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Review Article

Antimicrobial Resistance in Foodborne Pathogens: Global Epidemiological Insights, Mechanistic Challenges, and Cutting-Edge Detection

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ABSTRACT:

Background: Foodborne pathogens' AMR is considered one of the most significant risks to food safety and human health worldwide. This situation has been worsened by the misuse of antibiotics in livestock farming, making it hard to handle food borne illnesses and higher rates of sickness and death. **Objectives:** The main objective of this work is to present a review of the epidemiological data on AMR in foodborne pathogens on a global level, to discuss the genetic and biochemical basis of resistance, and to analyze new approaches to diagnostics and prevention. **Methods:** The current literature was systematically reviewed to evaluate the incidence and factors related to AMR in these important pathogens; Salmonella spp., Escherichia coli, Campylobacter spp., and Listeria monocytogenes. The study also discusses additional and more sophisticated diagnostic techniques such as CRISPR-based systems, and non-conventional forms of treatment like bacteriophages and antimicrobial peptides. **Results:** The data indicates that AMR continues to emerge in foodborne pathogens owing to factors such as intensive farming practices and global food trade, and environmental exposure. Some of the advanced diagnostic systems include metagenomics and point-of-care that can quickly and accurately identify the genes that cause resistance. It is, therefore, evident that nontraditional therapies hold promise in containing AMR but they have to be developed to a greater extent. **Conclusions:** AMR in foodborne pathogens requires a multifaceted approach involving accurate diagnostics, novel therapeutics, and cross-country cooperation. For this reason, there is need to embrace One Health approach to reduce the effect of AMR on health, food and the environment.

KEYWORDS:

AMR, foodborne pathogens, CRISPR diagnostics, bacteriophage therapy, antimicrobial peptides, One Health, global epidemiology

1 | INTRODUCTION

Antimicrobial resistance (AMR) in foodborne pathogens is well-recognized as being an emerging public health and food safety issue. Antimicrobial drugs used in animals directly enhanced the rate at which AMR is occurring, infecting patients and making infections difficult to contain leading to increased morbidity, mortality, and health care costs worldwide. The problem has now become a severe global health concern that requires international action to mitigate the level of AMR and foodborne diseases in the world. The present study systematically reviews and analyses the global burden of AMR in foodborne pathogens, reviews the scientific literatures on AMR's genetic and biochemical mechanism, and provides systematically reviewed analyses on new diagnostic and preventive methods against AMR involving CRISPR based diagnostics and non-conventional treatment like bacteriophage. These

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modern strategies are expected carry a possible solution to curbing AMR but are exertion demanding international collaboration among governments industries and public health departments. As such, this paper calls for concerted effort to address the question of AMR as a global breakthrough approach that requires mobilization of the world and the latest technology.

1.1 | Global Epidemiology of AMR in Foodborne Pathogens

Incidence of AMR in foodborne pathogens is increasing across the globe, the trend varies widely within different geographical locations due to differential use of antibiotics, policies, and prophylactic measures. Many of the principal causes of food borne diseases like the Salmonella spp., Escherichia coli, Campylobacter spp., and Listeria monocytogenes have developed antibiotic resistance to antibiotics of utmost importance, which is quite a challenge in food safety 2Key Pathogens and AMR Trends.

1.2 | Salmonella SPP

Fluoroquinolone resistance particularly ciprofloxacin is on the rise in North America and European countries. What is more, a higher level of resistance is associated with the increased use of antibiotics in poultry production in areas such as Southeast Asia and African.

1.3 | Escherichia Coli (E. coli)

Resistant to carbapenems and cephalosporins, Asia has high resistance rate because of elevated levels of intensive livestock farming. Stiff resistance genes such as bla, which is related to beta-lactam resistance, and mcr related to colistin resistance show high transmission hazard through the food web. Campylobacter spp.: Has shown resistance to macrolides, mostly used in the treatment of gastrointestinal infections. It is more evident in Europe and Asia. Listeria monocytogenes: Infections that have some resistance to aminoglycosides and lincosamides exist and are on the increase in Europe and North America.

