



One Health in Action: Tackling Antimicrobial Resistance through Integrated Human, Animal, and Environmental Health Approaches

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Abstract

The One Health approach is a collaborative framework that recognizes the interconnectedness of human, animal, and environmental health, aiming to address global health challenges effectively. This literature review focuses on antimicrobial resistance (AMR), a significant global health threat driven by the misuse and overuse of antibiotics in both human healthcare and animal agriculture. Projections suggest that AMR could result in 10 million deaths annually by 2050 if not addressed, threatening decades of medical advancements. The review outlines the objectives of the One Health approach in combating AMR, highlighting the challenges and opportunities in its implementation. Key drivers of AMR include inadequate access to clean water, poor sanitation, and lack of awareness. Environmental pollution exacerbates the issue, as antibiotic residues contaminate water, soil, and air, creating reservoirs for resistant microorganisms. The relationship between AMR and the triple planetary crisis climate change, biodiversity loss, and pollution is emphasized. Climate change increases temperatures that facilitate the emergence of resistant pathogens, while biodiversity loss disrupts microbial diversity essential for ecosystem health. The One Health approach advocates for integrated strategies, including surveillance, responsible antimicrobial use, and environmental management. Case studies from the Netherlands and Denmark illustrate successful applications of the One Health framework, demonstrating significant reductions in antibiotic use through coordinated efforts and policy implementation. However, challenges such as institutional barriers, limited resources, and socio-cultural factors persist. The review calls for sustained political commitment and funding to support research and public health initiatives aimed at reducing AMR. Future research should focus on developing metrics to evaluate One Health interventions, understanding socio-cultural dynamics, and exploring environmental drivers of AMR. Overall, the One Health approach offers a promising framework for mitigating AMR and safeguarding global health through coordinated, multisectoral strategies.

Keywords: Antimicrobial resistance, One Health approach, cross-sectoral collaboration, Interconnectedness

1. Introduction

1.1 Back ground of the literature

The One Health approach is a collaborative, multisectoral, and transdisciplinary structure that aims to attain optimal health consequences by recognizing the interconnectedness of human, animal, and environmental health. This approach underlines that the health of people, animals, and ecosystems are interdependent, requiring incorporated efforts across these domains to report global health challenges effectively. Main principles of One Health include collaboration, systems thinking, and prevention through integrated policies and actions that value all three sectors [1].

The interconnectedness of animal, human, and environmental health is evident in several cases. For example, zoonotic diseases,

such as, Ebola, COVID-19, and avian influenza, highlight how pathogens can spread from animals to humans, often influenced by environmental factors such as deforestation and habitat loss [2]. Correspondingly, pollution and environmental degradation disturb water and air quality, impacting both human and animal populations [3]. Agricultural practices that prioritize pesticide overuse or overgrazing also demonstrate how unsustainable environmental management can exacerbate health risks across sectors [4].

Antimicrobial resistance (AMR) is gradually recognized as a critical global health threat, necessitating an integrated approach that comprises the health of humans, animals, and the environment. The One Health structure provides a comprehensive perspective on AMR by acknowledging the interdependencies

A persistent issue that highlights the importance of the One Health approach is antimicrobial resistance (AMR). AMR arises when microorganisms (e.g., bacteria, viruses, fungi, and parasites) develop to resist the effects of antimicrobial drugs, adaptation treatments less effective and leading to increased mortality and economic burden. The misuse and overuse of antibiotics in both human healthcare and animal agriculture are important drivers of AMR. Globally, AMR threatens to undermine decades of medical progress, with projections estimating that it could cause 10 million deaths annually by 2050 if unaddressed [6]. This literature review makes key findings from current research, highlighting the importance of a coordinated response to combat AMR and identifying knowledge gaps that deserve future exploration.

1.2. Objectives of the review

- To provide an outline of the One Health approach in the perspective of antimicrobial resistance (AMR).
- To analyze the challenges and opportunities in implementing One Health strategies for AMR mitigation.
- To debate the role of intersectoral collaboration in addressing AMR

2. Literature review

2.1 Antimicrobial Resistance (AMR) as a One Health Concern

Antimicrobial resistance (AMR) happens when microorganisms such as bacteria, viruses, fungi and parasites change in ways that render useless the medications used to cure the infections they cause [7]. Antimicrobials resistant microorganisms can develop resistant to plural antibiotics, becoming so-called superbugs. AMR is among the top 10 threats to global health [8]. In 2019 alone, AMR was the direct cause of 1.27 million deaths and a complicit cause of 4.9 million deaths, making drug-resistant infections more deadly than HIV/AIDS or Malaria [9]. This figure may drastically increase in future years, with estimated 10 million annual deaths by 2050 due to AMR [3]. The latest Lancet analysis (2024) assessed the global burden of bacterial antimicrobial resistance from 1990–2021 and forecasts that without net improvements in healthcare, infection prevention, vaccination, minimization of inappropriate antibiotic use in farming and humans, and research into new antibiotics 1.91 million deaths attributable to AMR and 8.22 million deaths associated with AMR could occur globally in 2050. AMR also poses economic challenges, leading to at least USD 3.4 trillion annually by 2030 of GDP drop and increasing by 24 million the number of those living in extreme poverty [3,10]. Now days it is estimated that AMR will cause economic losses of US\$ 100 trillion in terms of lost global production by 2050 if no urgent actions are taken [11]. On top of

that, antimicrobials are a powerful supporter to cure infections, and the increasing resistance to those without the development of new antimicrobials poses a challenge to human, animal and plant health.

