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Swine waste, environmental contamination, and antimicrobial resistance under the One Health approach

Dejetos suínos, contaminação ambiental e resistência a antimicrobianos no contexto One Health

Mariana Oliveira-Silva, Miguel Augusto Moraes, André Pitondo-Silva*

Programa de Pós-Graduação em Tecnologia Ambiental, Universidade de Ribeirão Preto (UNAERP), Ribeirão Preto, SP, Brasil.
* Correspondence to: andre@pitondo.com.br.

ABSTRACT Swine farming is a key driver of global agribusiness and food security, but it generates millions of tons of liquid waste each year. This effluent is rich in organic matter, microorganisms, and antimicrobial residues, and when improperly managed, it becomes a major source of environmental pollution affecting soil, water, air, plants, animals, and humans. Anaerobic biodigestion is an effective and widely adopted process for managing this waste, producing both biofertilizers and biogas. However, biofertilizers may act as reservoirs of antimicrobial-resistant and multidrug-resistant bacteria, arising either from direct exposure to antimicrobial residues widely used in swine farming or through horizontal gene transfer among bacteria during digestion. The use of untreated biofertilizers can therefore disseminate resistance determinants into agricultural soils and beyond. In this context, understanding the microbiota of biofertilizers is essential to assess risks, improve waste management practices, and develop mitigation strategies. This narrative review synthesizes data on swine farming, waste generation, biodigestion processes, and antimicrobial-resistant microorganisms, with emphasis on their implications for the One Health approach. It also discusses emerging alternatives, such as probiotics, that may contribute to breaking the cycle of resistance dissemination and ensuring sustainable livestock production.
Keywords swine manure, biofertilizers, multidrug-resistant bacteria, probiotics, public health.

RESUMO O A suinocultura é um setor-chave do agronegócio e da segurança alimentar global, mas gera milhões de toneladas de resíduos líquidos a cada ano. Esses efluentes são ricos em matéria orgânica, microrganismos e resíduos de antimicrobianos e, quando manejados de forma inadequada, tornam-se uma importante fonte de poluição ambiental, afetando o solo, a água, o ar, as plantas, os animais e os seres humanos. A biodigestão anaeróbia está entre os processos mais eficientes e economicamente viáveis para o tratamento desses resíduos, gerando biofertilizantes e biogás. No entanto, os biofertilizantes podem atuar como reservatórios de bactérias resistentes e multirresistentes a antimicrobianos, seja pela exposição direta aos resíduos de antibióticos amplamente utilizados na suinocultura, seja pela transferência horizontal de genes entre bactérias durante a digestão. O uso de biofertilizantes não tratados pode, portanto, disseminar determinantes de resistência no solo agrícola e em outros ecossistemas. Nesse contexto, compreender a microbiota dos biofertilizantes é essencial para avaliar riscos, aprimorar as práticas de manejo de resíduos e desenvolver estratégias de mitigação. Esta revisão narrativa sintetiza dados sobre a suinocultura, a geração de resíduos, os processos de biodigestão e os microrganismos resistentes a antimicrobianos, enfatizando suas implicações no conceito One Health. Além disso, discute alternativas emergentes, como os probióticos, que podem contribuir para interromper o ciclo de disseminação da resistência e assegurar uma produção pecuária mais sustentável.
Palavras-chave dejetos suínos, biofertilizantes, bactérias multirresistentes, probióticos, saúde pública.

1. Introduction

Pork is the second most consumed type of meat in the world. Between 2023 and 2024, the global pork production was estimated at 116.24 million tons. China was the largest pork producer in 2023/2024, producing 57.94 million tons (totaling 50% of world production). Brazil ranks as the world's fourth-largest pork producer, trailing only China, the European Union, and the United States. Its output is 4.45 million tons, constituting approximately 4% of global pork production (USDA, 2025).

The livestock sector in Brazil is of great importance for structuring the economy, accounting for 25% of the national Gross Domestic Product (GDP) in 2022 (Cepea, 2022). However, the robustness of this sector also demands the development of effective animal waste treatment systems. According to a report by the Brazilian Institute of Geography and Statistics (IBGE, 2019), 1,703,773,970 tons of organic waste are generated annually in Brazilian livestock farming, of which 20,379,732 tons are swine waste from confinement systems. Due to their composition, animal waste is a concerning pollutant because, when improperly managed, it contaminates soil and rivers, emits foul odors, attracts insects that can be disease vectors, and can intoxicate people and animals. Consequently, this poses health risks to humans and causes environmental and economic damage to producers (Messa et al., 2016). Brasil, 2022).

In Brazil, it is estimated that only a small fraction of swine farms adopt biodigesters for manure treatment, which indicates that, despite its recognized efficiency, biodigestion is not yet the predominant method. This technology is part of a broader spectrum of manure management systems that include anaerobic lagoons, stabilization ponds, composting units, and solid–liquid separation systems, each with distinct operational characteristics and environmental implications (Hollas et al., 2023; Aneja et al., 2024). Studies have shown that these systems vary in cost, treatment efficiency, and potential for resource recovery. While anaerobic biodigestion enables biogas and biofertilizer production, its large-scale implementation is often constrained by installation costs, technical complexity, and the need for skilled operation and maintenance. In contrast, simpler systems such as lagoons or ponds remain common in small and medium-sized farms because they require lower capital investment and can be effective in reducing organic load and nutrient content when properly designed and managed. Recent techno-economic and life cycle assessments highlight that no single technology can be considered universally superior; instead, integrated waste treatment frameworks that combine physical, chemical, and biological processes provide the most sustainable outcomes, particularly when aligned with circular economy principles (Hollas et al., 2023; Aneja et al., 2024). Therefore, biodigestion should be viewed as a valuable but complementary approach within diversified manure management strategies aimed at minimizing environmental impacts and maximizing resource recovery.

Swine waste is comprised of liquid rich in organic matter, abundant macro and micronutrients, bacteria, and other microorganisms essential for biomass breakdown in biodigestion treatment. Exposure to antimicrobial residues and resistance genes can be selected for multidrug-resistant bacteria within the resulting biomass byproduct (Vital et al., 2018). Anaerobic and facultative anaerobic bacteria degrade the organic biomass during biodigestion, producing biogas and biofertilizer. These byproducts have potential applications as renewable energy sources and nutrient-rich soil amendments, supporting energy recovery and soil fertility maintenance (Vital et al., 2018).

