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Epistemological perspective on antimicrobial resistance in the one health context

Perspectiva epistemológica sobre a resistência antimicrobiana no contexto da saúde única

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ABSTRACT

Antimicrobial resistance (AMR), once a natural evolutionary phenomenon, has become a critical global public health threat due to the excessive and indiscriminate use of antibiotics. Over recent decades, widespread antibiotic use in clinical, agricultural, and environmental settings has exerted substantial selective pressure on microbial populations, accelerating the emergence and horizontal transfer of resistance genes. These resistant organisms, and their genetic elements, now circulate not only in healthcare systems but also in natural ecosystems, highlighting the scale and complexity of the problem. This study adopts a qualitative, applied research design grounded in a multiple case study methodology with cross-case synthesis, complemented by bibliometric network analysis using VOSviewer software. A literature review spanning the years 2014 to 2024 was conducted using a curated set of interdisciplinary keywords to capture the convergence of environmental science, microbiology, and public health. The findings revealed thematic clusters and knowledge structures associated with AMR, particularly its links to environmental contaminants such as heavy metals. By situating AMR within the One Health framework, this manuscript emphasizes the interconnectedness of human, animal, and environmental health. It calls for integrative and transdisciplinary strategies capable of responding to the biological, social, economic, and policy-related dimensions of AMR, underscoring the urgent need for systemic and coordinated global action.

Keywords: antibiotic overuse; ecosystem health; public health; resistant pathogens; sustainable management.

RESUMO

A resistência antimicrobiana (RAM), inicialmente um fenômeno evolutivo natural, transformou-se em uma ameaça crítica à saúde pública global em razão do uso excessivo e indiscriminado de antibióticos. Nas últimas décadas, a ampla utilização desses fármacos em contextos clínicos, agrícolas e ambientais exerceu intensa pressão seletiva sobre comunidades microbianas, promovendo o surgimento acelerado e a transferência horizontal de genes de resistência. Esses microrganismos resistentes e seus elementos genéticos passaram a circular não apenas em sistemas de saúde, mas também em ecossistemas naturais, sublinhando a complexidade e a escala transetorial da problemática. Este estudo adota uma abordagem qualitativa e aplicada, com base em metodologia de estudo de caso múltiplo e síntese comparativa, sendo complementado por uma análise de redes bibliométricas por meio do *software* VOSviewer. Realizou-se uma revisão de literatura referente ao período de 2014 a 2024, com o uso de um conjunto curado de palavras-chave interdisciplinares que permitiram capturar a convergência entre ciência ambiental, microbiologia e saúde pública. Os resultados revelaram agrupamentos temáticos e estruturas de conhecimento associados à RAM, com destaque para suas relações com contaminantes ambientais, como metais pesados. Ao situar a RAM no escopo do paradigma *One Health*, este estudo reforça a interdependência entre a saúde humana, animal e ambiental. Conclui-se pela urgência da adoção de estratégias integrativas e transdisciplinares, capazes de contemplar as dimensões biológicas, sociais, econômicas e políticas da resistência antimicrobiana que orientem ações coordenadas em escala global.

Palavras-chave: uso excessivo de antibióticos; saúde dos ecossistemas; saúde pública; patógenos resistentes; gestão sustentável.

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Introduction

Antibiotic resistance is a natural phenomenon that occurs within microbial communities in the environment. It is considered “ancient” and plays a crucial role in bacterial survival, preventing what has been termed “bacterial suicide” (D’Costa et al., 2011). Consequently, antibiotics themselves are not inherently resistance-promoting agents; rather, it is their excessive and indiscriminate use that imposes selective pressure on bacterial populations, leading to the selection of resistant strains. These adapted strains can cause severe infections that are difficult to treat (Baquero et al., 1998). In addition, resistant bacteria have been found in natural environments, including soils, rivers, seas, and oceans, posing a serious threat to human and planet health (Alkorta and Garbisu, 2024).

Antimicrobial resistance is a worldwide phenomenon that goes beyond healthcare systems and is intimately related to ecosystems and human activities. Addressing resistance in environmental sciences necessitates an examination of its diverse sources, which include excessive antibiotic usage in animals, water pollution, and poor hospital waste disposal. Excessive and frequently improper antibiotic prescription, as well as self-medication, are still common in many nations, including Brazil (Pellegrino et al., 2024). According to Brazil’s National Health Surveillance Agency (ANVISA), the most often prescribed and ingested antibiotic in the country is amoxicillin, a beta-lactam penicillin. Quinolones, including ciprofloxacin, are also commonly utilized. Despite ANVISA legislation barring the sale of medicines without a prescription, indiscriminate consumption continued significantly throughout the coronavirus epidemic, demonstrating the problems of implementing effective antimicrobial stewardship (Silva et al., 2021; Pellegrino et al., 2024).