AMR is a natural response that is both intrinsic and genetically acquired. Nevertheless, various factors favor its increase and fuel a dangerous rate of antibiotics ineffectiveness [12].

The main drivers indicated by World Health Organization are:

- The misuse and overuse of antimicrobials
- Lack of access to clean water, sanitation and hygiene (WASH) for both humans and animals
- Poor infection and disease prevention and control in health-care facilities and farms;
- Poor access to quality, affordable medicines, vaccines and diagnostics
- Lack of awareness and knowledge and
- Lack of enforcement of legislation.

These factors have an important environmental dimension as waterways, air and soil act as means of transmission and increasing temperatures and hazards associated with climate change contribute to greater development and the spread of antimicrobials and consequently increase resistance to their effectiveness.

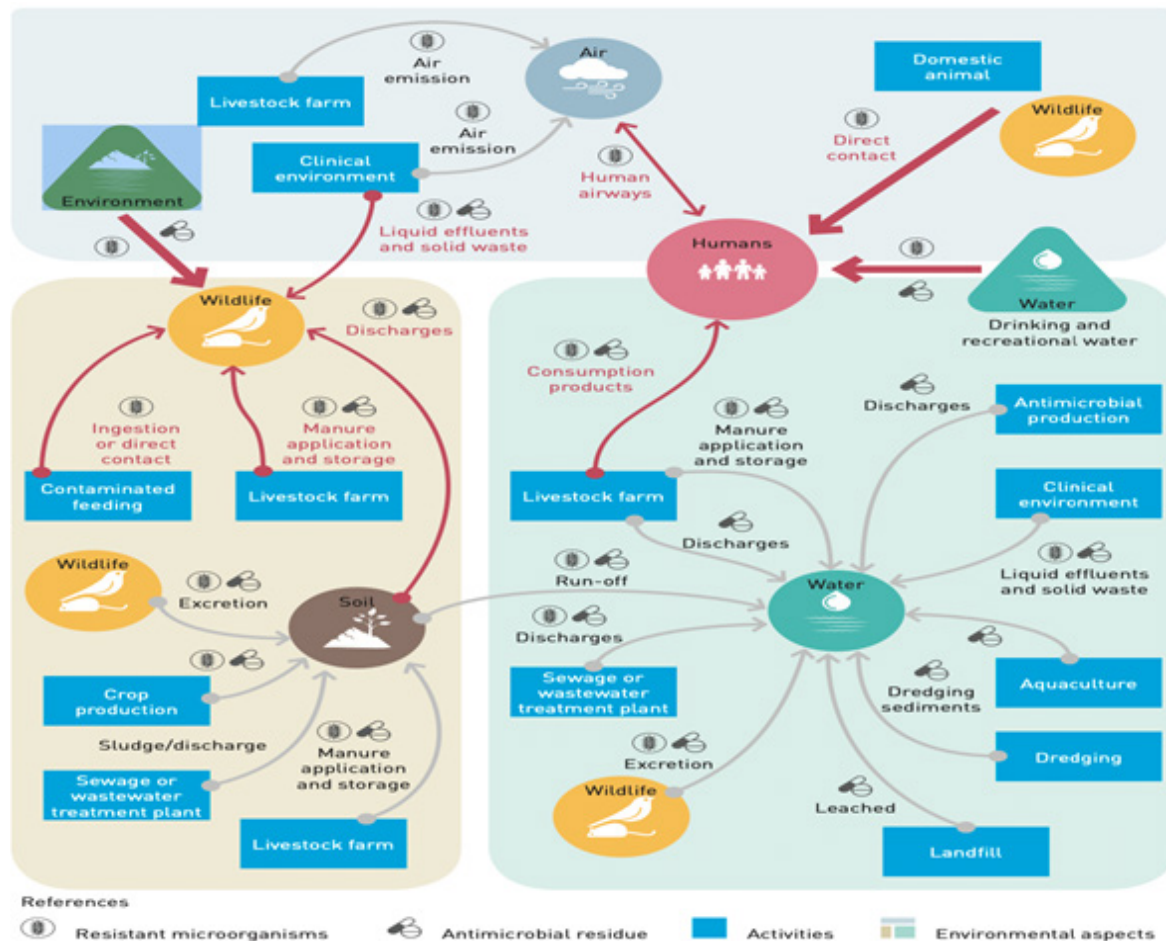
2.2 AMR and the Environment

The environment and AMR pandemic are severely linked. The environment is both a vehicle for spreading AMR microbes and a culprit of antimicrobial pollutants, which negatively impact biodiversity and ecosystems [3].

