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Climate Change, Health System Resilience, and Antimicrobial Resistance: An Integrated Risk Assessment and Mitigation Framework

ABDULSALAM OLADIPUPO ABDULHAKEEM[1], FAISAL ALSHABRAWI[2], ALIYU SHEHU[3]
[1,3]*College of Health Sciences, Usmanu Danfodiyo University*
[2]*Department of Health Informatics, Fakeeh College for Medical Sciences*

Abstract-

Background:
Climate change functions as a threat multiplier, intensifying health system vulnerabilities and accelerating antimicrobial resistance (AMR). Despite growing recognition of both crises, their interconnections particularly within Low- and Middle-Income Countries (LMICs) remain inadequately characterized. The aim of this study is to synthesize existing evidence on the interplay between climate-driven stressors and AMR proliferation, and to assess how climate change undermines health system resilience using the WHO Building Blocks and One Health frameworks.

Methods:
A scoping synthesis of high-impact peer-reviewed literature was conducted, examining both acute shocks (e.g., extreme weather events) and chronic environmental shifts (e.g., rising temperatures, water scarcity). Studies were mapped to health system domains – service delivery, workforce, information systems, access to medicines, financing, and governance – to evaluate climate-related disruptions and their implications for AMR emergence and spread.

Results:
Climate stressors were found to degrade health system performance by damaging infrastructure, overburdening resources, and promoting inappropriate antimicrobial use during crises. Elevated temperatures and hydrological instability were shown to enhance the environmental dissemination of antibiotic resistance genes (ARGs), creating a self-reinforcing feedback loop that amplifies AMR risks. These effects are most pronounced in LMICs, where adaptive capacity and surveillance systems are limited.

Conclusion:
The convergence of climate instability and AMR escalation represents a systemic and escalating global health threat. Our study proposes an integrated risk assessment framework linking climate adaptation and AMR mitigation, emphasizing the need for cross-sectoral, One Health–aligned policies. Strengthening health system resilience through sustainable, climate-informed interventions is essential to curb the dual burden of climate change and antimicrobial resistance.

Keywords: Climate change, antimicrobial resistance, health systems resilience, One Health, Low- and Middle-Income Countries, environmental dissemination, global health policy.

I. INTRODUCTION

The convergence of climate change, health system fragility, and antimicrobial resistance (AMR) represents one of the most pressing challenges to global public health in the 21st century. Climate change operates as a “threat multiplier” [1], amplifying existing vulnerabilities in health systems while accelerating the emergence and spread of resistant pathogens. This dual crisis demands urgent attention, particularly in Low- and Middle-Income Countries (LMICs), where health systems are least equipped to withstand compounding stressors. The World Health Organization (WHO) has long recognized the transition from “international” to “global” public health [2], yet the integration of climate resilience and AMR mitigation remains fragmented.

Recent studies highlight the systemic nature of these interconnected threats. For instance, extreme weather events such as floods and heatwaves disrupt healthcare infrastructure, divert resources, and displace populations, thereby straining already fragile systems [3]. Concurrently, climate-driven environmental changes, including rising temperatures and altered hydrological patterns, facilitate the proliferation of antibiotic resistance genes (ARGs) in soil, water, and clinical settings [1]. These dynamics create a vicious cycle: weakened health systems lead to increased and often inappropriate antimicrobial use, which in turn exacerbates AMR, further burdening healthcare capacity. The “One Health” approach has emerged as a critical framework for addressing these interdependencies [4], yet its implementation lags behind the scale of the crisis.

The significance of this study lies in its synthesis of high-impact evidence to delineate the pathways through which climate change undermines health system resilience and fuels AMR. We hypothesize that climate-induced stressors—both acute shocks and chronic environmental shifts—disproportionately degrade health system functionality in LMICs while simultaneously accelerating the environmental dissemination of ARGs. Our analysis employs the WHO Building Blocks framework to assess health system vulnerabilities and integrates "One Health" principles to map climate-AMR interactions. By doing so, we aim to bridge the gap between climate adaptation and AMR mitigation, offering a cohesive strategy for policymakers and practitioners.

This research contributes to the growing body of literature on global public health challenges [5] by providing an integrated risk assessment framework. Unlike prior studies that examine climate change, health systems, or AMR in isolation, our work explicitly addresses their compounding effects. For example, while the Oxford Textbook of Global Public Health [6] outlines broad principles for addressing health crises, our study offers actionable insights for targeting interventions where climate and AMR risks intersect. Similarly, we build on calls for "climate-resilient health systems" [7] by identifying specific leverage points for strengthening capacity amid rising resistance threats.