This paper follows an epistemological approach to the analysis of antibiotic resistance (AMR), emphasizing its complexity and the multifaceted interaction between science, society and politics. AMR represents a key threat to the health of the Earth, where microbial evolution is influenced by human activities and environmental degradation. Like climate change and biodiversity loss, AMR needs an epistemological approach that transcends disciplinary boundaries to uncover its complex drivers and update the design of effective integrated interventions. Here we explore how different scientific and methodological perspectives can improve our understanding of resistance and its extensive environmental and social impacts. A solid understanding of the concept of emotion is essential for the effective communication of research results to various audiences, including policy makers, health professionals and the general public, and for promoting informed decisions and collective action.

Methodology

This study uses a qualitative and applied research design based on the multiple case study approach and a cross-case synthesis, following the methodology framework proposed by Yin (2015). In order to complement and deepen the analysis, the method of bibliometrics was applied, following the procedure described by Ruthes and Silva (2015). The bibliography review was conducted using a series of keywords curated based on their relevance to cross-disciplinary research in the fields of microbiology, environmental sciences and public health, such as antibiotics, antimicrobials, resistant bacteria, heavy metals, environmental pollution, antibiotic resistance, metal resistance and one health. These terms reflect the conceptual convergence underlying the One Health paradigm, which emphasizes the interconnectedness of human, animal, and environmental health.

The literature search was limited to publications from 2014 to 2024, a timeframe selected to encompass the most recent scientific output and regulatory developments addressing the global rise of antimicrobial and metal resistance. The data were analyzed using VOSviewer (https://www.vosviewer.com/), a software tool designed for constructing and visualizing bibliometric networks. For this study, a minimum keyword co-occurrence threshold of seven was established to ensure that only substantively connected terms were included in the clustering process. The use of VOSviewer allowed for the generation of co-occurrence maps that revealed thematic clusters and knowledge structures across the selected literature. This methodological configuration enabled a multidimensional exploration of resistance mechanisms, environmental drivers, and their implications within the One Health framework.

Interconnection between environmental sciences and antibiotic resistance

Antibiotic resistance cannot be addressed only by microbiological means; it encompasses larger concerns such as natural resource utilization, waste management, environmental pollution, and ecosystem conservation (Goryluk-Salmonowicz and Popowska, 2022). Interdisciplinary and transdisciplinary research is critical for solving this complicated issue. Overuse of antibiotics in animal farming and aquaculture, as well as environmental degradation and social behaviors, are major contributors to resistance spread. A particularly major source of resistance is the indiscriminate use of antibiotics in animal husbandry, where they are frequently provided to treat infections and enhance development, worsening the problem (He et al., 2020). In 2017, cattle accounted for 73% of all antimicrobials used globally. This excessive usage is directly linked to the growth of drug resistance in both animals and people (Chantziaras et al., 2014; Van Boeckel et al., 2017).

The incorrect disposal of hospital, industrial, and pharmaceutical waste into water systems is a major conduit for antibiotic resistance propagation. Furthermore, antibiotic resistance is inextricably linked to social and economic issues such as uneven healthcare access and a lack of effective government measures. Despite antibiotics’ pioneering influence on bacterial illness therapy, Alexander Fleming cautioned in 1945, 17 years after their discovery, about the vital significance of using these medications with caution and the immediate possibility of bacterial resistance to antibiotics (Antimicrobial Resistance Collaborators, 2022).

Bacterial resistance to antibiotics is a natural phenomenon that results from the selection pressure exerted by their usage. However, antibiotic abuse and overuse have hastened the process (Silva et al., 2022). There is a disturbing association between growing antibiotic usage and rising levels of microbial resistance. As a result, the World Health Organization (WHO) has prioritized rational and responsible antibiotic usage in the 21st century.

The development of resistance includes the selection of bacteria that are naturally resistant to antibiotics, a phenomenon that has grown more common as these medications are increasingly misused. Authorities have expressed major worries, as seen by the increasing number of reports of resistant bacteria over time. Antibiotic resistance, along with diseases caused by resistant bacteria, is increasingly recognized as a worldwide health risk. It is one of today's most pressing public health challenges, with major clinical and economic implications (Antimicrobial Resistance Collaborators, 2022).

Staphylococcus aureus, specifically the methicillin-resistant strain (MRSA), is normally prevalent on the skin but can cause serious infections if it travels to other regions of the body, such as pneumonia and meningitis. Research indicates that *S. aureus* strains are resistant to almost all β-lactam antibiotics (Piltcher et al., 2018). *Burkholderia cepacia* is another highly resistant bacteria that can be especially dangerous to people who already have lung ailments. Furthermore, *Pseudomonas aeruginosa* is known for its fast mutation and capacity to respond to antibiotic treatments. The causative agent of tuberculosis, *Mycobacterium tuberculosis*, is one of the top causes of death due to antibiotic resistance (Antimicrobial Resistance Collaborators, 2022).

