Climate Change and Antimicrobial Resistance: The Silent Pandemic

Climate Change Disaster

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Abstract:

Climate change and antimicrobial resistance rank among the most pressing health and environmental challenges today. The study emphasizes the importance of addressing both crises through a comprehensive environmental health perspective, including cooperation among the health, environmental, and agricultural sectors. It highlights the need to develop strategies to combat antimicrobial resistance in the context of climate change while paying attention to social justice by directing solutions to the most vulnerable groups.

Key Points:

1. The relationship between climate change and antimicrobial resistance: Climate change leads to an increase in the spread of infectious diseases, which increases the use of antibiotics and, consequently, accelerates the development of antimicrobial resistance.
2. Health challenges resulting from climate change: Rising temperatures, extreme weather events, such as floods and droughts, and environmental pollution drive a surge in climate-related diseases and resistant infections.
3. Sustainable solutions to combat antimicrobial resistance: The study focuses on developing alternative solutions, such as vaccines and bacteriophage therapy, and promoting research into new treatments.
4. The role of social justice: It examines the impact of climate change on vulnerable groups, such as residents of developing countries, who experience greater health challenges despite their small contribution to greenhouse gas emissions.

Keywords: Antimicrobial Resistance, Climate Change, Alternative Therapies, Infectious Diseases, Global Warming

Importance of the Study

This study is particularly relevant amid today's global health and environmental challenges, as it links two critical and interconnected issues: climate change and antimicrobial resistance (AMR). Both have profound effects on public health and ecosystems. In recent years, the urgency of this issue has intensified, with climate change driving the spread of infectious diseases that are increasingly difficult to treat due to the escalation of antimicrobial resistance.

The study is significant because it:

- Contributes to understanding the relationship between climate change and antimicrobial resistance and their impact on human, animal, and environmental health.
- Supports the call for coordinated measures to combat antimicrobial resistance and mitigate climate change effects through collaboration across sectors.
- Aids in developing new strategies to address climate- and resistance-related health issues, including promoting innovation in alternative treatments and vaccines.

Research Problem

The research problem revolves around understanding how climate change influences the spread of antimicrobial resistance and its effects on human, animal, and environmental health. Climate change factors, such as rising temperatures, floods, droughts, and environmental pollution, contribute to the spread of infectious diseases, increasing pressure on healthcare systems worldwide. However, excessive antibiotic use leads to the evolution of drug-resistant microorganisms, making these diseases harder to treat.

Key Research Questions:

- How does climate change contribute to the increasing spread of antimicrobial resistance?
- What is the relationship between high temperatures and antibiotic resistant microorganisms?
- How can the impacts of climate change on antimicrobial resistance be mitigated?

Objectives of the Study

This study aims to:

1. Examine the impact of climate change on antimicrobial resistance and understand the relationship between rising temperatures, extreme weather events, and the spread of resistant bacterial infections.
2. Explore possible solutions to reduce the effect of climate change on antimicrobial resistance through prevention, health policies, and research into alternative treatments.
3. Highlight the need for cross-sectoral collaboration (health, environment, agriculture) to combat antimicrobial resistance in the context of climate change.
4. Provide practical recommendations for policymakers, health authorities, and international organizations to develop more effective strategies to address this global challenge.

Methodology

This study follows an analytical and descriptive methodology that combines:

- **Review of scientific literature:** Examining previous studies and articles discussing the relationship between climate change and antimicrobial resistance and their impact on public health.
- **Case studies:** Analyzing specific cases of infectious disease outbreaks in certain regions and documenting the link between climate change and antimicrobial resistance.
- **Surveys and interviews:** Collecting data through interviews with public health experts, veterinarians, and environmental scientists to explore their perspectives on the climate-antibiotic resistance relationship.
- **Statistical analysis:** Analyzing collected data to identify patterns and relationships among climate change, antimicrobial resistance, and disease spread.

Review of Previous Studies and Research Contributions

Studies addressing the relationship between climate change and antimicrobial resistance (AMR) are relatively recent but have garnered growing attention in recent years. Previous research falls into the following main categories:

1- Studies on the impact of climate change on human health:

- Several studies have explored how climate change affects public health, focusing on infectious diseases that become more prevalent due to environmental changes such as rising temperatures, floods, and droughts. For instance, **Edwards et al. (2019)** examined the relationship between increased heat and the spread of waterborne diseases like cholera and malaria. The study found that climate change increases the density and spread of disease-carrying insects, leading to higher antibiotic use and, consequently, greater resistance.

2- Studies on antimicrobial resistance:

- Many previous studies have focused on antimicrobial resistance without linking it to climate change. **Costello et al. (2020)** showed that excessive antibiotic use in medicine and agriculture is the primary driver of resistant bacterial strains. Other studies, such as **Shen et al. (2018)**, investigated the role of antibiotic use in farms.

3- Studies on environmental impacts on antimicrobial resistance:

- Some research has examined how environmental pollutants, such as industrial and agricultural waste, contribute to antimicrobial resistance. **Patel et al. (2019)** found that environmental contamination with antibiotics through agricultural waste or wastewater increases the likelihood of resistant bacterial strains.

4- Studies linking climate change and antimicrobial resistance:

- A limited number of studies have explored the direct relationship between climate change and antimicrobial resistance. For example, **Li et al. (2021)** confirmed that climate change alters patterns of infectious diseases and medication use, potentially increasing antimicrobial resistance. Ultimately, temperature changes affect bacterial growth and transmission rates.