The spread of antimicrobials and the consequent increases in antimicrobial resistance occurs especially through unsound release of residues into the environment [13]. Therefore, environmental degradation and pollution factors connected to the triple planetary crisis of climate change, biodiversity loss and pollution are the very same ones that alter microbial diversity and facilitate the development, transmission and diffusion of AMR [3].

Antimicrobials coming from these sources are present and transmitted through water (rivers, lakes and sediments), sewage, soil, air and wildlife. They represent a serious threat as their spread is not limited to the specific points where the contamination occurs (transient source), but it spreads in a diffuse and non-source way (figure: 1).

Figure 1: Strengthening environmental action in the One Health response to antimicrobial resistance



Source: Bracing for Superbugs. Strengthening environmental action in the One Health response to antimicrobial resistance [3].

In the past years due to the COVID-19 pandemic, zoonotic diseases have raised consideration and preoccupation. As antibiotics are more repeatedly used in animal husbandry, resistance is rapidly developed and spread through the environment in the shape of unmetabolized antibiotics. The transmission of diseases from animals to humans via zoonotic pathogens allows the risk of communicating also antibiotic-resistant genes (ARGs) through contact or consumption of animal products [14]. Therefore, people working in or living close to livestock facilities are extremely at risk.

2.3 The Effects of AMR on the Environment

The impact of antimicrobial pollutants on antimicrobial resistance (AMR) in the environment is a complex issue that has harvested increasing attention. Pollution of waterways, soils, and air contributes to environmental degradation and the proliferation of AMR. Several studies and reports have highlighted these concerns:

I. Environmental Media as Vectors for AMR Spread: Water, soil, and air serve as environmental media that facilitate the transmission and spread of drug-resistant microorganisms and

genes. Pollution from antibiotics originating from hospitals, communities, and food production can end up in municipal solid waste landfills and sewage, creating conditions conducive to the development and spread of AMR. (GEN)

II. Environmental Pollution as a Driver of AMR: Environmental pollution is considered a significant contributor to antimicrobial resistance. Factors such as antibiotic residues, industrial effluents, agricultural runoffs, heavy metals, biocides, pesticides, and sewage and wastewater create reservoirs for resistant genes and bacteria, facilitating the transfer to human pathogens [15].

III. Antibiotic Pollution and Resistance in the Environment: Extensive contamination of antibiotics in the environment exacerbates the emergence and spread of antibiotic-resistant bacteria. These bacteria are often exposed to low amounts of antibiotics, which can select for resistant strains [16].

These findings underscore the intricate relationship between environmental pollution and the development and dissemination of antimicrobial resistance, highlighting the need for comprehensive strategies to mitigate this global health threat.

2.4 AMR and the Triple Planetary Crisis

The United Nations Environment Programme (UNEP) highlights that the proliferation of AMR is linked to the triple planetary crisis. Specifically:

I. Climate Change

Increased temperatures associated with climate change are an important factor for the development of diseases such as bacteria, viruses, parasites, fungi and vector-borne diseases in humans, animals and plants, which might survive more easily in higher temperatures. This may cause the uprising of more antimicrobial resistant diseases. Climate change related hazardous events like floods that ravage human settlements increase the likelihood and frequency of uncontrolled leakage of antimicrobials into the environment and in communities.

II. Biodiversity Loss

Healthy soils are home to high microbial diversity, which is key to performing vital ecosystem functions. Antimicrobials have ecotoxicological effects that can disturb soil and plant health, reducing soil microbial diversity. Soil microbial diversity is an essential shield for the spread of AMR, as well as a main source of pharmaceutical discoveries. Soil microbial composition has been altered by human activities and climate change. Further research is necessary to establish how AMR affects biodiversity loss [3].

III. Pollution and Waste

Antimicrobials as pollutants to the environment come from multiple sources. The most harmful and threatening ones are treated and untreated human and animal excreta, residual waste from the pharmaceutical, manufacturing and healthcare sectors that leak into the environment through air, soil and waterways.

Addressing the triple planetary crisis is thus integral to combating AMR, as environmental factors play a crucial role in the emergence and spreading of resistance.

2.5 The One Health Approach to AMR

The growing threat of antimicrobial resistance (AMR) is a pressing global health challenge that necessitates a comprehensive and collaborative response. The One Health approach, which recognizes the interconnectedness of human, animal, and environmental health, has emerged as a critical framework for addressing this multifaceted issue [17].