The issue of "superbugs", bacteria resistant to several antibiotics, has gained significant attention due to its clinical, environmental, economic, and scientific implications. Despite considerable efforts to develop new antibiotics, particularly those derived from natural sources, the discovery of new drugs has not kept pace with the growing prevalence of resistant bacteria (Moreira and Cardoso, 2016; Piltcher et al., 2018). In 2017, WHO published its first list of "priority pathogen families" resistant to antibiotics, which includes 12 bacterial families posing the greatest threat to human health. This list aims to direct scientific and technological advancements toward the development of new drugs to combat these bacteria, most of which are Gram-negative and multi-resistant, meaning they are resistant to more than one type of antibiotic (Antimicrobial Resistance Collaborators, 2022).

Misuse of antibiotics

Unfortunately, the present approach to most antibiotic treatments is generic, with drugs provided without identifying which bacterium is causing the infection, and broad-spectrum antibiotics are frequently utilized. Antibiotics should be given only when the kind of bacteria causing the infection has been determined. If therapy must begin before clinical data or cultures are available, it is preferable to use narrow-spectrum antibiotics with short durations to reduce the side effects of these medications (Antimicrobial Resistance Collaborators, 2022).

The indiscriminate use of antibiotics contributes significantly to the selection of resistant microorganisms. This was especially visible during the COVID-19 pandemic, when antibiotics were widely and incorrectly used to treat viral infections (Romaszko-Wojtowicz et al., 2024). In response, the Pan American Health Organization (PAHO) and WHO issued guides to educate and raise public awareness about this issue during the pandemic (Del Fiol et al., 2022).

In April 2024, the WHO stated that, despite the fact that only 8% of hospitalized COVID-19 patients had bacterial coinfections that required antibiotic treatment, 75% of these patients were nevertheless given antibiotics on the notion that they "might help" (Romaszko-Wojtowicz et al., 2024). This trend shows a common practice of overprescribing antibiotics without strong clinical justification. Furthermore, statistics from 2014 provided by the European Centre for Disease Prevention and Control (ECDC) showed that 80 to 90% of all antibiotic prescriptions were granted by general practitioners, mostly to treat respiratory tract infections. However, the majority of these illnesses are caused by viruses that do not react to antibiotics, making their usage superfluous and contributing to the growth of antimicrobial resistance (Llor and Bjerrum, 2014; Romaszko-Wojtowicz et al., 2024).

Another concern with antibiotic therapy is that many patients fail to finish the entire course of medication. When patients notice an improvement in their symptoms, they discontinue the medication on their own, which can lead to reinfection by germs that survived the treatment. In other words, halting therapy allows for the selection of resistant germs. Furthermore, antibiotic usage can have an influence on the gut microbiota, which is made up of bacteria that live in symbiosis with humans and help the body defend itself by preventing the colonization of alien germs (Silva et al., 2021).

Several studies have found that antibiotic usage can impact neutrophil proliferation and activity, affecting their reactivity to different chemokines and thereby interfering with the immunological response. It is vital to remember that neutrophils are regarded as the primary cells in the body's first line of defense, since they are among the first to respond when an infection begins (Kraus and Gruber, 2021).

Epistemologies, implications for public policies, and environmental management

Environmental sciences necessitate ongoing conversation across many epistemologies, including those of the environmental, social, economic, and political sciences. In the case of antibiotic resistance, traditional techniques that focus primarily on biological features must be supplemented by methodologies that consider ecological dynamics as well as socioeconomic issues.

Understanding resistance from a biological standpoint, including the use of experimental methods to isolate and characterize resistant bacteria, is critical. However, cultural and social elements, such as human behavior and governmental policy, must also be considered in order to understand the emergence of antibiotic resistance. The integration of environmental, social, and economic data to produce viable solutions, including effective public policies, is critical for antibiotic management sustainability (Miethke et al., 2021).

Antibiotic resistance is a problem that necessitates an integrated response, including public policies that incorporate environmental components, such as controlling antibiotic usage in animal agriculture and ensuring adequate pharmaceutical waste disposal (Arnold et al., 2024). Furthermore, coordination across disciplines and sectors is critical for executing long-term solutions and reducing the impact of resistance on the environment and public health (Majumder et al., 2020).

Antibiotic-resistant bacteria are not just selected in clinical and hospital settings (Murray et al., 2024). Environmental issues such as incorrect antibiotic disposal, inappropriate use in aquaculture and animal production, and genetic factors all impose selective pressure on resistant microorganisms. Recent study has found that both meat and plant-based meals can transfer antibiotic resistance to the microbiota of the ultimate consumer. Furthermore, the growing use of antibiotics in agriculture is a big problem, as these treatments are used not only to treat sick animals, such as those with mastitis, but also as a preventative measure and to accelerate growth in healthy animals (Antimicrobial Resistance Collaborators, 2022; Murray et al., 2024).

