American Journal of Bioscience and Bioengineering
2025, Vol. 13, No. 3, pp. 43-54
https://doi.org/10.11648/j.bio.20251303.13

Research Article

Review of the Role of Veterinary Public Health in Preventing Antimicrobial Resistance: A One Health Perspective

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Abstract

Antimicrobial resistance (AMR) is a global public health threat that poses significant risks to both human and animal health. In the context of veterinary public health (VPH), AMR has far-reaching implications as it affects the treatment of animal diseases, impacts food safety, and can be transmitted to humans through direct contact or consumption of contaminated animal products. A One Health approach, which recognizes the interconnectedness of human, animal, and environmental health, is critical for addressing the challenge of AMR. This review explores the role of veterinary public health in preventing antimicrobial resistance, emphasizing the importance of responsible antimicrobial use in veterinary medicine, health surveillance, and regulatory frameworks. The paper discusses the mechanisms of AMR, the impact of antimicrobial misuse in veterinary settings, and the various strategies that can be implemented to mitigate its spread, including vaccination, education, and awareness programs. Furthermore, it highlights successful case studies, barriers to effective AMR management, and the importance of global collaborations in combating AMR. Future directions in research, innovations in surveillance, and the integration of technology and data analytics are also examined to improve antimicrobial stewardship. The review concludes by providing policy recommendations and reinforcing the need for a One Health approach to effectively combat AMR.

Keywords

Veterinary, Public Health, Antimicrobial, Resistance, Prevention, One Health

1. Introduction

1.1. Background on Veterinary Public Health

Veterinary Public Health is a vital component of global public health, encompassing the application of veterinary science to protect and improve human health. VPH addresses various issues such as food safety, zoonotic diseases, and animal welfare. As defined by the World Health Organization (WHO), VPH contributes to the physical, mental, and social well-being of humans through the prevention and control of diseases transmitted from animals [9].

AMR occurs when microorganisms evolve to resist the effects of antimicrobial agents, rendering standard treatments ineffective. The misuse and overuse of antibiotics in both human and veterinary medicine accelerate this process. According to the World Organization for Animal Health (WOAH, formerly OIE), antimicrobial resistance in animals not only threatens animal health but also has far-reaching implications for human health and food security.

The One Health approach recognizes that the health of people is closely connected to the health of animals and our

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Received: 21 April 2025; **Accepted:** 9 May 2025; **Published:** 18 June 2025

shared environment. As AMR transcends human and animal boundaries, OH provides a collaborative, multisectoral, and transdisciplinary framework for addressing this global challenge. By aligning efforts across health sectors, OH offers a strategic platform for coordinated action on AMR [2].

1.2. Purpose of the Review

This review aims to examine the role of Veterinary Public Health in preventing AMR from a One Health perspective. It intends to:

1) Provide an overview of AMR mechanisms and global trends.
2) Highlight the interconnectedness of human, animal, and environmental health in the context of AMR.
3) Discuss preventive strategies within veterinary practices.
4) Present case studies illustrating effective interventions.
5) Identify challenges and propose future directions for VPH to combat AMR effectively.

2. Overview of Antimicrobial Resistance

2.1. Definition and Mechanisms

Antimicrobial resistance refers to the ability of microorganisms such as bacteria, viruses, fungi, and parasites to withstand the effects of medications that were previously effective in treating infections caused by them. Resistance mechanisms include enzymatic degradation of antibiotics, alteration of target sites, reduced drug accumulation through efflux pumps, and biofilm formation [4].

These mechanisms are often driven by genetic changes that occur naturally or are facilitated through horizontal gene transfer between organisms. Selective pressure, resulting from antimicrobial overuse or misuse in humans and animals, accelerates the emergence of resistant strains. Bacteria such as Escherichia coli, Salmonella spp., and Staphylococcus aureus have shown increasing resistance to multiple drug classes, threatening both veterinary and human medicine [5].

2.2. Global Trends in AMR

Globally, AMR is recognized as a growing health crisis. Reports by the WHO and other health authorities suggest that without urgent action, AMR could cause 10 million deaths annually by 2050 (O'Neill, 2016). The highest burden of AMR is observed in low- and middle-income countries (LMICs), where antibiotic regulation is often weak, and over-the-counter antibiotic access is widespread.

The animal agriculture sector contributes significantly to global antimicrobial consumption. According to estimates, over 70% of medically important antibiotics are used in food-producing animals, often for growth promotion or disease prevention rather than treatment [7]. This widespread use increases the risk of resistant pathogens emerging and transferring to humans via direct contact, food products, or environmental pathways.

2.3. Impacts of AMR on Human, Animal and Environmental Health

The impact of AMR on human health is profound. Resistant infections lead to increased morbidity, mortality, and healthcare costs. Common infections become harder to treat, and routine medical procedures like surgeries or chemotherapy become riskier due to reduced efficacy of prophylactic antibiotics [9].

In animals, AMR compromises the ability to treat infectious diseases, affecting animal welfare and productivity. This is particularly problematic in intensive farming systems, where infectious diseases can spread rapidly. Loss of treatment options can also result in economic losses for farmers and threaten food security [8].

Environmental contamination with antibiotics, resistant bacteria, and resistance genes occurs through various pathways, including manure application, pharmaceutical manufacturing discharge, and wastewater. These environmental reservoirs serve as a breeding ground for resistant microbes that may re-enter the human or animal population [11].