The emergence of antimicrobial resistance (AMR) presents a significant global public health crisis, necessitating the adoption of a One Health approach that acknowledges the interconnectedness of human, animal, and environmental health. Implementing One Health strategies to combat AMR presents both challenges and opportunities. Challenges include

coordinating across sectors, resource limitations, and varying levels of awareness and commitment. Opportunities involve the potential for integrated surveillance systems, shared resources, and collaborative research efforts [18].

The One Health approach is fundamentally about collaboration across disciplines and sectors to address complex health issues like AMR. [19] highlight how the misuse of antibiotics in both healthcare and agriculture contributes to the emergence of resistant strains, underscoring the need for coordinated efforts across human, animal, and environmental health domains. This multifaceted nature of AMR is further echoed by [20], who advocate for a comprehensive strategy that involves various stakeholders, including governments, healthcare providers, and the public, to mitigate antibiotic overuse and improve surveillance.

In a similar vein, [21] argue for the necessity of defining and combating AMR from both One Health and global health perspectives. Their findings emphasize that effective strategies must be developed that account for the interconnectedness among human, animal, and environmental health, reinforcing the belief that AMR cannot be tackled in isolation.

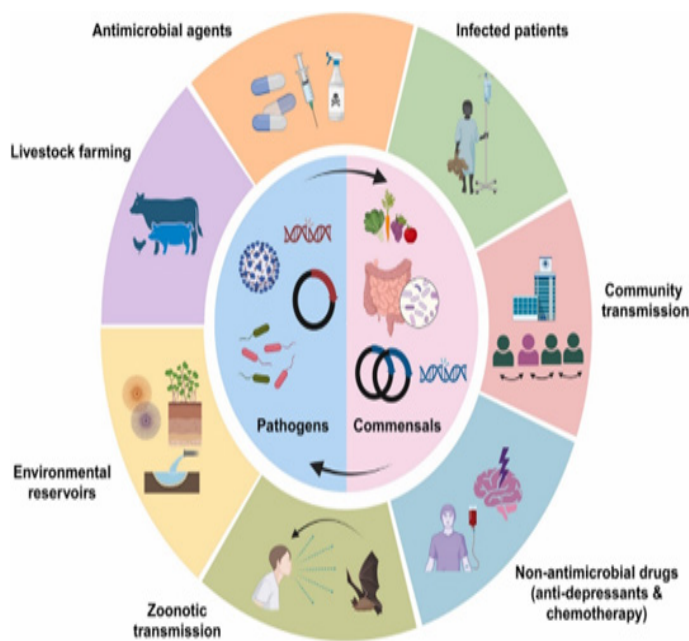
2.6 Emergence and Spread of AMR

AMR arises when microorganisms such as bacteria, viruses, fungi, and parasites develop the ability to resist the effects of antimicrobial drugs, making infections harder to treat. The emergence and spread of AMR are facilitated by interconnected pathways across the human, animal, and environmental sectors:

1. **Animal Sector:** The overuse and misuse of antibiotics in livestock, aquaculture, and agriculture contribute significantly to AMR. Antibiotics are often administered to animals to promote growth or prevent diseases in densely populated farms, leading to the selection of resistant strains. These resistant bacteria can spread to humans through direct contact, consumption of contaminated meat, or environmental contamination [22].
2. **Human Sector:** Inappropriate prescribing of antibiotics, self-medication, and inadequate healthcare infrastructure lead to misuse in human medicine. For example, the over-prescription of antibiotics for viral infections, which they cannot treat, accelerates resistance development [23].
3. **Environmental Sector:** Antimicrobial residues from human and animal sources enter the environment through wastewater, agricultural runoff, and improper disposal of pharmaceuticals. These residues create reservoirs of resistance in soil and water, where resistant genes can transfer between microorganisms, exacerbating the spread (figure: 2) [24].

Global prevalence of AMR in microbes is a complex interplay

of microbial-intrinsic, host-intrinsic and environmental factors. Despite AMR being a natural occurrence, unchecked drug consumption has exerted enhanced evolutionary pressure resulting in overwhelming growth of AMR in microbes. Due to ease of acquisition and transfer of drug resistance elements in microbial communities, it is essential to monitor not only microbial communities in human samples, but also in environmental sources like sewage, water, fecal matter, livestock and air pollutants. Hence, genomic surveillance of all these microbial AMR sources is necessary for prediction of global AMR trend [5].



Source: <https://www.google.com/url?sa=i&url=https3A2F2Fwww.cell.com>

Fig. 2: Determinants of antimicrobial resistance.

2.7 The Interconnectedness of Health Sectors

[25] articulates the essence of the One Health perspective, emphasizing that AMR is not simply a medical issue confined to human health; rather, it is occurrence that exceeds boundaries between human, veterinary, and environmental health. This interconnectedness is essential, as the misuse of antimicrobials in agriculture and healthcare settings serves as a significant driver of AMR. The findings underline the need for collaborative efforts across sectors to regulate antimicrobial use effectively, thereby mitigating the emergence and spread of resistant pathogens.