In addition to the undeniable importance of improving livestock management practices and reducing the environmentally improper disposal of animal waste, it is increasingly essential to monitor the microorganisms that permeate the environmental, animal, and human microbiota, as zoonoses remain a major cause of human infectious diseases. According to Jones et al. (2008), approximately 60.3% of emerging infectious diseases in the past six decades are zoonotic, and about 71.8% of these originated in wildlife rather than in domesticated or confined animals. The emergence of these diseases is associated with multiple factors, including ecological and land-use changes, wildlife trade, human encroachment into natural habitats, and climate change.

Nevertheless, livestock production systems also play a relevant role in this context, as intensive animal farming can act as an amplifying environment for pathogens once they spill over from wildlife reservoirs (Plowright et al., 2017; Gibb et al., 2020). The close contact between humans and production animals, combined with the extensive use of antimicrobials and exposure to contaminated environments, reinforces the interconnectedness of human, animal, and ecosystem health (Destoumieux-Garzón et al., 2018; Robinson et al., 2016; Woolhouse & Ward, 2013). Thus, even though most zoonotic emergences arise from wildlife, monitoring pathogens and antimicrobial resistance in livestock environments remains essential within the One Health framework to prevent secondary transmission, emergence of resistant bacteria, and broader public-health impacts (Grace, 2015; da Costa et al., 2013; Herrero et al., 2009).

Zoonoses harm the sector, reducing productivity, causing missed commercial opportunities due to health concerns, and increasing unemployment rates (Zanella, 2016; Bernstein; Dutkiewicz, 2021). Along with the global concern over the spread of new diseases, there is also the critical issue of the exorbitant increase in bacterial resistance to antimicrobials, the primary drugs used to combat bacteria and often administered prophylactically for animal welfare. However, bacterial resistance has increased due to the continuous use of these antimicrobial medications. Global projections indicate that by 2050, antimicrobial resistance could be responsible for up to 10 million deaths per year (O'Neill, 2016), representing a major global health threat. Therefore, this review aims to analyze how swine waste contributes to the dissemination of antimicrobial resistance within the One Health framework.

2. Material and methods

This study is a narrative review that sought to synthesize and critically discuss the main scientific evidence available on swine farming, waste management, anaerobic digestion, antimicrobial resistance, and biotechnological alternatives within the One Health framework. Bibliographic sources included scientific articles, technical reports, and official documents retrieved from databases such as PubMed, Scopus, Web of Science, and SciELO, in addition to institutional repositories (e.g., FAO, MAPA, USDA). The search covered literature from the 1980s to 2025, with emphasis on more recent studies.

Inclusion criteria comprised peer-reviewed publications addressing swine production systems, waste treatment, biofertilizers, pathogens, antimicrobial resistance, and probiotics. Exclusion criteria involved non-peer-reviewed sources and studies not directly related to these themes. The synthesis was organized thematically into six major axes: swine production, biodigestion, biofertilizers, pathogens, antimicrobial resistance, and biotechnological alternatives, thus providing an integrative overview of the topic.

3. Swine production and manure management

The global swine farming market is led by China, which alone produced nearly half of the world's total production in 2022 and 2023. The European Union and the United States follow in second and third place, respectively, with Brazil ranking fourth. According to the 2024/2025 data (Figure 1), the ranking remains unchanged, with China maintaining the leading position, producing 57.06 million tons (USDA, 2025).

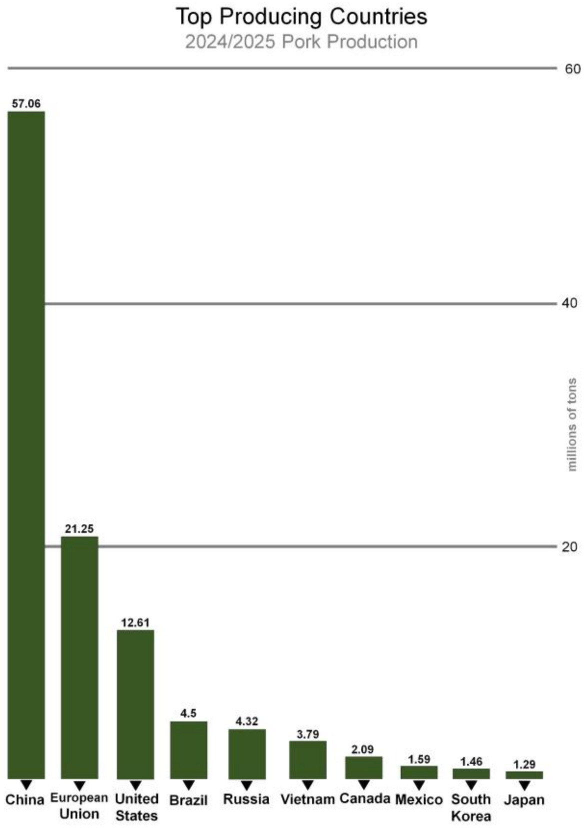

Figure 1 – Main pork-producing countries worldwide in 2024/2025.

Swine farming has been the fastest-growing sector in Brazilian agriculture in recent years. According to the Municipal Livestock Production report (IBGE, 2020), 41.1 million pigs were recorded in 2020, an increase of 1.4% compared to the previous year. In that year, approximately 901.1 thousand tons of pork were exported, making Brazil the third-largest producer and the fourth-largest exporter of pork worldwide. According to the Brazilian Institute of Geography and Statistics, in Brazil, 57.17 million pigs were slaughtered in 2023, setting a new national record for the sector, with an increase of 1.3% (+707.33 thousand pigs) compared to 2022 (IBGE, 2024).

Swine production involves small and large producers primarily engaging in industrial and technical management practices. There are various types of farms: piglet production units, weaned pig units, nursery units, finishing units, and farrow-to-finish units. The choice of farm type depends on the farm's infrastructure, resource availability, investments, and labor (Ferreira et al., 2014; Guimarães et al., 2017).

Despite good animal care practices, investments, and the profitability of the sector, swine farming presents several challenges, beginning with the extensive rearing of pigs. Daily management requires various antimicrobials in the finishing phase, from breeding sows to pigs. This is because the animals' quality of life is linked to disease control and weight gain, which is directly related to the microbiota in their intestines. The excessive use of antimicrobials throughout the swine-rearing process is one of the causes of the emergence of multidrug-resistant bacteria, the spread of resistance genes, and the contamination of soil and water with antimicrobial residues (Silva & Nörnberg, 2003; Budiño, 2009; Barko et al., 2018).