The complex and interconnected nature of AMR highlights the need for an integrated One Health approach that addresses the issue holistically across sectors and disciplines.

3. Veterinary Public Health: Concept and Practices

3.1. Definition and Scope

Veterinary Public Health (VPH) is defined as the sum of all contributions to the physical, mental, and social well-being of humans through an understanding and application of veterinary science (WHO, 2020). VPH encompasses diverse areas including zoonotic disease control, food hygiene, meat inspection, animal welfare, and prevention of antimicrobial resistance.

VPH practices are implemented through coordinated actions between public health authorities, veterinary services, agriculture ministries, and private stakeholders. They include:

Monitoring and controlling zoonotic diseases.

Ensuring food safety from farm to fork.

Promoting responsible use of veterinary medicines.

Surveillance of antimicrobial use and resistance in animals.

Implementing biosecurity measures to prevent disease spread.

These practices align with broader public health goals and enhance preparedness against public health emergencies, including pandemics [9].

3.2. Role in Health Surveillance

VPH is instrumental in national and international disease surveillance systems. By monitoring animal populations, veterinary services detect emerging pathogens and resistance patterns, providing early warnings for potential human health threats.

Programs like the Global Antimicrobial Resistance Surveillance System (GLASS) and the Tripartite AMR Surveillance (TrACSS) framework reflect growing global collaboration in this field [10]. Veterinarians also conduct epidemiological investigations, contribute to risk assessments, and report data to global databases, supporting timely and effective responses to AMR threats.

3.3. Regulations and Guidelines

Numerous international guidelines govern the use of antimicrobials in animals. The WOAH's Terrestrial Animal Health Code outlines standards for responsible use of antimicrobials in veterinary medicine. Similarly, Codex Alimentarius standards developed by FAO and WHO provide food safety measures, including antimicrobial residue limits in animal-derived products [3].

National regulations vary by country but commonly include restrictions on non-therapeutic antimicrobial use, prescription requirements, and antimicrobial classification. Compliance with these regulations is essential for reducing AMR risks and protecting public health.

Despite progress, enforcement and implementation of guidelines remain a challenge, particularly in low-resource settings. Strengthening veterinary infrastructure and capacity is critical for effective regulation and sustainable antimicrobial stewardship.

4. Interconnection between Human, Animal, and Environment Health

4.1. One Health Framework

The One Health (OH) framework promotes an integrated, unifying approach to balance and optimize the health of people, animals, and the environment. It is based on the recognition that health threats are interconnected across species and ecosystems. One Health supports coordinated responses across multiple sectors, including human medicine, veterinary services, environmental science, and public policy [2].

A One Health framework facilitates the early detection, prevention, and control of emerging health threats such as AMR. It promotes multisectoral collaboration and joint strategies to limit the misuse of antimicrobials, reduce transmission routes, and improve overall ecosystem resilience.

The interconnectedness of Human, Animal, and Environmental Health forming a triangle with bidirectional arrows among each node, all centered around AMR control presented in Figure 1.

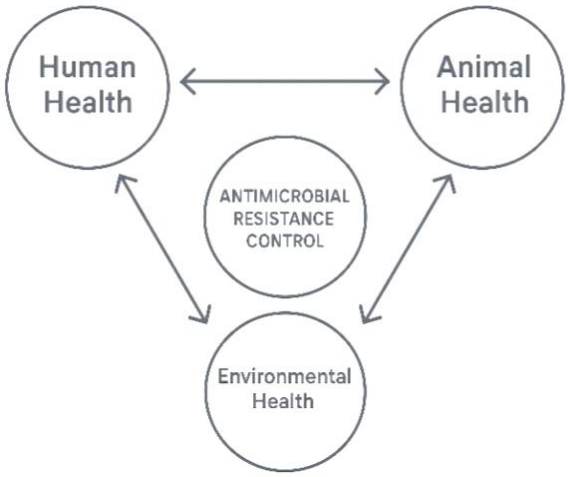

Figure 1. *Diagram Displaying One Health Framework.*

4.2. Zoonotic Diseases and AMR

Zoonotic diseases those transmissible from animals to humans account for over 60% of infectious diseases in humans [8]. Many zoonoses involve bacteria that can develop resistance to antimicrobials. Examples include resistant strains of Salmonella, Campylobacter, and Brucella spp., which are transmitted via animal contact or contaminated food.

Antimicrobial use in animals can create selection pressure favoring resistant zoonotic bacteria. These pathogens can infect humans through direct exposure, food consumption, or environmental contamination, thus amplifying public health risks [1].

4.3. Environmental Factors Contributing to AMR

Environmental compartments such as soil, water, and air serve as significant reservoirs and transmission pathways for resistant microorganisms and antimicrobial residues.

Livestock waste used as manure can introduce resistance genes into the soil, while effluents from pharmaceutical industries and hospitals may contaminate water sources [8].

1) *Climate change and land-use changes also influence AMR patterns. Rising temperatures and extreme weather can enhance the spread of resistant pathogens and facilitate gene transfer in microbial communities.*
2) *Mitigating environmental contributions to AMR requires stricter regulation of waste disposal, improved sanitation infrastructure, and monitoring of resistance genes in the environment as part of OH surveillance.*

Together, these elements underscore the critical need for a

unified, systems-based approach in tackling AMR that spans the human-animal-environment interface.