Research Contributions

Despite progress in studying the effects of climate change on public health, there is still a lack of studies that directly link climate change and antimicrobial resistance. This study aims to provide several innovative contributions:

1- A new perspective on climate change and resistance in ecosystems:

- Unlike previous research focusing only on health effects, this study integrates environmental and social impacts contributing to antimicrobial resistance.

2- Community-based research:

- This research adopts a participatory methodology, engaging local communities in high-risk areas to understand real-world conditions and risks associated with antimicrobial resistance.

3- Sustainable solution strategies:

The study proposes sustainable strategies combining technological solutions (e.g., sustainable agriculture) and health solutions (e.g., awareness campaigns and responsible antibiotic use).

4- Social justice:

- This research examines how climate change and antimicrobial resistance affect vulnerable populations in developing countries, a topic not adequately addressed in previous studies.

5- The role of alternative treatment therapies:

- The study shows the importance of new advanced treatment therapies other than antimicrobials to avoid the problem of drug resistance.

Conclusion

The relationship between climate change and antimicrobial resistance is complex and requires a coordinated and integrated response. By adopting a sustainable methodology, comprehensive solutions can be developed that consider environmental, social, and health aspects to address these challenges. Global cooperation and continuous commitment from all sectors are essential to safeguarding public health and protecting the planet for future generations.

Antimicrobial Resistance and Climate Change: The Silent Pandemic Climate Change Disaster

Global climate change is the most severe human-induced crisis confronting our world. To address this, international cooperation is required to reverse the impending climate change catastrophe. Human usage of fossil fuels and the resulting greenhouse gas emissions and carbon footprint are the main causes of climate change. Consequently, climate change is a disaster threatening the survival of humans and all other living species on Earth. Humans, animals, and the environment are closely interconnected through the One Health approach—an integrated and unified strategy that protects human and animal health while sustaining ecosystems. Promoting this approach highlights that a healthy planet sustains human life, just as human actions are essential to preserving planetary health.

Climate change affects human health and social justice. On the one hand, marginalized populations contribute a very small amount to global greenhouse gas emissions. Nevertheless, they are the most affected by the adverse impacts. On the other hand, the wealthiest 20% of the population is responsible for 80% of all carbon emissions **(Lenzen et al., 2020)**.

Heat-related morbidity and mortality, food and water insecurity, rising sea levels, wildfires-caused mortalities, novel mechanisms of infectious disease transmission, cardiovascular morbidity, and other health effects resulting from extreme weather events like droughts and floods are few examples of how climate change affects the world's One Health (Watts et al., 2021).

The impacts of climate change on human, animal, and environmental health are numerous and are getting worse rather rapidly. Microbial-caused infections and accompanied Antimicrobial Resistance (AMR) are areas where One Health and climate change interact in a largely undisclosed manner. This viewpoint review discusses climate change's direct and indirect impact on the development and spread of AMR.

Antimicrobials and Antimicrobial Resistance

Potent antibiotics for bacterial illnesses are one of the basic pillars supporting the efficiency of our modern healthcare system. In the absence of effective antimicrobials, procedures such as caesarean sections, hip replacements, cancer chemotherapy, and organ transplantation could become fatal. Even low-risk procedures taken for granted, from tooth extraction to small skin scratches, would be deadly.

According to the World Health Organization (WHO), AMR is one of the twentieth century's most dangerous threats to human health. To clarify, AMR is rising to dangerously high levels worldwide as novel resistance mechanisms develop and spread daily.

Treatment of patients with common infectious diseases such as pneumonia has been becoming harder and, in some cases, impossible as drug efficacy declines. Increasing microbial resistance has resulted in superbugs, multi- and pan-drug-resistant bacteria that are not treatable with existing antimicrobial drugs. As all antimicrobial drugs affect pathogens through limited mechanisms, developing other drugs with new mechanisms is impossible. Additionally, prolonged research periods (that can reach 20 years) and huge budgets are always needed to develop more antimicrobial drugs. It is worth noting that bacterial pathogens evolve more rapidly than humans can respond, often developing resistance faster than anticipated.

The cost of providing patient care is rising as more expensive medications take the place of primary therapy drug. The financial burden on patients and society increases with longer illness and treatment durations and frequent hospitalizations (WHO, 2023). In 2019, the global deaths due to AMR, either directly or indirectly, have reached 1.2 million cases more than deaths caused by HIV/AIDS and Malaria **(Murray et al., 2022)**. Moreover, AMR has a substantial financial impact on national economies and health systems as it reduces patient and their caretakers` productivity by necessitating longer hospital stays and more intensive treatment.

In addition to intrinsic resistance that exists naturally in some pathogens, AMR develops throughout time, typically due to genetic alterations resulting from mutations or horizontal gene transfer from the same genus members or even other genera (De Oliveira et al., 2020). AMR-producing pathogens exist in the environment (water, soil, and air), humans, animals, food, and plants. They can also be transmitted from one person to another or between humans and animals, especially through food of animal origin.

The misuse and overuse of antimicrobials are the main causes of AMR. Poor sanitary conditions for people and animals and inadequate disease prevention and control in hospitals and farms also contribute significantly to its spread. In addition, limited access to high-quality, affordable medications, vaccines, and diagnostics—combined with a lack of awareness, education, and legal enforcement—further exacerbates the problem.

Bacteria have developed resistance to every antimicrobial discovered so far, sometimes even before the drug has reached the market. Some of these drugs are critical and considered the last resort treatment options for serious infections in humans and animals (e.g., Linezolid, Ceftaroline, and Levofloxacin) (Kupferschmidt, 2016).

