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Review

Brazilian Challenges and Perspectives on *Klebsiella pneumoniae* Antimicrobial Resistance: A One Health Narrative Review

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Simple Summary

In Brazil, public health problems are more complex than ever, often involving connections between people, animals, and the environment. The increasing threat of multidrug-resistant pathogens like *Klebsiella pneumoniae* represents a complex challenge that requires a holistic approach. This strategy, known as One Health, promotes collaboration across human, animal, and environmental health sectors to effectively prevent and respond to health threats. This review explains the origins of this idea, starting with historical figures who saw the link between human and animal diseases. We then explore how the concept evolved into a global strategy supported by major international health organizations. The review highlights the importance of recognizing diseases that spread from animals to humans—called zoonoses—and how veterinarians play a central role in managing these risks. We also discuss the growing problem of antimicrobial resistance (AMR) and how this issue must be addressed with combined efforts across all sectors. With its rich biodiversity, large food production systems, and strong scientific institutions, Brazil has the tools and responsibility to be a leader in promoting One Health solutions. Applying this strategy now—before the next crisis—can help protect health, support the economy, and improve global well-being.

Abstract

The escalating complexity of interactions among humans, animals, and the environment has driven the global adoption of the One Health framework as a strategic framework to address health threats that transcend disciplinary boundaries. This is especially the case in Brazil, a country of global relevance where high rates of antimicrobial resistance (AMR) in *Klebsiella pneumoniae* intersect with structural limitations in veterinary practice, public health governance, and environmental surveillance. This narrative review synthesizes the existing literature to explore the evolution of the One Health concept, from its historical roots to its current recognition, reinforced by health emergencies such as the COVID-19 pandemic. Fundamental pillars of the approach—interdisciplinarity, cross-sectoral collaboration, and integrated surveillance—were discussed in light of the essential role of veterinarians in mitigating such threats. The discussion deepens the understanding of AMR within a multisectoral context, reinforcing the need for coordinated, preemptive actions rather than reactive responses. We advocate that the implementation of a robust One Health agenda, supported by advanced tools like metagenomics, is fundamental to ensuring population health, economic sustainability, and global security.

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1. Introduction

The increasing complexity of interactions between humans, animals and the environment in recent decades has driven a paradigmatic shift in the way the global community understands, researches and addresses public health problems. The One Health approach has emerged as an essential conceptual and practical framework for addressing threats that transcend traditional boundaries between biomedical, environmental and social disciplines [1,2]. Its effective implementation is essential for the prevention and mitigation of health crises, such as zoonosis outbreaks and the spread of antimicrobial resistance (AMR), challenges that require a coordinated and multisectoral response [3,4]. Exclusively regarding AMR, *Klebsiella pneumoniae* (*K. pneumoniae*) has gained prominence due to its multifactorial resistance mechanisms, which include genetic determinants [5–7], β-lactamase production, altered membrane permeability [6,8,9], and chromosomal mutations [8]. In this context, in countries recognized for the export of meat and other food products, the interplay between One Health perspectives and AMR further underscores the need to focus on *K. pneumoniae*.

From a One Health perspective, Brazil faces several structural weaknesses when compared to high-income countries. One critical challenge is the fragmentation between human, animal, and environmental health sectors, which often operate with limited integration and communication [10,11]. In addition, deficiencies in sanitation infrastructure and waste management remain a major barrier, particularly in rural areas and peripheral urban regions, facilitating the persistence of zoonotic and waterborne diseases [12]. Surveillance systems for emerging pathogens are frequently underfunded and unevenly distributed across the country [13]. Furthermore, the expansion of agriculture, livestock, and deforestation heightens the risk of cross-species transmission. These structural weaknesses not only hinder the implementation of an effective One Health framework but also create favorable conditions for the emergence and dissemination of multidrug-resistant pathogens such as *K. pneumoniae*.

Narrative reviews addressing either the One Health approach or *K. pneumoniae* in the context of AMR are available in the literature [12,14–25]. However, given Brazil's specific structural, epidemiological, and policy-related challenges, a balanced debate integrating these factors is still lacking. Such gap underscores the relevance of conducting a narrative review that situates AMR within the Brazilian context, particularly considering the last multicenter metagenomic investigation of the bacteriome and resistome in humans and food-producing animals across five Brazilian regions [26,27]. This study not only revealed a high microbial diversity and the widespread presence of resistance genes, including carbapenemase-encoding genes not previously reported in Latin America, but also highlighted the circulation of clinically significant pathogens such as *K. pneumoniae* in both humans and livestock.