5. Antimicrobial Resistance in Veterinary Medicine Preventing Strategies

Antimicrobial resistance (AMR) in veterinary medicine requires urgent action to prevent further escalation and its impacts on both animal and public health. Effective strategies to combat AMR in the veterinary sector must incorporate responsible antimicrobial use, vaccination programs, education initiatives, and robust surveillance systems [6].

5.1. Responsible Use of Antibiotics

The cornerstone of AMR prevention in veterinary medicine lies in the responsible use of antibiotics. Overuse and misuse of antibiotics in animals, particularly in food production, contribute significantly to the rise of resistant strains. To combat this, it is essential to enforce strict guidelines on antibiotic prescriptions and ensure that antibiotics are used only when necessary and appropriate for treating infections [3].

In many countries, the implementation of regulatory frameworks, such as restricting the use of antibiotics for growth promotion and adopting prescription-only practices, has proven effective in reducing unnecessary antibiotic consumption [1]. Veterinarians must prioritize the use of narrow-spectrum antibiotics and reserve broad-spectrum antibiotics for serious infections where no alternatives exist [10]. Furthermore, antibiotic stewardship programs, where veterinarians and farmers collaborate to ensure prudent antibiotic use, can foster responsible practices and promote long-term sustainability.

5.2. Vaccination and Disease Prevention

Vaccination plays a critical role in preventing the need for antibiotic treatments by reducing the incidence of infectious diseases in animals. Preventing infections from occurring in the first place reduces the necessity for antibiotics and helps lower the selective pressure that contributes to AMR. Animal vaccination programs have been instrumental in controlling diseases such as mastitis in dairy cattle and respiratory infections in poultry, which would otherwise require frequent antibiotic treatments [11].

Additionally, biosecurity measures that limit the spread of infectious agents and promote herd health can further reduce the need for antibiotics. Regular veterinary checkups, improving sanitation practices, and monitoring animal health at the farm level are essential practices in preventing disease outbreaks and minimizing antibiotic usage.

5.3. Education and Awareness Programs

Awareness programs targeting farmers, veterinarians, and the general public are pivotal in reducing AMR. Educating stakeholders on the risks of overusing antibiotics and the importance of following prescribed treatment regimens can reduce both intentional and unintentional misuse of antibiotics. Veterinary institutions and professional bodies must collaborate to provide training and guidance on best practices for antibiotic use and alternatives to antibiotics.

Global initiatives such as the WHO's Antimicrobial Stewardship program aim to educate veterinary professionals and farmers about AMR and encourage them to adopt best practices [11]. By building a culture of responsible antimicrobial use through educational campaigns, it is possible to create an informed community that is motivated to participate in combating AMR.

6. Case Studies and Examples

Real-world case studies and examples of successful veterinary public health interventions provide valuable insights into the effectiveness of strategies aimed at preventing antimicrobial resistance (AMR). By learning from global experiences, policymakers, veterinarians, and other stakeholders can develop and implement evidence-based strategies that tackle AMR more effectively. This section highlights key case studies, comparative analyses of AMR strategies, and the role of international collaborations.

6.1. Successful Veterinary Public Health Interventions

Several countries have implemented comprehensive veterinary public health interventions that demonstrate the positive impact of strong regulatory frameworks, stewardship programs, and collaboration between stakeholders. These interventions have led to measurable reductions in the use of antimicrobials and corresponding declines in resistance rates.

For example, the Netherlands has long been a global leader in reducing antimicrobial use in livestock farming. Over the past decade, the country has successfully decreased antibiotic use in the agricultural sector by more than 50%. A critical component of this success has been the ban on the use of antibiotics for growth promotion, alongside strict oversight of veterinary antibiotic prescriptions.

In 2011, the Dutch government introduced a national policy requiring that all antibiotics be used only for therapeutic purposes and that they be prescribed by a veterinarian. This policy, coupled with detailed surveillance of antimicrobial use and resistance patterns, has resulted in a significant reduction in AMR rates among both livestock and human pathogens [7].

In Sweden, the government has adopted a 'zero-tolerance' approach to the use of antibiotics for growth promotion. Additionally, Sweden has implemented stringent regulations regarding the use of antibiotics in veterinary medicine, with a focus on reducing unnecessary treatments.

The country also invests heavily in surveillance and re-

search, which has enabled it to effectively track AMR trends and respond rapidly to emerging threats. The success of Sweden's approach can be attributed to strong political will, a high level of public awareness, and robust collaboration between veterinarians, farmers, and policymakers [10].

6.2. Comparative Analysis of AMR Strategies

While high-income countries like the Netherlands and Sweden have implemented successful strategies to combat AMR, low- and middle-income countries (LMICs) face unique challenges in addressing this issue. Limited resources, inadequate veterinary infrastructure, and insufficient access to antimicrobials and diagnostics complicate the implementation of effective AMR control programs in these regions.

For instance, in parts of Sub-Saharan Africa, AMR is exacerbated by the over-the-counter availability of antibiotics and the widespread use of antibiotics without veterinary supervision. In these regions, many farmers lack access to alternative disease prevention methods such as vaccines, and antibiotics remain the primary tool for managing infections in animals.

Consequently, overuse and misuse of antibiotics have led to the emergence of resistant pathogens, which threaten both animal and human health [11]. However, international collaborations and programs aimed at strengthening AMR control in LMICs have shown promise. The FAO's Tripartite AMR Initiative, which brings together the WHO, WOAH and the FAO, has been instrumental in providing technical assistance and promoting good antimicrobial stewardship practices in these regions.

