Programa de Pós-Graduação Desenvolvimento Regional mestrado e doutorado

DOI: 10.17058/redes.v30i1.20037

Poultry and swine production viability should not (and cannot) depend on antibiotics

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Resumo
O objetivo deste ensaio é analisar mecanismos para a adoção do uso racional de antibióticos aplicados ao modelo de produção industrial de criação de aves e suínos. Por meio de uma revisão da literatura, os resultados encontrados apontam que o sistema atual pode alcançar este objetivo, adotando práticas de bem-estar animal e biosseguridade, bem como pelo uso de aditivos alternativos, o que não implica mudanças drásticas no sistema de produção de aves e suínos e condiz com a oferta de proteínas animais de acordo com as necessidades metabólicas dos seres humanos. O uso excessivo de antibióticos leva à resistência bacteriana, enquanto a carne e os dejetos podem ser vetores de transmissão de bactérias resistentes. Dado o imenso poder da indústria que domina essas atividades, recomendamos a adoção de um sistema de registro e controle estatal do uso de antibióticos nas criações concentracionárias de suínos e aves, atualmente desconhecido no país. No mesmo sentido, propomos que pesquisas para identificação de aditivos biológicos de plantas nativas sejam incentivadas, a fim de garantir maior segurança e soberania alimentar e nutricional na oferta de alimentos derivados dessa atividade, especialmente para consumidores brasileiros.

Palavras–chave: Bem-Estar Animal. Biosseguridade. Indústria Agropecuária. Resistência Microbiana a Medicamentos. Saúde Única

The viability of poultry and swine production should not (and cannot) depend on antibiotics

Abstract
This study aimed to analyze the mechanisms for adopting rational antibiotic use in the industrial production model of poultry and pig farming. A review of the literature indicates that the current system can achieve this goal by adopting animal welfare and biosecurity practices. We also highlight that alternative additives do not cause drastic changes to poultry and pig production. This is aligned with the supply of animal proteins that meet the metabolic needs of humans. Excessive antibiotic use leads to bacterial resistance, with meat and waste acting as vectors for the transmission of resistant bacteria. Given the immense power of the industry that dominates these activities, we recommend adopting a state registration system and control over antibiotic use in concentrated pig and poultry farming, as such a system currently does not exist in Brazil. We propose that research into identifying biological additives from native plants be encouraged to ensure greater food and nutritional security and sovereignty in food supply from farming, particularly for local consumers.

Keywords: Drug resistance. Microbial. Animal Welfare. Biosecurity. Livestock Production. One Health.

La viabilidad de la producción de aves y cerdos no debe (y no puede) depender de antibióticos

Resumen
El objetivo de este ensayo es analizar los mecanismos de adopción del uso racional de antibióticos aplicados al modelo de producción industrial de la avicultura y la porcicultura. A través de una revisión bibliográfica, los resultados encontrados indican que el sistema actual puede alcanzar este objetivo mediante la adopción de prácticas de bienestar animal y bioseguridad, así como el uso de aditivos alternativos, lo que no implica cambios drásticos en el sistema de producción avícola y porcina y está en consonancia con el suministro de proteínas animales de acuerdo con las necesidades metabólicas del ser humano. El uso excesivo de antibióticos conduce a la resistencia bacteriana, mientras que la carne y los residuos pueden ser vectores de transmisión de bacterias resistentes. Dado el inmenso poder de la industria que domina estas actividades, recomendamos la adopción de un sistema de registro y control estatal del uso de antibióticos en la cría concentrada de cerdos y aves, actualmente desconocido en el país. En el mismo sentido, proponemos que se fomente la investigación para la identificación de aditivos biológicos a partir de plantas nativas, con el fin de garantizar una mayor seguridad y soberanía alimentaria y nutricional en el suministro de alimentos derivados de esta actividad, especialmente para los consumidores brasileños.

Palabras clave: Farmacorresistencia Microbiana. Bienestar del Animal. Bioaseguramiento. Industria Agropecuaria. Salud Única.

1 Introduction

This study addresses antibiotic use in concentrated poultry and pig farming and their contribution to the increasing incidence of antibiotic-resistant bacteria (AMR-Bacteria) in humans, animals, and the environment. The search for answers to

AMR-Bacteria has gained prominence due to growing environmental and public health concerns, as bacterial resistance has caused greater harm to human health than initially expected by experts (CDC, 2019).

Brazil is the largest exporter of poultry meat and the fourth largest exporter of pork, responsible for marketing an equivalent of 36% and 11% of the global export volume, respectively, with a tendency to increase their share (FAOSTAT, 2022; Embrapa, 2023a, b). This is supported by technological innovations that have enabled the production of more animal products per unit of plant calories.

The expansion of intensive pig and poultry farming in Brazil is the result of a series of processes, including improvements in the yield of the crops that feed these animals (Heinke et al., 2020; El-Deek et al., 2021; Govoni et al., 2021), enhanced formulation of feed rations for monogastrics (Pandey; Kumar; Saxena, 2019; Gaillard; Brossard; Dourmad, 2020; Gaudaré et al., 2021; Bahaddad et al., 2023; Bikker; Jansman, 2023), greater efficiency in production systems often associated with intensification (Chaiban et al., 2021; Kopler et al., 2023), and favorable prices (Roiter; Vedenkina; Eremeeva, 2021; Proorocu et al., 2021; Farkałová; Országhová, 2023) driven by reduced transaction costs and advancing vertical integration (Dong et al., 2021; Herrero et al., 2023), 2020; Herrero et al., 2023), driven primarily by the close involvement of private industry in these dynamics (Sinclair; Yan; Phillips, 2019; Albernaz-Gonçalves; Antillón; Hötzel, 2022; Gržinić et al., 2023). Additionally, Brazilian poultry and pork exports have increased due to lower labor costs, particularly compared to other countries, which is considered a major "cost advantage" (Davis et al., 2013).