This narrative review aims to explore antimicrobial resistance in *K. pneumoniae* within a One Health framework, emphasizing the structural and epidemiological particularities of Brazil and their implications for surveillance, policy, and public health strategies. Secondarily, we sought to analyze data on animal scientists in Brazil and to understand how their professional roles may contribute to addressing antimicrobial resistance related to *K. pneumoniae* in the national context.

2. Methods for This Review

The databases PubMed, Web of Science, and Google Scholar were searched to identify studies addressing the association between *K. pneumoniae*, AMR, and the One Health approach, with a specific focus on Brazil. Considering the need for a literature search with a time frame appropriate to the objectives of this review, we included articles published over the past 25 years. In Web of Science and Google Scholar, combinations of the following keywords were applied: "*Klebsiella pneumoniae*", "antimicrobial resistance", "One Health", and "Brazil". For PubMed, advanced searches were conducted using Medical Subject Headings (MeSH) terms, including "*Klebsiella pneumoniae*" [MeSH], "Drug Resistance, Bacterial" [MeSH], "One Health" [MeSH], and "Brazil" [MeSH]. Narrative reviews, systematic reviews, or meta-analyses were included regardless of the time frame, provided they were necessary to support points previously established but subsequently updated or modified recently. Inclusion criteria consisted of peer-reviewed articles, reviews, and policy documents in English or Portuguese, published in the period of 2000–2025, relevant to conceptual, epidemiological, or policy aspects. Exclusion criteria consisted of abstracts, editorials, or purely clinical case reports. Information on agricultural and environmental policies and regulations was retrieved from official Brazilian government websites, including the Ministry of Agriculture and Livestock ("https://www.gov.br/agricultura", accessed on 1 September 2025), the National Health Surveillance Agency (ANVISA; "https://www.gov.br/anvisa", accessed on 1 September 2025), the Ministry of Health ("https://www.gov.br/saude", accessed on 1 September 2025), the Brazilian Agricultural Research Corporation (EMBRAPA; "https://www.embrapa.br", accessed on 1 September 2025), Federal Council of Veterinary Medicine (CFMV; "https://www.cfmv.gov.br/", accessed on 1 September 2025), and the Brazilian Association of Animal Scientists (ABZ; "https://abz.org.br/", accessed on 1 September 2025).

3. One Health Approach: Conceptual Development and Current Scientific Evidence

Although the term One Health was formalized in the early 2000s, its roots date back to the 19th century [28,29]. Rudolf Virchow, who coined "zoonosis," argued that human and veterinary medicine were inseparable [30]. In the mid-20th century, Calvin Schwabe advanced this vision with "One Medicine," promoting interdisciplinary collaboration and integration with the social sciences. The shift from "One Medicine" to "One Health" was driven by global health crises, notably SARS-CoV-1 (2002–2004) and the highly pathogenic avian influenza (HPAI) H5N1 threat, which revealed the risks of fragmented approaches [31,32]. The 2004 Manhattan Principles consolidated this framework, expanding it to include environmental health [33]. This paradigm evolved through crises, gaining traction after failures of compartmentalized public health, most recently with COVID-19. Yet, political will and funding often surge reactively, leaving the challenge of embedding One Health in governance and financing. Today, the Quadripartite Organizations—the Food and Agriculture Organization of the United Nations (FAO), the United Nations Environment Programme (UNEP), the World Organization for Animal Health (WOAH), and the World Health Organization (WHO)—formally endorse the approach, stressing intersectoral collaboration for twenty-first-century health challenges [4,34,35].

One Health is based on four structural pillars that make it a concrete and effective framework for public policy formulation, research and field interventions, meaning it is more than a philosophy [36]. The interaction between humans, animals and the environment forms a dynamic and complex triad, in which disturbances in one of the vertices can generate unpredictable and sometimes catastrophic consequences in the others [37]. Its key pillars are summarized as Interdisciplinarity, which integrates knowledge across medicine, veterinary,

biology, ecology, social sciences, and policy to address complex problems like AMR [38]; Cross-sectoral collaboration, engaging government, private sector, non-governmental organizations, and communities to translate research into policies and actions [34,39]; and Integrated surveillance, based on human, animal, and environmental health data for early detection of pathogens and resistance genes, enabling rapid, coordinated responses [40].