The Global Impact of Climate Change on AMR's Existence and Spread

The world is changing due to increasing populations and the expansion into untouched areas. Increasing travel of humans, animals, and products throughout the world, in addition to global climate change, has been contributing to the spread of the AMR crisis worldwide. Human, animal, and environmental health are strongly interconnected regarding One health. Hence, environmental changes and their health effects, including AMR, should not be ignored.

First: Infectious Diseases Exacerbated by Climate Change Risks

Increasing the Earth's temperature and global warming have resulted in the exacerbation of many infections in humans and animals, includins:

- **Viruses:** COVID-19, common cold, aseptic meningitis, and arboviral diseases
- **Bacteria:** Escherichia coli, vibriosis, botulism, MRSA and Q-Fever
- **Fungi:** Cryptococcosis, ROCM, chromoblastomycosis, and fungal allergic diseases
- **Protozoa:** Amoebiasis, Blastocystosis, Cyclosporiasis, and Acanthamoebiasis

Table 1: Impact of Temperature Increase on Antimicrobial Resistance (%)

Temperature Increase (°C)	*Escherichia coli* Resistance (٪)	*Klebsiella pneumoniae* Resistance (٪)	*Staphylococcus aureus* Resistance (٪)
+1°C	0.42%	0.22%	0.27%
+5°C	2.1%	1.1%	1.35%
+10°C	4.2%	2.2%	2.7%

Source: MacFadden et al., 2018.

Table 2: Seasonal Variation in AMR Rates for Key Pathogens

Pathogen	Winter Resistance (٪)	Summer Resistance (٪)	٪ Increase Due to Warmer Temperatures
E. coli	5.2%	9.4%	+80.8%
K. pneumoniae	3.7%	7.1%	+91.9%
S. aureus	6.5%	10.2%	+56.9%

Source: MacFadden et al., 2018.

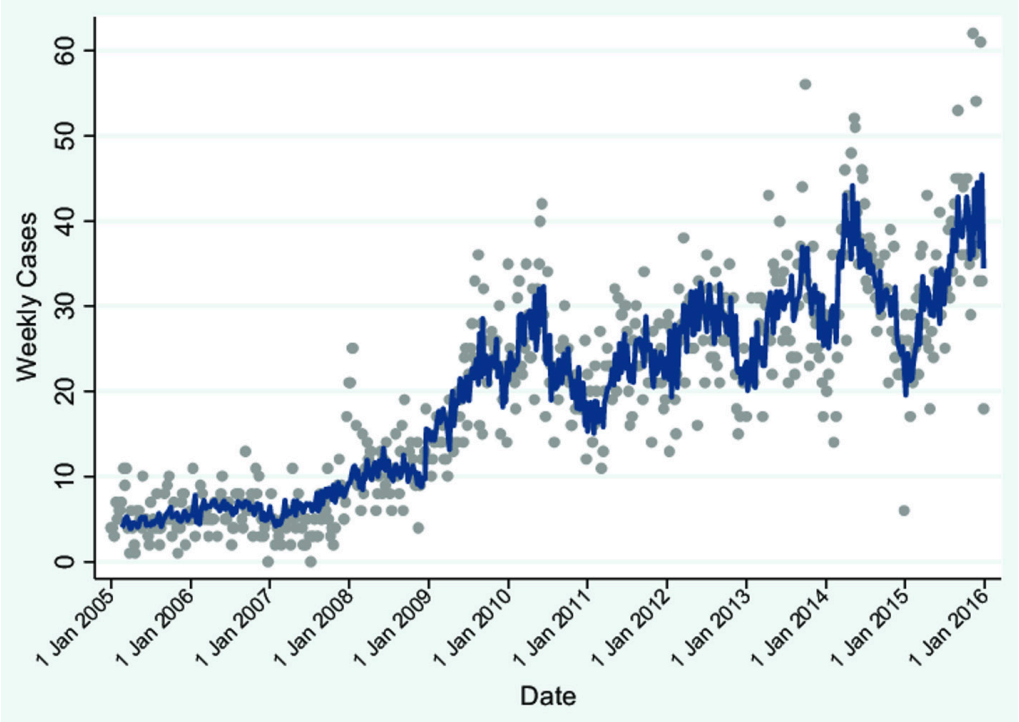
Second: Global Warming and Infection Rates

Increased temperature is closely linked with increased bacterial infections. Bacterial growth rates usually increase in high temperatures. Horizontal gene transfer, a major mechanism for acquiring AMR, also increases due to rising temperatures (Philipsborn et al., 2016).

There is critical proof that bacterial disease rates are related to increments in temperature. A worldwide survey of 22 cities found that proximity to the equator and low socioeconomic factors were associated with a higher risk of Gram-negative bacteremia (Fisman et al., 2014). Another study reported that elevated humidity and temperature were linked to increased rates of Gram-negative circulatory system infections in hospitalized patients (Burnham, 2021). Infections caused by less antibiotic-susceptible Acinetobacter species tend to occur more frequently during the winter months (Burnham et al., 2019). Salmonella spp., heat, and humidity are consistently associated with the most significant diarrhoeal pathogens. Furthermore, heat stress has been shown to increase Salmonella intestinal colonization in

fowl. Climate change has the potential to significantly elevate the global burden and morbidity of salmonellosis, given the millions of cases reported worldwide and the higher colonization rates in both humans and animals. The authors of this study suggest that public health authorities in tropical regions could consider rising average ambient air temperatures as a warning indicator for a potential increase in Salmonella infections. They also recommend that preventive measures prior to the warmer months—such as improving awareness and practices among food producers and consumers regarding food potentially contaminated with Salmonella—could help reduce disease incidence (Aik et al., 2018).