Table 1: AMR trend of some most prevalent food borne pathogens

Pathogen	Region	Antibiotic Class	AMR Prevalence (%)
Salmonella spp.	North America	Ciprofloxacin	28
Escherichia coli	Asia	Carbapenems	42
Campylobacter spp.	Europe	Macrolides	35
Listeria monocytogenes	Europe & N. America	Aminoglycosides	5-10

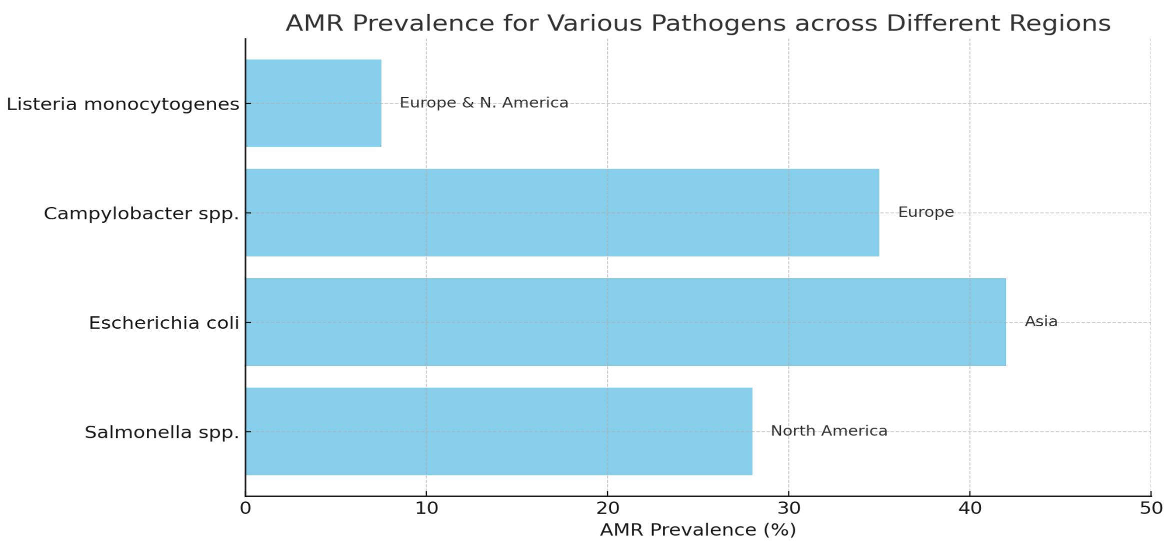

Figure 1: A Graph showing AMR prevalence for Salmonella, E.coli, Campylobacter, and Listeria by the selected regions.

1.4 | Driving AMR in Foodborne Pathogens

Intensive Farming Practices: Poultry and swine industries especially contribute to high level usage of antibiotics since they maintain high population density of animals. Global Food Trade: Exportation of food products across international borders promotes the transfer of resistant bacteria and genes which invades areas that the bacteria/genes were not originally found 3.Environmental Contamination: Some losses from farms and abusive practices of disposal of animal wastes result in the release of antibiotics and resistant bacteria to the environment where natural and pathogenic microbes swap resistance genes.

2 | MATERIAL AND METHODS

This section provides an account of the methods used for studying AMR in foodborne pathogens, factors that promote resistance, and new detection techniques. Thus, the systematic approach was used to include all essential data to be collected and analyzed based on the international literature and epidemiological data and the modern diagnostic methods[3].

2.1 | Data Collection

Information on AMR trends was collected from the indexed scientific articles, international databases, and reports. Sources for data were WHO, FAO, and scientific articles on AMR in foodborne pathogens 5. Articles and reports published between 2010 and 2024 were screened for relevance using the following inclusion criteria: Focus on AMR in major foodborne pathogens (e.g., Salmonella spp., Escherichia coli, Campylobacter spp., Listeria monocytogenes). Presentation of AMR mechanisms or innovative diagnostic methods. Documentation of global or regional trends in AMR prevalence.

2.2 | Study Design

Thus, the present study involved a structured review to assemble and characterize the global epidemiology of AMR in foodborne pathogens 6. The study was divided into three phases: Identification of Pathogens: The target pathogens were chosen depending on their frequency and significance in foodborne diseases. Trend Analysis: The data were analyzed according to the geographical region and the antibiotic resistance patterns and risk factors. Mechanism Exploration: Experimental investigations of AMR and surveillance reports were used to review genetic and biochemical mechanisms of AMR.