The effectiveness of the One Health approach relies on understanding the multiple factors that shape human, animal, and environmental interactions. Beyond biological and ecological aspects, contextual factors at local and global levels critically influence health outcomes. Social determinants, such as economic factors and poverty, unequal access to health and sanitation services, education, and cultural practices, shape population vulnerability to AMR and zoonoses. An effective One Health strategy must be coupled with inclusive public policies addressing these structural inequalities [41]. Political and governance factors also determine the success of integrated surveillance and response programs. Governance quality, public funding, and inter-ministerial coordination are crucial, while weak regulatory frameworks can undermine technical efforts [15]. Finally, One Health implementation raises ethical considerations that require transparency. These include data-sharing governance and open access to data and interoperability of data systems, defining interprofessional responsibilities in crises, and ensuring equitable allocation of scarce resources such as vaccines and new antimicrobials [42].

Considering these modulating factors is essential to design interventions that are scientifically sound, socially just, politically feasible, and ethically responsible. A major global health threat in the 21st century is the emergence and re-emergence of zoonotic diseases. It is estimated that more than 60% of all known human infectious diseases can be spread from animals, and 3 out of every 4 new or emerging human infectious diseases come from animals [31,43]. This underscores the importance of understanding pathogen transmission between animals and humans, increasingly shaped by human activities in the Anthropocene. Zoonotic threats span a broad spectrum of diseases, which can be categorized by epidemiological impact and global attention. A One Health strategy must balance preparedness for high-impact pandemics with ongoing control of neglected zoonoses affecting millions daily.

4. Antimicrobial Resistance

4.1. Antimicrobial Resistance and One Health

Alongside the threat of zoonoses, AMR is one of the most serious public health crises of the 21st century. AMR occurs when microorganisms such as bacteria, viruses, fungi, and parasites evolve, rendering treatments ineffective. The emergence and spread of multidrug-resistant (MDR) and pandrug-resistant (PDR) bacterial strains threaten decades of medical progress, making routine procedures like surgery and chemotherapy risky and increasing morbidity and mortality [44].

Understanding AMR requires shifting from a clinical problem confined to hospitals to a comprehensive ecological crisis, framed within One Health. Environmental microbiomes, especially soil and water, are vast reservoirs of antibiotic resistance genes (ARGs) [45]. The set of all ARGs in a niche is called the resistome. Horizontal gene transfer connects the environmental resistome to clinical problems. Through conjugation, transformation, and transduction, bacteria exchange genetic material, even between distant species. Mobile genetic elements (MGEs), such as plasmids, transposons, and integrons, transport ARGs. This allows resistance genes from harmless soil bacteria to reach commensals in farm animals and then human pathogens [45]. Indiscriminate use of antibiotics in human medicine, veterinary medicine, and agriculture creates selective pressure, favoring bacteria that acquire these genes and accelerating their spread across the One Health triad.

The complexity of AMR and zoonosis epidemiology, involving interactions between humans, animals, and the environment, demands advanced surveillance tools. Metagenomics, enabled by next-generation sequencing (NGS), allows investigation of entire microbial communities at unprecedented detail [46]. Traditional microbiological surveillance relies on isolating and cultivating microorganisms, but over 99% of bacterial species are not cultivable. Whole Metagenome Sequencing (WMS) sequences all DNA from environmental or host samples [47]. This provides a holistic view, identifying species composition, abundance, ARGs (including novel ones), and MGEs, revealing the potential for resistance spread [48,49].

Metagenomics enables understanding of transmission mechanisms, emergence of new pathogens, and AMR dynamics. These data inform public health policies, preventive measures, and mitigation strategies. NGS platforms such as Illumina generate billions of short, high-precision DNA reads, allowing large-scale analyses [50].

4.2. Antimicrobial Resistance and K. pneumoniae

K. pneumoniae isolates are traditionally classified into two categories: classical *K. pneumoniae* (cKp) is linked to nosocomial infections in patients with comorbidities, often multidrug-resistant but of low virulence [51]; hypervirulent *K. pneumoniae* (hvKp) causes severe infections in healthy individuals, producing siderophores and excessive capsules (serotype K1), and is historically sensitive to most antibiotics [52]. The boundary between these types is becoming blurred. Convergent strains now combine cKp multidrug resistance with hvKp virulence, causing severe infections in healthy people while resisting available antibiotics [52]. Their global spread represents a major AMR threat.