By focusing on capacity building, improving regulatory frameworks, and enhancing surveillance systems, the Tripartite Initiative has made significant strides in combating AMR in resource-constrained settings [1].

6.3. Global Collaborations and Initiatives

The fight against AMR is inherently global, as resistant pathogens can easily spread across borders through the movement of animals, food products, and people. As such, international collaborations have become a cornerstone of AMR management. Global initiatives aimed at reducing AMR emphasize the importance of a One Health approach, which recognizes the interconnectedness of human, animal, and environmental health.

The WHO, FAO, and WOAH have been at the forefront of global efforts to combat AMR through the Tripartite AMR Surveillance System (TrACSS). This platform facilitates the sharing of data on antimicrobial use and resistance patterns across countries, helping to track and monitor AMR trends on a global scale. By enhancing data sharing, the TrACSS allows countries to better understand the global AMR landscape and respond proactively to emerging threats [10].

The United Nations (UN) has also played a pivotal role in driving global awareness and action on AMR. In 2016, the UN adopted the Political Declaration on AMR, which calls for coordinated, multisectoral action to combat AMR and highlights the critical role of international cooperation [16]. The declaration stresses the need for a collaborative response to AMR at the human-animal-environment interface, emphasizing the importance of shared responsibility among governments, international organizations, and the private sector [9].

Case studies from countries like the Netherlands and Sweden demonstrate the effectiveness of strong regulatory frameworks, surveillance systems, and international collaboration in combating AMR. While high-income countries have made significant progress in reducing antimicrobial use, LMICs continue to face challenges that require targeted support and capacity building. Global initiatives such as the Tripartite AMR Surveillance System are critical for fostering collaboration and facilitating data-sharing to curb AMR worldwide. Moving forward, global cooperation and the integration of One Health principles will be essential for addressing the complex and evolving challenge of antimicrobial resistance.

7. Challenges and Barriers

Despite significant progress in addressing antimicrobial resistance (AMR) through veterinary public health interventions, numerous challenges and barriers remain in the fight against this global issue. These barriers are multifaceted, involving regulatory constraints, economic factors, public awareness gaps, and the complexity of integrating a One Health approach. Understanding these challenges is crucial for developing effective strategies and policies aimed at curbing AMR.

7.1. Regulatory and Policy Limitations

One of the primary challenges in combating AMR is the lack of robust regulatory frameworks in many countries. While high-income countries have implemented strict policies on antimicrobial use, many low- and middle-income countries (LMICs) continue to struggle with weak regulations and insufficient enforcement mechanisms. In some regions, antibiotics are sold over-the-counter without a prescription, leading to the inappropriate use and overuse of these drugs in both human and veterinary medicine.

Even in countries with established regulations, enforcement can be inconsistent. Veterinarians may not always follow antimicrobial stewardship guidelines due to inadequate monitoring systems or economic pressures to provide quick solutions to farmers [14]. Additionally, in some cases, government policies may not align with the realities of the agricultural industry, where antibiotic use is often viewed as necessary for maintaining livestock health and productivity. Bridging the gap between policy development and enforcement remains a

key challenge in reducing AMR.

Moreover, the international nature of antimicrobial resistance means that policies must be harmonized across borders. Differences in regulatory frameworks and the lack of global standards for antibiotic use make it difficult to implement coordinated AMR control strategies at a global level. There is a pressing need for international agreements on the regulation of antimicrobial use in veterinary medicine, particularly in regions where veterinary practices remain poorly regulated.

7.2. Economic Factors

Economic factors play a significant role in the overuse and misuse of antibiotics in veterinary medicine. In many LMICs, the cost of veterinary care, including diagnostics and prescription medications, can be prohibitive for farmers. As a result, antibiotics may be used as a cheap and immediate solution to treat infections in animals, often without a prescription or proper diagnosis. This overreliance on antibiotics increases the risk of developing resistant pathogens.

In some high-income countries, economic pressures also contribute to the challenge. For example, intensive farming systems prioritize maximizing productivity, and the use of antibiotics is often seen as a cost-effective method for preventing disease outbreaks in large animal populations [15]. The economics of such systems can conflict with efforts to reduce antimicrobial use, especially when farmers are not incentivized to adopt alternative disease prevention strategies, such as vaccination or improved animal husbandry practices.

Furthermore, the development of new antibiotics is costly and time-consuming, and the economic incentives for pharmaceutical companies to invest in antibiotic research are limited. Unlike other types of drugs, antibiotics are used for short durations and are often reserved for serious infections, reducing their commercial profitability. This lack of financial motivation for the development of new antimicrobial drugs exacerbates the global AMR crisis, as resistance continues to limit the efficacy of existing antibiotics.

7.3. Public Awareness and Education Gaps

Public awareness and education regarding AMR remain significant barriers to effective control. In many countries, there is limited understanding of the dangers posed by antimicrobial resistance, both within the general public and among healthcare and veterinary professionals [16]. Farmers, in particular, may not fully understand the implications of antimicrobial overuse or misuse, viewing antibiotics as a quick fix to health problems in livestock without realizing the long-term consequences.