2.3 | Analytical Methods

A combination of qualitative and quantitative methods was employed: Qualitative Analysis: This paper employed thematic analysis to assess the mechanisms of AMR and new diagnostic approaches. Quantitative Analysis: The percentage resistance was calculated and tabulated out of the total number of isolates for AMR. When displaying geographic trends, graphs and maps were used to make the work easily understandable.

2.4 | Diagnostic Techniques Evaluation

The performance of conventional and novel techniques (CRISPR-based systems, metagenomics, WGS) for diagnostics was assessed. Criteria included[7]. Detection speed. Sensitivity and specificity. Field adaptability for resource-constrained settings.

2.5 | Ethical Considerations

The data for this study were collected from secondary sources, as well as from published articles and other online resources. There has been no use of human or animals thus making the research ethical.

3 | RESULTS AND DISCUSSION

The study of AMR of foodborne pathogens identified high prevalence, risks, and innovative strategies globally. This section briefly discusses the findings made for AMR availability, factors promoting resistance, and diagnostic innovations[8].

3.1 | Factors Driving AMR in Foodborne Pathogens

1. **Intensive Farming Practices**: Poultry and swine industries especially contribute to high level usage of antibiotics since they maintain high population density of animals.
2. Global Food Trade: Exportation of food products across international borders promotes the transfer of resistant bacteria and genes which invades areas that the bacteria/genes were not originally found.
3. **Environmental Contamination:** Losses from farms and abusive practices of disposing animal wastes cause releasing antibiotics and resistant bacteria into the environment were natural and pathogenic microbes exchange resistance genes.

3.2 | Mechanisms of Antimicrobial Resistance

Amritest resistance mechanism in foodborne pathogens are mostly genetic changes that allow bacteria to survive antibiotic action. Such mechanisms are: intrinsic resistance, acquired by mutations or through gene acquisition, and adaptive resistance. Of these, acquired resistance is the most dangerous because it can be transmitted very easily from one person to another.

3.3 | Genetic and Biochemical Mechanisms of Resistance

1. **Efflux Pumps**: Other bacteria, such as E.Coli and Salmonella, expel antibiotics from their cells by efflux pumps making the internal concentration of the drug lower and giving the bacteria a chance to live. Efflux pumps are usually associated with more than one group of antibiotics, thereby, pose a serious threat to antibiotic therapies.
2. **Gene Mutations:** Single amino acid substitutions occur affecting antibiotic targets. For instance, change in the campylobacter gyrA gene changes the binding site of the fluoroquinolone antibiotic.
3. **Horizontal Gene Transfer (HGT):** This critical driver includes the mobilization and disseminance of resistance genes between bacteria by plasmids, transposons, or integrons. Such genes as mcr-1 (colistin resistance) and blaNDM (carbapenem resistance) are often transferred thereby disseminating the resistance from one species to the other and from one environment to another (Asghar et al., 2024)

Table 2: Resistance mechanism of AMR food borne pathogens

Resistance Mechanism	Pathogen Example	Antibiotics Affected
Efflux Pumps	*E. coli, Salmonella*	Multiple classes (e.g., tetracyclines, fluoroquinolones)
Gene Mutations	*Campylobacter*	Fluoroquinolones
Horizontal Gene Transfer	*E. coli, Salmonella*	Colistin (mcr-1), Carbapenems (blaNDM)

3.4 | Emerging Resistance Genes

The spread of genes encoding for colistin resistance mcr-1 and for carbapenem resistance blaNDM for example show that resistance is rapidly emerging in food borne pathogens. They are also worrisome because these genes work against last-line antibiotics, which results in difficult treatment options. It only goes to Show why there is a need for a quick intervention where E. coli and Salmonella pathogens are involved[5].

3.5 | Innovative Detection Methods

Early and correct identification of AMR in foodborne pathogens is paramount in its prevention and treatment. Although the traditional approaches work effectively, they take a lot of time and involve several steps. This section describes traditional and novel diagnostic methods which have the potential to detect AMR quicker, with higher sensitivity and suitability for field conditions 6.