[26] further reinforce this view by illustrating how the overuse of critically important antimicrobials in both human and veterinary medicine poses severe risks to public health. Their research highlights the necessity for a coordinated response involving stakeholders from various health sectors, including policymakers, healthcare providers, and agricultural practitioners [26]. By adopting a One Health approach, these stakeholders can work synergistically to implement effective infection

control measures, improve sanitation, and regulate antimicrobial usage, which are crucial for preserving the efficacy of existing treatments against resistant infections.

2.8 Key Strategies in the One Health Approach

The literature identifies several strategies that are pivotal in the One Health framework for combating AMR:

To begin with, the control of antimicrobial utilize over segments is foremost. As highlighted within the inquire about by [25], the aimless use of antimicrobials in animals and agribusiness specifically pays to the choice and spread of safe microscopic organisms, which can subsequently influence human health. A One Health approach advocates for exacting directions and checking of antimicrobial applications in both human and veterinary practices [25].

Moment, effective sanitation and cleanliness practices is critical. The collaboration between human health experts and veterinarians can encourage the advancement of comprehensive sanitation conventions that address the chance variables related with AMR. By making strides sanitation in agricultural practices and healthcare settings, the spread of safe microscopic organisms can be reduced, subsequently securing both creature and human populaces [27].

One Health encompasses a unified approach that merges inter-domain efforts focused on improving the interconnected well-being of humans, animals, and the environment, at both regional and global levels. Initially conceived to monitor the origins and transmission of infectious diseases, its present goals encompass ongoing surveillance of circulating infectious agents or antimicrobial-resistant pathogens and their cross-species and cross-border transmission (figure: 3). It rigorously assesses the influence of biotic, abiotic, and environmental factors, as well as socioeconomic variables, which potentially shape the epidemiology of diseases [5].

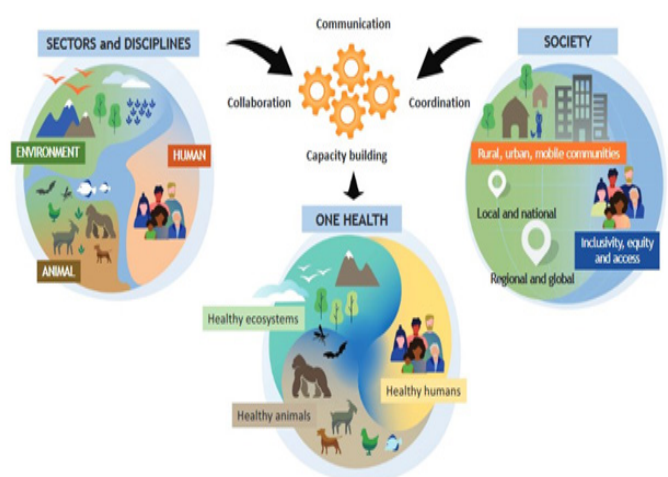


Fig. 3. Illustration of the One Health approach by the OHHLEP

2.9 Consequences of AMR on each sector

Antimicrobial resistance (AMR) has severe significances across the different sectors of animal, human, environmental and as a whole society. (Table-1)

Animal sector	Human sector	Environmental sector	For Society as a Whole
-Reduced effectiveness of antibiotics to treat animal diseases, leading to economic losses. -Increased mortality and morbidity in livestock and aquaculture. (Van Boeckel et al., 2015)	-Prolonged illness, increased healthcare costs, and higher mortality rates. -Limited treatment options for common infections and surgical procedures. (WHO, 2014)	-Persistent contamination by antimicrobial agents affects microbial diversity and ecosystem balance. -Spread of resistance genes to wildlife, amplifying ecological risks. [16]	-AMR threatens global health, food security, and economic stability. -Projections suggest AMR could cause 10 million deaths annually by 2050, with a cumulative economic impact of \$100 trillion [29].

Table-1: Consequences of AMR on each sector

2.10 One Health in Action: Case Studies

Some case studies explain the practical application of the One Health framework in addressing AMR. For instance, [29] discuss the implications of AMR on public health and the economy, advocating for antimicrobial stewardship programs (ASP) to promote rational use of antimicrobials. By employing a One Health perspective, these programs can foster collaboration across sectors, thereby enhancing their effectiveness.

Moreover, [25] presents a systematic review framework for addressing environmental health questions related to AMR. This methodology aims to integrate evidence across human, animal, and environmental studies, aligning well with One Health principles and offering a robust approach to understanding the

health impacts associated with AMR.

Furthermore, [30] emphasize the health risks posed by poorly managed animal feces, illustrating the direct transmission pathways of pathogens from animals to humans. Their findings advocate for improved hygiene and veterinary care, showcasing how managing animal health is crucial for enhancing human health outcomes. This case exemplifies the One Health principle that animal health directly impacts human health.

