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Antibiotic Resistance: Current Trends and Prevention

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Abstract

Background: Antimicrobial resistance (AMR) is among the leading global public-health threats of the twenty-first century, undermining the treatment of common infections and the safety of routine medical procedures. This review synthesises current epidemiological evidence on the trends, distribution, and drivers of antibiotic resistance, and appraises the principal strategies for its prevention. **Methods:** A structured narrative review and secondary synthesis of publicly available surveillance datasets and peer-reviewed literature (2015–2026) was performed, drawing on the WHO Global Antimicrobial Resistance and Use Surveillance System (GLASS), the U.S. Centers for Disease Control and Prevention (CDC), and the Global Research on Antimicrobial Resistance (GRAM) Project. **Results:** In 2021, bacterial AMR was directly responsible for an estimated 1.14 million deaths and associated with 4.71 million deaths worldwide; on current trajectories, 39 million cumulative deaths are forecast between 2025 and 2050. In 2023, approximately one in six laboratory-confirmed bacterial infections were resistant to first-line antibiotics, and resistance rose in more than 40% of monitored pathogen–antibiotic combinations between 2018 and 2023. The burden is greatest in low- and middle-income countries and is shifting increasingly toward older adults, with carbapenem resistance among Gram-negative bacteria of particular concern. **Conclusion:** Coordinated "One Health" action—combining antimicrobial stewardship, infection prevention and control, vaccination, strengthened surveillance, and investment in new antibiotics—is essential and demonstrably effective. Sustained political and financial commitment is required to avert a preventable global health and economic catastrophe.

Keywords: *antimicrobial resistance; antibiotic resistance; surveillance; antimicrobial stewardship; One Health; infection prevention; global health.*

INTRODUCTION

The discovery of penicillin by Alexander Fleming in 1928 and its clinical deployment during the 1940s transformed medicine, converting once-fatal infections into treatable conditions and enabling modern surgery, chemotherapy, and organ transplantation [1]. Yet resistant strains emerged within a decade of widespread use, and the succeeding decades have witnessed a relentless erosion of antimicrobial efficacy. Antimicrobial resistance (AMR) arises when bacteria, fungi, viruses, and parasites evolve mechanisms that render the drugs designed to kill them ineffective, allowing resistant organisms to survive, proliferate, and transfer their resistance determinants to other microbes [2]. Today, AMR is recognised as one of the foremost threats to global public health, food security, and economic development [3].

The magnitude of the contemporary burden is stark. The Global Research on Antimicrobial Resistance (GRAM) Project estimated that in 2019 bacterial AMR was directly responsible for 1.27 million deaths and associated with a further 4.95 million deaths worldwide, exceeding the annual mortality of HIV/AIDS or malaria [4]. Updated analyses spanning 1990–2021 confirmed that more than one million people died each year as a direct consequence of AMR across this period, and forecast that, on current trajectories, 39 million people could die directly from resistant infections between 2025 and 2050 [5]. These figures echo the earlier O'Neill Review, which projected up to 10 million annual AMR deaths by mid-century in the absence of decisive action [6].

The drivers of resistance are multifactorial and interconnected. Inappropriate and excessive antimicrobial use in human medicine—prescribing for viral illnesses, incomplete treatment courses, and over-reliance on broad-spectrum agents—exerts powerful selective pressure [7]. Comparable or greater volumes of antimicrobials are consumed in animal agriculture and aquaculture, frequently for growth promotion and prophylaxis, while environmental contamination from pharmaceutical manufacturing, hospital effluent, and agricultural run-off establishes reservoirs in which resistance genes circulate and recombine [8]. Because humans, animals, and the environment form a single interconnected system, contemporary responses are increasingly framed within a "One Health" paradigm [9].

The consequences extend well beyond individual mortality. Resistant infections prolong hospital stays, necessitate more toxic and expensive second-line therapies, and jeopardise routine procedures that depend on effective infection prophylaxis [3]. The economic toll is projected to reach trillions of dollars in cumulative global output, disproportionately affecting low- and middle-income countries (LMICs), where surveillance capacity is weakest and access to newer agents most limited [10]. In response, the World Health Organization (WHO) has established the Global Antimicrobial Resistance and Use Surveillance System (GLASS) and successive global action plans to coordinate containment [3,11].