Another major issue in swine farming is the environmental impact caused by animal waste, which becomes a pollutant due to its high organic load. When directly deposited on soils, this organic load can cause saturation and leaching into water bodies, affecting the available biochemical oxygen demand and impacting the balance of aquatic life (Cardoso et al., 2015).

According to the Diagnostic Report on Organic Waste from the Agrosilvopastoral Sector (Ipea, 2012), approximately 20 million tons of swine manure are generated annually in Brazil. Despite advances in waste-to-energy technologies, a significant portion of this material is still managed without adequate environmental control. When disposed of directly onto soils without proper stabilization or nutrient management planning, swine effluent can lead to high operational costs, nutrient accumulation, and environmental contamination. Furthermore, its predominantly liquid composition increases transportation costs and often results in deposition near production sites, contributing to soil saturation and local pollution hotspots.

4. Anaerobic digestion and biofertilizers

Biodigesters represent a sustainable technology for generating energy from biomass. The first model emerged in 1939 at the Kanpur Research Institute in India. Since then, many modifications have been made to the designs, with the Chinese and Indian models being the most widely used due to their low cost and high productivity. However, the fundamental processes of biodigestion remain the same (Messa et al., 2016). In Brazil, the use of biodigesters began to be promoted by the federal government in the 1970s (Spindler, 2018).

A biodigester consists of a closed tank lined with impermeable material. In this tank, animal waste or other organic residues are deposited and degraded by anaerobic and facultative anaerobic bacteria originating from the biomass. The anaerobic biodigestion process involves four essential phases for the formation of byproducts. To achieve optimal bacterial activity, it is necessary to control temperature, pH, hydraulic retention time, and volatile acidity (Messa et al., 2016). Biodigesters are characterized by the frequency and method of feeding, solid containment in the reactor, and the agitation system. The first widely disseminated biodigesters were the Chinese and Indian models. The Chinese model was primarily used to meet fertilizer demand for crops, while the Indian model was developed to meet the energy demands of its respective countries (Rajendran et al., 2012).

According to Kunz et al. (2019), Brazil's most commonly used model is the Covered Lagoon Biodigester (CBL). The CBL model is widely disseminated in Brazil due to its advantages, such as being suitable for both small and large properties, having a low technological level, and being accessible to construct and operate. It is commonly known as the Canadian or Canvas model. This model consists of a masonry box built horizontally into the ground, with greater width than depth, waterproofed and covered with geosynthetic material. Furthermore, it is essential to consider the safety of the process, which relates to occupational and environmental risks, and the effectiveness of biogas generation.

Biodigestion is a biotechnological process that produces clean and renewable environmental energy. However, it remains difficult for small farmers to access, either due to deficiencies in institutional programs for specialized technical assistance or a lack of concern from environmental agencies. Given the operational efficiency and environmental benefits of this treatment approach, adaptations of biodigestion systems have been developed for family farming and small producers (Schalch et al., 2019). The effluent from biodigestion, known as digestate, still contains high concentrations of nutrients and organic matter, making it suitable for agricultural use. However, excessive concentrations of nitrogen and phosphorus in the residues derived from biodigestion can lead to nutrient imbalance in the soil and eutrophication of nearby water bodies if not properly managed (Vital et al., 2018; Lin et al., 2022; Kabeyi & Olanrewaju, 2022). Therefore, there are alternative methods to complement biodigestion for treating digestate, one of which is the implementation of stabilization ponds. These ponds are constructed for digestate storage and help stabilize nitrogen and phosphorus levels (Kunz et al., 2005).

The fermentation of biomass in biodigestion is divided into four stages (Manyi-Loh et al., 2013) (Figure 2). However, the process is dynamic within the digestion tank, generating byproducts through various reactions. Biodigestion includes the phases of hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The degradations occurring in these four phases are carried out exclusively by anaerobic or facultative anaerobic bacteria, each involving a specific group of bacteria (Messa et al., 2016).

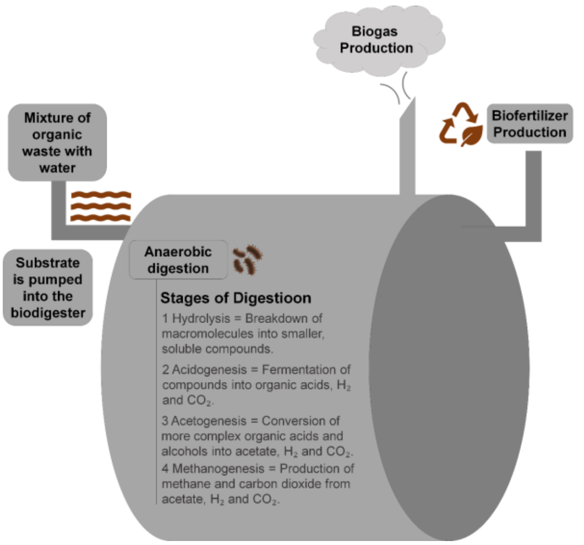

Figure 2 – Simplified diagram of the anaerobic digestion process.

The hydrolysis phase is performed by hydrolytic bacteria that secrete enzymes to break down insoluble compounds into soluble ones, converting proteins into amino acids, carbohydrates into sugars, and lipids into fatty acids. After this conversion, another group of bacteria continues the biodigestion of these soluble compounds. In the acidogenesis phase, the products from the hydrolysis phase are converted into organic acids, acetic acid, molecular hydrogen, carbon dioxide, and alcohol. The acetogenesis phase is carried out by syntrophic bacteria that metabolize the products from the acidogenesis phase, producing hydrogen gas, carbon dioxide, acetic acid, and short-chain organic acids. In the final methanogenesis phase, methanogenic bacteria transform the products from the acetogenesis phase into methane and carbon dioxide (Rizzoni et al., 2012).

Anaerobic biodigestion requires balanced conditions to ensure a good yield of the involved reactions. The control of methane gas production depends on several factors, including the amount of organic matter introduced daily into the system, pH, alkalinity, temperature, and the quality of the organic matter in the influent. This quality can be assessed by biochemical oxygen demand, chemical oxygen demand, total solids, volatile solids, and total nitrogen (Rizzoni et al., 2012).