Antimicrobial Resistance (AMR) requires a holistic One Health approach that integrates human, animal, and environmental sectors. The following real-world examples illustrate successful interventions, strategies employed, challenge faced, and outcomes achieved. (Table-2)

Case Study Name	Strategies Used	Challenges	Outcomes	Reference
MARAN System (Netherlands)	- Collecting resistance data from livestock, retail meat, and clinical isolates in humans. -Establishing guidelines for antibiotic use. - Incorporating environmental monitoring to track antimicrobial residues in agricultural runoff.	- Coordinating data-sharing across sectors. - Sustaining funding for long-term surveillance programs.	- A 63% reduction in veterinary antibiotic use (2009–2013). - Improved cross-sector understanding of AMR trends, leading to effective policy	[31]
DANMAP Initiative (Denmark)	- Banning antibiotics as growth promoters in livestock since 2000. - Mandating documentation of antimicrobial prescriptions by veterinarians. - Implementing educational campaigns for healthcare providers and farmers.	- Resistance from stakeholders due to economic concerns. - Balancing animal health needs with reduced antibiotic use.	- Livestock antibiotic use dropped by 40% (1994–2014) with no loss in productivity. -Decrease in resistant bacteria in both humans and animals.	

ZED Initiative (India)	Initiative	- Enforcing strict effluent treatment standards in pharmaceutical manufacturing.	- Resistance from industries due to higher costs.	- Reduction in antimicrobial residues in water bodies near industrial zones.	[33]
		- Encouraging adoption of cleaner production methods.	- Limited enforcement capacity in rural areas.	- Decreased prevalence of resistant bacteria in local aquatic ecosystems.	

2.11 Potential for Broader One Health Application in Ethiopia

A One Health approach in Ethiopia holds significant promise for mitigating antimicrobial resistance (AMR) by fostering collaboration between human, animal, and environmental health sectors. By integrating surveillance data across these sectors, Ethiopia can develop more targeted interventions and create a stronger, more resilient strategic plan (table: 3).

Case Study Name	Strategies Used	Challenges	Outcomes	References
Operationalizing One Health to Combat AMR in Ethiopia	Inter-sectoral Coordination: Establishing multisectoral surveillance and regulation systems involving human, animal, and environmental health sectors. Environmental Management: Strengthening waste disposal and pollution controls to reduce environmental reservoirs of AMR. Community Engagement: Raising awareness about responsible antimicrobial use through community conversations and educational programs.	- L i m i t e d infrastructure and resources for coordinated surveillance. - I n a d e q u a t e w a s t e management systems leading to environmental contamination. - Low public awareness and understanding of AMR and its implications.	- Initiation of a National AMR Surveillance S y s t e m integrating data across sectors. - Implementation of waste management policies aimed at reducing environmental AMR spread. - E n h a n c e d community knowledge and behavioral changes regarding antimicrobial use.	Ethiopia's A M R Strategic Plan [34].

Table 3-: Case study highlighting the potential for broader application of the One Health approach in Ethiopia.

These case studies underline the importance of incorporated, multisectoral approaches to fighting AMR, emphasizing environmental regulation, responsible antimicrobial use, and surveillance systems. Familiarizing these models to the Ethiopian context can enhance the interconnected management of animal, human, and environmental health, ultimately reducing the problem of antimicrobial resistance across the region.

2.12 Lessons Learned from One Health Interventions

1. Collaborative Frameworks: Success depends on robust partnerships between governments, industries, and communities.
2. Education and Awareness: Empowering stakeholders with knowledge about AMR improves compliance with responsible practices.
3. Sustained Funding and Policy Support: Long-term interventions require stable financial backing and legislative action.
4. Global Applicability: While interventions like MARAN and DANMAP are country-specific, they offer replicable models for other nations.

2.13 Challenges in Implementing One Health Approaches

2.13.1 Institutional Barriers and Lack of Coordination between Sectors

A recurring theme in the literature is the institutional barriers that hinder effective One Health implementation. Many studies highlight the lack of coordination and communication among the various sectors involved in AMR management. For instance, [35] note that collaboration across human, animal, and environmental health sectors is often insufficient, which impedes the development of cohesive strategies. Similarly, [36] emphasize the irresponsible and excessive use of antimicrobials due to poor inter-sectoral communication, illustrating how these institutional challenges perpetuate AMR.

2.13.2 Limited Resources and Funding

Limited resources and inadequate funding emerge as critical challenges in the implementation of One Health approaches. Research indicates that significant political will and financial investment are necessary to address AMR effectively. [36] suggest that adequate investment is crucial for analyzing the AMR problem, while [37] highlight that healthcare systems in low- and middle-income countries (LMICs) often suffer from underfunding, limiting their capacity to tackle AMR comprehensively.