β-Lactam antibiotics, including penicillins, cephalosporins, and carbapenems, inhibit bacterial cell wall synthesis [53]. Carbapenems (e.g., imipenem, meropenem) are potent drugs reserved for serious infections [9]. Resistance mainly arises from carbapenemases that hydrolyze these antibiotics. Genes encoding carbapenemases often reside on MGEs, facilitating spread among bacterial species. Genomic surveillance also reveals less common but potentially dangerous resistance genes in human, animal, and environmental reservoirs [54]. Their presence in agriculture highlights the need for continuous monitoring.

The mechanisms driving AMR in KP are diverse and multifactorial. First, the bacterium frequently acquires resistance genes through MGEs such as plasmids, transposons, and integrons. This horizontal gene transfer promotes the spread of extended-spectrum β-lactamases (ESBLs) and carbapenemases, including bla_{KPC}, bla_{NDM}, and bla_{OXA} [5–7,9]. β-lactamase production is a major resistance mechanism. ESBLs confer resistance to penicillins and cephalosporins, while carbapenemases (e.g., KPC, NDM, OXA-48-like) inactivate carbapenems, often considered last-resort antibiotics. Mutations in these genes can also reduce susceptibility to newer agents like ceftazidime-avibactam [55,56]. Changes in outer membrane permeability, such as loss or modification of porins OmpK35 and OmpK36, limit antibiotic entry, especially β-lactams and carbapenems. This often works in combination with β-lactamases to produce high-level resistance [6,8,9]. The upregulation of efflux pumps enables the bacterium to expel multiple antibiotics, including tigecycline and fluoroquinolones, contributing to multidrug resistance [8,56]. Additionally, chromosomal mutations affecting ribosomal proteins, regulatory genes, or lipid A modifications (as in colistin resistance) further enhance resistance under antibiotic selection pressure [6].

Clinically, MDR and carbapenem-resistant *K. pneumoniae* significantly limit treatment options and increase morbidity and mortality, particularly in bloodstream and urinary tract infections [57]. Surveillance shows rising resistance to carbapenems, cephalosporins, aminoglycosides, and fluoroquinolones, with some regions reporting carbapenem resistance in over 40% of clinical isolates [7]. The spread of AMR is influenced by antibiotic use,

socioeconomic factors, environmental conditions, and the genetic background of strains. Clonal expansion and plasmid transmission play key roles in persistence and dissemination [5,6]. The pathogen's genomic plasticity and ability to acquire resistance from diverse sources, including environmental reservoirs, further complicate control.

In summary, AMR in *K. pneumoniae* results from a combination of acquired and intrinsic mechanisms, producing resistance across multiple antibiotic classes and posing a major challenge to infection management and public health.

5. How Does Brazil Address Zoonoses and Antimicrobial Resistance?

5.1. Governance of Zoonosis Control and One Health Implementation in Brazil

The governance of zoonosis control and One Health implementation is still limited by structural barriers. Although the Unified Health System provides a nationwide framework, institutional fragmentation occurs between sectors like the Ministries of Health, Agriculture, and Environment [10]. In this scenario, poor communication channels and verticalized programs hampers coordinated action, highlighting the weaknesses in environmental surveillance and intersectoral coordination [58]. These problems result in inefficient intersectoral coordination and limited integration of human and veterinary surveillance data. Furthermore, the decentralization of Zoonosis Surveillance Units is uneven, leaving several municipalities without adequate infrastructure to detect and respond to emerging threats [59] (Figure 1). These structural weaknesses hamper the full operationalization of a One Health strategy and highlight the urgent need for investments in capacity building, information systems, and governance mechanisms.