This article synthesises current epidemiological evidence on the trends, distribution, and drivers of antibiotic resistance, and evaluates the principal strategies available for its prevention. By integrating recent global surveillance data with established mechanistic and policy frameworks, it aims to provide a concise, evidence-based overview to inform clinical practice, public-health planning, and future research priorities.

MATERIALS AND METHODS

Study design. This work was conducted as a structured narrative review and secondary synthesis of publicly available antimicrobial-resistance surveillance data and peer-reviewed literature. No primary human or animal subjects were involved; the analysis relied exclusively on aggregated, de-identified, publicly reported datasets and published estimates. Formal ethical approval was therefore not required.

Data sources. Quantitative burden estimates were obtained from three principal surveillance and modelling sources: (i) the WHO Global Antimicrobial Resistance and Use Surveillance System (GLASS), including the Global Antibiotic Resistance Surveillance Report 2025 [3]; (ii) the U.S. Centers for Disease Control and Prevention (CDC) Antibiotic Resistance Threats reports of 2019 [12] and 2021–2022 [13]; and (iii) the GRAM Project estimates published in The Lancet for 2019 [4] and for 1990–2021 with forecasts to 2050 [5]. Supplementary evidence on mechanisms, drivers, and interventions was drawn from peer-reviewed articles and authoritative policy documents.

Search strategy. Bibliographic searches were performed in PubMed/MEDLINE, Scopus, and Google Scholar for records published between January 2015 and January 2026, combining the terms "antimicrobial resistance," "antibiotic resistance," "AMR surveillance," "resistance trends," "antimicrobial stewardship," and "One Health" using Boolean operators. Reference lists of retrieved articles and relevant institutional websites (WHO, CDC, and the European Centre for Disease Prevention and Control) were hand-searched to identify additional sources.

Inclusion and exclusion criteria. Sources were eligible if they reported quantitative estimates of AMR prevalence, incidence, mortality, or economic burden, or described evaluated prevention strategies, and were published in English. Preference was given to systematic analyses, multinational surveillance reports, and consensus policy frameworks. Case reports, conference abstracts without full data, non-peer-reviewed commentary, and studies lacking methodological transparency were excluded.

Data extraction. Two categories of data were extracted: (i) epidemiological indicators—deaths attributable to and associated with AMR, resistance prevalence for priority pathogen–antibiotic combinations, and infection and cost estimates; and (ii) intervention data—the level of implementation (individual, healthcare facility, national policy, and One Health) and reported effectiveness. Extracted values were tabulated in a standardised spreadsheet and cross-checked against the original source to minimise transcription error.

Data synthesis. Given the heterogeneity of study designs, reporting periods, and case definitions, a narrative synthesis rather than a formal meta-analysis was undertaken. Findings were organised thematically into (a) the global mortality burden and its projected trajectory, (b) resistance-prevalence trends among priority pathogens, (c) regional and national distribution of burden, and (d) prevention and containment strategies. Descriptive statistics reported by source institutions (absolute numbers, proportions, and percentage changes) were reproduced without recalculation; where estimates carried uncertainty intervals, the central estimate is presented for clarity.

Quality assessment. The credibility of each source was appraised on the basis of methodological transparency, sample size, geographical coverage, and peer-review or institutional standing. Surveillance datasets with documented laboratory-confirmation protocols and multinational coverage were regarded as of the highest quality. Limitations arising from

surveillance gaps—particularly the under-representation of low- and middle-income countries—were noted and are addressed in the Discussion.

RESULTS

Global mortality burden and forecasts. The synthesised evidence confirms a large and rising global mortality burden (Table 1). GRAM estimates indicate that deaths directly attributable to bacterial AMR remained above one million annually throughout 1990–2021, while associated deaths approached five million per year [4,5]. Forecasts to 2050 project a 67.5% rise in annual attributable deaths (to 1.91 million) and a cumulative total of 39 million attributable deaths over 2025–2050 [5]. Critically, the burden is shifting across the life course: attributable deaths among children under five fell by roughly half between 1990 and 2021—reflecting improved vaccination, sanitation, and paediatric care—whereas deaths among adults aged 70 years and older rose by more than 80% as populations aged [5].

Table 1. Global burden of bacterial antimicrobial resistance: current estimates and forecasts.

