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Addressing Antimicrobial Resistance: Evidence-Based Strategies And Innovations

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Abstract. Antimicrobial resistance (AMR) is a significant global public health challenge, involving complex interactions across medical, environmental, economic, and social domains. This study integrates multidisciplinary perspectives, utilising literature reviews and case analyses to examine the current state and challenges of AMR, critique the limitations of existing strategies, and propose innovative solutions based on cutting-edge research. The study finds that environmental resistance genes, as emerging pollutants, pose underestimated threats to ecosystems and human health. Cross-disciplinary collaboration demonstrates significant advantages in AMR governance. This research proposes the establishment of a "Global Health Compact on AMR" and the integration of AI with precision medicine as innovative directions, providing theoretical support and practical solutions for global AMR governance, thereby contributing to addressing this critical issue.

Keywords: Antimicrobial resistance; One Health; Environmental resistance genes; Precision medicine; AI-driven drug discovery; Global governance.

1. Introduction

Antimicrobial resistance (AMR) is one of the most serious global public health threats of this century, with impacts spanning medical, environmental, economic, and social dimensions [1]. Since the widespread use of antibiotics, significant progress has been made in treating infectious diseases. However, excessive and inappropriate use has led to the rapid spread of resistant microorganisms.

Despite numerous global measures, AMR continues to spread, posing severe threats to human health and socio-economic development [2]. Low-income countries are disproportionately affected, with mortality rates from resistant infections far exceeding those in high-income countries, reflecting the inequitable distribution of global health resources.

To address these challenges, recent studies highlight the need to shift from isolated efforts to a unified approach that recognises the interconnected drivers of AMR. Previous research has predominantly focused on the medical aspects of AMR, with insufficient attention to its environmental and socio-economic impacts. In recent years, the One Health concept has gained traction, viewing human, animal, and environmental health as interconnected, providing a new perspective for comprehensively understanding and addressing AMR. This framework emphasises that solutions to AMR must integrate diverse sectors—from agriculture to urban planning—to disrupt the cycle of resistance. Integrating the latest advancements in public health and precision medicine allows for a deeper analysis of the underlying drivers of AMR and the exploration of innovative strategies.

This paper will address the current state, critique existing strategies, and propose innovative solutions based on the One Health concept, aiming to provide theoretical support and practical pathways for global AMR governance.

2. Current State and Challenges of Antimicrobial Resistance

2.1. Global Spread of Drug-Resistant Microorganisms and Latest Epidemiological Data

Resistant microorganisms have established a global transmission network through international travel and trade. For instance, methicillin-resistant Staphylococcus aureus (MRSA) exhibits a global spread trend, with detection rates in hospital environments ranging from 20% to 50%, and even higher in intensive care units (ICUs).

The incidence of community-associated MRSA (CA-MRSA) is rising annually, with transmission routes including close contact and shared items [3]. MRSA resistance primarily stems from gene mutations, horizontal gene transfer, and biofilm formation, rendering it resistant to multiple antibiotics. This leads to limited drug options, high treatment failure rates, and significant challenges in infection control, posing severe threats to global public health [4].

The global spread of resistant microorganisms not only endangers individual health but also poses risks to public health security, as outbreaks in any region can rapidly disseminate globally. As in Figure 1.

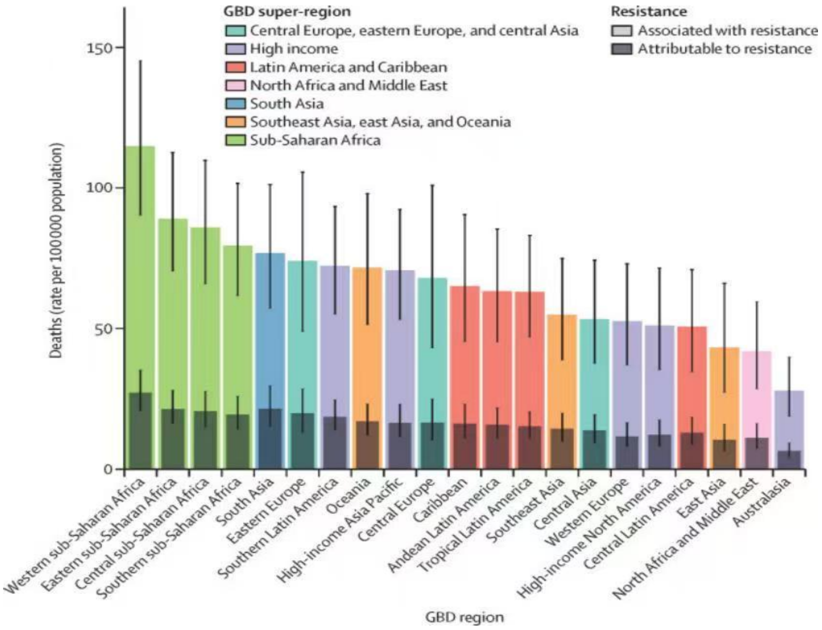

Fig.1 All-age rate of deaths attributable to and associated with bacterial AMR (cited from biomedicine and public heath lectures 2025)