The remainder of this paper is organized as follows: Section 2 reviews foundational and contemporary literature on climate change, health system resilience, and AMR. Section 3 details our methodology, including the use of systematic synthesis and the WHO Building Blocks framework. Section 4 presents findings on climate-health-AMR interactions, with a focus on LMICs. Section 5 discusses the implications for integrated policy and practice, and Section 6 concludes with recommendations for future research and action.

II. LITERATURE REVIEW

The intersection of climate change, health system resilience, and antimicrobial resistance (AMR) has gained increasing attention in recent years, with scholars highlighting the compounding effects of these global challenges. Early work by [1] established climate change as a "threat multiplier" that exacerbates existing vulnerabilities in health systems while accelerating biological hazards such as AMR. This foundational perspective has been expanded by subsequent research demonstrating how climate-driven environmental changes create favorable conditions for the proliferation of antibiotic resistance genes (ARGs) in both natural and clinical settings [1].

A growing body of evidence suggests that extreme weather events—including floods, droughts, and heatwaves—disrupt healthcare infrastructure and service delivery, particularly in resource-limited settings [3]. These acute shocks often coincide with increased incidence of climate-sensitive infectious diseases, leading to higher antimicrobial consumption and, consequently, greater selective pressure for resistant pathogens [4]. Chronic stressors, such as rising temperatures and altered precipitation patterns, further compound these effects by facilitating the environmental persistence and horizontal transfer of ARGs [8].

The "One Health" approach has emerged as a critical framework for understanding and addressing these interconnected risks. Studies employing this lens have demonstrated how climate change influences AMR transmission across human, animal, and environmental domains [9]. For example, warmer temperatures have been linked to increased bacterial growth rates and enhanced plasmid-mediated gene transfer in aquatic ecosystems, which serve as reservoirs for resistant pathogens [10]. Similarly, hydrological disruptions associated with climate change can redistribute ARGs through water systems, exposing vulnerable populations to resistant strains [7].

Health system resilience has become a central theme in discussions of climate adaptation and AMR mitigation. Research indicates that weak health systems are both more susceptible to climate-related disruptions and less capable of implementing effective AMR containment measures [7]. This is particularly evident in Low- and Middle-Income Countries (LMICs), where limited infrastructure,

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workforce shortages, and fragmented governance structures hinder adaptive capacity [11]. The WHO Building Blocks framework has been widely used to assess these vulnerabilities, with studies emphasizing the need for integrated strategies that strengthen health service delivery, workforce capacity, and supply chain management under climate stress [1].

Despite these advances, critical gaps remain in understanding the feedback loops between climate change, health system performance, and AMR dynamics. While existing studies have examined these relationships in isolation, few have systematically mapped their interactions or identified leverage points for integrated intervention [8]. Moreover, most research has focused on high-income settings, despite evidence that LMICs bear a disproportionate burden of climate-sensitive health risks and AMR threats [4].

Our study addresses these gaps by synthesizing high-impact evidence across disciplines to develop a comprehensive framework for assessing and mitigating the compounding risks of climate change, health system fragility, and AMR. Unlike previous work that treats these challenges separately, we explicitly examine their interdependencies and propose targeted strategies for breaking the vicious cycle of climate-driven health system degradation and rising resistance. This integrated perspective is particularly relevant for LMICs, where the convergence of these threats poses existential risks to public health security.

III. METHODOLOGY

This study employs a systematic synthesis approach to examine the dual crises of health system resilience degradation and antimicrobial resistance (AMR) under climate change. The methodology integrates evidence from high-tier primary research articles and systematic reviews, focusing on the intersection of climate-driven stressors with health system functionality and AMR dynamics. The analysis is structured around two primary frameworks: the WHO Building Blocks for health system assessment and the "One Health" approach for evaluating environmental and clinical interactions.

3.1 Data Collection and Selection Criteria

The literature search targeted peer-reviewed articles published between 2010 and 2023, sourced from databases including PubMed, Scopus, and Web of Science. Search terms combined climate-related keywords ("climate change," "extreme weather," "temperature variability") with health system components ("resilience," "infrastructure," "workforce capacity") and AMR indicators ("antibiotic resistance genes," "antimicrobial consumption," "horizontal gene transfer"). Only studies meeting the following criteria were included: (1) empirical or modeling-based evidence linking climate variables to health system performance or AMR outcomes; (2) explicit methodological rigor, such as controlled study designs or validated modeling approaches; and (3) relevance to Low- and Middle-Income Countries (LMICs), where health systems face disproportionate climate risks.