Even in high-income countries, where public health campaigns on AMR have been more prevalent, knowledge gaps persist. Veterinarians may not always be adequately trained in antimicrobial stewardship, and farmers may be unaware of the role they play in the emergence of resistant pathogens. This lack of education contributes to a culture of overprescribing and misuse of antibiotics, which undermines efforts to combat AMR.

To address these gaps, targeted education and outreach programs are needed at all levels. This includes improving the training of veterinarians in antimicrobial stewardship, increasing public awareness of the consequences of AMR, and promoting responsible antibiotic use in agriculture. Governments, international organizations, and professional associations all have roles to play in developing and disseminating educational materials and programs that encourage responsible antimicrobial use.

7.4. Challenges in Implementing the One Health Approach

The One Health framework, which integrates human, animal, and environmental health, is widely recognized as the most effective way to address AMR [15]. However, implementing this approach presents several challenges. First, coordination between different sectors such as public health, veterinary medicine, and environmental science—can be difficult. Different ministries, agencies, and organizations may have conflicting priorities, resources, and expertise, which can lead to fragmented efforts in AMR control.

Additionally, the One Health approach requires significant investments in surveillance systems, research, and data-sharing platforms to monitor AMR across human, animal, and environmental domains [13]. Many countries, particularly LMICs, lack the infrastructure and resources to implement these systems effectively. Furthermore, data collection and sharing are often hindered by political, economic, and logistical barriers, making it challenging to develop a comprehensive understanding of AMR trends.

There is also the challenge of overcoming the siloed nature of many public health and veterinary practices. In some regions, veterinary professionals and medical professionals may not regularly collaborate, limiting the effectiveness of AMR surveillance and control efforts. To successfully implement a One Health approach, there must be greater integration of human, animal, and environmental health practices, which requires changes in policy, governance, and professional training.

The challenges and barriers to addressing AMR are complex and multifaceted, encompassing regulatory, economic, educational, and systemic issues. While some countries have made significant progress in combating AMR, others, particularly LMICs, face considerable obstacles in implementing effective AMR control measures [14]. Overcoming these barriers requires coordinated action at the national, regional, and global levels, as well as a commitment to the One Health approach. Addressing AMR will also require continued investment in research, education, and surveillance systems, alongside stronger regulatory frameworks and economic

incentives to reduce antimicrobial use.

8. Future Directions in Veterinary Public Health and AMR

As antimicrobial resistance (AMR) continues to threaten both human and animal health worldwide, the need for innovative solutions and strategic actions is more urgent than ever. The future of veterinary public health in combating AMR hinges on overcoming current barriers, embracing new technologies, and expanding research efforts.

In this section, we will explore the research gaps, innovations in surveillance and monitoring, and the potential role of technology and data analytics in the fight against AMR. Furthermore, we will outline future directions for policy and practice that can help shape the global response to AMR.

8.1. Research Gaps and Priorities

The fight against AMR requires continuous research to fill the many gaps in our understanding of the problem. While significant progress has been made in recent years, several key areas of research remain underexplored and require urgent attention. These research gaps can be categorized into four primary areas: basic science, surveillance, policy evaluation, and alternative therapies.

Basic Science and Mechanisms of Resistance: A deeper understanding of the biological mechanisms driving antimicrobial resistance is crucial for the development of new treatment options and effective intervention strategies. Current research primarily focuses on identifying the genetic mutations that lead to resistance, but more work is needed to understand how resistant genes spread across different environments—human, animal, and environmental—and how they evolve in response to the selective pressure exerted by antimicrobial use.

Antimicrobial Stewardship and Use Patterns: There is a need for more research on the patterns of antimicrobial use in veterinary medicine, particularly in low- and middle-income countries (LMICs). Understanding how antibiotics are prescribed, administered, and consumed in agricultural settings is crucial for developing targeted interventions. Research into the effectiveness of stewardship programs and the economic implications of antimicrobial use is also vital to guide policymaking.

Alternative Therapies: As antibiotic resistance continues to limit the efficacy of traditional antibiotics, the development of alternative treatments is a priority. Research into the use of probiotics, phage therapy, immunomodulators, and novel antimicrobials could provide promising alternatives. Furthermore, enhancing our understanding of the role of vaccines in preventing the need for antibiotics in animal populations is a key area of exploration.

One Health Surveillance Systems: Strengthening One Health surveillance systems, particularly in LMICs, is essential for tracking AMR trends across human, animal, and environmental health sectors. Research into integrated surveillance systems that connect human, veterinary, and environmental data could help identify emerging resistant strains more quickly and enable more coordinated responses to outbreaks.

To address these research gaps, greater collaboration between academic institutions, government agencies, international organizations, and the private sector is required. Additionally, funding for AMR research should be increased to ensure that these gaps are filled, leading to more effective solutions for preventing and mitigating AMR.

8.2. Innovations in Surveillance and Monitoring

Advancements in surveillance and monitoring technologies are critical for identifying and tracking the spread of AMR. Effective monitoring systems provide valuable data that can guide intervention strategies, inform public health policy, and ensure that resources are directed toward the most pressing areas.

Integrated Surveillance Systems: One of the most promising innovations in AMR surveillance is the development of integrated systems that combine data from human, animal, and environmental health sources. These systems can help to detect and track AMR across different sectors and geographic regions. By linking veterinary surveillance data with public health data, authorities can better understand the movement of resistant pathogens and identify hotspots where AMR is emerging.