Factors influencing the biodigestion process are directly related to the metabolism and growth of bacteria within the biodigester environment (Rizzoni et al., 2012; Schalch et al., 2019). The system is maintained by chemical and biochemical reactions that require optimal temperatures between 15°C and 65°C. This temperature range supports the growth of most microorganisms, including psychrophilic bacteria (optimal growth below 20°C), mesophilic bacteria (between 30°C and 40°C), and thermophilic bacteria (between 50°C and 65°C). Although these are the activity ranges for microorganisms, it is notable that at 37°C, the biodigestion process becomes more effective. Thus, abrupt temperature changes can affect the growth and metabolism of digesting bacteria and, in some cases, even lead to their death. Therefore, biodigestion can deactivate pathogenic microorganisms (Craveiro et al., 1982; Schalch et al., 2019).

The ideal pH range for the fermentation process should be around neutral, between 6.5 and 7.2, favoring the growth of neutrophilic bacteria. Overloading the system with organic matter can make it more acidic due to the metabolites produced during the acidification phase. Specific ions are essential for bacterial metabolism; therefore, besides the organic material metabolized by microorganisms as nutrients, the presence of inorganic ions such as phosphate, calcium, magnesium, and iron is necessary for the fermentation process to occur without negatively affecting the production of effluents (Rizzoni et al., 2012; Schalch et al., 2019).

5. Effluents: Biogas and Biofertilizer

5.1. Biogas

After the fermentation stages, the transformed biomass generates two by-products: biogas, which includes

CH_4, CO_2, and other gases, and biofertilizer (liquid effluent). These are crucial for maintaining sustainable agriculture, as both are reused in the agricultural system, reducing costs for energy and soil fertilization (Kabeyi & Olanrewaju, 2022).

Since the late 1960s, the scientific community has increasingly focused on the depletion of the Earth's ecosystem. The late 19th and early 20th centuries' industrial revolutions, along with technological advances, population growth, and globalization, improved the agro-industrial sector. However, this also led to increased use of non-renewable fuels and resources, soil depletion due to monoculture, deforestation, and pollution of air and water bodies (Hariram et al., 2023).

To reduce environmental impacts, the scientific community proposed a new form of economic development based on sustainability, aiming to minimize environmental impacts through using renewable energies and reusing waste generated by human activities. In this context, the production and use of biogas have become a way to reduce the impacts generated by agriculture, which is responsible for the largest source of methane emissions into the atmosphere, one of the leading gases responsible for the greenhouse effect. Simultaneously, costs associated with non-renewable energies are reduced, generating the Certified Emission Reductions, also known as carbon credits (IEA, 2020).

The biogas produced in anaerobic digestion systems comprises 65% methane, 35% CO_2, and 5% other gases. In addition to having high calorific value, it is a viable renewable energy alternative for utilizing organic waste, as its combustion does not generate toxic gases. Although it releases CO_2, it is 21 times less harmful than methane, and the biomass by-product can still be reused as fertilizer (Schalch et al., 2019).

5.2. Biofertilizer

China and India are the largest producers of biofertilizers, having some of the highest numbers of small-scale biodigesters, primarily used in rural areas (Vasco-Correa et al., 2018; IEA, 2020). The digestate resulting from anaerobic fermentation is rich in organic matter and can be applied as a fertilizer in various crops. When properly treated and monitored, it can provide nutrients at a lower cost compared with mineral fertilizers, without significantly altering soil pH or structure. Additionally, the preparation method of the organic matter, decomposition time, microbial population, temperature, pH, and the material of origin influence the chemical composition of this fertilizer (Vital et al., 2018).

Beyond its physicochemical stability, the agronomic use of the liquid biofertilizer derived from swine effluent has been demonstrated to improve soil fertility and crop productivity. Studies in tropical regions have shown increases in soil organic carbon, available nitrogen, phosphorus, potassium, calcium, and magnesium after successive applications of digestate, with positive effects on crops such as maize, sugarcane, pastures, and horticultural species (Kunz et al., 2019; Kabeyi & Olanrewaju, 2022). In maize cultivation, for instance, application rates between 40 and 80 $m^3\ ha^{-1}$ have resulted in yields comparable to mineral fertilizers, with lower costs and improved soil biological activity (Souza & Lage Filho, 2014).

The liquid fraction of the digestate is typically applied by fertigation or spray irrigation, favoring rapid nutrient uptake and improving soil moisture retention. Its solid fraction, when separated, can be used as a soil conditioner, enhancing structure and water infiltration. These processes contribute to nutrient recycling within circular agriculture models, where livestock residues are reapplied to soil as fertilizers. (IEA, 2020). In addition, the biofertilizer stimulates microbial activity in the rhizosphere, favoring the proliferation of beneficial bacteria and fungi, such as nitrogen-fixing and phosphate-solubilizing microorganisms. These interactions enhance plant growth and confer indirect protection against phytopathogens through antibiosis, induced resistance, and competition for ecological niches (Souza & Lage Filho, 2014; Bhattacharyya & Jha, 2012).

However, safe use requires adequate treatment and monitoring. The digestate should only be applied after stabilization and preferably after complementary maturation or pasteurization steps to ensure pathogen inactivation. Application rates must consider the crop nutrient demand, soil type, and local environmental legislation to avoid nutrient leaching or eutrophication of nearby water bodies (Lin et al., 2022; Álvarez-Fraga et al., 2025). Using organic waste from biological reactors as fertilizer is a critical way to reduce soil contamination sources and mitigate the impacts caused by agricultural waste (Vital et al., 2018). This approach integrates waste management, renewable energy generation, and nutrient recovery, potentially reducing dependence on synthetic fertilizers and mitigating environmental contamination (Vital et al., 2018; Kunz et al., 2019).

6. Pathogens in Biofertilizer

Prokaryotic organisms from *Archaea* and *Bacteria* are found in the anaerobic biodigestion process carried out in biodigester systems. Methanogenic *Archaea*, responsible for methane production, grow slowly and depend highly on optimal growth conditions, requiring vitamins, minerals, and sulfur sources. Bacteria present in other stages of biodigestion, belonging to the domain *Bacteria*, are strictly anaerobic and facultative fermenters distributed among various genera such as *Bacteroides*, *Clostridium*, *Enterobacter*, and *Citrobacter*, among others, found in the acidogenesis phase (Schalch et al., 2019; Rocha, 2020).