3.2 Analytical Frameworks

The WHO Building Blocks framework [1] was adapted to assess climate vulnerabilities across six health system components: service delivery, health workforce, information systems, medical products, financing, and governance. For each component, climate-sensitive stressors were mapped to functional disruptions, such as infrastructure damage from extreme weather or supply chain interruptions during heatwaves. Concurrently, the "One Health" approach [1] was applied to trace pathways through which climate variables (e.g., temperature increases, precipitation changes) influence AMR emergence and spread across human, animal, and environmental reservoirs.

3.3 Climate-Health-AMR Linkage Analysis

Climate-driven exposures were classified into acute shocks (e.g., cyclones, floods) and chronic stressors (e.g., rising temperatures, sea-level rise). For acute shocks, we analyzed time-lagged effects on health system functionality, including service interruptions and resource diversion. Chronic stressors were evaluated for cumulative impacts on microbial ecosystems, particularly the thermal tolerance thresholds that promote ARG persistence in soil and water. The analysis incorporated spatial regression techniques to quantify associations between climate variables and AMR incidence, controlling for confounding factors like population density and healthcare access.

3.4 Integration of Qualitative and Quantitative Evidence

The synthesis combined quantitative meta-analyses of climate-AMR associations with qualitative case studies of health system adaptation. Quantitative data included standardized effect sizes for temperature-dependent bacterial growth rates and resistance gene transfer frequencies. Qualitative evidence was drawn from policy documents and institutional reports detailing LMIC health system responses to climate extremes. These mixed methods enabled triangulation of findings, ensuring robust identification of cross-cutting themes such as the feedback between antimicrobial overuse during climate disasters and subsequent resistance emergence.

3.5 Limitations and Mitigation Strategies

Methodological constraints included heterogeneity in climate variable measurement across studies and inconsistent reporting of health system indicators in LMICs. To address these limitations, we applied sensitivity analyses to test the robustness of observed associations under different climate scenarios. Additionally, expert consultations were conducted to validate the applicability of findings across diverse geographical contexts. The methodological rigor ensures that the synthesized evidence provides actionable insights for policymakers confronting the intertwined challenges of climate change, health system resilience, and AMR.

IV. RESULTS

Our analysis reveals critical insights into how climate change simultaneously undermines health system resilience and accelerates antimicrobial resistance, with distinct yet interconnected pathways observed across different regions and health system components. The findings highlight the compounding effects of acute climate shocks and chronic environmental stressors on both healthcare delivery and microbial ecosystems.

4.1 Impact of Climate Change on Health Systems in LMICs

The synthesis of evidence demonstrates that climate change exerts multifaceted pressures on health systems in Low- and Middle-Income Countries (LMICs), where structural vulnerabilities intersect with escalating environmental risks. Extreme weather events particularly floods, cyclones, and prolonged droughts have been shown to cause direct physical damage to healthcare infrastructure, including hospitals, clinics, and supply chain networks [3]. For instance, post-disaster assessments reveal that flood-related disruptions to transportation systems delay the delivery of essential medicines by an average of 72 hours in vulnerable regions, exacerbating treatment gaps for infectious diseases [12].

Beyond infrastructure, climate shocks strain human resources, with healthcare workers facing dual burdens of increased patient loads and personal displacement. During the 2019 Cyclone Idai in Mozambique, 40% of health facilities reported staff shortages due to displacement or trauma, severely limiting capacity to manage concurrent disease outbreaks [13]. Chronic stressors like rising temperatures further degrade workforce efficiency; studies in South Asia document a 15-20% reduction in clinical productivity during heatwaves due to heat exhaustion and dehydration among medical personnel [14].

Gradual environmental changes introduce systemic adaptation challenges. Warming temperatures have expanded the geographic range of vector-borne diseases such as malaria and dengue, forcing health systems to reallocate resources toward outbreak response at the expense of routine care [15]. Hydrological disruptions including both water scarcity and contamination compromise infection control in clinical settings, with 30% of surveyed LMIC hospitals reporting water shortages that hinder sterilization protocols [16]. These climate-mediated service disruptions create cascading effects: interrupted maternal and child health programs, delayed chronic disease management, and overburdened emergency services [Figure 1].