In 2019, an estimated 1.27 million deaths worldwide were directly caused by drug-resistant bacterial infections. AMR has a profound impact on human and animal health, food production, and the environment. Without effective control, it is projected to result in annual global GDP losses of 1 trillion to 1 trillion to 3.4 trillion by 2030 and an additional $1 trillion in healthcare costs by 2050. Beyond causing deaths, AMR leads to widespread morbidity and disability, placing a heavy burden on health systems and complicating responses to public health emergencies [5].

2.2. Amplifying Effects of Socio-Economic Factors on AMR

Socio-economic factors play a critical role in the spread and exacerbation of AMR. AMR has become a global public health challenge affecting all regions and income levels.

The World Health Organisation (WHO) highlights that poverty and inequality exacerbate the drivers and consequences of AMR, with low- and middle-income countries bearing the heaviest burden [2]. In India, AMR has evolved into a major crisis for the healthcare system. Studies indicate that AMR significantly reduces the effectiveness of infectious disease treatments, leading to increased mortality, prolonged hospital stays, and higher medical costs [6]. For example, research published in the

"Journal of the Association of Physicians of India" found that the mortality rate among patients infected with highly virulent, carbapenem-resistant Klebsiella pneumoniae in an Indian hospital was as high as 56%.

In low-income countries, poverty and antibiotic misuse form a vicious cycle. The lack of clean water forces residents to consume water containing antibiotic residues, facilitating the spread of resistance genes within communities.

Additionally, global inequalities in antibiotic supply chains exacerbate the issue. The World Bank reports that high-income countries effectively control antibiotic use through stringent regulatory systems, while low-income countries, due to inadequate drug regulation, often become dumping grounds for expired antibiotics and counterfeit drugs, accelerating the spread of AMR [7].

These socio-economic disparities not only threaten local health but also have far-reaching implications for global public health through international trade and population mobility.

3. Limitations and Critical Analysis of Existing Strategies

3.1. Challenges in Policy Implementation and Surveillance Coverage

Existing antimicrobial stewardship programmes (ASPs) face significant disparities in implementation efficacy between high- and low-income countries. In high-income nations, ASPs supported by advanced technologies (e.g., electronic prescribing systems and real-time monitoring) have reduced inappropriate antibiotic prescriptions by 50% [8]. However, in low-income countries, inadequate healthcare infrastructure and regulatory gaps severely limit ASP effectiveness. For example, Tanzanian clinics using digital decision support tools reduced antibiotic prescriptions from 70.1% to 23.2%, yet such tools remain inaccessible in most African regions [9]. The Lancet highlights systemic issues in Africa, including high antibiotic misuse during pandemics, widespread non-prescription access, and insufficient public awareness, which drive increased drug-resistant infections and mortality [10]. Additionally, the African CDC's 2024 report warns that limited surveillance capacity and fragmented health systems in Africa exacerbate AMR risks, with over 60% of healthcare facilities lacking standardised resistance data reporting protocols [11].

Global surveillance systems like WHO's GLASS (Global Antimicrobial Resistance Surveillance System, a WHO system for global AMR monitoring and policy guidance) aim to standardize AMR data but face critical challenges [12]. Inconsistent laboratory standards and low coverage in low-income countries undermine data comparability and completeness [9,13].

For instance, sub-Saharan Africa lacks standardised resistance surveillance networks [13], and India's national AMR data remains fragmented, with only 30% of hospitals reporting standardised profiles [13]. This data gap delays timely interventions and obscures global AMR trends.

The World Bank emphasises that inadequate surveillance in resource-limited settings perpetuates AMR spread, as expired antibiotics and counterfeit drugs flood unregulated markets [7].

3.2. Structural Barriers to Global Coordination

Although artificial intelligence (AI) has immense potential in AMR surveillance, emerging technologies such as AI and genomic sequencing still face significant adoption barriers in resource-limited settings. While deep learning models (D-MPNN) have accelerated the screening of antibiotic molecules, and the activity of the novel antibiotic halicin has been validated [14], these tools rely on high-performance computing infrastructure, which is extremely scarce in impoverished regions worldwide. This situation has led to technological inequity, severely constraining the development of digital health innovations. Specifically, the implementation of AI for AMR surveillance in sub-Saharan Africa (SSA) is hindered by data scarcity, infrastructural limitations, and ethical challenges [15].