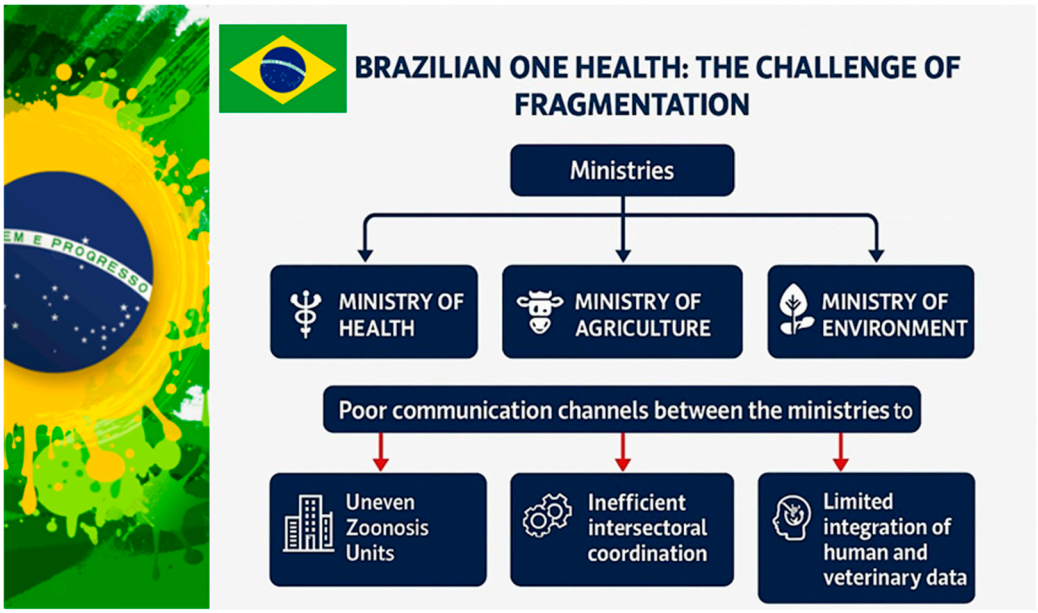


Figure 1. Institutional fragmentation as a challenge to the implementation of One Health in Brazil. The flowchart illustrates the structural barriers impeding the effective implementation of the One Health strategy in Brazil. Top-level ministries (Health, Agriculture, and Environment) are depicted, with arrows indicating their intended collaboration.

After years of neglect, the Brazilian Federal Government has begun to implement several measures to adopt the One Health approach. In 2024, the Interinstitutional Technical Committee for One Health was established to promote comprehensive health, fostering collaboration among different sectors to develop an integrated national policy [58]. In addition, the Ministry of Health, the Ministry of the Environment, and the Oswaldo Cruz

Foundation (Fiocruz)—the leading Brazilian public research institution in health science and technology—are jointly developing a National One Health Action Plan. Finally, on 5 January 2024, Law no. 14,792 was enacted, establishing the National One Health Day, with the goal of "raising public awareness of the inseparable relationship among animal, human, and environmental health" [60].

Municipal examples illustrate that despite structural challenges, localized One Health-focused initiatives can yield measurable improvements in zoonosis surveillance and control. In Foz do Iguaçu, the Zoonosis Control Center transitioned over ~23 years from a sectorized, paper-based surveillance system to a digital, integrative model encompassing zoonotic diseases, vector-borne diseases, and venomous animal injuries [61]. The implementation included merging field teams, adopting software tools like QGIS for real-time mapping, empowering health agents, and conducting active surveys. These changes led to a ten-fold increase in notifications of zoonoses and a 21-fold increase in venomous animal incidents, without compromising arbovirus surveillance.

The municipality of Bertópolis implemented a comprehensive One Health approach to manage human rabies cases in the Pradinho Indigenous village. This initiative involved coordinated efforts among health, veterinary, and environmental agencies to conduct surveillance, prevention, and control measures, demonstrating the effectiveness of integrated strategies in remote communities [62]. In southeastern Minas Gerais, a surveillance and control program were established for feline sporotrichosis, a zoonotic fungal infection. The program evaluated various strategies to identify suspected and infected cats, reinforcing the One Health approach by linking animal health surveillance with human health outcomes [63]. Another study in the region reported feline cases of sporotrichosis and correlated them with human diagnoses. This correlation underscores the importance of the One Health approach in implementing prophylactic measures and protocols for evaluating both positive and suspected cases, highlighting the interconnectedness of human and animal health [64]. Recently, Montenegro experienced Brazil's first highly pathogenic avian influenza outbreak in a commercial poultry farm. The response included rapid veterinary intervention, movement restrictions, and spatial risk assessments, exemplifying a One Health approach to managing zoonotic disease outbreaks in agricultural settings [65].

Despite the ongoing challenges and disorganization in intersectoral communication aimed at zoonosis control in Brazil, numerous initiatives led by researchers can be found in the literature, demonstrating the potential for localized One Health interventions. However, further discussion is warranted when addressing *K. pneumoniae*, given its unique characteristics, high resistance potential, and complex epidemiological dynamics, which pose distinct challenges compared to other zoonotic pathogens.

5.2. Challenges Faced by Brazil in Addressing K. pneumoniae Resistance

Brazil, like many countries, faces a major challenge with *K. pneumoniae* resistance. This pathogen is associated with both healthcare- and community-acquired infections in this country, with a significant and growing burden of MDR, extensive drug resistance (XDR), and, more recently, sporadic PDR. It is a leading cause of bloodstream and urinary tract infections. Recent data indicates a high prevalence of MDR isolates even in community-acquired infections, with carbapenem resistance rates approaching 5% in these settings. Community-acquired bloodstream isolates tend to be more resistant and more likely to produce ESBLs and carbapenemases than urinary isolates [1].