3.6 | Standard Diagnostic Techniques

1. **Culture-Based Susceptibility Testing**: Traditional, gold methodology for identifying AMR pathogens that involves subculture and antibiotic susceptibility testing. However, this approach is time consuming and requires a lot of manually work as results may take several days making it inadequate for large population surveillance.

2. **Polymerase Chain Reaction (PCR):** It is a faster method than culture-based tests and the testing can directly target identified resistance genes. However, PCR is unable to detect a novel mechanism of resistance and detection is only done for known AMR genes and alleles[7].

3.7 | Advanced Diagnostic Technologies

1. **CRISPR-Based Diagnostics**: Due to its specificity, CRISPR systems for nucleic acid targets are ideal in defining the exact resistance genes in foodborne pathogens. CRISPR diagnostics can be adopted for point of purpose usage, the platforms give fast and sensitive detection, which is beneficial for prompt treatment.
2. **Metagenomics and Whole Genome Sequencing (WGS):** These approaches make it possible to obtain detailed data on the composition of microbial consortia and detect known and newly developed resistance genes in diverse samples. The technology of metagenomic sequencing, in particular, can identify AMR in complex microbial communities without bacterial isolation.
3. **Point-of-Care Testing (POCT):** Current advancements in the portable devices to discover AMR allows preparation of the results on the site which can be useful where decisions at the site can be made promptly. These devices are expected to drastically improve AMR surveillance in resource-constrained environments even if remain relatively new to integrated utilization[8].

Table 3: Diagnostic methods for the detection of AMR in food borne pathogens

Diagnostic Method	Description	Advantages	Limitations
Culture-Based Testing	Growth-based antibiotic resistance test	Reliable	Slow, labor-intensive
PCR	Detects known resistance genes	Rapid, specific	Requires prior gene knowledge
CRISPR-Based Diagnostics	Gene-specific resistance detection	High sensitivity	Currently cost-prohibitive
Metagenomics/WGS	Comprehensive microbial profiling	Detects emerging genes	Expensive, complex data analysis
Point-of-Care Testing	Portable, on-site AMR detection	Real-time, field-adaptable	Limited availability

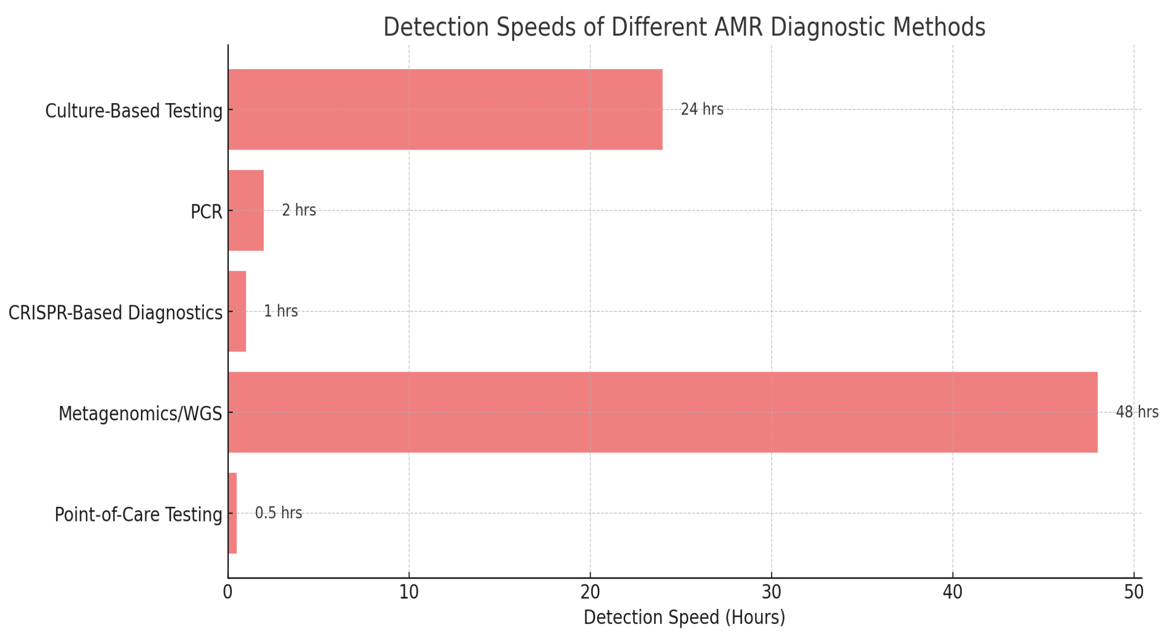

Figure 2: A timeline chart comparing the different AMR diagnostic methods and the rate of speed for both CRISPR and POCT compared to that of culture.