It is necessary to understand the microbiota and the kinetics of biodigestion to properly stimulate the growth of microorganisms and the production of effluents. Physicochemical and nutritional factors also help select the most well-adapted microorganisms. The microbiota present in biodigesters comes from pig waste, mainly composed of feces, urine, water from drinking troughs and cleaning, feed residues, hair, dust, and other compounds from the pigsty that end up being leached together into the waste tank (Rizzoni et al., 2012).

It is of utmost importance that anaerobic treatment efficiently inactivates pathogens that threaten public health to prevent the environmental dissemination of these pathogens that could affect plants, animals, and humans. Recent studies have demonstrated that pathogen inactivation during anaerobic digestion is strongly influenced by temperature, hydraulic retention time, and operational conditions (Table 1).

Enteric viruses show markedly higher inactivation rates under thermophilic conditions, with reductions up to 15–17 times faster at 55 °C compared to mesophilic regimes (Zhao & Liu, 2019; Seruga et al., 2020). Enteric bacteria such as *Salmonella* spp. and pathogenic *E. coli* exhibit only partial reduction under mesophilic digestion but can reach non-detectable levels within hours under thermophilic operation (Lin et al., 2022; Seruga et al., 2020). Mycobacteria, although more resistant, are more effectively reduced in thermophilic than in mesophilic systems (Mazzone et al., 2018; Slana et al., 2011). Helminth eggs (*Ascaris* spp.) remain one of the most persistent biological contaminants, requiring exposure to ≥ 55°C for complete inactivation within hours, while protozoan cysts and oocysts (e.g., *Giardia* and *Cryptosporidium*) are partially inactivated under mesophilic conditions but show greater reduction when thermophilic digestion or complementary pasteurization steps are applied (Naidoo et al., 2018; Naidoo et al., 2020; Seruga et al., 2020; Zhao & Liu, 2019).

Moreover, a recent meta-analysis emphasizes that artificially spiked pathogen data may overestimate inactivation efficiency under real operational conditions, reinforcing the need for conservative and evidence-based modeling of AD hygienization barriers (Álvarez-Fraga et al., 2025). These findings highlight that thermophilic anaerobic digestion, often combined with additional hygienization steps, provides a more reliable barrier against the environmental dissemination of pathogens (Table 1).

Microorganisms, due to their simple morphology and great genetic and metabolic diversity, are found in various habitats, including those with high pressure, high salinity, different pH values, high temperatures, inside rocks, in thermal springs, volcanic vents, polar regions, and many others (Araujo & Hungria, 1994). The functions of microorganisms in the environment have yet to be fully described. However, they are known to participate in biological processes such as photosynthesis, organic matter cycling, biogeochemical cycles, and maintaining soil fertility and composition. In more complex beings of the large Eukaryote kingdom, there are diverse interspecific relationships involving these microorganisms, especially bacteria. Despite being beneficial and playing fundamental roles in nutrient production, such as in the gut microbiota of invertebrates and chordates, these microorganisms are

Table 1 – Inactivation of pathogens during anaerobic digestion (AD).

Group of pathogens	Temperature range (°C)	Typical retention time	Observed reduction	Key observations	References
Enteric viruses (e.g., poliovirus, adenovirus, norovirus)	Mesophilic 35–37; Thermophilic 50–55	≥ 3 days at 55°C: strong reduction; much slower at 25–37°C	1–5 log; ~15–17× faster at 55 °C	High variability depending on virus type and matrix; thermophilic digestion accelerates inactivation.	Zhao & Liu (2019); Seruga et al. (2020)
Enteric bacteria (S*almonella* spp., pathogenic *E. coli*)	Mesophilic 24–40; Thermophilic 50–55	MAD: 7–56 d: 0–1.8 log; TAD: up to non-detectable in ≤ 24 h	0–1.8 log in MAD; ≥ 3 log in TAD	Influenced by pH, VFAs, ammonia; TAD at full scale often leads to ND.	Lin et al. (2022); Seruga et al. (2020)
Mycobacteria (*M. avium* subsp. paratuberculosis, related complexes)	Mesophilic 35–37; Thermophilic 50–55	Persist in MAD; greater removal in TAD	Variable reduction; persistence documente d in MAD	Detected in biogas plants; thermophilic digestion improves inactivation.	Mazzone et al. (2018); Slana et al. (2011)
Helminth eggs (*Ascaris* spp.)	Mesophilic 34–37; Thermophilic 50–55	3-log: ~57.5 d at 34 °C: ~2.1 d at 45 °C; 0–12 h at 55–60°C	≥3 log with increasing T; 100% within hours at ≥ 55°C.	Extremely resistant in MAD; pasteurization/TAD recommended.	Seruga et al. (2020); Naidoo et al. (2018); Naidoo et al. (2020)
Protozoa (cysts/oocysts, e.g., *Giardia, Cryptosporidium*)	Mesophilic 35–37; Thermophilic 50–55	Partial inactivation in MAD; greater in TAD with pretreatment	Partial in MAD; higher reduction in TAD	Heterogeneous data; complementary steps (pasteurization) recommended by WHO.	Zhao & Liu (2019); Seruga et al. (2020)

Notes: MAD = mesophilic anaerobic digestion; TAD = thermophilic anaerobic digestion; VFAs = volatile fatty acids; ND = not detected.

often associated with human, animal, and plant diseases (Moran, 2006).

A typical bacterium in the biodigestion system is *E. coli*, a Gram-negative bacillus belonging to the Enterobacteriaceae family. It is a well-studied commensal enterobacterium and an important pathogen responsible for causing various diseases, such as urinary tract infections and bacteremia in humans, mammals, and birds. This species is found in the gut microbiota of many animals and the environment, especially in areas contaminated by domestic and animal production sewage (soil, water, and food) (Blount, 2015).

E. coli was first described in 1885 by Theodor Escherich, who isolated it from the feces of children with diarrhea. This bacterium presents pathogenic serotypes for mammals and birds, observed in 1893 by a Danish veterinarian. It is classified into more than five serotypes according to the clinical syndromes they cause. According to the WHO (1980), the first serotype classifications were made in the 1940s using surface antigens O (lipopolysaccharide), K (capsular), and H (flagellar). The first three classes described were Enterotoxigenic *E. coli* (ETEC), Enteroinvasive *E. coli* (EIEC), and Enteropathogenic *E. coli* (EPEC).