Based on these premises, this study focuses on integrated and concentrated poultry and pig production systems that are primarily responsible for supplying the domestic and export markets. Brazil has undergone high implementation rates of integrated systems for raising farm animals commonly present in southern Brazil (Alves; Johann; Oliveira, 2023; Ceretta; Matte; Villwock, 2025).

This production model is made possible by high animal population densities, mortality rate due to suboptimal environmental conditions for animal well-being, and incorporation of antibiotic use in a protocol-based manner, regardless of whether there is a real need. It is a model whose political and cultural legitimacy is based on the idea that the demand for meat is rapidly increasing (Whitton et al., 2021; Govoni et al., 2022; Neeteson et al., 2023; Matte et al., 2024). Notably, recent studies have reported that the consumption of animal products is much higher than necessary to fulfill the metabolic needs of humans globally (Lancaster et al. 2018). As highlighted in an article by Abramovay et al. (2025), this trend is also observed in Brazil.

On these concentrated farms, animals are threatened by diseases that do not materialize due to large-scale antibiotic use. This scenario is conducive to the cross-resistance of bacteria to antibiotics used for human health. However, the risk of continuing this model lies in the potential emergence of new pandemics in the production sector. Studies indicate that between 2025 and 2050, approximately 39.1 million lives could be lost directly due to AMR-Bacteria, while another 169 million could be impacted by its consequences (Naghavi et al., 2024).

This farming model triggered an urgent need to adopt changes, particularly considering the high risks of contamination to human health. For example, there is an emerging alert regarding new avian influenza strains in the United States, in which the avian influenza virus (H5N1) is spreading rapidly not only among birds and wild mammals but also in cattle and domestic cats (Kozlov, 2025). Accordingly, this study aimed to analyze the mechanisms for adopting rational antibiotic use in an industrial production model of poultry and pig farming without reducing production scale.

2 Material and methods

This study aimed to answer the following guiding question: "Is the urgent need to reduce antibiotic use in concentrated farms compatible with the supply of animal products that meet the metabolic needs of humans?". This underlying is the premise that the issue is not about renouncing the mass supply of animal proteins but rather adapting this supply to the real metabolic needs of humans. This opens the path for methods that ensure large-scale production while eliminating the need for permanent antibiotic use in industrial operations (Lymbery, 2021).

To achieve this goal, this study focused on three central concepts of health, animal welfare, and rational antibiotic use. The One Health approach is described as an "integrative and unifying strategy that aims to achieve sustainable balance and optimize the health of people, animals, and the ecosystem" (FAO et al., 2021, p. 13). Animal health within the One Health approach includes criteria such as animal welfare (Gunnarsson, 2006), balance with the environment, public health, and the economic viability of production activities (Ducrot et al., 2011).

There is no consensus in the literature regarding the concept of animal welfare. Until recently, this topic was associated with the provision of food, water, and medication to enable animals to perform the economic functions for which they were bred. Recently, this notion has expanded, and today, a vast body of literature associates welfare with the dignity, intelligence, playfulness, and sociability of beings endowed with intelligence (Sigsbee, 2023; Singer, 2023; Nusbaum, 2024).

Considering that the dominant production model in pig and poultry farming harms animal welfare and contributes to excessive antibiotic use, it is necessary to discuss their rational use, and this also encompasses various definitions. According to the World Organization for Animal Health (WOAH), rational use includes implementing practical measures and recommendations aimed at improving animal health and welfare and simultaneously preventing or reducing AMR-Bacteria selection, emergence, and spread in animals and humans. For example, the European Union has banned antibiotic use as growth-promoting feed additives and for preventive use, and they should only be used metaphylactically in groups of animals in cases of a high risk of spreading infectious diseases to the entire herd (European Parliament, 2018).

Having established these concepts, to answer the research question, a literature review focusing on integrated and cooperative poultry and pig production in agro-industrial systems was conducted. The results are organized into three sections. The first section presents a brief history of the production sector transformation and discusses its high socioenvironmental costs. The second section characterizes the current poultry and pig production model in Brazil and discusses the relationship between excessive antibiotic use on industrial farms and the spread of AMR-Bacteria to humans. The third section proposes alternatives to promote animal welfare and reduce antibiotic use in the production sector.

3. Results

The following subsections analyze the main advances and recommendations for adjustments in concentrated pig and poultry production systems to reduce antibiotic use. These analyses, supported by recent literature, are dedicated to proposing mechanisms of change for the sector and are structured into five topics: changes in poultry and pig production; the relationship between the excessive antibiotic use in animal production and bacterial resistance in humans; reducing antibiotic use by promoting animal welfare (pigs and poultry); pig and poultry biosecurity; the use of alternative additives to antibiotics as growth promoters.