2.13.3 Data Gaps and the Need for More Research

Data gaps constitute another significant barrier to effective One Health strategies. The complexity of AMR, influenced by several factors including social anthropology and healthcare systems, necessitates comprehensive research to understand these dynamics fully [35]. Woodward *et al.* (2019) further underline the need for more research to explore the intricate relationships between AMR and climate change, which remain largely unexplored. The absence of robust data complicates the measurement of the impact of One Health initiatives and hinders informed decision-making [30].

2.13.4 Socio-Cultural Factors Influencing Antimicrobial Use Practices

Socio-cultural factors play a crucial role in shaping antimicrobial use practices and influencing resistance patterns. [35] highlight the importance of public awareness and health literacy, while [36] discuss how cultural attitudes towards health and medicine impact antimicrobial management. In LMICs, socio-cultural dynamics may drive inappropriate antimicrobial use, further complicating efforts to implement effective One Health strategies [38].

2.14 Opportunities and Potential Benefits of One Health

Despite these challenges, the One Health approach presents numerous opportunities to enhance AMR management.

1. Improved Effectiveness of Interventions

One of the primary benefits of the One Health framework is the potential for improved effectiveness of interventions through a holistic understanding of AMR. By integrating strategies across human, animal, and environmental health sectors, stakeholders can develop more comprehensive responses to AMR [35,36]. This systemic approach is crucial for addressing the multifaceted nature of AMR and fostering sustainable solutions.

2. More Efficient Use of Resources

The One Health approach also promotes more efficient resource utilization by addressing AMR from multiple angles. By fostering collaboration among different sectors, stakeholders can allocate resources more effectively and reduce redundancy in interventions [38]. This collaborative dynamic is particularly beneficial in resource-limited settings, where integrated strategies can enhance the impact of available funding [37].

3. Enhanced Collaboration and Communication

Enhanced collaboration and communication between sectors are essential components of the One Health approach. [39] emphasize that fostering inter-sectoral partnerships can lead to increased public awareness and engagement in AMR issues, ultimately driving change in antimicrobial use practices. This collaborative environment is vital for establishing a unified response to shared health threats.

4. Increased Public Awareness and Engagement

Another opportunity presented by the One Health framework is the potential for increased public awareness and engagement regarding AMR. By educating the public about the links between AMR and various health sectors, stakeholders can foster a greater understanding of the issue and encourage responsible antimicrobial use [38]. This heightened awareness is critical for driving behavioral change and improving health outcomes.

2.15 Knowledge Gaps and Future Research Directions

Despite the promising insights gained from the application of the One Health framework in combating AMR, several knowledge gaps remain. For instance, while the interconnectedness of human, animal, and environmental health is well-established, there is a lack of empirical studies that quantify the impact of specific interventions across these domains. Future research should focus on developing metrics and methodologies to assess the effectiveness of One Health interventions in reducing AMR.

Despite the advancements in understanding AMR, several knowledge gaps remain. There is a need for more comprehensive research on the transmission dynamics of resistant bacteria across different sectors, including the environment [40]. Additionally, innovative strategies to combat resistance, such as nonantibiotic alternatives, require further exploration [41,36].

Future research should also focus on developing robust frameworks for evaluating the effectiveness of interventions across various sectors. This includes assessing the impact of education and public awareness campaigns on antibiotic prescribing behaviors [42,43]. Enhanced collaboration among stakeholders will be essential for addressing these gaps and fostering a more integrated approach to AMR.

Additionally, the role of environmental factors in the spread of resistant bacteria remains insufficiently explored. [44] underscore the environmental and health impacts of various pollutants, but their findings do not directly address how these factors intersect with AMR. Research that specifically investigates the environmental drivers of AMR could provide valuable insights for the One Health framework.

Lastly, the operationalization of One Health in low-resource settings is an area that warrants further investigation. The complexities and challenges faced in these contexts require tailored strategies that account for local conditions and resource availability. Research focused on understanding and overcoming these barriers could enhance the effectiveness of One Health initiatives globally [45]. A systematic review by [45] highlights these challenges and emphasizes the importance of developing context-specific solutions to enhance the effectiveness of One Health initiatives globally.

While the existing literature highlights various challenges and opportunities associated with One Health approaches to AMR, significant knowledge gaps remain. Future research should focus on the following areas:

- I. Inter-sectoral Coordination:** Studies examining the effectiveness of specific interventions aimed at improving coordination among human, animal, and environmental health sectors are needed to identify best practices and scalable models.
- II. Funding Mechanisms:** Research exploring innovative funding mechanisms and strategies to enhance financial investment in One Health initiatives, particularly in LMICs, is crucial for addressing the resource limitations that hinder AMR management.
- III. Cultural Influences:** More research is needed to understand the socio-cultural factors that influence antimicrobial use practices across different communities. This knowledge can inform targeted interventions that resonate with cultural attitudes and values.
- IV. Impact Measurement:** Developing concrete metrics to evaluate the effectiveness of One Health initiatives will be essential for justifying policy decisions and resource allocations, as highlighted by [39].
- V. AMR and Climate Change:** Further investigation

into the complex interactions between AMR and climate change is necessary to elucidate the broader implications of these challenges on public health and inform integrated strategies.