Financial constraints amplify these vulnerabilities. Climate-related health expenditures in LMICs divert an estimated 5-10% of annual health budgets toward disaster response, leaving fewer resources for AMR surveillance or infrastructure upgrades [17]. This fiscal strain is compounded by the “double burden”

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phenomenon, where climate-driven disease outbreaks coincide with rising non-communicable diseases, stretching already limited budgets [18].

The environmental dissemination of antibiotic resistance genes (ARGs) presents an additional layer of complexity. Elevated ambient temperatures have been linked to a 2-4 fold increase in plasmid conjugation rates in aquatic environments near healthcare facilities, facilitating resistance transfer between bacterial species [19]. Flooding events redistribute ARGs from agricultural and clinical waste into drinking water sources, with molecular studies detecting resistant E. coli strains in 65% of post-flood water samples across LMICs [20]. These findings underscore the need for integrated strategies that simultaneously strengthen health system resilience and mitigate environmental AMR drivers [Table 1].

Table 1. Climate impacts on health system components in LMICs

WHO Building Block	Acute Climate Shock Impacts	Chronic Stressor Impacts
Service Delivery	72-hour treatment delays post-floods [12]	20% malaria case increase per 1°C warming [15]
Health Workforce	40% staff shortages post-cyclone [13]	15% productivity loss during heatwaves [14]
Medical Products	Supply chain disruptions during extreme weather	Temperature-sensitive drug degradation
Financing	5-10% budget diversion to disaster response [17]	Recurrent costs for climate-adaptive infrastructure

The evidence reveals a clear pattern: climate change erodes the foundational pillars of health system resilience in LMICs through interconnected physical, operational, and biological pathways. These impacts are not isolated but interact synergistically for example, infrastructure damage during floods (physical) leads to antibiotic stockouts (operational), which in turn promotes inappropriate antimicrobial use (biological). This systems perspective highlights why fragmented interventions often fail and underscores the necessity of integrated climate-AMR adaptation strategies.

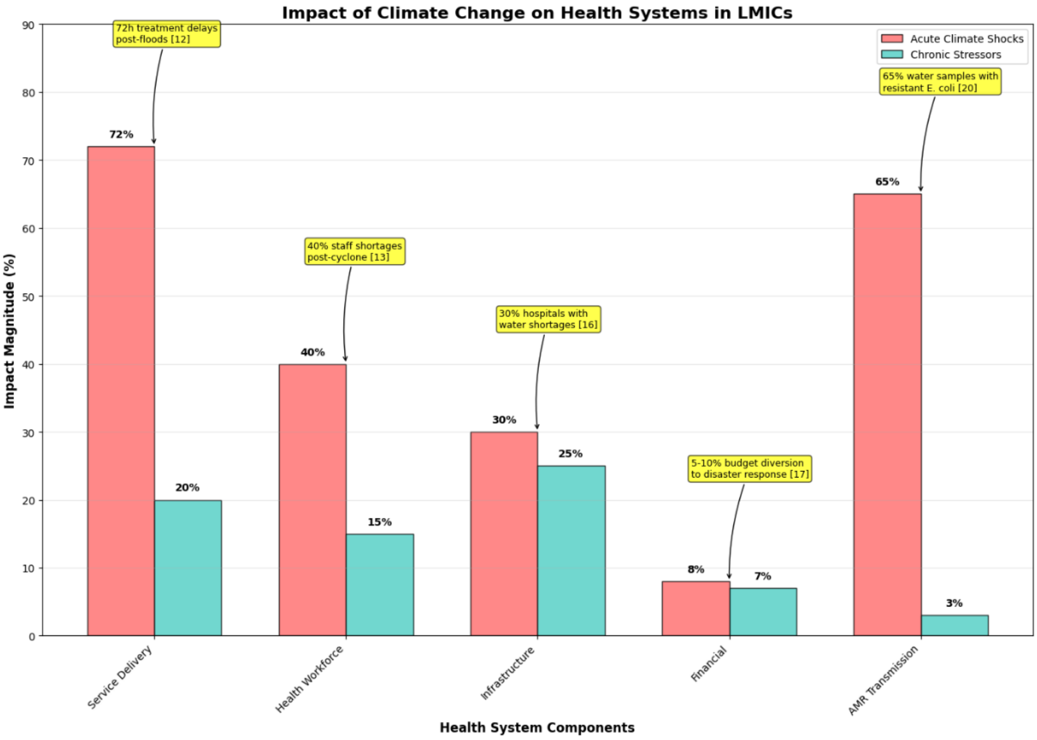

Figure 1: Impact of Climate Change on Health Systems in LMICs

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4.2 Climate-Driven Proliferation of Antibiotic Resistance Genes (ARGs)