3.1 Changes in poultry and pig production

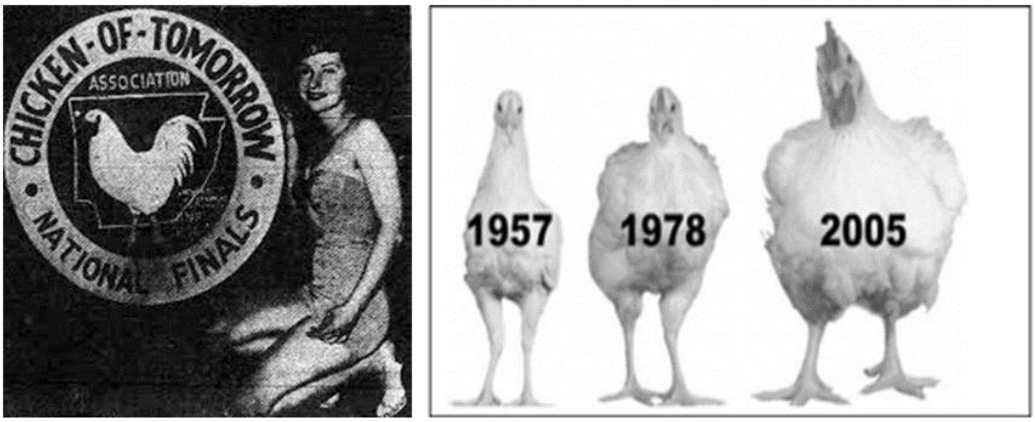
Since the 1950s, based on the *Chicken-of-Tomorrow* program, raising animals for human consumption has undergone a series of technological innovations that have enabled a spectacular increase in supply (Bennett et al., 2018). These innovations are based on the concentration of animals in small spaces, genetic homogeneity (which produces animals capable of high feed conversion), large-scale antibiotic use, and a controlled environment (Albernaz-Gonçalves *et al.*, 2024). In 1948, British biologist Thomas Hughes demonstrated that introducing small doses of antibiotics to the diet of chicks and chickens increased their growth rate, even in the absence of disease symptoms. Antibiotics have been used both preventatively and to stimulate animal growth. Scientific research has promoted transformations that, from the mid-20th century to the present day, have increased the average weight of industrial poultry five-fold (Bennet *et al.*, 2018).

The favorable context for this advance in production is related to the observation that animal husbandry is contractually integrated with the agri-food industries that supply all of the inputs (grains, medicines, and day-old chicks) and whose genetics are controlled globally by a few companies (Moraes & Capanema, 2012; Schlosser, 2024) that buy and industrialize production. According to the research group Erosion Technology and Concentration (ETC Group), just two companies control over 90% of the world's broiler genetics (ETC Group *et al*., 2022).

In the same vein, this is the supply of grain to industry. Corn and soybean production has substantial consequences for land use and environmental impacts, as they are homogenized crops and cultivations with intensive pesticide use, that continue to compete with human food (Monbiot, 2022; Godfray et al., 2018) and carry immense liabilities for ecosystem service destruction. For example, Tong et al. (2023) stated that China could reduce its national environmental footprint by increasing the import of animal feed (soy and corn) and pork, which in turn impacts other countries. Brazil is part of this equation, as it is the main exporter in Latin America and the Caribbean (30.6% of grain traded), whereas Asia is the main importer (Erenstein et al., 2022). This indicates that Brazil is treated as a supplier of raw materials, and its importers are aware of the environmental production impacts.

In 1930, the amount of breast meat produced by commercial chickens was 80% less than it is today (Figure 1) (Guo et al., 2023). Similarly, in 1970, a typical slaughterhouse in the United States processed 3,000 chickens/h. This number increased to 8,000 in the 1980s, ultimately reaching 15,000 animals/h (Molteni, 2020).

Figure 1- Chicken of tomorrow



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Genetic characteristics selected over decades of commercial activity include large breasts, white feathers to avoid skin pigmentation that might deter consumers, fast and efficient growth, consistent size, and a gentle temperament (Barbut & Leishman, 2022; Weimer et al., 2022; Guo et al., 2023).

Rapid muscle mass gain requires almost constant food consumption in a controlled environment, with lighting to encourage extended feeding periods and minimal physical effort to access this food. The monotony of breeds and natural behavior inhibition (Queiroz & Cromber, 2006) result in an environment that disregards animal welfare, promotes chronic stress, and, consequently, lowers immunity. At the end of their lives, animals suffer due to their inability to cope with rapid weight gain (Singer, 2023).

The same is true of pig farming. Although Brazil possesses diverse native breeds, they are absent from supermarket shelves. Pig farming has experienced a slower trajectory of change than that of poultry farming, and this can be explained by the predominance of activities aimed at subsistence and local markets with few rules on supply standards. The change in pig farming goes hand-in-hand with changes in fat sources for food preparation, with lards giving way to vegetable oils, leading to a demand for animals with more meat and less fat (Fávero, 2011; Chernukha et al., 2023).

The current model of industrial pig-farming houses sows in extremely small spaces, sufficient for farrowing, and they remain in contact for a few days with their piglets (Albernaz-Gonçalves; Antillón; Hötzel, 2022). After weaning, the animals are placed in finishing sheds and housed in groups of similar size. Weaning, transportation, and housing practices generate high-stress peaks and a consequent reduction in immunity, with occurrences of diarrhea, respiratory problems, locomotor disorders, and lesions on the tail, ears, and body (Ortin-Bustillo et al., 2022; Bučková et al., 2022). During finishing, male animals are subjected to testosterone production control commonly injected to avoid the strong meat odor for consumers (Tavares & Silva, 2024).

