotic degradation is an effective strategy to combat environmental pollution through advanced oxidation processes. One such approach involves leveraging the effects of active manganese. Research on manganese oxidation has revealed that manganese oxides, the products of heavy metal oxidation, can play a crucial role in this process. These manganese oxides, particularly manganese (IV), are produced from manganese (II), a soluble and toxic form of manganese that can pose significant risks to human health. However, through the action of certain microorganisms, manganese (II) can be oxidized to manganese (III) and predominantly to manganese (IV), which is less harmful.

When combined with biochar, these manganese oxides can create a modified biochar that is effective in treating or removing antibiotics, such as tetracycline, through adsorption. The potential for using manganese oxides on different biochar materials to remove antibiotics is still being explored. Initially, biochar without modification was used to consider cost factors. It has been observed that manganese oxides are naturally produced through bacterial oxidation, allowing for their collection and attachment to biochar for use in antibiotic removal.

In a similar study (Zhang et al. 2024), tetracycline removal from livestock wastewater was examined using four systems: activated persulfate (PS), biochar (BC) loaded with PS, δ-MnO_2/PS, and BC

loaded with δ-MnO_2/PS. The tetracycline removal rates were tested under different temperatures, revealing that higher temperatures facilitated the reaction. At lower temperatures (15°C), the removal effect for all systems decreased; however, the δ-MnO_2/BC/PS system showed only a slight decrease, from 83% to 79%. When temperatures dropped further to 5°C–10°C, the effectiveness of all systems declined, but the δ-MnO_2/BC/PS system maintained a tetracycline removal rate of 40% at 5°C, outperforming the other systems (Figure 9).

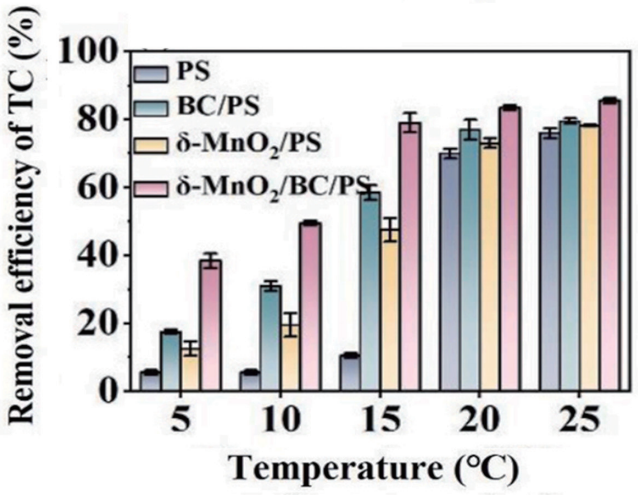


Figure 9. Tetracycline removal efficiency at different temperatures. Source: (Zhang et al. 2024)

This indicates that tetracycline removal remains a challenge, even when combining manganese oxides and biochar. Temperature conditions play a critical role in the efficiency of the process. The use of manganese oxides for wastewater treatment is an area that continues to develop. Ongoing research aims to identify which types of manganese oxides and what modifications can be implemented to enhance the effectiveness of

manganese oxides and biochar, especially in the treatment of antibiotics from farm wastewater.

(5) Combined Manganese Oxides and Modified Biochar

Modifying biochar is crucial for creating multifunctional materials with enhanced capabilities for remediating contaminated water. A promising approach involves using sunlight-sensitive micro-catalysts (SSMs), created by loading MnO_2 onto the porous structure of honeycomb-like KOH-modified biochar (MBC) to enhance photocatalytic performance. Ma et al. (2023) demonstrated the effectiveness of this composite material in degrading CTC under various conditions. The SSM exhibited significantly higher photocurrent intensity compared to pure MnO_2, underscoring its superior ability to transfer and separate photoinduced carriers, a key factor for efficient photocatalysis. This improvement is attributed to the confinement effect of the KOH-modified biochar, which enhanced MnO_2 dispersion and increased sunlight absorption for photocatalysis. Furthermore, electrostatic interactions between MnO_2 and CTC contributed to higher CTC removal efficiency. Overall, the integration of MnO_2 with KOH-modified biochar not only boosts photocatalytic performance but also ensures optimal CTC removal across a range of pH conditions. Figure 10 illustrates the synthesis process of SSM and the chlortetracycline degradation process by SSM.

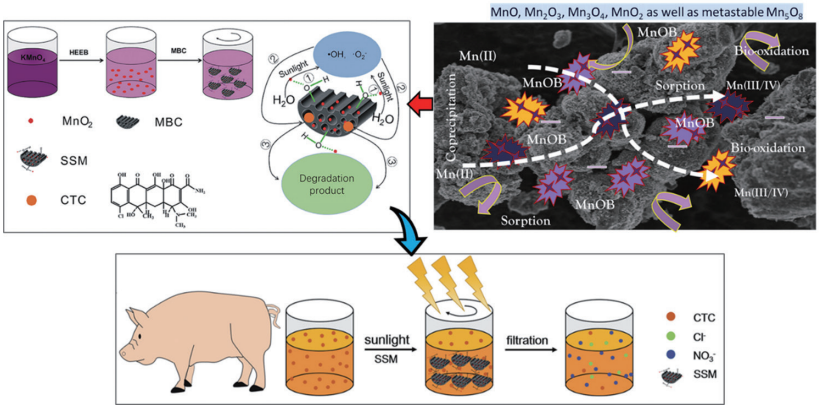


Figure 10. The synthesis process of SSM and the chlortetracycline degradation process by SSM in swine urine. Sources: (Gotore et al. 2025; Ma et al. 2023).

4. Conclusion

Intensive pig farming significantly contributes to environmental pollution, including antibiotic contamination. Many countries are implementing policies to address this issue by focusing on the treatment of swine wastewater and the safe recycling of livestock manure and wastewater in ways that minimize environmental harm. The combination of biochar and nanomaterials, such as manganese oxides, presents a cost-effective solution with enhanced antibiotic removal capacity while promoting environmental safety.

Manganese oxides are abundant, easy to process, and environmentally friendly. Biochars modified with manganese oxides often exhibit a high point of zero charge, strong positive surface charges, high oxidation potential, and a remarkable ability to immobilize antibiotics. These properties make them highly effective in mitigating

the spread of ARGs in agricultural environments. Furthermore, manganese oxide-modified biochar demonstrates a strong capacity for the adsorption and immobilization of antibiotics, further enhancing its utility in addressing pollution challenges.

Given these advantages, further research is essential to optimize the use of nanomaterials, including biochar and its modified forms, for effectively removing antibiotics from swine wastewater. This approach not only minimizes the environmental impact of intensive livestock farming but also reduces the risk of spreading ARGs, contributing to a safer and more sustainable agricultural system.

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Chapter 3. Challenges of Veterinary Antibiotic Pollution from Swine Farms and Possible Wastewater Treatment Options

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