This improper practice not only contributes to the selection of resistant microorganisms in animals' bodies, which can then spread to the environment via feces, but it also leads to the accumulation of these drugs in the environment due to improper disposal or excretion by animals (Murray et al., 2024). As a result, soil and other environmental samples have been identified as potential reservoirs of antibiotic resistance. However, few research studies have investigated how environmental samples influence the transmission of antibiotic-resistant "superbugs" (Martinez et al., 2015). The complexity of microbial communities and their interactions in the environment, both among microorganisms and within biogeochemical cycles and other ecosystem components, makes it difficult to appreciate the entire scope of the problem (Pacheco et al., 2021). Studies have also highlighted an important component of antibiotic resistance: the impact of environmental contamination in worsening this worldwide problem (Table 1).

This table highlights typical research on the co-selection of antibiotic and metal resistance in various ecological situations. The mentioned publications use methodological techniques such as metagenomics, culture-based analysis, and critical reviews to investigate ecosystems ranging from mangroves and hot springs to agricultural waste. Collectively, these studies illustrate the complicated relationship between environmental contaminants and AMR, emphasizing the significance of interdisciplinary approaches within the One Health paradigm.

Environmental pollution, which has long been associated with ecosystem degradation and biodiversity loss, is now well recognized as a potent cause of AMR via co-selection processes. Recent high-resolution metagenomic investigations have shed light on how heavy metals and other environmental pollutants exert selective pressure, preserving and amplifying resistance gene pools in natural ecosystems. For example, Imchen et al. (2018) discovered a pervasive resistome in mangrove ecosystems around the world that was closely related to metal concentrations, whereas Jardine et al. (2019) discovered intrinsic resistance traits in microbial communities from South African hot springs exposed to geochemically enriched waters. Samreen et al. (2021) compiled further data from soil, water, and air matrices, demonstrating that AMR extends well beyond clinical settings, indicating substantial environmental entrenchment. In addition to these findings, Liu et al. (2022) discovered substantial co-localization of metal and antibiotic resistance genes in animal manure, indicating agricultural practices as crucial nodes in the environmental spread of resistance. These findings all point to the same conclusion: environmental contamination is a critical, often ignored aspect of the global AMR pandemic that must be included into One Health surveillance and policy frameworks immediately.

Table 1 – Key studies addressing antimicrobial resistance (AMR) and its environmental drivers.

Study	Objective	Key Findings	Relevance to One Health / AMR
Baker-Austin et al. (2006)	Examine the phenomenon of co-selection between antibiotic and metal resistance	Demonstrated that metal contamination can co-select for antibiotic resistance genes via mobile genetic elements	Introduced co-selection as a key mechanism linking environmental pollution and AMR under the One Health lens
Imchen et al. (2018)	Compare mangrove microbiomes globally to identify AMR and metal resistance genes	Revealed the global prevalence of both heavy metal and antibiotic resistance genes in mangrove ecosystems	Highlighted the environmental dissemination of AMR and its ecological persistence
Jardine et al. (2019)	Assess intrinsic resistance in bacteria from geothermal environments	Identified naturally occurring resistance to antibiotics and metals in isolated strains	Suggested that some resistance is ancient and environmental, complicating anthropogenic attributions
Liu et al. (2022)	Characterize the resistome in animal manure	Found high abundance of both antibiotic and metal resistance genes in livestock waste	Reinforced the role of agricultural practices as AMR reservoirs with environmental and public health implications
Samreen et al. (2021)	Synthesize knowledge on environmental AMR drivers and their health impact	Identified pollution, waste management, and inadequate sanitation as key AMR drivers	Advocated for environmental governance reforms within AMR mitigation strategies and One Health policies

While the link between heavy metal pollution and the rise of antibiotic resistance is now of great interest, it is not new, albeit underexplored. Baker-Austin et al. (2006) published substantial research on co-resistance and co-selection of heavy metal resistance genes and antibiotic resistance genes in 2006, confirming this association through molecular and biochemical pathways. These include membrane transporters and efflux pumps, which are resistant to both antibiotics and heavy metals. Many variables impact antibiotic resistance. The clustering of terms from significant studies in the area demonstrates the issue's intricacy and interdisciplinary nature, which goes much beyond a clinical concern (Figure 1).