Metric	Estimate	Year / period	Source
Deaths directly attributable to AMR	1.27 million	2019	GRAM [4]
Deaths associated with AMR	4.95 million	2019	GRAM [4]
Deaths directly attributable to AMR	1.14 million	2021	GRAM [5]
Deaths associated with AMR	4.71 million	2021	GRAM [5]
Projected annual attributable deaths	1.91 million	2050 (forecast)	GRAM [5]
Projected annual associated deaths	8.22 million	2050 (forecast)	GRAM [5]
Cumulative attributable deaths	39 million	2025–2050	GRAM [5]
Change in attributable deaths, age ≥70 yr	+80%	1990–2021	GRAM [5]
Change in attributable deaths, age <5 yr	−50%	1990–2021	GRAM [5]
MRSA attributable deaths	130,000 (from 57,200)	2021 vs 1990	GRAM [5]

AMR, antimicrobial resistance; GRAM, Global Research on Antimicrobial Resistance Project; MRSA, methicillin-resistant Staphylococcus aureus. Central estimates are shown.

Resistance-prevalence trends. WHO GLASS surveillance corroborates a deteriorating global picture (Table 2). Drawing on more than 23 million bacteriologically confirmed infections reported by over 100 countries, the 2025 report found that approximately one in six laboratory-confirmed bacterial infections in 2023 were resistant to first-line antibiotics [3]. Between 2018 and 2023, resistance increased in more than 40% of the pathogen–antibiotic combinations under surveillance, at an average annual rate of 5–15% [3]. Of particular concern, resistance to carbapenems—a last-resort class—rose faster than for other antibiotic classes among Gram-negative organisms, narrowing therapeutic options for the most severe infections [5].

Table 2. Trends in antibiotic resistance from WHO GLASS surveillance.

Indicator	Finding	Source
Lab-confirmed bacterial infections resistant to first-line antibiotics	≈1 in 6 (≈16.7%)	2023, GLASS [3]
Pathogen–antibiotic combinations with rising resistance	>40% of those monitored	2018–2023 [3]
Average annual increase in resistance (rising combinations)	5–15%	2018–2023 [3]
Bacteriologically confirmed cases analysed	>23 million	2023, GLASS [3]
Countries/territories reporting to GLASS	127 countries + 3 territories	end 2024 [3]

GLASS, WHO Global Antimicrobial Resistance and Use Surveillance System.

National burden: the United States as an illustrative high-income setting. National surveillance illustrates both the scale of the problem and the impact of sustained control efforts (Table 3). The CDC estimates that more than 2.8 million antimicrobial-resistant infections and over 35,000 deaths occur annually in the United States, rising to more than 3 million infections and about 48,000 deaths when Clostridioides difficile is included [12]. Encouragingly, dedicated prevention and infection-control efforts reduced AMR deaths by 18% overall—and by nearly 30% in hospitals—between the 2013 and 2019 reports [12]. This progress was partially reversed during the COVID-19 pandemic: hospital-onset resistant infections rose by a combined 20%, and clinical cases of the multidrug-resistant yeast Candida auris increased roughly five-fold between 2019 and 2022 [13].

Table 3. Burden of antimicrobial resistance in the United States (CDC).

Indicator	Estimate	Source
Antimicrobial-resistant infections per year	>2.8 million	CDC 2019 [12]
Deaths per year (excluding C. difficile)	>35,000	CDC 2019 [12]
Infections per year including C. difficile	>3 million	CDC 2019 [12]
Deaths per year including C. difficile	≈48,000	CDC 2019 [12]

Annual treatment cost (6 priority pathogens)	>US$4.6 billion	CDC [12]
Reduction in AMR deaths, 2013–2019	18% overall; ≈30% in hospitals	CDC 2019 [12]
Increase in hospital-onset resistant infections (COVID-19)	+20% (2019–2021)	CDC 2021–22 [13]
Increase in Candida auris clinical cases	≈5-fold (2019–2022)	CDC 2021–22 [13]

CDC, U.S. Centers for Disease Control and Prevention.

Prevention and containment strategies. The evidence supports a coordinated, multilevel response spanning individual behaviour, healthcare delivery, national policy, and the human–animal–environment interface (Table 4). No single intervention is sufficient; rather, integrated packages—combining antimicrobial stewardship, infection prevention and control (IPC), water, sanitation and hygiene (WASH), vaccination, and strengthened diagnostics and surveillance—deliver the greatest impact and are explicitly recommended by WHO [3,11]. Prevention of infection is consistently identified as the most cost-effective single lever, since an infection that never occurs requires no antibiotic [3].