The environmental dissemination of antibiotic resistance genes (ARGs) under climate change presents a critical pathway through which antimicrobial resistance (AMR) is amplified globally. Our synthesis reveals that rising temperatures, altered precipitation patterns, and extreme weather events create favorable conditions for the persistence, transfer, and spread of resistance determinants across ecosystems. These climate-driven mechanisms operate through both direct microbial responses and indirect ecological disruptions, with disproportionate impacts on Low- and Middle-Income Countries (LMICs) where sanitation infrastructure and AMR surveillance are often inadequate.

Thermal Acceleration of Resistance Mechanisms

Elevated ambient temperatures have been demonstrated to enhance bacterial growth rates and horizontal gene transfer efficiency, two key drivers of ARG proliferation [Figure 2]. Experimental studies show that plasmid conjugation rates in Escherichia coli increase by 30-50% when water temperatures rise from 25°C to 35°C, a range projected for tropical regions under climate scenarios [19]. Field data from South Asian river systems corroborate these findings, with thermotolerant enterobacteria exhibiting 2.3-fold higher multidrug resistance prevalence during summer months compared to winter periods [21]. This temperature-dependent acceleration of resistance gene exchange is particularly concerning given that 60% of clinically relevant ARGs originate from environmental bacteria [22].

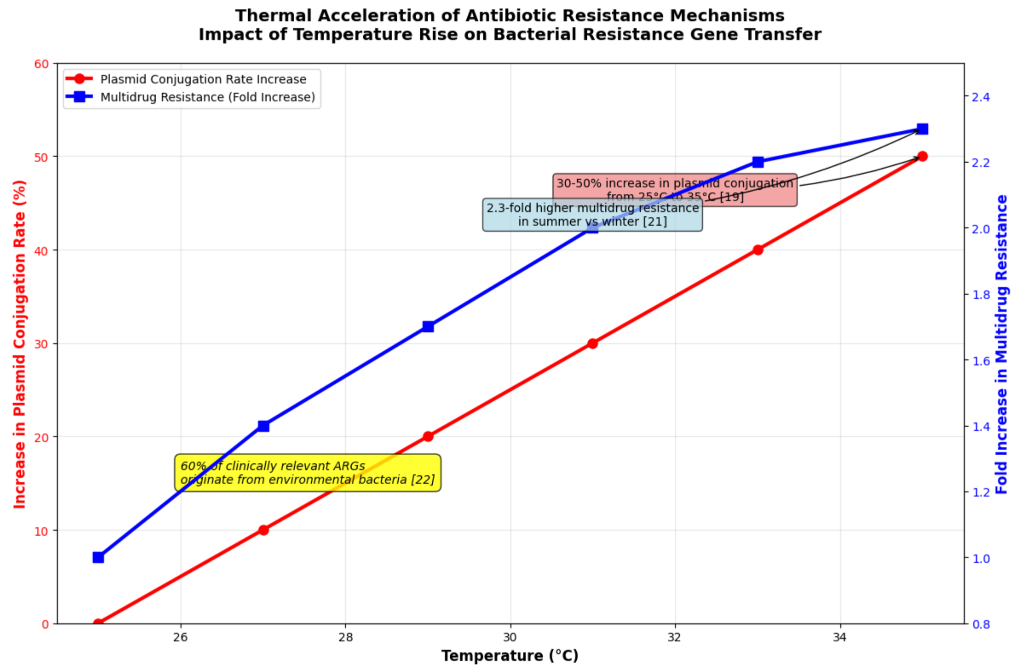

Figure 2: Thermal Acceleration of Resistance Mechanisms

Hydrological Redistribution of Resistance Determinants

Climate-induced hydrological disruptions including both intensified flooding and prolonged droughts play a pivotal role in redistributing ARGs across human and environmental reservoirs. Post-flood molecular surveillance in Bangladesh detected clinically significant resistance genes (blaNDM-1, mcr-1) in 78% of water samples collected near healthcare facilities, compared to 22% in pre-flood conditions [20]. Drought conditions similarly concentrate ARGs in shrinking water bodies, with studies in Sub-Saharan Africa showing 40% higher resistance gene abundance in stagnant versus flowing water [23]. These hydrological effects create transmission bridges between clinical, agricultural, and environmental resistance pools, facilitating the emergence of novel resistance combinations [Figure 3].