Technological packaging has led to lower meat prices and increased worldwide access and consumption (Borlaug, 2002). Products generated by pig and poultry farming are those whose consumption has increased the most globally compared to that of other meats. Herrero et al. (2023) reported that the fastest production growth occurred for poultry meat and almost tripled globally between 1990 and 2015, and this was followed by egg and pork production. The authors refer to this increase as a "monogastric explosion". This explosion is characterized by the consumption of food of animal origin that exceeds healthy levels in almost all regions of the world (Ranganathan et al., 2016; Berners-Lee et al., 2018), except in some areas of Africa and Asia. Herrero et al. (2023) pointed out that Brazil is a global champion of this growth, particularly regarding poultry, cattle, and pigs in China.

The significant participation of animal products in the human diet, particularly those originating from monogastric animals, is based on practices that violate animal welfare. This has led to a concentrated breeding model that is highly dependent on excessive antibiotic use. The relationship between concentrated production and large-scale application of these drugs is detailed in the next section.

3.2 The relationship between excessive antibiotic use in animal production and bacterial resistance

In animal production, antibiotics are used for therapeutic, prophylactic, and metaphylactic purposes, and as growth promoters (Woolhouse, 2015). Excessive use of these drugs exerts selective pressure on the bacteria present in animals that can develop resistance through mechanisms such as mutations or horizontal gene transfer (Albernaz-Gonçalves et al., 2022). It is estimated that 70% of the antibiotics produced globally are destined for animal production, with the main consumer countries being China (45% of the total), Brazil, and the USA (approximately 8% of the total each) (Tiseo et al., 2020; Albernaz-Gonçalves *et al.,* 2024).

Overuse occurs due to the structural context of an intensified production environment with reduced genetic diversity (Albernaz-Gonçalvez et al., 2024), lack of adaptation to the animals' needs to express their intrinsic behaviors (Fu et al., 2024), and painful handling practices without analgesia (Wallace, 2009). This stressful environment reduces the ability of the animal immune system to slow the transmission of infections (Ma et al., 2021). Additionally, the size, density, and inadequate health of animals all facilitate a higher rate of disease transmission in the herd (Atterby et al., 2019). Therefore, the conditions maintained by the livestock sector are reflected in their dependence on excessive antibiotic use.

Molecular studies have observed the presence of microorganisms with similar genetic resistance profiles in animals, humans (Díaz et al., 2013), and animal meat (Lazarus et al., 2015), demonstrating the transmission of AMR-Bacteria through contact with animals and food consumption, either through whole microorganisms or antimicrobial resistance genes (ARGs) between bacteria (Verraes et al., 2013). The recent evolution of H5N1 contamination in the United States is the most recent corroboration for these studies (Kozlov, 2020).

Although compliance with the grace period during the animal's life cycle and processing techniques (cooking, cooling, freezing, and others) reduces the risk of spreading AMR-Bacteria (Rana et al., 2019; James et al., 2021), there is a possibility that ARGs are transferred to human bacterial flora, as bacterial DNA is resistant to high temperatures and possibly human digestion (Bennani et al., 2020). Although it is not yet possible to measure the relevance of ARG genetic transfer to public health (Codex Alimentarius, 2021), progress has been made in this direction.

Even though there are acceptable Maximum Residue Limits (MRLs) in food as a safety measure as determined by governments and international institutions (Ben et al., 2019), chronic exposure to low amounts of residues of broad-spectrum veterinary antibiotics can exert selective pressure on pathogenic and commensal bacterial flora (Wang et al., 2016). The MRL of some antibiotics is 1,000-fold higher than the minimum dose required to select or promote resistance in a bacterium (Ji et al., 2010).

Another possible route is the dumping of animal waste containing high doses of active antibiotics into the environment, thereby contaminating soil, air, and water sources (Wang et al., 2016). Although the lifespan of antibiotic residues in the environment is short (ranging from hours to 100 days) (Hamscher et al., 2002), these residues can be considered persistent contaminants due to the uninterrupted dumping of drug residues through animal production and other sources such as the pharmaceutical industry, human sewage, and landfill leaching (Anthes & Mandavilli, 2024). Once in the environment, these residues can exert selective pressure on the bacteria in the microbiome, contributing to the formation of an environmental reserve of resistant bacteria and resistance genes (Wang et al., 2016).

Evidence has demonstrated that pathogens can spread among different species. This could have been the case in April 2024, when cows were contaminated with bird flu (H5N1.) Experts have investigated the possibility of this contagion through the consumption of food-containing poultry waste and products (Karesh et al., 2012). The selective pressure produced by bacteria and the development of resistance caused by antibiotic use are examples of how these microorganisms can evolve over a short period of time (British Poultry Council, 2023).

The existing technological frameworks often disregard the ethical and health requirements of sustainable animal husbandry. In contrast, it promotes the proliferation of infectious diseases and excessive and improper antibiotic use. This has contributed to the worsening of a sustainable contemporary problem highlighted by the World Health Organization: AMR-Bacteria. In 2019, 4.95 million deaths were associated with resistant bacterial infections (Murray, 2020), and AMR-Bacteria possess the potential to become the leading cause of death by 2050 (O'Neil, 2016; Albernaz-Gonçalves et al., 2024). Additionally, there are records of resistant antibiotics that are being developed or have recently been approved for clinical use (Martins et al., 2025), and this reinforces the urgency of reducing antibiotic use in this sector.

Although AMR-Bacteria is not limited to the impacts of antibiotic use on industrial farms and overuse by humans, scientific papers and global health authorities are advocating changes in production systems that can contribute jointly to human health to address the issue (UNEP, 2023). These changes include animal welfare promotion, biosecurity measure implementation, and adoption of alternative additives to reduce antibiotic use in the production sector. It is essential to recognize the progress made in this direction since the beginning of the 21st century.