Other serotypes were discovered and classified in the 1980s and 1990s according to adhesins and toxins produced, the infected host, the affected organ, and the type of adherence caused in cells, including Shiga/Verotoxigenic (Stx/VTEC), Enterohemorrhagic (EHEC), Enteroaggregative (AAEC), Diffusely Adherent E. coli (DAEC), Necrotoxigenic (NTEC), Uropathogenic (UPEC), Neonatal Meningitis-Associated (NMEC), Avian Pathogenic *E. coli* (APEC), among other pathotypes (Denamur et al., 2020; Vila et al., 2016; Blount, 2015; Mainil, 2013).

Pathotypes of *E. coli* possess specialized virulence factors such as adhesins, toxins, iron acquisition systems (siderophores), polysaccharide coatings, and invasins in some strains. Additionally, these microorganisms can exhibit high resistance to antimicrobials used in human and veterinary medicine, leading to the death of over 40,000 people annually in the United States. They also cause significant losses in animal production, being one of the leading agents of neonatal diarrhea in pigs, causing colibacillosis and leading to 25% of animal deaths if no measures are taken (Vila et al., 2016; Zanella et al., 2016).

According to Denamur et al. (2020), different populations of *E. coli* exist both in the intestines of vertebrates and in the environment, and both can be commensal or pathogenic. Extraintestinal Pathogenic *E. coli* (ExPEC) and Intestinal Pathogenic *E. coli* (InPEC) have evolved to improve colonization and persistence in the environment, with diarrhea being an effective way to reach the environment. Virulence is a common mechanism for enhancing permanence in the intestinal mucosa, highlighting the importance of pathogenicity islands that can be present in both commensal and pathogenic ExPEC or InPEC *E. coli.*

In addition to virulence, multidrug-resistant *E. coli* (EC-MDR) strains are widely dispersed worldwide and pose a global public health problem. These strains typically have well-established resistance mechanisms such as Extended-Spectrum Beta-Lactamases (ESBLs), carbapenemases, plasmid-mediated quinolone resistance (PMQR), and other mechanisms like ribosomal methylases affecting fosfomycin resistance, mediated by aminoglycosides. These mechanisms have been associated with high-risk clones, which are highly disseminated and already found in humans, animals, and the environment, making *E. coli* problematic in various areas (Vila et al., 2016).

Another microorganism frequently present in biodigestion processes is *Enterococcus*, Gram-positive cocci that are commensals of the digestive and urinary tracts of invertebrates and vertebrates (Gilmore et al., 2014). These bacteria can appear in pairs or chains and are commonly associated with healthcare-associated infections (HAIs), causing urinary tract infections, bacteremia, endocarditis, infections from burns and surgeries, and are one of the leading causes of nosocomial infections (Sparo et al., 2018).

Enterococcus species are frequently found on various surfaces and in the microbiota of invertebrates and vertebrates. They are also associated with plant and food fermentation. In the mid-1980s, they were classified as group D Streptococci; however, due to genotypic differences found between the Streptococci family, they were given a separate genus, and now more than 50 *Enterococcus* species are described (Fiore et al., 2019).

The success of *Enterococcus* in being a significant agent of hospital infections is mainly associated with intrinsic resistance to cephalosporins, aminoglycosides, lincosamides, streptomycin, ciprofloxacin, and vancomycin. Besides intrinsic resistance mechanisms that complicate treatments and favor the survival of these commensal bacteria, we have pathogenicity (Arias & Murray; 2012; Conwell et al., 2017).

Sometimes, these pathogens do not produce toxins. However, they have a high capacity to evade the immune system, attack host cells, extracellular matrix, and inert materials such as medication, produce adhesins, and form biofilms that increase resistance to antimicrobials, functioning as a physical barrier and benefiting pathogen survival (Garcia-Solache & Rice, 2019).

The most common *Enterococcus* species found in the clinical area are E. faecium and E. faecalis. E. faecium was classified along with eight other pathogens with a high risk of multidrug resistance. Together, these two species are responsible for 75% of *Enterococcus* HAIs, with high resistance mainly related to the spread of Vancomycin-Resistant *Enterococcus* (VRE) strains (Garcia-Solache & Rice, 2019; De Oliveira et al., 2020).

Recent studies suggest that cross-resistance between Vancomycin (used in humans) and Avoparcin (used in animals) may have arisen in food-producing animals. In these animals, antimicrobials like glycopeptides, macrolides, and oligosaccharides have been used as growth promoters and prophylactically, especially Avoparcin, since 1975. Until 2008, no VRE strains had been isolated in animals; however, once cross-resistance was discovered, Avoparcin was banned as a growth promoter in several countries

(Garcia-Solache & Rice, 2019; De Oliveira et al., 2020).

Between the 1970s and 1980s, infections caused by multidrug-resistant *Enterococcus* species emerged, and they are now among the leading causes of HAIs, being the third major cause of endocarditis in humans (García-Solache & Rice, 2019; Bräiek & Smaoui, 2019). Vancomycin was an antimicrobial primarily used intravenously in hospitals to combat strains resistant to macrolides. However, in the mid-1980s, vancomycin-resistant strains (VR) emerged. Currently, 80% of *E. faecium* isolated from hospitals are VRE and are widely spread across the globe, alarming global public health, which has lost an essential antimicrobial as a last-resort therapy (Lebreton et al., 2014; Fiore et al., 2019).

7. Use of Antimicrobials in Livestock and Antimicrobial Resistance

Antimicrobials are indispensable for livestock farming and have been applied to promote animal welfare, prevent contagious epidemic diseases, improve animal productivity, prevent the transfer of zoonoses from animals to humans, ensure the safety of animal products, and prevent foodborne diseases. Approximately 50% of antibiotics produced worldwide are used for prophylaxis and treatment of companion animals, pest control in agriculture, and promoting animal growth. It should be noted that they belong to the same classes as those prescribed for humans (Arias & Carrilho, 2012).

According to the annual report on the use of antimicrobials for animals, which compiled data for the years 2017, 2018, and 2019 (OIE, 2021), 93 tons were used, with 60% being used in Asia and the Middle East. According to Martinez (2009), it is estimated that between 1997 and 1999, antibiotic consumption in animals increased by 10% in two years in veterinary therapy in Europe.