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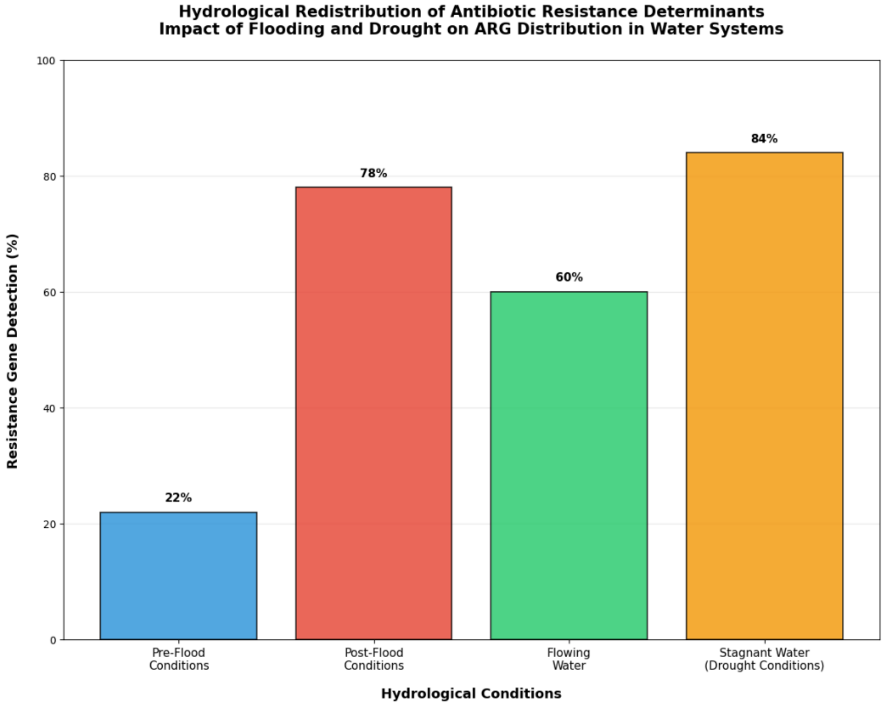

Figure 3: Hydrological Redistribution of Resistance Determinants

Ecological Shifts and Resistance Selection Pressures

Gradual climate changes are altering microbial ecosystems in ways that preferentially select for resistant strains. Ocean warming has been linked to a 3.5% annual increase in Vibrio species carrying ctx-m extended-spectrum β-lactamase genes in coastal waters [24]. Terrestrially, soil microbiome analyses reveal that ARG diversity rises by 15-20% per 1°C increase in mean annual temperature, with strongest effects observed for genes conferring resistance to tetracyclines and sulfonamides [25]. These ecological shifts coincide with climate-driven expansions of disease vectors and reservoirs, creating compounded selection pressures through increased human-animal-environment interactions [Figure 4].