For example, the European Surveillance of Antimicrobial Consumption (ESAC) and the WHO's Global Antimicrobial Resistance Surveillance System (GLASS) are already examples of integrated systems that gather data from multiple sectors. However, these systems must be expanded globally, particularly in LMICs, to provide comprehensive data for policymaking and response.

Digital Technologies and Big Data: The application of digital technologies and big data analytics offers new opportunities for AMR surveillance. Machine learning and artificial intelligence (AI) can be used to analyze large datasets from veterinary and public health sources, providing insights into trends and risk factors associated with AMR [12]. Additionally, the use of mobile technologies and apps can facilitate real-time data collection, enabling veterinarians, farmers, and public health officials to monitor antimicrobial use and resistance patterns more effectively.

Remote sensing technologies and *geographic information systems* (GIS) can also play a role in monitoring environmental contamination and the spread of resistant pathogens, further enhancing the One Health approach to AMR surveillance.

Antimicrobial Resistance Rapid Diagnostic Tests: One of the most pressing challenges in veterinary medicine is the lack of rapid diagnostic tools for detecting resistant infections. The

development and deployment of affordable and accessible rapid diagnostic tests could revolutionize antimicrobial stewardship by enabling veterinarians to make more informed decisions about treatment. Point-of-care diagnostic tools that can rapidly identify resistant pathogens in animals will reduce the reliance on empirical antibiotic treatments and help curb unnecessary use of antimicrobials.

8.3. Role of Technology and Data Analytics

Technology and data analytics are playing an increasingly important role in combating AMR. From improving surveillance systems to enhancing decision-making in veterinary medicine, technology can support a more targeted and efficient response to AMR.

Predictive Analytics: Predictive analytics can be used to forecast outbreaks of resistant infections in animal populations, allowing for proactive measures to prevent the spread of AMR. By analyzing data from various sources, including weather patterns, animal movement, and antimicrobial use, predictive models can help identify at-risk regions and enable timely interventions.

Blockchain for Traceability: Blockchain technology can be used to improve the traceability of antimicrobial use in the veterinary and agricultural sectors. By creating a secure and transparent system for tracking antibiotic use from farm to table, blockchain can help ensure that antibiotics are used responsibly and that any breaches in stewardship are quickly identified.

Telemedicine and Remote Veterinary Care: Telemedicine is another technological advancement that can improve veterinary care and AMR management. Through telemedicine, veterinarians can provide remote consultations, increasing access to professional advice and reducing the need for unnecessary antimicrobial prescriptions. This technology is particularly useful in rural and remote areas where access to veterinary services is limited.

Veterinary Informatics: The integration of electronic health records (EHRs) in veterinary practice can help veterinarians track antimicrobial use, monitor disease trends, and ensure adherence to antimicrobial stewardship guidelines. Veterinary informatics can also support research by providing large datasets that can be analyzed to understand the patterns and drivers of AMR.

8.4. Future Directions for Policy and Practice

Looking ahead, there are several key directions for future policy and practice that will help address the growing threat of AMR:

Strengthening Global Regulations and Governance: There is a critical need for stronger global governance and regulations to control antimicrobial use in veterinary medicine. International organizations like the WHO, FAO, and WOAH must work together to develop harmonized regulations that can be adopted globally. Policies should focus on reducing antimicrobial use for non-therapeutic purposes, encouraging alternative disease prevention strategies, and increasing investment in AMR research.

Incentivizing Responsible Antimicrobial Use: Incentive-based policies, such as subsidies for vaccines, diagnostics, and alternative treatments, can encourage farmers and veterinarians to adopt responsible antimicrobial stewardship practices. Additionally, governments and international bodies should provide financial support for the development and implementation of AMR control programs, particularly in LMICs.

Building Public and Professional Awareness: Education and awareness campaigns should be expanded to include both the general public and veterinary professionals. Veterinarians need continuous training on antimicrobial stewardship, and farmers should be educated about the risks of overusing antibiotics in animal farming. Public awareness campaigns should highlight the One Health approach and the interconnectedness of human, animal, and environmental health.

The future of veterinary public health in combating AMR lies in addressing critical research gaps, leveraging technological innovations, and strengthening policy frameworks at the national and global levels.

By embracing the One Health approach, improving surveillance systems, and fostering collaboration between human, animal, and environmental health sectors, it is possible to mitigate the threat posed by antimicrobial resistance. Going forward, a concerted effort from governments, the private sector, and the scientific community will be necessary to achieve sustainable solutions to the AMR crisis.

9. Conclusion and Recommendations for Future Research

The rising threat of antimicrobial resistance (AMR) has become one of the most pressing global health challenges of our time. The convergence of human, animal, and environmental health under the One Health framework underscores the critical importance of addressing AMR from an integrated, cross-sectoral perspective. Veterinary public health (VPH) plays a pivotal role in this fight by safeguarding animal health, preventing the spread of zoonotic diseases, and mitigating the overuse and misuse of antimicrobials in veterinary practice. However, despite the progress made, significant challenges persist, and continued efforts are needed to stem the tide of antimicrobial resistance. Future research should explore the following areas to strengthen the role of VPH in AMR prevention:

1) Surveillance and Data Integration: Investigate effective systems for integrated AMR surveillance across human, animal, and environmental sectors, particularly in low-resource settings.
2) Antimicrobial Stewardship Strategies: Evaluate the ef-

fectiveness of targeted stewardship programs in livestock systems and assess their socio-economic impact on farming communities.