Figure 1: Time series of actual and model-predicted weekly counts of Salmonella cases in Singapore from 2005 to 2015



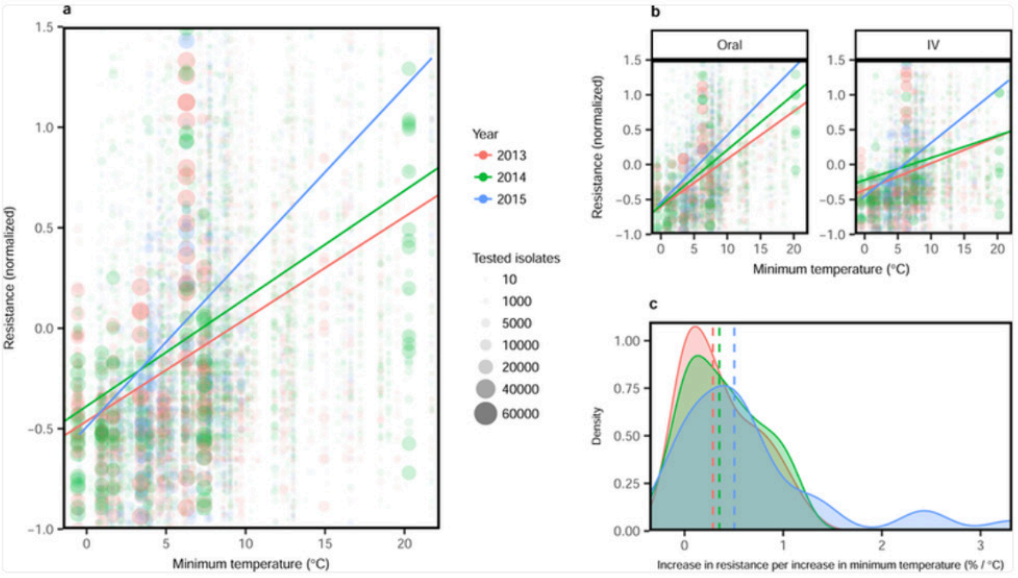
Source: Anthony et al., 2018.

The grey circles represent the actual weekly number of *Salmonella* reports, while the blue line represents the weekly number of Salmonella reports predicted from the final multivariable negative binomial regression model over the 11-year study duration. Temperature and urinary tract infections had a dose-response association. Likewise, the correlation between infection rate and temperature is valid for surgical site infections following hip and knee replacements as well as other surgical site infections (Anthony et al., 2018).

Third: Global Warming and Bacterial Resistance

In addition to increased bacterial dissemination and infection rates, AMR also rises with higher tem-peratures, showing a clear association among AMR rates, local temperature, and human population den-sity. For the worldwide pathogens like Escherichia coli, Klebsiella pneumoniae, and Staphylococcus aureus, there was a correlation between temperature and population density (MacFadden et al., 2018). The study further revealed that rising temperatures driven by climate change are linked to increases in AMR. As climate change intensifies, the combination of higher infection rates and the proliferation of AMR-producing organisms will inevitably lead to the emergence of more resistant pathogens.

Figure 2: Change in the relationship between minimum temperature and antibiotic resistance over time



Source: Veilleux et al., 2018.

(A) Mean normalized antibiotic resistance versus minimum temperature (°C) for all pathogens and antibiotics, stratified by year (2013–2015). Unadjusted weighted linear relationships for the years 2013–2015 are shown.

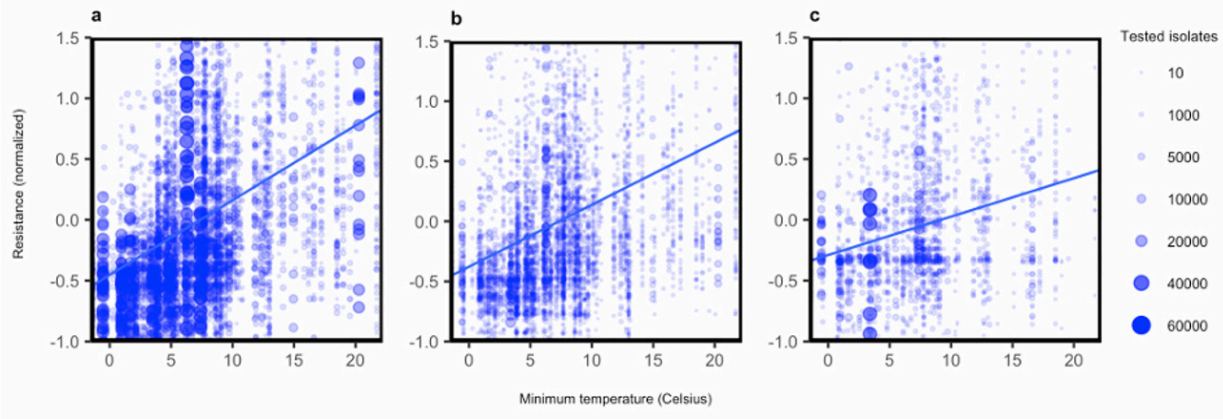
(B) Mean normalized antibiotic resistance versus minimum temperature (°C) for all pathogens and antibiotics, stratified by year and route (oral versus IV).

(C) Density distributions of association measures (slopes) between antibiotic resistance and minimum temperature, stratified by time and with median densities (by year) marked by vertical dashed lines.

Passive heat stress, which influences human behaviour, is another indirect consequence of rising temperatures, causing irritability and reduced critical thinking. These symptoms are common in many different diseases that lead to misdiagnosis and increasing prescriptions for unneeded antibiotics (Veilleux et al., 2018).