From 2012 to 2023, data from the British Poultry Council indicated a 98.7% reduction in antibiotic use that are of critical importance to human health in poultry farming in the UK (British Poultry Council, 2023). These results were achieved by increasing ionophore antibiotic use (which is not important for human health) without implementing measures to improve animal welfare. This means that the results can be maximized if welfare measures, biosecurity, and additive use as alternatives to antibiotics are implemented (Nunan, 2022).

3.3 Reducing antibiotic use by promoting animal welfare: pigs and poultry

This topic presents animal welfare practices, starting with pig and poultry farms. Several techniques can be used to promote animal welfare, the first of which is genetic selection and the search for traits that reduce the demand for antibiotics. For example, selecting species with greater resilience to environmental stress factors and pathogens (Fu et al., 2024) or sows that produce a number of piglets corresponding to the number of teats reduces stress for the sow and piglets and improves animal health (Andersson et al., 2020; Fu et al., 2024). Additionally, the production of males with low levels of the hormone scatol, eliminating the need for castration, would reduce conflicts during the fattening period and, at the same time, guarantee meat quality (Lazul, 2021).

Another possibility is to modify the management of these animals to improve their well-being. The Brazilian Agricultural Research Corporation (Embrapa), a Swine and Poultry Unit, has proposed a system for family pig production without collective antibiotic use. This practice involves allocating piglets to siblings for finishing in the same stalls, and this provides conditions to reduce the stress caused by environmental changes. Currently, there is no control over the degree of kinship between animals when allocating them to the farms responsible for finishing (Wilbert et al., 2019).

Wilbert et al. (2019b) pointed out that by using the principles of reduced density, family rearing, and good production practices, it is possible to raise pigs without collective antibiotic use, with good production and health results. In family farming, the frequency of fights and aggressions between pigs is only 5%, regardless of the housing system (Li & Wang, 2011). Bernaerdt et al. (2022) reported that pig farms that adopted litter management did not use antibiotics for preventive purposes. We noted that family production management is still geared towards small-scale production (85-300 pigs). Future studies should replicate this model in large-scale production so that it can be widely adopted by integrated cooperative and agro-industrial systems.

It is proposed that this management protocol be implemented by painlessly marking the litter to individually identify the animals according to their genetic affiliation, to allocate them to stalls organized based on family ties, as opposed to the conventional practice of classifying them solely based on their body dimensions. Therefore, it is possible to apply family breeding for large-scale production. These strategies are interesting, as pigs possess a strong familial nature. Respecting the intrinsic characteristics of pigs create a less stressful environment, resulting in strengthened immunity (Hallenberg et al., 2020; Huong et al., 2021), thus indicating a lower need for antibiotics and respect for dignity.

Environmental enrichment also plays an important role in the health of pigs, contributing to positive affective states throughout the rearing phases and reducing behaviors such as tail biting among animals sharing a pen (Melotti et al., 2011). In general, enriched housing can favor the immunity of animals and the establishment of intestinal microbiota early in life (Henry et al., 2021; Fu et al., 2024). Exploratory behavior is innate in pigs; therefore, enriched environments are essential (Henry et al., 2021). For example, nurseries enriched with chewable materials possess the potential to induce exploratory tendencies among piglets and simultaneously promote more frequent and painless interactions between the piglets and the udder. Ultimately, this can lead to a reduction in stress levels and severity of skin lesions in lactating sows (Herskin et al., 2016).

These practices are scientifically recognized and exhibit proven effectiveness, and they are also inexpensive and in line with the intensive livestock system (D'Eath et al., 2016; Peden et al., 2018). However, despite these findings, the use of environmental enrichment is rarely guided by integrative industries and rarely observed in intensive breeding establishments (Fu et al., 2024). This may demonstrate ineffective communication among the scientific community, local consultants, and farmers (Olmos et al., 2018).

Switching from gestational crate use to collective stalls is necessary to promote the welfare of sows. Chronic stress can lead to frustration and aggression in sows during the pre-laying period (Verdon et al., 2015). Additionally, the correct management of collective stalls, with the provision of nutrients and environmental enrichment, can improve the reproductive efficiency and longevity of individuals (WAP, 2018), in addition to providing a more efficient financial performance than gestation in cages (Mauro et al., 2016).

Brazilian Normative Instruction No. 113 of 2020 (Brasil, 2020) established that by 2045, pig producers must implement production systems in collective stalls. This long implementation period was due to the financial costs involved in the production system.

The percentage of sows maintained in collective housing systems in Brazil varies according to the supplier. According to a Swine Observatory report (Alianima, 2023), Pamplona, Aurora, and JBS had more than 79% of their sow herds in this system, whereas Alegra and Frimesa had less than 50%. These figures indicate that the pig industry could adapt to these practices without losing productivity. However, more welfare practices need to be adopted to substantially reduce antibiotic use by pig farmers.

The suckling period can also affect piglets' immune responses throughout their lives, due to the importance of this phase for the production of antibodies, heat, and energy (Quesnel et al., 2012). The supply of colostrum during the first few hours after birth is crucial for intestinal protection and the piglets' passive immunity (Lynegaard et al., 2021). Weaning at an older age (> 28 days) with correct feeding management contributes to a more diverse and abundant bacterial microflora in the gastrointestinal tract, and this tends to reduce the incidence of diarrhea and antibiotic use at this stage of life (Weary et al., 2008; Pluske et al., 2018). Farm floors should be constructed to prevent slips and falls, promote health, and reduce the possibility of injuries to the locomotor system, specifically to the hooves of animals.