This bibliometric network (Figure 1) was constructed and visualized using VOSviewer software, which generates network maps based on the co-occurrence of terms in scientific publications. VOSviewer visually organizes the data into clusters, enabling the identification of emerging themes and connections across different domains of knowledge (Arruda et al., 2022), particularly in areas such as antibiotic resistance, environmental impacts, and public health. Based on the adopted parameters, seven clusters were identified, each represented by a different color. The relative size of each node (sphere) reflects the number of publications associated with a given keyword, allowing for a visual comparison of the volume of research across related topics and fields. The interconnections between clusters are depicted as a network of links, revealing how themes such as heavy metals, pollution, and bacterial resistance are interrelated within the broader research landscape. This analysis provides valuable insights into the multifactorial dynamics that drive the dissemination of AMR, underscoring the importance of an integrated, multidisciplinary approach, aligned with the One Health perspective, to effectively address this global challenge.

Although bacterial infections, antibiotics, and antibiotic resistance are primarily addressed as health-related issues, it is increasingly evident that these problems cannot be confined to a single area of expertise or knowledge. There is a growing need for a multisectoral, transdisciplinary, and integrated approach that unifies various fields of study. It is essential to acknowledge, once and for all, that health is not isolated; humans, domestic and wild animals, plants, and the environment are all intimately connected and interdependent (Silva et al., 2022).

Strategies to combat antimicrobial resistance should integrate an epistemological perspective within environmental sciences and the One Health context, as discussed in this work. Among these strategies, the development and implementation of rapid diagnostics stand out, as they can reduce unnecessary prescriptions and accurately determine a pathogen's susceptibility to medications. This not only aids in selecting the most appropriate drug but also guides critical decisions regarding dosage and the need for therapeutic escalation or de-escalation (Kaprou et al., 2021).

The control of antibiotic use requires strategies that address abusive prescription practices while balancing the need to restrict excesses with preserving medical autonomy and patient satisfaction (Mohareb et al., 2021). Furthermore, it is essential to strengthen control over the use of antibiotics in livestock, emphasizing the importance of collaboration among farmers, veterinarians, and other stakeholders in designing and implementing effective strategies to combat antimicrobial resistance (McKernan et al., 2021).

Research on new drugs, through innovative approaches such as the use of artificial intelligence (AI), is enabling the discovery of novel antibiotics (Swanson et al., 2024). Bacterial vaccines can reduce both infections and the use of antibiotics, helping to combat AMR (Mullins et al., 2023). Additionally, tracking changes and trends in microbial populations improves treatment protocols, allows the evaluation of intervention effectiveness, and guides the development of new antibiotics (Canton et al., 2023). It is important to note that more than 170 countries have implemented national action plans, focusing on four key pillars: infection prevention, access to essential health services, rapid and accurate diagnostics, and high-quality treatments (Antimicrobial Resistance Collaborators, 2022).

Brazil is among the world's largest consumers of pharmaceuticals, and the improper disposal of medications poses significant environmental risks. These include contamination of soils, rivers, seas, and groundwater, as well as negative impacts on human health and quality of life. Perhaps most critically, such practices contribute to the escalating problem of antibiotic resistance (MMA, 2020). Although the National Solid Waste Policy (PNRS) has addressed the issue to some extent, it was not until 2020 that a federal decree formally established a system for the disposal of expired or unused household medications (FEBRAFAR, 2024). The delay in implementing a coherent disposal policy is compounded by the uneven rollout of the reverse logistics system, which has so far been deployed mainly in large urban centers, leaving smaller and rural municipalities without access to appropriate collection infrastructure (Lima et al., 2023). In light of these challenges, it is crucial to promote complementary strategies aimed at mitigating pharmaceutical pollution, particularly through public education and engagement, as well as epistemological investigations that can illuminate the complex and systemic nature of environmental antibiotic resistance within an integrated, One Health framework.

In Brazil, the National Plan for the Prevention and Control of Antimicrobial Resistance in Healthcare Services (ANVISA, 2023) emphasizes the role of the National Health Surveillance Agency (ANVISA) in guiding states and municipalities through a One Health approach. The plan aims to reduce the incidence of healthcare-associated infections (HAIs), particularly those caused by multidrug-resistant microorganisms. It also seeks to strengthen the performance of Hospital Infection Control Committees (CCIHs) in the evaluation of antibiotic use and its contribution to AMR, thereby promoting more effective epidemiological surveillance through the establishment of specific indicators. Moreover, effective disinfection procedures, such as the use of sodium hypochlorite (Silva, 2021), are necessary to prevent microbial dissemination. Equally important is the training of both permanent and outsourced healthcare professionals, incorporating an expanded understanding of AMR dynamics within and beyond hospital environments.