According to the OIE (2021), 26% of antimicrobial use in 160 countries is for growth promoters, and 70% is for therapeutic use. In 2017, it was estimated that 93 tons of antimicrobials were used, going against the warnings of FAO (Food and Agriculture Organization), OIE (World Organization for Animal Health), and WHO. Since 2015, these entities have had committees to combat antimicrobial resistance and promote the conscious use of antimicrobials. According to the surveys, the most used classes of antibiotics were tetracyclines (33.9%), polypeptides (11.1%), penicillin (10.9%), macrolides (10.4%), amphenicols (4.8%), aminoglycosides (4.4%), glycopeptides (3.3%), and fluoroquinolones (3%) (OIE, 2021).

Concerns about increasing bacterial resistance due to clinical and non-clinical use of antimicrobials in veterinary medicine intensified in the 1970s, since these bacteria can be reservoirs of resistance genes and potent disseminators to pathogenic and commensal bacteria. The result of antimicrobial use in animals does not differ from human use; the amount and usage pattern determine the resistance rate (Martinez, 2009; Gilmore et al., 2014). The use of antibiotics in hospitals, agriculture, and veterinary medicine generates two types of residues: antimicrobial metabolites and resistance genes, which are released into natural ecosystems and influence the local microbiota.

It should be highlighted that antimicrobials are not biodegradable and are released in large quantities in farm and hospital effluents, contaminating surface water, groundwater, and soil. However, in the soil, many antimicrobials are naturally produced by bacteria and fungi, which are necessary to maintain the ecosystem's dynamism. Many resistance genes were already present in primitive bacteria, which used this mechanism to compete and select the most adapted individuals in the ecosystem (Martinez, 2009; Erken et al., 2013).

Antimicrobial resistance becomes problematic when these resistance genes constantly migrate through different environments. Commercial activities and the transport and exchange of people between countries have facilitated the spread of resistant bacteria to remote locations. Additionally, the close relationship between humans, domestic animals, and livestock has allowed the transition of these resistant pathogens among different hosts (Arias & Carrilho, 2012; Gilmore et al., 2014).

Society has increasingly sought ways to reduce the impacts caused by human actions on the planetary ecosystem, which has been deforested and polluted since the Industrial Revolution and technological advances in agribusiness. However, climate change, soil depletion, and ecological imbalance resulting from irresponsible human actions threaten not only food production and animal husbandry but also the stability of the global ecosystem and human survival. Like other sectors, agriculture has sought sustainable ways of planting and raising animals (Hariram et al., 2023).

In Brazil, to prevent and mitigate the already visible impacts of antimicrobial resistance, the Ministry of Agriculture, Livestock, and Supply (MAPA), in conjunction with the Ministry of Health and various other departments, published the National Action Plan for the Prevention and Control of Antimicrobial Resistance in the One Health Context (Brasil-Pan-Br-2018). This initiative aligns with the actions of the WHO, OIE, and FAO. Additionally, it standardizes, whenever necessary, ordinances restricting the use of various antimicrobials as animal growth promoters with high levels of bacterial resistance. A public consultation has even been discussed to impose more significant restrictions on antimicrobials in veterinary medicine. Such actions, norms, and resolutions regulating the use of antimicrobials in veterinary medicine should be adopted by all countries as a preventive measure.

Livestock farming is a sector of great socioeconomic importance for Brazil. However, it is also one of the largest environmental polluters due to cattle raising, pig farming, and other activities. The amount of waste produced, and its incorrect disposal and management, pollute the soil, surface water, and groundwater, in addition to contamination by pathogens from the waste (Dick et al., 2021).

To reduce this impact, farmers have invested in an environmental technology implemented in the country in the mid-1960s, when global discussions on eco-development began: anaerobic digestion systems of organic matter and biodigesters. The applicability of the biofertilizers produced in biodigesters has countless advantages, from low cost to improved crop quality. However, contamination evaluation is necessary, as some studies indicate the survival and persistence of significant pathogens in the effluent after anaerobic digestion (Guan & Holley, 2003; Ducey & Rashash; Szogi, 2019). Furthermore, the use of antimicrobials in veterinary medicine is inevitable. However, estimates suggest that 40% to 80% of this use is unnecessary, with the aggravating factor that indiscriminate use contributes to bacterial resistance (Arias & Carrilho, 2012). Therefore, methodologies that allow the identification and phenotypic and molecular characterization of these microorganisms are necessary, aiding in characterizing contamination sources, routes, and transmission mechanisms contributing to better environmental health surveillance.

Therefore, it is crucial to identify the microbiota found in effluents from livestock farms, mainly those aimed at the food industry, characterizing their pathogenic potential and antimicrobial resistance profile. This approach would enable the correct management and treatment of this product, eliminating potential pathogens and preventing their dissemination into the environment, which could contaminate crops, livestock, and the local human community. This could occur given the integration of environmental, human, and animal areas, which is a problem that should be considered as One Health.

8. One Health and Antimicrobial Resistance

One Health emerged from the necessity to integrate the significant issues affecting human, animal, and environmental health. The term has been frequently used, mainly due to urgent global challenges related to climate change, deforestation, soil saturation from agriculture, extensive animal farming, disease spread, and globalization, which impact planetary health and threaten the existence of all living beings, according to Carneiro and Pettan-Brewer (2021).

In 2008, the WHO, OIE, and FAO proposed the "One World, One Health" initiative, emphasizing the inseparability of human, animal, and environmental health and the need for interdisciplinary and intersectoral measures to improve planetary health and achieve the goals of the 2030 Agenda for Sustainable Development.

One of the issues addressed within the One Health framework is antimicrobial resistance, one of the most significant concerns of global public health since the 20th century. Many researchers consider the current era to be post-antibiotic. Antimicrobials should be cautious and precise, but this is often not the case, primarily due to the high global demand for animal protein (Cohen, 1992; Hansson & Brenthel, 2022).

Antimicrobials for animal welfare, such as growth promotion and prophylaxis, reduce sector losses and, in agriculture, prevent the action of phytopathogens. The therapy has also extended to pets, which, besides care, require antimicrobials for disease treatment and quality of life improvement (Gilbert et al., 2021; Rhouma et al., 2022). Therefore, the issue of antimicrobial resistance needs urgent attention, and actions must be taken across various fields.

The most appropriate and sensible first step is discussing antimicrobial issues within the One Health perspective. As this topic is interdisciplinary and involves various professionals, improving epidemiological surveillance and providing reliable data for decision-making can mitigate the problems arising from the continuous use of antimicrobials in the respective demand areas.