4. Innovative Solutions Based on the One Health Concept

4.1. Long-Term Ecological Risks of Environmental Resistance Genes

Resistance genes, as emerging environmental pollutants, impose long-term and profound impacts on ecosystems.

Their persistence in soil, water, and other environments, coupled with horizontal gene transfer (HGT, a process where bacteria acquire resistance genes via plasmids or transposons from other species, accelerates the spread of resistance across ecosystems), can alter microbial community structures and functions [16].

Long-term application of organic fertilisers (e.g., chicken manure) significantly facilitates the vertical migration of antibiotic resistance genes (ARGs), such as aminoglycoside- and β-lactamase-encoding genes, in soil. The leaching of ARGs in acidic soils can reach three times that of unfertilised soils [17].

Global studies on soil microorganisms reveal that agricultural soils with long-term antibiotic use exhibit higher resistance gene abundance compared to untreated soils [18]. This not only affects soil ecosystem material cycles and energy flows but also threatens food safety and human health through the food chain. For example, resistant bacteria in soil can contaminate crops, increasing the risk of human infections.

Therefore, addressing AMR must consider environmental ecosystems, adopting comprehensive measures to reduce the spread and accumulation of resistance genes in the environment.

4.2. Practical Pathways for Cross-Disciplinary Collaboration

The core of the One Health concept lies in breaking down disciplinary barriers and integrating human medicine, veterinary medicine, and environmental science.

The European Union's "One Health Action Plan" has demonstrated significant success, treating human, animal, and environmental health as interconnected and establishing multi-sectoral joint surveillance mechanisms to promptly detect and respond to cross-species transmission of resistant bacteria [19]. For instance, upon detecting resistant bacteria in an animal farm, the plan coordinated health, agriculture, and environmental departments to monitor human health and environmental resistance gene distribution, implementing control measures to prevent further spread.

Interdisciplinary teams can analyse and address AMR from various perspectives, formulating more comprehensive and effective control strategies. This proves that cross-disciplinary collaboration is not only theoretically feasible but also practically effective. For example, veterinarians provide expertise on animal health, environmental scientists assess antibiotic impacts on the environment, and policymakers develop guiding policies.

4.3. Practical Cases of AI in AMR

Recent significant growth in medical and biological data has spurred the development of many artificial intelligence (AI)-based technologies. These technologies enable computers to learn and adapt to increasingly complex information [20]. In the context of antibiotic failure, AI offers substantial opportunities for disease diagnosis and drug discovery [21].

The application of AI has significantly improved the efficiency and accuracy of monitoring resistant bacterial strains, providing more precise guidance for clinical treatment. For instance, Zagajewski et al. developed a method based on convolutional neural networks (CNNs) that can distinguish between susceptible and resistant phenotypes at the single-cell level, thereby enabling rapid phenotypic analysis of antibiotics [22]. In addition to this, AI's application in antimicrobial drug development primarily focuses on new drug discovery and drug repositioning. For example, Stokes et al. utilised deep learning models (such as graph neural networks, GNNs) to reposition known molecules, successfully identifying compounds with broad-spectrum antimicrobial activity [23]. Furthermore, Wan et al. developed a deep learning-based model that discovered novel antimicrobial peptides by mining the gene sequences of extinct organisms [24]. This demonstrates the immense potential of AI in accelerating drug development and reducing research costs.

Although AI has shown potential in the governance of AMR, its application needs to directly confront ethical risks. Biases in training data will exacerbate the unfairness in the field of health.

A study on algorithms used for managing population health found that an algorithm widely applied and affecting millions of patients has significant racial biases. Under the same risk score, Black patients are actually much more severely ill than White patients, yet the algorithm fails to accurately reflect this situation.

If this bias is corrected, the proportion of Black patients receiving additional assistance will increase from 17.7% to 46.5% [25]. This algorithm predicts medical expenses rather than the diseases themselves. Moreover, due to the disadvantages that Black people face in accessing medical resources, their medical spending is lower than that of White people, which leads to the generation of racial biases in the algorithm.

In addition, in similar medical scenarios, if there are problems with the proxy indicators relied on by the algorithm, such as using expenses to replace the severity of diseases, it may lead to unfair treatment of patients of different races, thereby further exacerbating health inequalities.

5. Discussion

Through literature review and analysis, this study identifies the following key findings.