Exclusively in the hospital setting, according to the 2024 national health surveillance bulletin, *K. pneumoniae* was the second most frequently isolated Gram-negative agent in bloodstream infections and urinary tract infections in adult intensive care units [66]. Resistance levels are alarming, reflecting strong selective pressure in Brazilian hospitals. MDR

and XDR *K. pneumoniae* are highly prevalent, with resistance profiles including ESBLs (predominantly CTX-M types), carbapenemases (almost exclusively KPC-2), and resistance to last-resort agents such as colistin and tigecycline [67–70]. The emergence and dissemination of high-risk international clones, particularly those belonging to clonal complex 258 (CC258, including ST11, ST23, ST340), have been documented across multiple regions, including the Amazon, Southeast, and Midwestern Brazil [67,69,71]. These clones frequently harbor both resistance and virulence determinants, and convergence of these traits has been observed since at least 2013 [68].

Virulence factors such as hypermucoviscosity, biofilm formation, and the presence of genes like *entB*, *iutA*, *mrkD*, and *ycfM* are variably distributed among Brazilian isolates, with some strains displaying hypervirulent phenotypes alongside MDR or XDR profiles [68,71,72]. Colistin resistance, often associated with higher virulence, has reached alarming rates in some regions, notably São Paulo [67,70]. The genetic basis for resistance is multifactorial, involving both acquired mobile elements (e.g., $bla_{\text{CTX-M-15}}$, $bla_{\text{NDM-1}}$) and chromosomal mutations affecting regulatory and efflux systems [69].

Comparative genomics studies highlight the unexplored diversity of *K. pneumoniae* in Brazil, with the identification of globally disseminated sequence types (e.g., ST15) and novel clones, as well as the persistence of strains lacking classical virulence factors but still capable of causing severe disease [73]. Historical collections from the 1980s and 1990s show that while virulence factors were present, clinically significant resistance mechanisms were less common, underscoring the recent acceleration of resistance dissemination [72].

5.3. Veterinarians and Zootechnicians in Brazil: Distribution and Role in Zoonotic Disease Management

Brazil, with a population of approximately 214 million inhabitants, had around 166,000 active veterinarians in 2022, according to data from the CFMV [74]. The country also hosts 536 veterinary schools, making it one of the nations with the largest number of veterinary professionals and educational institutions. These figures reflect a rapid expansion of the veterinary workforce over recent decades, although the distribution of professionals is uneven, with higher concentrations in the southern and southeastern regions of the country. Additionally, as of 2023, there were 47,891 registered animal scientists (zootechnicians) in Brazil, with 19,889 students currently enrolled in undergraduate programs [75]. This indicates a growing number of professionals in the field, complementing the veterinary workforce and contributing to the country's agricultural and livestock sectors. However, as of July 2025, Brazil had a total of 279,847 registered veterinarians, of which 212,530 were actively practicing, representing approximately 76% of the total registered professionals. In parallel, by 2023 the country counted 47,891 registered zootechnicians, with 37,354 actively practicing, corresponding to roughly 78% of registered individuals [75] (Figure 2). These figures highlight a substantial veterinary workforce with a high proportion of active professionals, while the zootechnician workforce shows a lower rate of active engagement relative to the total registered. The distribution of both professions varies across regions, reflecting potential disparities in workforce availability for animal health, agricultural support, and zoonosis control initiatives.

Despite the rapid growth in the number of veterinary professionals in Brazil, the quality of veterinary education remains a central concern. The same document provided by CFMV reports that while 95% of veterinarians express satisfaction with their profession, criticisms persist regarding the structure and rigor of undergraduate programs. The proliferation of veterinary schools without adequate curricular standardization has raised concerns about graduates being insufficiently prepared to meet professional challenges. Careful evaluation of existing courses and implementation of measures to ensure educational

excellence are therefore essential. In terms of remuneration, veterinarians in Brazil face disparities between the responsibilities of the profession and compensation. The absence of a nationally regulated minimum salary contributes to professional undervaluation and may hinder the attraction of new graduates to strategic areas such as public health and zoonosis control. Other key findings from the report include the uneven regional distribution of veterinarians, with higher concentrations in the southern and southeastern regions, while other areas face workforce shortages. Despite these challenges, most professionals report high job satisfaction, and overall employability within the field remains strong, although salaries and working conditions vary significantly across regions and sectors.