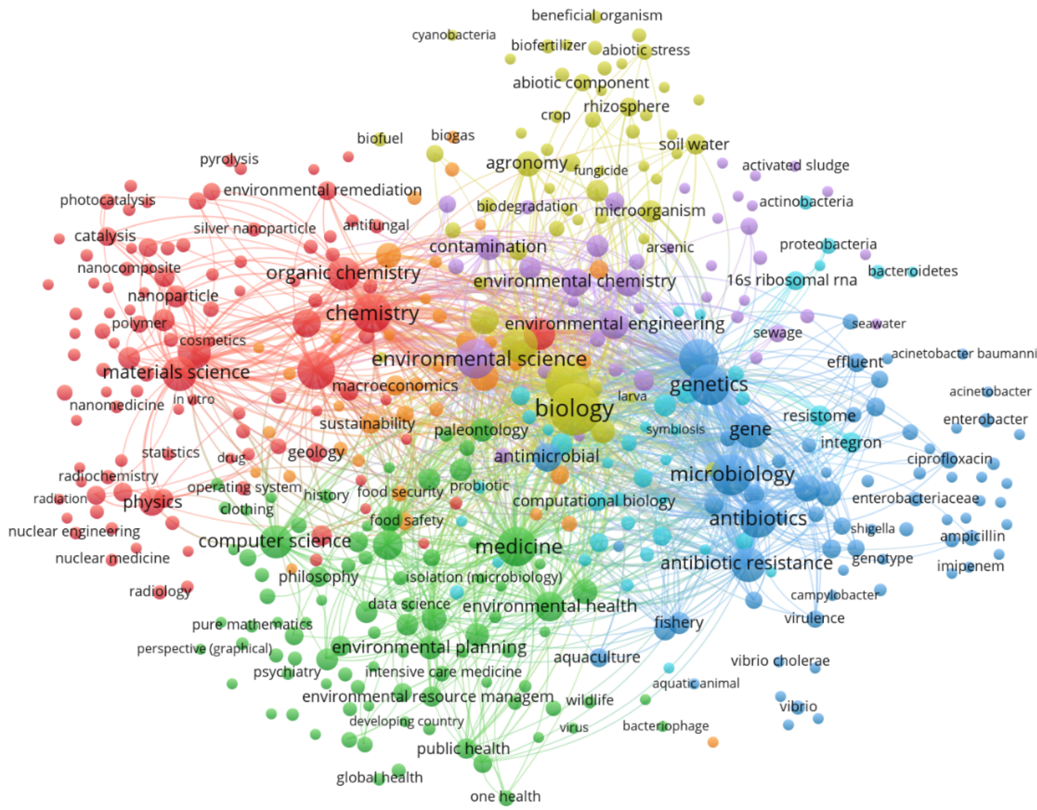

Figure 1 – Cluster linking important terms from the scientific literature, using keywords such as: antibiotics, antimicrobials, resistant bacteria, heavy metals, environmental pollution, antibiotic resistance, metal resistance, and One Health. For the construction and visualization of bibliometric networks, the VOSviewer software (https://www.vosviewer.com/) was used.

In recent decades, epistemology, the philosophical study of the nature, origins, and scope of knowledge, has become an essential analytical tool for navigating complex and interdisciplinary scientific challenges. Rather than treating knowledge as neutral or fixed, epistemological inquiry critically examines how concepts are constructed, legitimized, and operationalized across different fields. This approach is particularly relevant in the study of AMR, where biological, environmental, and sociopolitical factors are deeply intertwined. In this context, the One Health concept has emerged as a key integrative framework. Defined by the WHO as an approach that recognizes the interconnectedness of human, animal, and environmental health, One Health encourages the design of cross-sectoral strategies to address threats such as AMR, zoonoses, and ecosystem degradation. As Tesser (1994) and Silva and Arcanjo (2021) argue, epistemological approaches broaden our analytical lens, promoting multidisciplinarity and transversality in the understanding of public health phenomena. By explicitly situating AMR within these broader systems of knowledge and interaction, this study contributes to a more reflexive and integrated scientific discourse, one capable of supporting more nuanced interventions at the human-animal-environment interface.

Addressing AMR within a One Health framework requires acknowledging the complex, systemic nature of the issue, which is intensified by global phenomena such as climate change. Rising temperatures, extreme weather events, and shifting ecological boundaries can increase the spread of resistant pathogens, and disrupt sanitation and healthcare infrastructure, especially in vulnerable regions (Grilo et al., 2021; Moreira et al., 2025). These dynamics pose significant challenges to policy-making, which must now consider both environmental and epidemiological uncertainties when crafting interventions. Furthermore, the socioeconomic dimensions of AMR are often overlooked. Health inequalities, lack of access to appropriate diagnostics, and the over-the-counter availability of antibiotics in many low- and middle-income countries exacerbate misuse. Health literacy plays a critical role in this context: patients' limited understanding of antibiotic resistance and its long-term consequences diminishes their capacity to make informed decisions. Equally, physicians, especially those operating under time pressure or in resource-constrained settings, may find it difficult to prioritize stewardship over short-term symptomatic relief. What happens when the recommended solutions, such as surveillance systems, antimicrobial stewardship programs, or access to clean water, are inaccessible? These questions highlight the urgent need for globally coordinated, equity-centered strategies that address not only microbial mechanisms but also the structural determinants of AMR. Also, inappropriate prescribing has been linked to rising rates of antibiotic resistance worldwide, underscoring the need for more in-depth investigations into the clinical decision-making process. The prescription of antibiotics is a complex practice influenced by a range of interdependent factors that involve all stakeholders, physicians, other healthcare providers, the health system, patients, and the general public. These factors are mutually dependent and must be understood in an integrated manner to inform more effective interventions (Rodrigues et al., 2013).