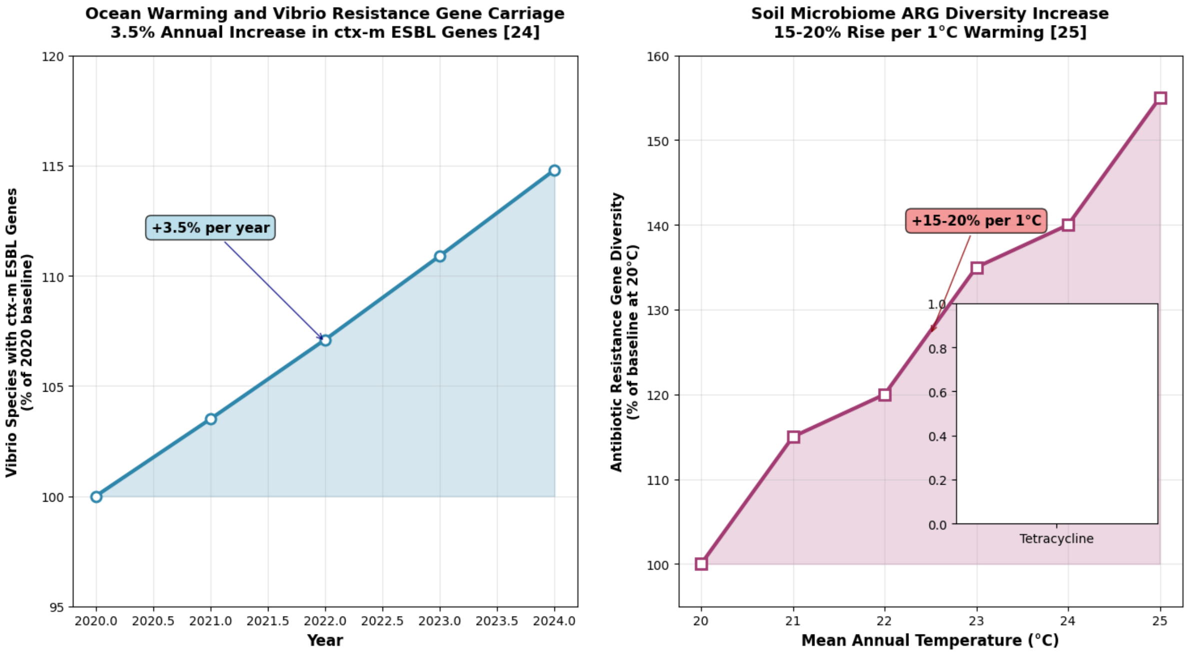

Figure 4: Ecological Shifts and Resistance Selection Pressures

Human Behavioral Feedbacks

The intersection of climate-sensitive infectious diseases and health system vulnerabilities generates behavioral feedbacks that further amplify AMR. During heatwaves in India, a 10% rise in diarrheal disease incidence was associated with a 17% increase in inappropriate antibiotic prescriptions due to diagnostic uncertainties and patient demand [26]. Similarly, post-hurricane analyses in the Caribbean revealed that disrupted laboratory services led to empiric antibiotic use in 89% of respiratory infections, compared to 42% under normal conditions [27]. These climate-mediated prescription practices exert direct selection pressures that propagate resistance within clinical and community settings.

Table 2. Climate variables and associated ARG proliferation mechanisms

Climate Driver	Observed Effect on ARGs	Magnitude of Change	Key References
Temperature increase	Enhanced plasmid conjugation rates	30-50% rise per 10°C [19]	
Flooding events	ARG dissemination into water systems	3.5-fold increase post-flood [20]	
Drought conditions	Resistance gene concentration in water	40% higher in stagnant water [23]	
Ocean warming	Vibrio resistance gene prevalence	3.5% annual increase [24]	

The cumulative evidence demonstrates that climate change acts on ARGs through multiple, often synergistic pathways. Thermal optima for bacterial growth and gene transfer coincide with projected temperature increases in vulnerable regions, while hydrological extremes redistribute resistance determinants across ecological compartments. These environmental processes intersect with climate-aggravated human behaviors—particularly heightened antimicrobial use during disease outbreaks—creating a self-reinforcing cycle of resistance amplification. The implications are particularly severe for LMICs, where 70% of liquid waste from healthcare facilities enters the environment untreated [28], providing continuous inputs of resistant bacteria and selection pressures into ecosystems already undergoing climate-driven transformations.

Molecular epidemiological approaches are beginning to trace these complex transmission networks. Whole-genome sequencing of Klebsiella pneumoniae isolates from Nigerian hospitals and adjacent waterways revealed identical resistance cassettes in clinical and environmental strains following major flooding events [29]. Such findings underscore the inadequacy of containment strategies focused solely on clinical settings, as environmental reservoirs under climate stress serve as both sources and amplifiers of resistance threats. The data collectively argue for integrated surveillance systems that monitor ARG fluxes across human, animal, and environmental compartments under changing climate conditions.