3) Behavioral Drivers of Antimicrobial Use: Examine the behavioral, cultural, and economic factors that influence antimicrobial usage among veterinarians and livestock owners.
4) Alternatives to Antibiotics: Explore the development and practical application of alternative treatments such as vaccines, probiotics, and phytochemicals in animal health.
5) Policy Implementation and Compliance: Assess the implementation, enforcement, and impact of existing AMR-related policies and regulatory frameworks at national and regional levels.
6) Educational Interventions: Evaluate the effectiveness of public awareness campaigns and veterinary education programs in promoting responsible antimicrobial use.
7) Environmental Dimensions of AMR: Study the role of environmental contamination in the spread of AMR, especially from agricultural runoff and waste disposal.

By advancing research in these areas, we can better equip veterinary public health systems to confront AMR and contribute meaningfully to global health security through a unified One Health approach.

9.1. Summary of Key Findings

Throughout this review, several key findings have emerged regarding the role of veterinary public health in preventing AMR from a One Health perspective:

1) *The Complexity of AMR*: AMR is a complex, multifactorial issue that involves the interconnections between human, animal, and environmental health. The overuse and misuse of antibiotics in both human and veterinary medicine have led to the emergence of resistant pathogens that threaten both public and animal health.
2) *Veterinary Public Health's Role*: Veterinary public health plays a critical role in monitoring, regulating, and promoting responsible antimicrobial use in animals. Through disease surveillance, antimicrobial stewardship, and the promotion of alternative disease prevention measures (such as vaccination), veterinary public health can help curb the spread of AMR in animal populations and prevent its transmission to humans.
3) *One Health Approach*: The One Health framework offers a comprehensive approach to addressing AMR by recognizing the interconnectedness of human, animal, and environmental health. By integrating data and efforts across these sectors, the One Health approach provides a more holistic and effective strategy for tackling AMR at the global level.
4) *Challenges and Barriers*: Several barriers continue to impede the effective implementation of AMR control measures. These include regulatory limitations, economic factors, gaps in public awareness, and challenges in implementing the One Health approach across sectors. Addressing these barriers will require coordinated action at the national and international levels.
5) *Future Directions*: The future of veterinary public health and AMR control lies in increased investment in research, improved surveillance systems, and the adoption of new technologies and practices. The development of rapid diagnostic tools, the integration of big data and AI in surveillance, and the promotion of alternative therapies are critical areas for innovation.

9.2. Implications for Policy and Practice

The findings from this review highlight several important implications for policy and practice in the fight against AMR:

1) *Strengthening Regulatory Frameworks*: National and international regulatory frameworks must be strengthened to control the use of antimicrobials in both human and veterinary medicine. This includes ensuring the responsible use of antibiotics, banning the use of antibiotics as growth promoters, and improving enforcement of existing regulations.
2) *Promoting the One Health Approach*: The One Health approach must be embraced and implemented more widely to address AMR. Governments, international organizations, and stakeholders from human health, animal health, and environmental sectors should work together to coordinate efforts, share data, and develop comprehensive AMR control strategies.
3) *Incentivizing Responsible Use of Antimicrobials*: Policies should encourage the responsible use of antimicrobials through incentives for alternative disease prevention methods (e.g., vaccines), diagnostics, and improved farming practices. Financial support for antimicrobial stewardship programs, particularly in low- and middle-income countries (LMICs), is also essential.
4) *Investing in Education and Training*: Education and training programs for veterinarians, farmers, and the general public are crucial in raising awareness about the risks of AMR and promoting responsible antimicrobial use. Veterinary professionals must be equipped with the knowledge and tools to make informed decisions about antimicrobial therapy, and farmers should be educated about alternative disease prevention strategies.
5) *Strengthening Surveillance and Monitoring Systems*: Investments in integrated One Health surveillance systems are essential for tracking AMR across human, animal, and environmental sectors. These systems should be expanded to provide real-time data on antimicrobial use and resistance patterns, enabling more effective response strategies.
6) *Fostering International Collaboration*: AMR is a global problem that requires international collaboration. Countries must work together to harmonize regulations,

share best practices, and support research initiatives aimed at developing new antibiotics, alternative therapies, and diagnostic tools.

9.3. Final Thoughts on the One Health Approach

The One Health approach provides a comprehensive framework for addressing the multifaceted issue of antimicrobial resistance. By recognizing the interdependence of human, animal, and environmental health, One Health promotes a more integrated and effective response to AMR. However, the successful implementation of the One Health approach requires sustained collaboration, investment, and commitment across sectors.

To truly tackle AMR, veterinary public health must continue to evolve, incorporating the latest scientific advancements and innovations in surveillance, diagnostics, and antimicrobial stewardship. Veterinary professionals must be empowered to make evidence-based decisions regarding antimicrobial use, and farmers should be supported in adopting practices that minimize the need for antibiotics. At the same time, global efforts must focus on strengthening regulatory frameworks, increasing public awareness, and encouraging responsible antimicrobial use in all sectors.

In conclusion, while AMR poses a significant threat to global health, the veterinary public health sector has a critical role to play in preventing its spread. By adopting a One Health approach, improving surveillance and monitoring, and fostering international collaboration, we can work towards a future where antimicrobial resistance is effectively managed, ensuring the health and well-being of both animals and humans.