Recent studies have investigated the relationship between rising temperatures and the spread of antimicrobial resistance (AMR). A notable study published in Nature Climate Change analysed data from various regions in the United States and found that an increase in local temperature correlates with higher rates of antibiotic resistance in common pathogens. Specifically, a 10°C rise in temperature was associated with increases in antibiotic resistance of 4.2% for Escherichia coli, 2.2% for Klebsiella pneumoniae, and 2.7% for Staphylococcus aureus (MacFadden et al., 2018).

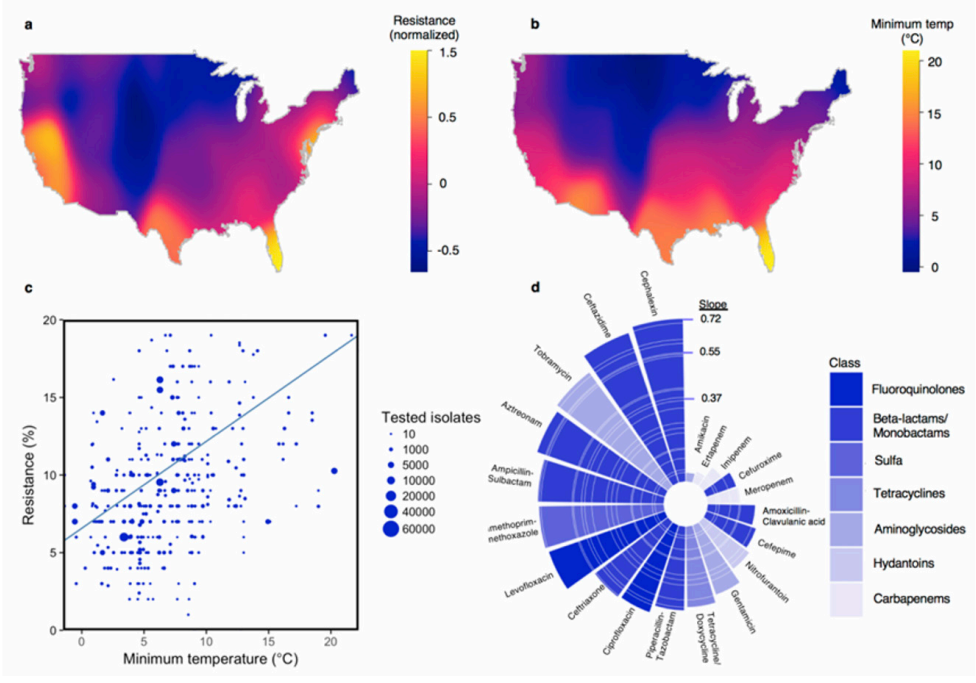
Figure 3: Association between minimum temperature and antibiotic resistance



Source: MacFadden et al., 2018.

Scatter plots of mean normalized antibiotic resistance versus minimum temperature (°C) for all tested antibiotics by pathogen: (A) E. coli; (B) K. pneumoniae; and (C) S. aureus. Unadjusted weighted linear trend lines are shown in blue.

Figure 4: Antibiotic resistance and minimum temperature (S. aureus)



Source: MacFadden et al., 2018.

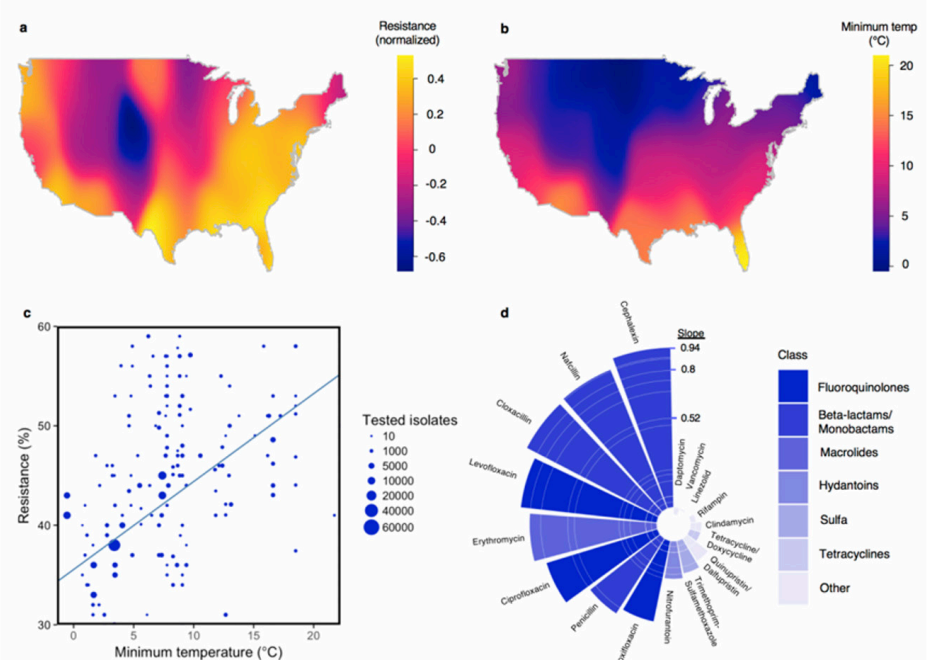
(A) A heatmap of mean normalized antibiotic resistance for S. aureus for all antibiotics across the United States.

(B) A heatmap of 30-year average minimum temperature (°C) across the United States.

(C) A scatter plot of antibiotic resistance versus minimum temperature for S. aureus and cloxacillin. The Unadjusted weighted linear trend line is shown in blue.

(D) The slope of unadjusted relationship (% Resistance/ °C) between minimum temperature and antibiotic resistance by antibiotic for S. aureus. Antibiotic class coded by color shading.