Cage elimination, adapted housing, management that guarantees the welfare of pigs, and family reunification favor better animal welfare conditions and can be adapted to integrated and cooperative production methods without any loss in economic performance. The implementation of these alternatives tends to increase animal immunity, thereby reducing both antibiotic use and expense, while simultaneously improving production efficiency.

Under natural conditions, birds, more specifically laying hens, exhibit natural behaviors such as scratching, taking sand baths, making nests for their eggs, taking short flights, running away from dominant birds, stretching their wings, squatting, pecking at objects, and foraging. These behaviors are restricted to caged production systems. To ensure greater welfare, it is important to consider semi-intensive production systems (or cage-free production) in which the space for behavior expression is expanded compared to conventional systems. Reducing stress and improving bird welfare requires attention to flock size, litter quality, and the presence and distribution of perches, nests, free movement spaces, and environmental enrichment (Silva et al., 2020). For example, providing a less stressful environment through adequate feed management, access to paddocks, and the provision of high perches and nests are strategies that can help prevent severe feather pecking in laying hens.

The same applies to broiler production, particularly regarding the demand for antibiotics in intensive production systems stems from high animal densities and low welfare levels. High stocking densities, without the opportunity for these animals to express their nature, negatively affect comfort and health (Mocz et al., 2022; Eijk et al., 2023; Grandin et al., 2023). For example, Eijk et al. (2023) reported that broiler chickens housed in low-density environments (24 and/or 30 kg/m2) exhibited superior welfare, litter quality, and performance indicators compared to those housed at higher densities (36 and/or 42 kg/m2).

Lannetti et al. (2021) demonstrated that broiler production on a commercial scale could be performed without antibiotics, producing animal welfare and health results equal to or better than those of conventional systems. Mortality rates were similar in both production systems. Additionally, reducing the density of chickens to 30 kg/m^2 increases production costs by 5%. This demonstrates the production potential of antibiotic-free rearing systems that meet conditions that prioritize animal welfare and simultaneously allow mass production at relatively low costs (Nunan, 2022).

According to Embrapa's recommendations (Silva et al., 2020) that are aimed at the welfare of laying hens, severe feather pecking and cannibalism should be prevented, as well as avoiding induced molting (food fasting), and natural lighting and euthanasia should be favored in the event of an animal's pathology.

Due to the high sensitivity of birds to light, light can be used to improve productivity and animal welfare in production systems. When natural light cannot be provided, artificial lighting must follow certain parameters such as a program of gradual reduction and increase (Silva et al., 2020). In contrast, exposure to white light tended to cause birds to exhibit aggressive behavior and discomfort.

Environmental stress resulting from exposure to high or low temperatures and high population densities negatively affects the health of birds and causes losses in the growth, quality, and quantity of meat and eggs, resulting in economic losses

(Bilal et al., 2021). Heat stress contributes to behavioral, physiological, and immunological changes in animals. The adoption of intermittent light programs, improved ventilation systems, adequate animal density, rearing in open cages, and adequate nutrition are alternatives for mitigating these effect.

3.4 Biosecurity for pigs and poultry

Biosecurity is a crucial issue linked to the economy, public health, human food, and nutritional safety. A biosecurity program consists of several steps related to access to the production system, including transport of animals, employees, and visitors, quarantine and adaptation to infection vectors, a cleaning and disinfection program (PLD), monitoring the health of the herd, and management of waste and carcasses (Barcellos et al., 2008).

The increase in the scale of production, ineffectiveness of antibiotics against viruses, and pressure to reduce the use of these drugs have made biosecurity measures even more important for guaranteeing the health and safety of the herd (Morés et al., 2015). These measures should be combined with animal welfare practices, environmental enrichment, nutrition, and vaccination programs.

One biosecurity practice is a sanitary vacuum, a cleaning and disinfection process that aims to eliminate as many disease-causing agents as possible that may be remnants of the previous batch of animals or may have developed due to environmental conditions. This process involves a rough wash followed by a thorough rinse using hot/cold water with disinfectant detergents. Additionally, the environment remains controlled to eliminate conditions that could promote viruses or bacteria proliferation. Morés and Gava (2017) pointed out that washing and disinfection eliminated approximately 97% of microorganisms, while the remaining microorganisms are retained in the roughness and pores of the floor. The aim is not to sterilize the environment but to eliminate possible pathogenic bacteria that could affect the herd.

Each cleaning stage significantly reduced the proportion of contaminating agents. In Brazil, fallowing is mandatory only for notifiable diseases such as Aujeszky's disease in pigs (Brasil, 2007) and Newcastle or avian influenza in poultry (Brasil, 2002). The practice of feeding pigs was conducted over an insufficient period of time (<5 days). Therefore, it is recommended that the Ministry of Agriculture and Livestock (MAPA) order cooperatives and integrators to implement a minimum acceptable period of sanitary vacuum, cleaning, and disinfection practices, even when there is no record of disease. The minimum time for pigs is 7 days (Morés & Gava, 2017), and for poultry, it is at least 15 days (Bassi et al., 2006), depending on the occurrence of diseases. There are no economic losses in this process when compared to the production profits (Martinelli et al., 2020).