Epistemological discussions play a pivotal role in shaping more effective public policies to address antibiotic resistance. The study of antibiotic resistance benefits from interdisciplinary approaches that integrate microbiology, biophysics, and computational modeling. These collaborations have provided a deeper understanding of how antibiotics interact with bacterial membranes at an atomic level, which is critical for the development of new antimicrobial strategies (Li et al., 2017). This integration highlights how epistemological insights can bridge gaps between scientific disciplines. Key implications include promoting educational campaigns for healthcare professionals, farmers, and the public on the responsible use of antibiotics and the dangers of self-medication, enforcing stringent regulations on antibiotic use in human medicine, veterinary care, and agriculture, and making substantial investments in research. Encouraging interdisciplinary studies on new antimicrobial therapies, natural alternatives, and the environmental impact of antimicrobials is also essential. Furthermore, enhancing monitoring and surveillance through global systems to track the spread of resistance genes in both natural and urban environments is crucial (Seid et al., 2022).

Environmental management, on the other hand, is vital in minimizing antibiotic resistance since antibiotic-contaminated areas, such as hospital effluents, farms, and industries, are hotspots for resistance propagation. Implementing modern technology to handle hospital and agro-industrial waste, as well as eliminating antibiotic residues before disposal, are examples of effective techniques. Furthermore, it is critical to promote environmental restoration measures in regions affected by antimicrobial pollution, implement integrated water resource management, and improve antibiotic and biological waste pollution control in rivers, lakes, and aquifers (Murray et al., 2024). These strategies can limit the spread of resistance genes among bacteria. A greater knowledge of resistance dynamics will assist to generate more efficient antibiotic usage guidelines in both human medicine and agriculture, thereby reducing the development of resistant strains (Kumar et al., 2022).

Epistemological paradigms and the understanding of antimicrobial resistance

Antimicrobial resistance is a complicated issue that extends beyond the scope of microbiology, necessitating research via several epistemological lenses for a comprehensive understanding. The philosophical assumptions that support our scientific investigation and public health strategies impact our approach to and interpretation of AMR. By taking positivism, constructivism, and critical realism into account, we may better understand how knowledge about AMR is produced, evaluated, and used.

Positivism, which holds that genuine knowledge comes from experience and accurate observation, has been the foundation of conventional biomedical research. In the domain of AMR, the positivist approach manifests itself in the search for universal rules and observable cause-and-effect correlations. This includes finding genetic causes of resistance, measuring the incidence of resistant bacteria, and testing the efficiency of novel antimicrobial medicines in controlled clinical trials (Antimicrobial Resistance Collaborators, 2022). AMR research is conducted within a positivist framework, with an emphasis on objective and results. This technique is clearly demonstrated by studies that trace the dissemination of resistance genes in bacterial populations or evaluate links between antibiotic usage and resistance development. The emphasis is on rigorously collecting empirical data, developing testable hypotheses, and statistically validating outcomes. The objective is to create evidence-based therapies that can be used widely to reduce AMR (Canton et al., 2023).

However, the positivism viewpoint alone may be insufficient to handle the whole scope of AMR. By focusing solely on quantitative and visible characteristics, it risks overlooking the social, cultural, and political factors that drive antibiotic usage and resistance transmission. The intricacy of the interaction of biological, environmental, and social elements necessitates a method that goes beyond just explaining visible events. Constructivism, unlike positivism, contends that knowledge is a social creation rather than the finding of an existent objective reality. Constructivism in AMR emphasizes how social, cultural, historical, and linguistic factors influence our understanding of the problem. This means that the perception of AMR as a threat, research priorities, and intervention strategies are influenced by the values, beliefs, and interests of various social actors, such as policymakers, healthcare professionals, the pharmaceutical industry, and the public (Nijsingh and van Bergen, 2019).

A constructivist approach to AMR, for example, might investigate how media narratives about "superbugs" are produced and propagated, impacting public perception and political choices. It would also investigate how antibiotic prescribing practices are influenced by societal norms, economic constraints, and power dynamics within healthcare systems. The emphasis would be on examining the social interactions, discourses, and interpretations that shape the reality of AMR (Rodrigues et al., 2013). Constructivism explains why simply scientific solutions to AMR may fail if they do not take into account complicated social processes. For example, awareness efforts regarding the sensible use of antibiotics may be useless if they do not consider cultural views about health and sickness, as well as socioeconomic impediments to proper healthcare access. Under this lens, AMR is viewed as a dynamic and negotiated process requiring communication and participation from various perspectives.