5.1. Environmental Resistance Genes as Emerging Pollutants

In environmental resistance gene research, past studies focused on clinically resistant bacteria, while recent research reveals the long-term presence and underestimated ecological risks of resistance genes in the environment. Resistance genes, as emerging environmental pollutants, are widely distributed in soil, water, and other environments with long half-lives, capable of altering microbial community structures and functions through HGT [16]. Global soil microorganism studies show that agricultural soils with long-term antibiotic use have higher resistance gene abundance compared to untreated soils [18]. This not only affects soil ecosystem material cycles and energy flows but also threatens food safety and human health through the food chain. This finding expands the boundaries of AMR research, revealing the close links between AMR and ecosystems.

5.2. Cross-Disciplinary Collaboration in AMR Governance

In cross-disciplinary collabouration to address AMR, one study bridges qualitative veterinary research and social sciences, emphasising the need for interdisciplinary approaches encompassing animal disease management knowledge, practises, technologies, labour conditions, professional competencies, and business models [26]. Traditional approaches often focus on single disciplines, while this plan integrates multiple disciplines. Additionally, numerous cases demonstrate that multidisciplinary collaboration is an effective way to address the complex issue of AMR, providing a model for other regions and highlighting the importance of breaking down disciplinary barriers and promoting knowledge sharing and collaboration.

This study argues that AMR is a complex systemic issue that cannot be addressed solely from a medical perspective but requires consideration of socio-economic and environmental factors. Based on the One Health concept, systems thinking should be applied, viewing human, animal, and environmental health as interconnected to comprehensively understand AMR transmission mechanisms and influencing factors.

5.3. Policy and Technical Integration

The fragmented global governance of antimicrobial resistance (AMR)—evidenced by inconsistent implementation of the 2015 Global Action Plan (GAP) [27]—necessitates establishing a "Global Health Compact on AMR" to harmonize antibiotic stewardship under the International Health Regulations. This compact could adopt the financing model of the Global Alliance for Vaccines and Immunisation (Gavi) [28], creating a phased compliance mechanism. For instance, low-income countries may implement tools like Tanzania's digital decision support system, which reduced antibiotic prescriptions from 70.1% to 23.2% [9], while high-income nations provide funding and technology transfer. Public-private partnerships should address funding gaps through mechanisms such as the "Advance Market Commitment", enabling predefined responsibilities and benefits to incentivize multilateral collaboration.

At the technical level, integrating AI with precision medicine demonstrates transformative potential. The collaboration between Eli Lilly and OpenAI leverages generative AI to accelerate the discovery of compounds targeting multidrug-resistant pathogens (e.g., carbapenem-resistant Enterobacteriaceae) within months—compared to traditional timelines of years. Early results indicate AI-generated candidates exhibit 40% higher binding affinity to bacterial targets than conventional methods [29].

5.4. Ethical Challenges in AI-Driven Solutions

While AI offers significant advantages in AMR surveillance and drug development, challenges persist. Federated learning technology addresses data privacy concerns by enabling decentralised modelling across institutions (e.g., sub-Saharan African hospitals), improving prediction accuracy without centralised data sharing [30]. However, ethical risks emerge from algorithmic biases. A healthcare management algorithm predicting medical costs (rather than disease severity) underestimated illness severity in Black patients due to systemic disparities in healthcare access. Correcting this bias increased Black patients eligible for additional care from 17.7% to 46.5% [25], underscoring the need for equitable data governance frameworks to prevent AI from exacerbating health inequities.

6. Conclusion

Through comprehensive literature analysis, the complexity of AMR exceeds traditional understanding, with its spread influenced by multiple intertwined factors.

This study advances antimicrobial resistance (AMR) governance through three multidisciplinary insights. First, agricultural practises, such as long-term livestock manure application, triple the abundance of antibiotic resistance genes (ARGs) in farmland soils compared to unfertilised soils, posing risks to human health via crop contamination and food chain transmission [17]. Second, the proposed Global AMR Health Convention addresses fragmented governance by introducing a "phased compliance" mechanism for resource-limited regions, supported by financing models from the Gavi Vaccine Alliance (e.g., Advance Market Commitments) and mobile health tools, exemplified by Tanzania's digital decision support system reducing antibiotic prescriptions from 70.1% to 23.2% [9]. Third, while AI technologies like graph neural networks accelerate antimicrobial discovery [23], ethical challenges—such as racial biases underestimating disease severity in Black patients due to healthcare cost proxies—necessitate equitable data governance frameworks [25].

Despite reliance on secondary data and theoretical methodologies, the One Health framework integrates environmental and socio-economic factors, offering extensible ecosystem-level solutions for global AMR governance.

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