Figure 2. Regional disparities and uneven professional engagement in Brazil's One Health Workforce.

5.4. Are Animal Science Professionals in Brazil Prepared to Manage K. pneumoniae?

As previously reported, the management of *K. pneumoniae* depends on factors such as access to diagnostic equipment as well as clinical expertise. Another important aspect to consider is the distinction between domestic and non-domestic animals. Management of *Klebsiella* infections is guided by antimicrobial susceptibility, infection severity, and the increasing prevalence of MDR strains. Regarding bovine mastitis, initial therapy with cefazolin may be considered if supported by local susceptibility. However, clinical response should be assessed within the first 24 h; if there is no improvement, prompt escalation to a fluoroquinolone is associated with improved cure rates, reflecting the need for early adjustment based on clinical response and likely resistance patterns [76].

For severe or refractory *K. pneumoniae* infections, especially those caused by MDR or carbapenem-resistant strains, combination antimicrobial therapy may be warranted. While most data are from human and experimental models, combinations such as ceftazidime-

avibactam with a carbapenem or aminoglycoside have demonstrated synergistic effects and improved outcomes in severe infections due to KPC-producing *K. pneumoniae* [77]. The use of combination therapy is particularly important in critically ill or hypotensive patients, where monotherapy may be insufficient; in less severe cases, monotherapy with an agent active against *K. pneumoniae* (e.g., β-lactam or aminoglycoside) may be adequate, provided susceptibility is confirmed [78].

Emerging alternatives such as bacteriophage therapy are under investigation. Experimental models demonstrate that phage therapy, alone or in combination with antibiotics like ceftazidime-avibactam, can significantly reduce bacterial burden and may offer a future adjunct or alternative to traditional antimicrobials, though clinical application in veterinary medicine remains investigational [79,80].

Management of *K. pneumoniae* infections in veterinary medicine should rely on local susceptibility data, rapid clinical assessment, and timely escalation to broader-spectrum or combination therapy when needed. The question is whether Brazil is equipped, both in terms of evidence-based knowledge and the necessary diagnostic resources, to achieve this goal. The study published by Ribeiro et al. [81] provides further evidence of these challenges, reporting, from 1997 to 2019, 697 cases of *K. pneumoniae* -induced infections in domestic animals in Brazil. The findings revealed a wide spectrum of clinical manifestations, including urinary, enteric, mammary, reproductive, and respiratory disorders. Alarmingly, more than 90% of isolates were resistant to ampicillin, and 20.4% exhibited multidrug resistance, severely restricting therapeutic options. The study also highlighted limitations such as the lack of standardized susceptibility testing and scarce epidemiological data, which complicate both diagnosis and treatment in veterinary practice in this country. These issues emphasize the need for improved diagnostic capacity, systematic surveillance, and specialized training for veterinarians to effectively manage *K. pneumoniae* in Brazil.

6. Strengths, Limitations, and Insights into Future Research

This review is the first to highlight the role and distribution of animal scientists and their contribution to the national workforce regarding *K. pneumoniae* antimicrobial resistance in Brazil. By integrating epidemiological, structural, and professional aspects, the study offers relevant insights to guide future research and policy. However, its scope is limited by the scarcity of studies directly linking AMR, *K. pneumoniae*, and One Health in Brazil, as well as by the heterogeneity of the available evidence. These gaps preclude a more consistent nationwide or global analysis and underscore the need for more systematic and regionally representative investigations.

Future research in Brazil must directly address the structural and scientific gaps that hinder the effective management of *K. pneumoniae* under the One Health framework. Investigations should map the availability of diagnostic resources across regions, assess the preparedness of veterinarians and animal scientists, and evaluate how antimicrobial stewardship protocols are implemented in real-world settings. Expanding genomic and metagenomic surveillance of animal and environmental reservoirs in Brazil would also provide crucial data on the emergence and dissemination of resistance genes, supporting evidence-based interventions tailored to the country's heterogeneous contexts.

At the policy level, Brazilian research should explore how governance structures, intersectoral coordination, and workforce distribution influence the ability to control *K. pneumoniae*. Comparative analyses between municipalities with integrated zoonosis programs and those lacking such initiatives could highlight best practices and critical barriers. Furthermore, studies examining the relationship between veterinary education quality, professional training, and AMR outcomes are essential for guiding national strategies (Figure 3). By generating Brazil-specific evidence that links professional practice, infrastruc-

ture, and policy to health outcomes, future research can contribute to building a coherent and sustainable response to antimicrobial resistance in *K. pneumoniae* within the Brazilian One Health agenda.