Figure 5: Antibiotic resistance and minimum temperature (K. pneumoniae)



Source: MacFadden et al., 2018.

(A) A heatmap of mean normalized antibiotic resistance for K. pneumoniae for all antibiotics across the United States.

(B) A heatmap of 30-year average minimum temperature (°C) across the United States.

(C) A scatter plot of antibiotic resistance versus minimum temperature for K. pneumoniae and trimethoprim-sulfamethoxazole. The unadjusted weighted linear trend line is shown in blue.

(D) The slope of unadjusted relationship (% Resistance/ °C) between minimum temperature and antibiotic resistance by antibiotic for K. pneumoniae. Antibiotic class coded by color shading.

Disasters and Dissemination of Infections and AMR

Flooding

As temperatures rise, the atmosphere retains more moisture, leading to increased precipitation and more severe storms. This heightened rainfall often results in flooding, which can spread water contamination and waterborne infections, as floodwaters frequently mix with sewage or animal waste. Such contaminated water transports large quantities of resistant bacteria to new areas where these infections were previously uncommon. Moreover, flood-displaced populations can act as reservoirs, carrying infection-related pathogens and associated resistance genes into new environments (Burnham, 2021). The study concludes that urgent, multi-level action is required to counter the looming climate crisis. Preventing antibiotic resistance in the context of climate change must begin now rather than relying on reactive measures in the future. Antibiotic resistance and climate change are deeply interconnected crises that must be addressed together to safeguard both public health and the planet.

Table 1:

Climate change sequelae and their effects on bacterial and viral infections

Climate change factor	Bacterial infections	Viral infections
Extreme weather events	+5	+5
Increased global temperature	+5,8,10–16,18	+5
Droughts	+5	+4 0
Floods	+29	+/–
Vector transmission	n/a	+5
Vector range	n/a	+5

Tuberculosis (TB) is a clear form of AMR related to climate refugees and the resulting overcrowding, as increased population density is strongly associated with the spread of AMR tuberculosis. AMR TB, poverty, and a lack of access to healthcare contribute to a massive outbreak of treatment-resistant tuberculosis (Liu et al., 2015). The study also shows that TB prevention, health resources, health services, TB treatment, TB detection, geography, and climate factors were associated with the occurrence of multidrug resistance.

Nitrogen-fertilized soil increases the spread of AMR, as most fertilizers originate from animal excreta. Further, eutrophication due to floodwater caused by climate change will result in the spread of AMR genes and resistant pathogens (Li et al., 2020). The growing spread of AMR will need the gradual usage of broad-spectrum antibiotics, leading to a lethal cycle of AMR and its spread.

Pollution

Elevated precipitation will result in more water overflow and, eventually, higher water pollution levels. Climate change-induced flooding can release pollutants into the environment, such as heavy metals from manufacturing and industrial processes. Given that metals in soil are known to make bacteria more resistant, through what is called selective pressure that leaves only the very resistant pathogens alive. These pathogens are termed superbugs that are resistant to the most lethal factors that can kill bacteria. Increased agricultural runoff (i.e., eutrophication from fertilizers) will increase bacterial blooms in water systems and related AMR genes, and pollutants are also known to drive the expression of AMR genes and bacterial mutagenesis (Chen et al., 2019). Climate change, with its associated extreme weather events and pollution, has also proved to contribute to cardiopulmonary morbidity and prolonged treatment.

Drought

Extreme weather events will cause drought in some areas in addition to flooding. During droughts, there is a shortage of water, which results in poor sanitation and more people sharing a single water source. Waterborne outbreaks are more common when people are crowded and share water. Lack of food and water could lead to poorer nutrition and a rise in diarrhoeal illnesses. Malnutrition affects children's chance of contracting AMR enteric infections. Lowered immunity converts commensal bacteria that are normally inhabitants of the body into pathogenic bacteria, leading to increased morbidity and mortality rates, especially if adequate treatment is not administered (Huynh C, 2019).

Wildfire

Along with the loss of biodiversity caused by large-scale wildfires, both human and animal survivors would experience chronic respiratory problems. Wildfires have been linked to both short-term and long-term increases in cardiovascular morbidity and mortality. Additionally, bronchiectasis and irreversible lung damage can be caused by direct fire exposure. Patients with bronchiectasis are known to have numerous infections, harbor AMR bacteria, and need intensive treatment (Du et al., 2016; Tapia et al., 2020). Both studies show that the major strategy in decreasing the harmful effects of air pollution is to reduce the air pollutants, as air pollution is becoming an ecological and social dilemma in the world, especially in developing countries.

Indirect Impacts of Climate Change on AMR

More vector-borne infections are a result of the expansion of vector habitats and an increase in bacterial and viral infections brought on by climate change. Insect vector activity is also increased by warmer temperatures. For instance, mosquitoes, a carrier of malaria, will proliferate in any remaining stagnant water pools. Hospital admissions from vector-borne diseases will rise as a result of populations being exposed to more of them. It is anticipated that the number of people at risk for vector-borne illnesses will increase due to climate change, reaching roughly 500 million additional individuals by 2050 (Ryan et al., 2019). For instance, climate change-related above-normal rainfall will provide more standing water, which will encourage mosquito growth. With the help of mosquitos, the infection spreads to places that were previously not endemic (Watts et al., 2021).