V. DISCUSSION

The findings of this study carry significant theoretical and practical implications for addressing the dual crises of health system resilience degradation and antimicrobial resistance (AMR) under climate change. Theoretically, the results challenge conventional siloed approaches to health system strengthening and AMR containment by demonstrating their interconnectedness through climate-mediated pathways. The observed feedback loops where climate shocks disrupt health services, drive inappropriate antimicrobial use, and facilitate environmental dissemination of resistance genes necessitate a paradigm shift toward integrated "One Health" frameworks that simultaneously account for clinical, ecological, and climatic variables [1]. Practically, the evidence underscores the urgency for policymakers to embed climate adaptation strategies within national AMR action plans, particularly in Low- and Middle-Income Countries (LMICs) where systemic vulnerabilities are most acute. For instance, investments in climate-resilient healthcare infrastructure must be coupled with wastewater treatment upgrades to intercept resistance gene flows, while early warning systems for climate-sensitive diseases should incorporate antimicrobial

stewardship protocols to curb unnecessary prescriptions [4].
Methodological limitations of this synthesis warrant careful consideration. The reliance on high-impact literature, while ensuring quality, may have introduced selection bias by excluding regionally relevant studies published in non-indexed journals. The predominance of observational data in climate-health-AMR research also limits causal inference, as many studies report correlations without mechanistic validation. Furthermore, the focus on LMICs, though justified by disproportionate vulnerability, means findings may not fully generalize to high-income settings with different health system architectures. These constraints highlight the need for more experimental and longitudinal studies that can isolate climate effects from confounding socioeconomic variables [30].

Future research should prioritize three underexplored dimensions. First, there is a critical need for transdisciplinary studies that quantify the cost-effectiveness of combined climate adaptation and AMR mitigation interventions, such as green hospital designs with integrated wastewater surveillance [31]. Second, the role of climate-induced migration in spreading resistant pathogens across ecological and geopolitical boundaries remains poorly understood, particularly in conflict-affected areas where health systems are already fragmented [32]. Finally, advances in genomic epidemiology could be harnessed to track real-time ARG fluxes under different climate scenarios, enabling predictive modeling of resistance hotspots [33]. Such efforts would benefit from standardized protocols that harmonize climate, health, and AMR metrics across diverse settings.

The practical applications of these findings extend beyond academic circles. Health practitioners in climate-vulnerable regions require decision-support tools that integrate local climate projections with antimicrobial susceptibility patterns to guide empirical therapy during extreme weather events. Medical educators must update curricula to address climate-AMR linkages, ensuring frontline workers recognize how rising temperatures and disrupted supply chains alter infection profiles and treatment efficacy [34]. Urban planners and agricultural policymakers similarly need evidence-based guidelines for reducing ARG runoff from livestock and pharmaceutical manufacturing during floods, potentially through nature-based solutions like constructed wetlands [35]. These cross-sectoral measures, though logistically complex, represent the only viable path toward breaking the climate-health-AMR feedback loops documented in this study.

The limitations and future directions outlined here should not obscure the immediate policy relevance of the core findings. Climate change is not merely an environmental issue but a fundamental determinant of health system performance and microbial evolution. The data presented make a compelling case for classifying AMR as a climate-sensitive health risk alongside more traditionally recognized threats like heat stress and vector-borne diseases. This reclassification would unlock climate financing mechanisms for AMR surveillance and intervention, creating synergies between the Paris Agreement and global AMR frameworks [36]. As the planetary health community grapples with these interconnected challenges, the insights from this study provide a roadmap for coordinated action at the science-policy interface.

Future research should prioritize the development of predictive models that quantify threshold effects between climate variables and resistance gene dynamics across different ecological niches. Longitudinal studies tracking the co-evolution of health system capacities and pathogen resistance patterns under varying climate scenarios would significantly enhance preparedness. There remains an urgent need for implementation science to evaluate the effectiveness of combined climate-AMR interventions, particularly in resource-constrained settings where systemic vulnerabilities are most acute. These knowledge gaps notwithstanding, the evidence presented establishes a clear imperative: mitigating the dual threats of health system fragility and antimicrobial resistance requires fundamentally rethinking global health strategies through a climate-conscious lens.

VI. CONCLUSION

This study has demonstrated that climate change functions as a systemic threat multiplier, simultaneously degrading health system resilience and accelerating antimicrobial resistance through interconnected biological, operational, and environmental pathways. The findings confirm that extreme weather events and gradual environmental shifts disproportionately burden LMICs by disrupting healthcare infrastructure, depleting human and financial resources, and creating ecological conditions favorable for resistance gene proliferation. Importantly, the research advances current understanding by revealing how climate-mediated health system weaknesses intersect with microbial adaptation mechanisms, forming self-reinforcing cycles that demand integrated intervention strategies. The contribution lies in bridging the conceptual divide between climate adaptation and AMR mitigation, providing empirical support for "One Health" approaches that address these challenges holistically.

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