9. Probiotics and Future Perspectives

The use of probiotics in pig farming has increased in response to antimicrobial resistance concerns, mainly due to the development and advancement of antimicrobial resistance caused by continuously using antimicrobials as growth promoters. The European Union was the first to stop using antimicrobials as growth promoters since 2003 and has been urging global authorities to follow suit (Barba-Vidal et al., 2019). In this growing scenario of antimicrobial resistance (AMR) worldwide, new additives such as organic acids, plant extracts, prebiotics, and probiotics are necessary opportunities (National Pork Board, 2015).

Using probiotics in pig production aims to establish a healthy intestinal microbiota, thereby improving the health and well-being of the animals. These compounds can be part of the commensal intestinal microbiota and contribute to various metabolic complexes. Probiotics exhibit mechanisms such as pathogen antagonism, modulation of gut microbiota, and enhancement of immune response, contributing to intestinal health (Kim & Isaacson, 2015; Suvorov, 2020).

Probiotics vary in composition, dosage, and distribution, as well as factors such as strain specificity, mechanism of action, and host interaction. The bacterial genera used include *Lactobacillus, Enterococci, Bifidobacterium, Pediococcus, Bacillus, Leuconostoc, Propionibacterium*, and some fungal species (Silva & Nörnberg, 2003; Amachawadi et al., 2018). However, some of these species still present a duality between probiotics and pathogens, which is being discussed in the literature.

To be considered a probiotic in the industry, according to Musa et al. (2009), Gaggìa et al. (2010), and Barba-Vidal et al. (2019), specific characteristics are necessary, including four main ones: the ability to colonize or be metabolically active in the intestine; health promotion, such as improving immunoregulatory responses; applicability in the animal industry, such as efficacy in different hosts; and safety, being genetically stable, non-toxic, non-pathogenic, and without transmitting resistance genes.

Humanity has been using bacteria-fermented foods for centuries, including Enterococcus, one of the most prevalent bacterial groups in probiotics. Additionally, they are used to prevent and treat diarrhea in pigs, poultry, and cattle, as well as to treat recurrent upper respiratory tract diseases in humans (Zommiti et al., 2022).

Enterococci have characteristics that favor them in fermentation and food spoilage processes. They produce lactic acid and bacteriocins, which help them survive in various environments, especially in the intestines of humans and animals. In recent years, the use of some strains of enterococcal probiotics has been discouraged due to two major concerns: the spread of vancomycin-resistant *Enterococcus* (VRE) strains and the high capacity for genetic exchange with intestinal pathogens, acquiring virulence and resistance genes (Suvorov, 2020; Xu et al., 2021).

This is due to their ability to survive for long periods on environmental surfaces, their tolerance to heat, chlorine, and even contaminated sites with antibiotics (Gilmore et al., 2014), and their versatility. Their adaptability complicates control efforts, especially in hospital settings, as strains with such characteristics can cause many infections and lead to death once established in hospital environments.

Thus, various studies have been conducted to evaluate the probiotic and pathogenic capacities of certain widely used enterococcal species in livestock to validate their safe use as probiotics, given that they have been one of the main alternatives to the use of antimicrobials, especially in the animal and food industries (Suvorov, 2020; Xu et al., 2021; Zommiti et al., 2022).

Therefore, identifying and characterizing enterococcal strains from farm environments is crucial for assessing pathogenicity, as the use of probiotics has become routine in these environments. This prevents the dissemination of multi-resistant bacteria in agricultural residues derived from the use of probiotics.

In addition to *Enterococcus* species, several *Bacillus* strains, particularly *B. subtilis* and *B. licheniformis*, have been widely applied as probiotics in pig production systems due to their ability to form spores, which ensures greater resistance to feed processing and gastric conditions. Studies have demonstrated that their inclusion in pig diets can improve feed conversion, enhance nutrient digestibility, and stabilize intestinal microbiota, contributing to better growth performance and overall herd health (Zhang et al., 2020; Kim et al., 2022). These benefits are largely associated with the production of enzymes, organic acids, and antimicrobial peptides capable of inhibiting enteric pathogens and supporting gut integrity (Cutting, 2011; Elshaghabee et al., 2017). Nevertheless, as observed for *Enterococcus*, some *Bacillus* strains may carry antimicrobial resistance genes or produce toxic metabolites, which reinforces the importance of strain-level evaluation and biosafety assessment prior to their large-scale application. Although probiotics represent a promising strategy to reduce antimicrobial use in swine production, further research is needed to confirm their long-term efficacy and safety under field conditions.

10. Conclusions

Swine production sustains food security and rural economies but generates manure that, if mismanaged, disseminates pathogens, antimicrobial residues, and resistance genes. Anaerobic digestion is a cornerstone technology for stabilizing waste, producing renewable energy, and recycling nutrients; however, its hygienization efficiency depends strongly on operating conditions, and complementary measures may be necessary to ensure biosafety.

To reduce the risks associated with manure reuse, actions must integrate engineering controls, veterinary practices, and public policy under the One Health framework. Antimicrobial stewardship in swine production is essential to reduce selective pressure, while systematic monitoring of pathogens and resistome in digestate should be implemented before land application. In situations where anaerobic digestion alone is insufficient, complementary hygienization steps such as thermal treatments or maturation ponds are recommended. Furthermore, the safe use of probiotics requires strain-level validation to guarantee benefits without transferring resistance or virulence determinants.

By combining sustainable waste treatment, prudent antimicrobial use, and safe biotechnological alternatives, swine production can reconcile productivity with environmental sustainability and public health protection, contributing to the prevention of antimicrobial resistance and reinforcing global health resilience.

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The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability
This study is a narrative review based exclusively on previously published literature. No new data were generated or analyzed.

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Mariana Oliveira-Silva: Conceptualization; Methodology; Investigation; Writing – Original Draft; Visualization; **Miguel Augusto Moraes:** Data Curation; Formal Analysis; Writing – Review & Editing; **André Pitondo-Silva:** Conceptualization; Supervision; Project Administration; Funding Acquisition; Writing – Review & Editing.

ORCID ID
Mariana Oliveira-Silva: https://orcid.org/0000-0003-0459-8284
Miguel Augusto Moraes: https://orcid.org/0000-0002-3569-9267
André Pitondo-Silva: https://orcid.org/0000-0003-0098-9667

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