2.16 Stakeholder Roles in Addressing AMR

Stakeholders play important roles in addressing antimicrobial resistance (AMR) through coordinated efforts.

2.16.1 Government Regulations

The role of government in regulating antibiotic use cannot be overstated. Governments must enforce comprehensive regulations that limit the misuse and overuse of antibiotics in both human and veterinary medicine. This is critical for reducing the selective pressure that drives the development of resistant strains [20,46]. Moreover, policies should extend to agricultural practices, where antibiotics are often used prophylactically, contributing to the resistance problem [36,47].

2.16.2 International Organizations

International organizations, notably the World Health Organization (WHO), play a crucial role in fostering global collaboration and knowledge sharing. They can help develop and promote action plans that encourage countries to share data and best practices [41,48]. Enhanced global surveillance of AMR is essential for tracking resistance patterns and informing policy decisions.

2.16.3 Researchers and Healthcare Professionals

Researchers are tasked with investigating the mechanisms of resistance and developing innovative strategies, such as new antibiotics and alternative therapies [49-54]. Healthcare professionals are equally important, as they must prioritize infection prevention and control measures while implementing antimicrobial stewardship programs to educate patients about the responsible use of antibiotics [47,51].

2.16.4 The Public

The public's role in advocating for responsible antibiotic use is vital. Education campaigns are necessary to inform the public about the risks associated with antibiotic misuse and to encourage them to engage in safe practices [42,52]. A well-informed public can act as a powerful ally in the fight against AMR.

2.16.5 Importance of Political Commitment and Funding

Sustained political commitment is essential to secure adequate funding for research and public health initiatives aimed at reducing AMR [48,52]. Political will is crucial for implementing effective policies and ensuring that they are enforced. Furthermore, continuous investment in surveillance systems and education will help ensure that effective measures are in place to combat this growing threat [41,46].

3. Conclusion and Recommendations

3.1 Conclusion

The assessment underscores the critical importance of the One Health approach in addressing the difficult and multifaceted challenge of antimicrobial resistance (AMR). It highlights the interconnectedness of human, animal, and environmental health sectors, emphasizing that real mitigation of AMR wants coordinated, multisectoral strategies. Key findings tell that antimicrobial misuse across sectors, environmental pollution, climate change, and socio-cultural influences significantly results to the emergence and spread of resistant pathogens. Successful case studies demonstrate that integrated surveillance, responsible antimicrobial use, and environmental management can lead to substantial reductions in resistance. However, persistent challenges such as institutional barriers, resource limitations, data gaps, and socio-cultural influences hinder progress. Addressing these subjects is important for safeguarding the effectiveness of antimicrobials and protecting global health.

3.2 Recommendations

- **Strengthen Intersectoral Collaboration:** Nurture strong partnerships among governments, healthcare providers, agricultural sectors, environmental agencies, and communities to develop and implement cohesive AMR strategies.
- **Improve Surveillance and Data Sharing:** Invest in incorporated surveillance systems like MARAN and DANMAP to monitor resistance patterns across sectors, enabling timely and informed decision-making.
- **Implement Responsible Antimicrobial Stewardship:** Implement regulations to control misuse and overuse of antimicrobials in human medicine, veterinary practices, and agriculture, together with public education campaigns.
- **Develop Environmental Management:** Regulate pharmaceutical waste, encourage cleaner production technologies, and decrease antimicrobial residues in water, soil, and air to limit environmental reservoirs of resistance.
- **Address Climate and Biodiversity Causes:** Incorporate climate change mitigation and biodiversity conservation into AMR action plans, identifying their influence on microbial dynamics.
- **Build Capacity and Resources:** Distribute adequate funding and resources, especially in low-resource settings, to support research, infrastructure, and staff development.
- **Foster Public Engagement and Education:** Growth awareness about responsible antimicrobial use and the interconnectedness of health sectors to encourage behavior change.
- **Line up Research and Innovation:** Support studies on

transmission dynamics, environmental drivers, and alternative therapies, and develop metrics to evaluate intervention effectiveness.

- **Ensure Political Commitment:** Advocate for continuous political will and policy support to maintain momentum and safe long-term investments in One Health initiatives.

Declarations

Lists of abbreviation:

MARAN, Monitoring of Antimicrobial Resistance and Antibiotic Usage in Netherlands;

DANMAP, Danish Integrated Antimicrobial Resistance Monitoring and Research Program;

ARG, Antibiotic Resistance Genes;

WHO, World Health Organization;

ASP, Antimicrobial Stewardship Programs;

GEN, Geneva Environmental Networks;

NCBI, National Center for Biotechnology Information;

OHHLEP, One Health High Level Expert Panel;

LMIC, Low- and Middle-Income Countries;

WK, Wikipedia

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