Human-animal contact is growing as a result of climate change, and outbreaks of zoonotic and vector-borne illnesses with the potential to become pandemics will persist (Jamshidi et al., 2020; McMullen et al., 2020). The health and well-being of individuals in low and middle-income countries will be disproportionately impacted by climate change, which is a social justice issue. We currently need to act on all fronts to reverse the flow of an oncoming climate catastrophe. Being resistant to antimicrobials has no negative effects on a bacterium's fitness. Therefore, it is preferable to avoid it now rather than attempt to deal with it later. Climate change and antimicrobial resistance must be addressed by all relevant authorities worldwide.

Global Action Plan on Antimicrobial Resistance (GAP)

During the 2015 World Health Assembly, countries made global commitments to the framework outlined in the 2015 Global Action Plan (GAP) on antimicrobial resistance (AMR), as well as to the development and implementation of multisectoral national action plans. In collaboration with the World Health Organization (WHO), the Food and Agriculture Organization of the United Nations (FAO), and the World Organization for Animal Health, strategies were established requiring countries to implement these plans across all sectors and secure appropriate financing to ensure sustainable progress. Prior to the endorsement of the GAP in 2015, a key international initiative to combat AMR, was the WHO Global Strategy for the Containment of AMR; it was developed in 2001 and provided a framework of actions to limit AMR emergence and spread.

Potential Alternative Treatment Options to Combat Antimicrobial-Resistant Pathogens

Although antimicrobial treatment remains the main strategy for managing most infectious diseases, its effectiveness is becoming limited. This limitation has resulted in the evolution of many AMR-producing strains of pathogens, which in turn has become a critical challenge to human health. The problem of AMR emergence is provoked further due to slow-paced inventions in the development of novel antibiotics.

Therefore, it appears that finding effective alternative methods to eradicate drug-resistant bacterial organisms is now a necessity rather than a luxury, especially those derived from natural organ-ic materials like plants and animal by-products.

The continuously developed non-antimicrobial strategies are safer for humans and livestock and effective against infectious pathogens (Kumar et al., 2016). The usage of antimicrobial peptides (AMPs) or bacteriocins (Garcia-Gutierrez et al., 2019; Kumar et al., 2016), antimicrobial adjuvants, vaccines, faecal microbiota transplant (FMT), bacteriophage (Shatzkes et al., 2017), genetically modified probiotics and postbiotics and nanoparticles are the prospective alternative strategies.

Stem Cell-Derived Antimicrobial Peptides

Mesenchymal stem cells (MSCs) have been used for years as safe and promising therapeutic products against a broad range of chronic diseases through promoting immunomodulation and tissue healing. Recently, human MSCs have been employed to produce antimicrobial peptides (AMPs), which kill bacteria by inhibiting the formation of their cell walls, among other ways. Therefore, AMPs represent a promising treatment against various infections (Cortés-Araya et al., 2018; Harman et al., 2017; Marx et al., 2020).

CRISPR-Cas Against AMR- Pathogens

In bacteria and archaea, clustered regularly interspaced short palindromic repeats (CRISPR)-Cas is a distinctive adaptive immunological trait that offers defense against bacteriophages that invade the body. Spacers are short sequences from bacteriophages or plasmids that are incorporated into the bacterial genome as part of a CRISPR array. The Cas protein machinery uses the spacers' guide RNAs to target the invasive nucleic acid that carries the same sequence (Pursey et al., 2018). Numerous studies have demonstrated how CRISPR-Cas can be used to selectively eliminate AMR genes from bacterial populations, increasing the bacteria's susceptibility to antibiotics (Bikard et al., 2014). Nonetheless, the limited host range of CRISPR-Cas vectors and resistance resulting from anti-CRISPR genes are seen as constraints on the application of CRISPR-Cas (Pursey et al., 2018).

Development of Vaccines

By strengthening the host's immune system, vaccines continue to hold promise as a treatment for a variety of bacterial and viral illnesses. The primary mechanism by which the immune system fights infections is the maintenance of a healthy neutrophil count in the blood. Over time, vaccines have decreased the incidence of primary and secondary bacterial infections, which has led to a decrease in the usage of different antibiotics. One of the most important methods of illness prevention is still vaccination. However, not all pathogens, such as Coxiella burnetii, have an effective vaccine until now. Developing more vaccines is still targeted by many pharma companies (Kumar et al., 2021).

Phage Therapy

Phage therapy is considered an alternative therapy to combat the infections of bacteria and AMR. These genetically engineered phages were first introduced in the 1920s in Georgia, having the advantage of being ubiquitous, host-specific, and harmless. They can be received orally with food, topically on open wounds, or intravenously in case of systemic infections (Wittebole et al., 2014). Recombinant phages are engineered to introduce antimicrobial proteins into target bacteria. The highly specialized peptidoglycan hydrolases known as antibiotics are bacteriophage lysins. Gram-negative bacteria are among the pathogens that lysins can be created to destroy. These enzymes are appealing because they do not trigger a negative immunological reaction, and no resistance is developed. Lysins are considered a new model of effective therapy to fight AMR-producing pathogens (Vázquez et al., 2018).

Probiotics, Postbiotics, and Synbiotics

The animal-derived probiotics, the non-viable microbial postbiotics, and the probiotic metabolites that have biological activities inside host are all recently used as alternative therapeutic combinations (Aguilar-Toalá et al., 2018).

Two kinds of lactic acid-producing microorganisms are found in probiotics, which are live microorganisms, including lactic acid bacteria (LAB) and Bifidobacteria, which include species like Enterococcus, Lactobacillus, Lactococcus, and Streptococcus spp. The GI tract, mammary gland, and feminine genitourinary tract contain the majority of probiotics, which are safe (Singh & Madhup, 2013). By competing for nutrients, bioengineered probiotics, also known as pharmabiotics, are emerging as a biotherapeutic approach to bacterial infection. Compared to standard drug administration regimens, they have the benefit of high site specificity. Recombinant probiotic-based vaccines have been developed to protect against various bacterial species, and studies in murine models have demonstrated favorable immune responses. These promising results support their potential for future application in humans.