Abbreviations

AI	Artificial Intelligence
AMR	Antimicrobial Resistance
AMRNet	Antimicrobial Resistance Network
AMU	Antimicrobial Use
ARGs	Antibiotic Resistance Genes
CDC	Centers for Disease Control and Prevention
EHRs	Electronic Health Records
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems
GLASS	Antimicrobial Resistance Surveillance System
LMICs	Low- and Middle-Income Countries
OH	One Health
TrACSS	Tripartite AMR Surveillance
UN	The United Nation
VPH	Veterinary Public Health
VPHI	Veterinary Public Health Interventions
WHAH	World Organization for Animal Health
WHO	World Health Organization

Acknowledgments

The author wishes to extend sincere appreciation to the distinguished experts in veterinary medicine, public health, and environmental science for their invaluable insights into the complex issue of antimicrobial resistance. Gratitude is also owed to the dedicated research teams and institutions engaged in AMR surveillance and stewardship initiatives across the globe. Special acknowledgment is reserved for colleagues whose critical feedback significantly enriched the development of this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Glossary of Terms

Alternative Therapies: Treatment options other than traditional antimicrobial drugs, such as vaccines, probiotics, phage therapy, or herbal medicines, that can help in preventing or treating infections and reduce reliance on antibiotics.

AMR Surveillance Network: A network of organizations and institutions that collect data and monitor the prevalence of antimicrobial resistance across different regions and species.

Antibiotic Resistance Genes (ARGs): Genetic material in bacteria that enables them to resist the effects of antibiotics. ARGs can be transferred between bacteria, spreading resistance.

Antibiotics: A type of antimicrobial that specifically targets bacteria to kill or inhibit their growth. Antibiotics are used in both human and veterinary medicine to treat bacterial infections.

Antimicrobial Prescribing Guidelines: Evidence-based recommendations for the appropriate use of antimicrobials in both human and veterinary medicine. These guidelines help reduce misuse and overuse, which contributes to the development of resistance.

Antimicrobial Resistance (AMR): The ability of a microorganism (bacteria, fungi, viruses, or parasites) to resist the effects of drugs that once killed them or inhibited their growth. This leads to the failure of standard treatments and requires alternative treatment options.

Antimicrobial Resistance (AMR): The ability of a microorganism to resist the effects of an antimicrobial drug that it was previously susceptible to.

Antimicrobial Stewardship: The careful and responsible management of antimicrobial use to reduce the risk of developing resistance. This includes prescribing antibiotics only when necessary, selecting appropriate drugs, and ensuring proper dosing and duration.

Antimicrobial Use (AMU): The application of antimicrobial agents in the treatment or prevention of disease in humans

and animals. It includes the use of antibiotics, antivirals, antifungals, and antiparasitic.

*Antimicrobia*l: A substance that kills or inhibits the growth of microorganisms such as bacteria, fungi, or viruses. Antimicrobials can include antibiotics, antifungals, antivirals, and antiparasitic.

Antimicrobial: A substance that kills or inhibits the growth of microorganisms such as bacteria, fungi, or viruses.

Environmental Health: A field of public health that focuses on the interactions between humans, animals, and their environment, especially concerning how environmental factors (like pollution, waste management, and chemicals) impact health.

Infectious Disease: A disease caused by the invasion and multiplication of microorganisms in the body. Infectious diseases can be transmitted between animals and humans, often via direct or indirect contact.

Microbiome: The community of microorganisms (bacteria, fungi, viruses) that inhabit a specific environment, such as the gut, skin, or respiratory tract. The human and animal microbiome plays a key role in health and disease.

One Health Surveillance: A multi-sectoral approach to monitoring health threats, including zoonotic diseases and AMR, by integrating data from human health, animal health, and environmental health sectors.

One Health: An approach that recognizes the interconnectedness of human, animal, and environmental health. It promotes an integrated way of addressing health issues, particularly those that span across multiple sectors, such as antimicrobial resistance (AMR).

Pathogen: A microorganism, such as a bacterium, virus, or fungus, that causes disease in its host.

Pharmacovigilance: The monitoring of the safety and effectiveness of antimicrobial drugs after they have been marketed. This includes tracking side effects and the development of resistance.

Resistance Mechanism: The ways in which microorganisms adapt to evade the action of antimicrobial agents. This includes changes in the target site of the drug, the production of enzymes that degrade the drug, or the active expulsion of the drug from the cell.

Surveillance: The ongoing, systematic collection, analysis, and interpretation of health data to track disease trends and detect new or emerging threats, such as antimicrobial resistance.

Vaccination: The administration of vaccines to prevent specific infectious diseases. Vaccination reduces the need for antimicrobial use by preventing disease outbreaks, particularly in livestock and humans.

Veterinary Public Health (VPH): A field that combines veterinary medicine with public health to safeguard the health of animals and people. VPH focuses on preventing diseases, ensuring safe food, and managing environmental factors that impact both animal and human health.

Zoonotic Disease: A disease that can be transmitted from animals to humans.

Zoonotic Disease: A disease that is transmitted from animals to humans. Examples include rabies, salmonella, and tuberculosis. Zoonotic diseases can play a significant role in the transmission of antimicrobial-resistant pathogens.

Additional Resources

FAO AMR Portal:
http://www.fao.org/antimicrobial-resistance/en/

WHO AMR Website:
https://www.who.int/antimicrobial-resistance/en/

WOAH AMR Resources:
https://www.woah.org/en/disease/antimicrobial-resistance/

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