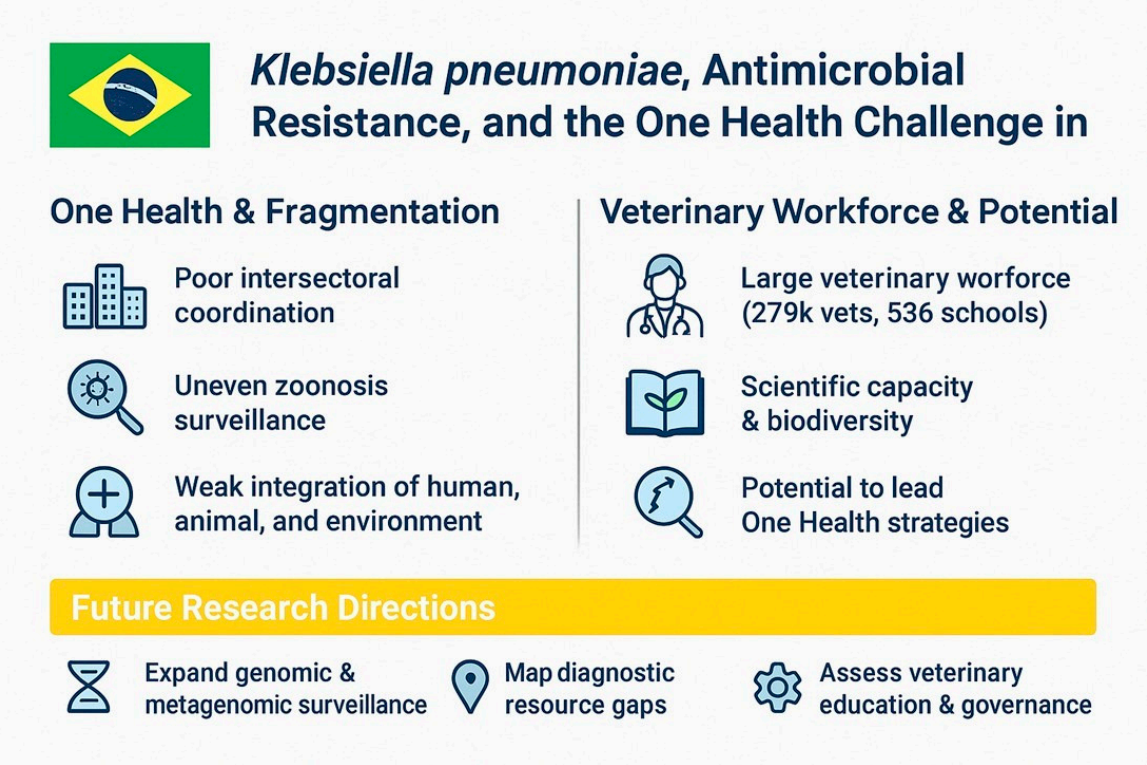


Figure 3. The challenges and opportunities for tackling *K. pneumoniae* antimicrobial resistance in Brazil.

The inclusion of the One Health approach in higher education programs related to human, animal, and environmental health is essential to prepare future professionals who would work in interdisciplinary collaboration. Integrating One Health into the curricula of Medicine, Nursing, Biomedical Science, Veterinary Medicine, Animal Science, and Biology would foster a holistic understanding of health challenges at the human–animal-ecosystem interface. This approach would encourage students to think beyond disciplinary boundaries and to recognize how zoonotic diseases, antimicrobial resistance, and environmental degradation are interconnected. By promoting collaborative problem-solving and shared responsibility, universities would cultivate a new generation of professionals capable of designing and implementing integrated health interventions. Ultimately, incorporating One Health into higher education would strengthen preparedness for global health threats and promote sustainable health outcomes for all species.

7. Conclusions

This narrative review highlights that *K. pneumoniae* represents a critical challenge for Brazil, where high rates of antimicrobial resistance intersect with structural limitations in veterinary practice, public health governance, and environmental surveillance. Despite the presence of a large veterinary workforce and strong scientific institutions, the country continues to face barriers related to uneven access to diagnostic resources, insufficient intersectoral integration, and gaps in professional training. Integrating the One Health approach into higher education would promote interdisciplinary training and prepare professionals to address the interconnected challenges of human, animal, and environmental health.

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