Nanoparticles

Nanoparticles (NPs) are tiny particles ranging in size from 1 to 100 nm. Their use as antimicrobial agents is gaining more attention due to their reduced cost and exceptional physicochemical properties. Notably, NPs have shown antimicrobial effects, particularly those synthesized using green methods (Liu et al., 2021). Decreased metabolism or bacterial integrity, disruption of transcription and replication, protein denaturation, tRNA, ATPases, membrane-bound enzymes, inhibition of biofilms, and the generation of reactive oxygen species (ROS) are some of the antibacterial effects of NPs. The bactericidal effects of a variety of NPs, including gold (Au), silver (Ag), and less expensive NPs, including zinc oxide (ZnO), silica (SiO2), nickel (Ni), titanium oxide (TiO), and bismuth (Bi), have been determined to be effective. Metal or metal-oxide NPs, polymeric NPs, carbon NPs, and liposomes are some of the ways that NPs are delivered to cells for antibacterial action. Nanoparticles have been used as inexpensive prognostic and therapeutic agents in a variety of biomedical science applications. The use of green synthesis and inexpensive components like albumin and chitosan improves the effectiveness of NPs for treatment applications (Zarenezhad et al., 2022).

The endlessly increasing AMR in pathogenic bacteria necessitates the development of unconventional non-antibiotic therapies to tackle the emergence of infectious pathogenic microorganisms and associated multidrug resistance. Since antibiotics entered modern medicine, their effectiveness has been reducing. Decreasing the dependence on chemical therapeutics is a must in the present scenario. Additionally, overprescription and inappropriate use of antibiotics and non-therapeutic prophylactic uses must be avoided. Good hygiene and appropriate infection control measures are eagerly needed to decrease the need to therapeutic interventions.

Recommendations

- Strengthen international cooperation to combat climate change and antimicrobial resistance.
- Improve oversight of antibiotic use and develop strategies to prevent infections.
- Support research into alternative therapies and vaccines.
- Provide sustainable health solutions in the most vulnerable communities.

- **Promote community outreach and health education:**

  » Launch awareness campaigns to educate about the risks of antimicrobial resistance and the importance of using antibiotics with caution.

  » Target groups most vulnerable to the effects of climate change in rural or low-income areas to enhance their understanding of infectious disease prevention and good health practices.

- **Support national and international policies:**

  » Coordinate health and environmental policies aligned with global goals to address climate change and antimicrobial resistance.

  » Provide technical and material support to developing countries to develop effective strategies to combat antimicrobial resistance in the context of climate change.

- **Promote innovation in research:**

  » Encourage interdisciplinary studies that explore the relationship between climate change and drug resistance through deeper analyses of the evolution of bacterial strains under environmental changes.

  » Promote collaboration between academic institutions and international bodies to develop innovative technological solutions to address the effects of climate change on antimicrobial resistance.

- **Integrate One Health into policies:**

  » Expand the concept of One Health to include integrated strategies across public health, environment, and agriculture sectors to combat health crises related to climate change and antimicrobial resistance.

Conclusion: Research clearly shows that climate change and antimicrobial resistance are escalating challenges that pose significant threats to human, animal, and environmental health. As their impacts on ecosystems and vulnerable populations continue to intensify, there is an urgent need for globally coordinated, cross-sectoral strategies. Addressing this crisis demands immediate action, including innovation in treatment approaches, strengthened health policies, and enhanced international collaboration to secure a more sustainable and healthier future for generations to come.

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المستخلص:

التغير المناخي ومقاومة المضادات الحيوية هما من أكبر التحديات الصحية والبيئية التي تواجه العالم في الوقت الحاضر. تؤكد الدراسة أهمية التصدي لكلا الأزمتين من خلال منظور صحي بيئي شامل يتضمن التعاون بين القطاعات الصحية والبيئية والزراعية. كما تسلط الضوء على ضرورة تطوير استراتيجيات لمكافحة مقاومة المضادات الحيوية في سياق التغير المناخي، مع الاهتمام بالعدالة الاجتماعية من خلال توجيه الحلول إلى الفئات الأكثر هشاشة.

النقاط الرئيسة التي تم تناولها في البحث تشمل:

١- العلاقة بين التغير المناخي ومقاومة المضادات الحيوية: التغير المناخي يؤدي إلى زيادة انتشار الأمراض المعدية مما يزيد من استخدام المضادات الحيوية وبالتالي ظهور مقاومة لهذه الأدوية.

٢- التحديات الصحية الناتجة عن التغير المناخي: تشمل الأمراض الناتجة عن ارتفاع درجات الحرارة، الفيضانات، الجفاف، والتلوث البيئي، مما يزيد من معدلات الإصابة بالأمراض والعدوى المقاومة.

٣- الحلول المستدامة لمكافحة مقاومة المضادات الحيوية: تركز الدراسة على تطوير حلول بديلة، مثل: اللقاحات والعلاج بالبكتيريوفاج، وتعزيز البحث في العلاجات الجديدة.

٤- أهمية العدالة الاجتماعية: تدرس الدراسة تأثير التغير المناخي في الفئات الضعيفة مثل سكان البلدان النامية، الذين يعانون من تحديات صحية أكبر رغم أن مساهمتهم في انبعاث الغازات الدفيئة ضئيلة

الكلمات المفتاحية: كوفيد ١٩ – تغير المناخ – مقاومة مضادات الميكروبات