To ensure thermal comfort, poultry systems use litter. This bedding is comprised of dry, soft materials such as rice husks, shavings or sawdust, crushed corncobs, sugarcane bagasse, peanut shells, coffee husks, or grass hay. This material allows animals to express their instinct to scratch and reduces injuries in areas such as the thorax, joints, and legs (Dittoe et al., 2018; Dornelas et al., 2023). The litter is commonly reused for other batches, respecting and controlling ammonia production, as volatilization in inadequate quantities of this gas harms the animals' eyes and lungs (Dornelas et al., 2023). As a strategy for controlling ammonia production and stabilizing pH basicity, Dornelas et al. (2023) stated that composting techniques with biological treatment guarantee the efficient reuse of litter for other poultry flocks without it being used as animal feed, as is the case in some countries, such as Brazil.

Transporting animals is extremely stressful. Human contact, imprisonment, and loading and unloading stages increase cortisol levels. This stress is reflected in the low immunity of the animals, and this explains the frequent antibiotic use at the beginning of piglet housing for finishing and chicks on breeding farms. This situation can be mitigated using two strategies. The first is to transport the animals in accordance with animal welfare regulations. The second concerns the environment in which the animals were housed. In the case of pigs, keeping animals with their families and providing enrichment in stalls is necessary. In the case of poultry, there is environmental enrichment and an optimal temperature.

Laws and regulations related to the transportation of live animals as cargo vary across countries. At the international level, the reference is WOAH's "International Convention for the Protection of Transport Animals" (2024). In Brazil, there are no standards that guarantee animal welfare during transportation. Bill No. 173/23 (Brasil, 2023), still pending in the legislative chamber, is an attempt to make progress in regulating the transportation of farm animals in Brazil. According to this proposal, transport vehicles must be adapted (width and height) to each species and built to avoid suffering and injury and minimize animal agitation.

3.5 Use of alternative additives to antibiotics as growth promoters

Alternative products to antibiotics as growth promoters include herbal plants, acidifiers, enzymes, probiotics, prebiotics, symbiotics, bacteriophages, and antimicrobial peptides (Rahman et al., 2022).

Enzymes are biologically active proteins that break down chemical bonds of nutrients into smaller compounds for subsequent digestion and absorption by animals. They increase intestinal stability and improve the ability of the intestine to protect itself against the accumulation of unwanted bacteria. Use of exogenous α-*mannanase* enzyme has been demonstrated to reduce post-weaning diarrhea in young piglets without compromising intestinal health or reducing weight gain efficiency (Roofchaei *et al*., 2019). Other studies have demonstrated the efficiency of various enzymes, alone or in combination with other compounds such as acidifiers, in reducing episodes of diarrhea in young piglets post-weaning (Vangroenweghe et al., 2023).

Herbal plants possess lipophilic properties and the ability to bind to or damage membranes, which enables synergistic antimicrobial activity (Rahman *et al*., 2022). Oils such as thymol and carvacrol extracted from thyme and oregano promoted animal growth and demonstrated antioxidant enzymatic activity in chickens, as well as digestive and immunological responses (Hashemipour et al., 2013). Furthermore, in another study, the use of oregano as a feed additive suppressed the growth of harmful coliform bacteria in chicken, without affecting the growth of beneficial bacteria (Navarro *et al.,* 2015).

All acids exhibited antibacterial activities. Their modes of action are diverse and can reduce the number of bacteria, modulate pancreatic secretion and mucosal morphology, and inhibit inflammatory processes (Ferronato & Prandini, 2020) (Markazi et al., 2019). Products containing propionic and formic acids or acetic acid and cinnamaldehyde can reduce the immune response and *Salmonella spp* counts in laying hens (Markazi et al., 2019). A systematic review revealed that the use of acids as additives promotes weight gain in pigs, particularly in young piglets in the nursery phase (Wang *et al*; 2022).

Bacteriophages are viruses that infect bacterial cells and cause cell death (Rahman *et al.*, 2022). They have also been demonstrated to modulate the adaptive immune response through phagocytosis and activation of inflammatory cytokines (Zheng *et al*; 2021). The use of bacteriophages as biological control in chickens reduced *Campylobacter jejuni* without adverse effects on the intestinal flora (Richard et al., 2019). Hong *et al*. (2013) demonstrated a reduction in the number of bacteria isolated and in mortality rates in chickens treated with bacteriophages, compared to the control group.

Probiotics are live microorganisms (bacteria or fungi) that are administered in adequate quantities to protect the health of the host (Rahman *et al*., 2022). Their use promotes an increase in beneficial microorganisms such as *Lactobacillus* and *Bifidobacterium* and prevents the growth of harmful bacteria such as *Salmonella enteritidis* (Abd-El Hack *et al*., 2020). Liao and Nyachoti (2017) reviewed studies that reported improved intestinal health, nutrient digestibility, and weight gain in pigs following the use of probiotics. The use of these compounds also promotes increased daily feed intake and conversion in pigs and chickens (Bajagai *et al*., 2016).

Prebiotics are compounds that serve as a food source for beneficial microorganisms in the gut, stimulating their growth (Scott, et al; 2020). While symbiotics are a combination of probiotics and prebiotics. Their use has been demonstrated to be more effective than when administered separately (Rahman *et al;* 2022*)*

The use of prebiotics in pigs reduces the abundance of pathogenic bacteria such as *Escherichia coli* and *Salmonella enterica* and increases the abundance of beneficial bacteria such as *Bifidobacteria spp* and *Lactobacillus spp* (Tzortis et al., 2005). The administration of symbiotics in chicken feed increased the abundance of beneficial bacteria and restricted pathogenic growth (S'liz˙ewska et al., 2020).