Critical realism bridges the gap between positivism and constructivism by accepting the presence of an objective reality (for example, the biology of bacterial resistance) but emphasizing the relevance of social structures and underlying causal mechanisms that may not be readily apparent. Critical realism holds that science tries to identify the generative principles behind things rather than just describing their empirical forms. Critical realism in AMR analysis would allow for the investigation not only of the prevalence of resistant bacteria (observable), but also of the structures and mechanisms that cause this resistance, such as health policies, economic systems that promote antibiotic overuse, and social inequalities that affect access to sanitation and healthcare. It aims to understand the underlying causes of AMR, which might be entrenched in complex social and economic systems (Arnold et al., 2024). For example, critical realism research may examine how agricultural policies that encourage the use of antibiotics as growth boosters in animals (causal mechanism) lead to greater resistance in people (observable reality), even if the exact link is not immediately obvious. It would also address how power dynamics in the pharmaceutical business or global health governance affect new antibiotic research and development, as well as the execution of AMR control strategies (Samreen et al., 2021). Critical realism thus provides a strong framework for approaching AMR as a multidimensional problem encompassing biological reality, societal constructs, and underlying causal mechanisms. It allows for a more in-depth examination of the links between human, animal, and environmental health, as advocated by the One Health concept, and directs the development of more effective and fair strategies to prevent AMR.

Integrating these epistemic frameworks into AMR research and policymaking is critical to furthering the One Health concept. A solely positivist approach may result in technological solutions that overlook social and behavioral hurdles to deployment. On the other hand, an overly constructivist viewpoint may ignore the biological foundation and accurate evidence of resistance. Critical realism, by acknowledging the interconnectedness of objective reality and social constructs, provides a road to a more thorough knowledge and the development of more effective and long-lasting remedies. An epistemologically informed approach is important because it may depict AMR science as a dynamic area impacted by numerous influences. This provides deeper, more contextual communication that appeals to a wider audience, including scientists from many fields, policymakers, and the public. Recognizing that AMR is an issue rooted in complex biological, social, and economic connections is critical for motivating coordinated and transdisciplinary activities to address this global health threat.

Conclusions

Antimicrobial resistance (AMR) must be handled not as a clinical or microbiological issue, but as a complex, multidimensional phenomena requiring coordinated solutions from the environmental, social, and health sciences. This article, which is framed under the One Health paradigm, discusses how the convergence of human, animal, and environmental health provides a more solid foundation for understanding the systemic causes of resistance and creating long-term solutions.

Unlike traditional reviews that focus primarily on biomedical mechanisms or surveillance data, this study contributes a novel epistemological perspective by explicitly interrogating how different paradigms, positivism, constructivism, and critical realism influence the ways in which AMR is conceptualized, studied, and governed. This pluralistic approach allows for the recognition of both observable patterns including gene transfer, selective pressure, genome, diversity, and less tangible but equally influential factors, such as institutional behavior, public perception, and structural inequalities. The bibliometric analysis presented confirms the fragmented character of current AMR knowledge generation and emphasizes the necessity for epistemic integration to cross discipline barriers. By combining bibliometric mapping with case-based synthesis, the study identifies emerging intersections between environmental pollution (e.g., heavy metals), microbial evolution, and antibiotic use, domains that remain underexplored in conventional AMR literature.

This integrative perspective advances the field by demonstrating that combating AMR necessitates not only scientific and technological innovation, such as the development of new antimicrobials, vaccines, and probiotic therapies, but also extensive involvement in health literacy, public policy, and environmental justice. Effective methods must involve education, appropriate prescription, proper medication disposal, and increased public awareness. Furthermore, a change to tailored and context-specific antibiotic stewardship is required to minimize dependence on broad-spectrum medicines and slow the emergence of resistance. Finally, this study promotes a more reflexive and systemic view of antimicrobial resistance that is epistemologically sound, environmentally based, and socially sensitive.

Authors' Contributions

Berbert, L.C.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Caufield**, A.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Flores**, V.R.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Succar**, J.B.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Oliveira**, C.E.A.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Lima**, I.: Data Curation, Formal Analysis, Investigation, Methodology, Resources, Software, Writing – Original Draft. **Direito**, I.C.N.: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Writing – Original Draft, Writing – Review & Editing. **Vieira**, J.M.B.D.: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Writing – Original Draft, Writing – Review & Editing. **Pellegrino**, F.L.P.C.: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Writing – Original Draft, Writing – Review & Editing. **Cardoso**, A.M.: Conceptualization, Formal Analysis, Investigation, Methodology, Project Administration, Resources, Software, Supervision, Validation, Writing – Original Draft, Writing – Review & Editing.

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