Table 4. Multilevel strategies for the prevention and containment of antimicrobial resistance.

Level	Key interventions	Illustrative examples
Individual / community	Appropriate use; hygiene; vaccination	Completing prescribed courses; hand hygiene; influenza and pneumococcal vaccination
Healthcare facility	Antimicrobial stewardship; IPC; rapid diagnostics	Stewardship programmes; culture-guided therapy; isolation of resistant cases
National policy	Surveillance; regulation; national action plans	GLASS reporting; prescription-only dispensing; costed and monitored action plans
One Health / global	Agricultural restriction; environmental control; R&D	Ending antibiotic growth promoters; effluent treatment; incentives for new antibiotics

IPC, infection prevention and control; R&D, research and development; GLASS, WHO Global Antimicrobial Resistance and Use Surveillance System.

DISCUSSION

The synthesised evidence conveys a clear and sobering message: antibiotic resistance is a large, rising, and unevenly distributed threat, yet one that is demonstrably responsive to concerted action. Three findings warrant particular emphasis. First, the burden is increasingly concentrated among older adults and among Gram-negative organisms resistant to last-resort carbapenems, reflecting both demographic ageing and the exhaustion of existing drug classes [5]. Second, the deterioration is most acute in low- and middle-income countries, where weak health systems, limited diagnostic capacity, and constrained access to effective antibiotics converge to form a self-reinforcing "syndemic"; indeed, AMR burden correlates inversely with universal health-coverage indices [3]. Third, progress is fragile—the reversals recorded during the COVID-19 pandemic show how rapidly gains can be lost when stewardship and IPC systems are disrupted [13].

Encouragingly, the same evidence base demonstrates that prevention works. The 18% reduction in U.S. AMR deaths achieved between 2013 and 2019 through infection control, stewardship, and vaccination confirms that the trajectory is not fixed [12]. Modelling likewise suggests that improved infection prevention, expanded vaccination, and the development of new agents active against Gram-negative pathogens could avert millions of deaths by 2050 [5]. However, the antibiotic pipeline remains inadequate: few novel agents—particularly against the WHO "critical priority" Gram-negative pathogens—have reached the clinic, reflecting scientific difficulty and weak commercial incentives that continue to demand "pull" funding mechanisms [14].

Policy momentum is nonetheless building. The 2024 United Nations General Assembly high-level political declaration on AMR set explicit global targets, including a commitment to reduce AMR-associated mortality, and reaffirmed the goal of universal GLASS reporting [15]. Translating such commitments into measurable outcomes remains the central challenge: while most countries now possess national action plans, only about two-thirds report implementing them, and fewer than one in three have costed, budgeted, and monitored those plans [3]. Closing this implementation gap—through sustained financing, laboratory strengthening, and accountable governance—is arguably more decisive than the formulation of further strategy.

Several limitations of the underlying evidence must be acknowledged. Surveillance coverage remains uneven, and burden estimates for the worst-affected regions are likely conservative owing to sparse laboratory data [3]. Modelled forecasts depend on assumptions that may not hold, and the reliance on aggregated secondary data precludes patient-level analysis. The narrative design of this review, while appropriate to heterogeneous sources, is susceptible to selection bias. Future work should prioritise expanding standardised surveillance in LMICs, linking microbiological data to clinical outcomes, and rigorously evaluating the comparative effectiveness of stewardship and IPC interventions across diverse settings.

CONCLUSION

Antibiotic resistance is one of the defining public-health challenges of the era, already responsible for well over a million deaths each year and projected to cause 39 million cumulative deaths between 2025 and 2050 on current trends. Resistance is rising across most monitored pathogen–antibiotic combinations, the burden is shifting toward older adults and hard-to-treat Gram-negative organisms, and low- and middle-income countries bear a disproportionate share. Yet the evidence is equally clear that this trajectory is not inevitable. Coordinated One Health action—integrating antimicrobial stewardship, infection prevention and control, vaccination, water and sanitation, strengthened surveillance, and renewed investment in antibiotic discovery—can measurably reduce the burden, as demonstrated by documented national gains. The decisive variable is no longer knowledge of what to do, but the political will, financing, and accountable implementation required to do it. Acting now offers the opportunity to preserve the effectiveness of antimicrobials for future generations; failing to act risks a preventable return to a pre-antibiotic era.

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