Despite their proven benefits, these alternatives can also result in adverse effects such as possible changes in meat odor and potential toxicity, thus requiring studies on palatability for consumers and minimum safe concentrations for human and animal health (Valenzuela-Grijalva et al., 2017). In addition to adverse effects, the main challenge for effective implementation lies in mass production, such as the high cost of extracting and synthesizing herbs (Tzortzis et al., 2005), the expensive synthesis of antimicrobial and acidifying peptides, the stabilization of pharmaceutical preparations of bacteriophages, and lack of laws establishing quality standards.

In Brazil, there are 783 registered additives, of which 20% are acidifiers, 52% are enzymes, 23% are probiotics, and 5% are prebiotics authorized for sale in poultry and pigs. However, there are no registered herbal plants, symbiotics, bacteriophages, or antimicrobial peptides (Brasil, 2023). Based on this information, the MAPA could create a list of all alternative additives available in the Brazilian market and make them accessible to integrators and cooperatives as possible substitutes in pig and poultry production, encouraging the replacement of antibacterial additives.

Therefore, it is crucial to investigate their positive effects on Brazilian plants for the purpose discussed. Biavatti et al. (2003) observed that fluid extracts of *Alternanthera brasiliana* and propolis resin could be used as antimicrobials in broiler farming. The authors stated that the additive could perform the same function as that of antibiotics as feed additives without compromising the taste and smell of chicken meat.

It is important to mention that although there are Brazilian government programs to monitor antibiotic use and antimicrobial resistance in animals, no official data has yet been published on the subject (Silva et al., 2023). Dutra et al. (2021) reported that pig production animals receive antibiotics for 70% of their lives. The results revealed that the amount used in Brazil (358.4 mg/kg) for pigs was higher than that used in most European countries (Dutra et al; 2021). In 2024, antibiotic consumption by farms in the state of Minas Gerais reached 434.17 mg/kg (Oliveira et al; 2024).

Given that most producers are integrated into agro-industries and receive veterinary assistance (Embrapa, 2023 a,b), it is possible to use prescriptions and/or health programs signed by veterinarians as a data source. The agro-industry should be responsible for providing these data that should be used to structure a government surveillance database on antibiotic consumption and made available for public access. Additionally, these data should be used to guide the implementation of welfare and biosecurity measures as well as the next steps for responsible and prudent antibiotic use on industrial farms. It is important to note that Brazil, despite accounting for 8% of antibiotic consumption, does not have consolidated data or official monitoring of antibiotic consumption during animal production. Therefore, antibiotic consumption should be monitored as an indicator of animal welfare.

4 Conclusions

A global surge in the production and consumption of pork and poultry occurred in the second half of the 20th century, driven by industrial intensification, lower production costs, and decrease in animal protein prices. Systems integrated into cooperatives and agro-industries, dominated by a handful of companies that control the genetic monotony of the species, have been generalized globally.

The behavioral nature of these animals is altered and they are subjected to stressful environments, thus making them more vulnerable to infectious diseases. This has been addressed by industry through the large-scale antibiotic use. Excessive antibiotic use leads to bacterial resistance, and meat and waste can act as vectors for the transmission of resistant bacteria. Given the immense power of industry that dominates these activities, it is essential to implement state policies that regulate their use. Additionally, it is necessary to encourage research on the identification of biological additives from native plants to guarantee greater nutritional security and sovereignty in the supply of food derived from this activity, particularly for Brazilian consumers.

Multilateral organizations and international civil society are pressuring Brazilian agribusinesses to adopt such practices. Despite some progress in product exports, products that use fewer antibiotics are still aimed at niche consumers in the domestic market. As noted, some national industries are gradually adopting animal welfare practices; however, they are still insufficient to significantly reduce their use. The first step toward effective change is the adoption of a broader concept of animal welfare that goes beyond the availability of water, food, and medicines. Recognizing this broader concept involves investments in infrastructure and human resource training. The studies mentioned in this review corroborate the hypothesis that the gains from these investments would outweigh the losses resulting from herd mortality due to infectious diseases and the losses resulting from low animal welfare indices. However, further studies are required to confirm this hypothesis.

The current integrated system can significantly reduce antibiotic use in farming by adopting better production practices and respecting the nature of animals. For pigs, increasing the maternity areas for expressing piglets and sows, raising animals in families for finishing, enriching stalls, and adopting biosecurity practices are effective measures to reduce the need for antibiotics. For poultry, reducing the stocking density per aviary, using natural light during part of the day, and enriching the environment contributed to this reduction.

The adoption of welfare and biosecurity practices as well as the use of alternative additives does not imply drastic changes in the current production model. This implies that the quantity produced by systems promoting rational antibiotic use through the adoption of the aforementioned techniques is compatible with supplying animal products that meet human metabolic needs. These approaches reduce antibiotic costs and have been demonstrated to increase production efficiency in this sector, as there are fewer animal losses due to the disease, and increased welfare typically improves production results. Therefore, they should not reduce production or profitability, allowing safer products to be offered to consumers while also reducing the risk of bacterial resistance resulting from excessive and often unnecessary antibiotic use.

The transition to a production model that prioritizes animal welfare, biosecurity, and rational antibiotic use will reduce the risks associated with bacterial resistance and guarantee production chain sustainability in the long term. Implementing these changes requires collaboration among producers, industries, government agents, and international organizations, as well as investment in the research and development of technologies that promote animal health and food safety. In this manner, safer products can be offered to consumers without compromising the sector's profitability, while also mitigating the environmental and health impacts associated with excessive antibiotic use.

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