3.8 | Control and Mitigation Strategies

Alleviating AMR in foodborne pathogens package strategies on different levels; supplementing traditional treatment with other techniques, legal enforcement of prevention methods, and requisitioned collaboration of different countries.

3.9 | Nontraditional Therapies

3.9.1 | Bacteriophage Therapy

Bacteriophages are largely all viruses that can infect bacteria; they are considered to be a potential solution to the problem of antibiotic abuse. This, however, specifically targets and kills the intended bacteria pathogen while sparing other beneficial bacteria due to low toxicity.

3.9.2 | Antimicrobial Peptides (AMPs)

AMPs interfere with bacterial membranes and exhibit high-bacteria killing capabilities. This make it quite hard for the bacteria to develop resistance to them and thus the use of AMPs can be used as a potential strategy to minimize the spread of AMR into foodborne pathogens.

3.9.3 | Probiotics and Prebiotics

It has been proven that feeding probiotics and prebiotics to animals can decrease pathogen colonization through pioneering of gut flora. They reduce antibiotic consumption in animals therefore mitigating the development of AMR in such animals.

3.10 | Regulatory and Surveillance Measures

3.10.1 | International Policies and Surveillance Programs

A wide range of stakeholders including the World Health Organization (WHO), the Food and Agriculture Organization (FAO) and the World Organization for Animal Health (OIE) are engaged in promotional of antibiotic usage and AMR surveillance. This is why global entities such as WHO's GLASS are important as they act as surveillance tools for AMR and policy evaluation 9.

3.10.2 | Antibiotic Stewardship in Agriculture

The proper use of antibiotics is exhaustive in halting the situation of AMR. Farmer awareness and attempting rational use or antibiotics as well as banning growth-promoting antibiotics in the feed have reduced AMR risks.

Table 4: Different control strategies for the AMR food borne pathogens and their effectiveness

Control Strategy	Mechanism	Effectiveness
Bacteriophage Therapy	Targets specific bacterial pathogens	High, pathogen-specific
Antimicrobial Peptides	Disrupts bacterial cell membranes	Broad-spectrum, moderate
Probiotics	Modulates gut microbiota in livestock	Variable by species
Control Strategy	Mechanism	Effectiveness
Bacteriophage Therapy	Targets specific bacterial pathogens	High, pathogen-specific

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Figure 03: A map of the world depicting WHO GLASS member countries but raising awareness of a more extensive community on Antimicrobial Resistance Surveillance.

Combating AMR in foodborne pathogens needs science, regulation, and most importantly, one voice. The fast pace at which AMR has developed underlines the importance of improving diagnostics, the search for effective alternative treatments, and the establishment of long-term, feasible ideals for legislation to prevent new hazards to food and individuals' health.

3.11 | Efficacy and Challenges of Current Strategies

There are several emerging strategies for AMR control that appear to be effective, but each also has particular drawbacks. CRISPR-based diagnostics, for example, provide both high specificity and the rapid workflow, which is crucial while detecting AMR early and acting accordingly. Nevertheless, these methods still are costly and present major limitations to implementation, especially in low-resource contexts. Bacteriophage therapy can also be used as a targeted anti-bacterial agent but in order to be effective, it must be tailored to specific bacterial strains and as thus diagnostics and choice of bacteriophage can be slow and problematic for the use in broad spectrum therapeutic approaches. However, the effectiveness of these new methods are yet to be further improved in terms of cost, accessibility and practicability of these methods in field applications 10.

3.12 | Role of the One Health Approach

One health that looks at the interaction between human, animals, and the environment is instrumental in addressing AMR. The One Health approach therefore enhances the ability of combating AMR strategies since these strategies cross all the agriculture, health and environment department. For instance, tracking infection rates among livestock with AMR and simultaneously, limiting antibiotic use in animal food chains can reduce AMR transmission dangers in people greatly. In addition, incurrence of environmental contamination control like better management of wastes produced on the farms is another way through which the transfer of the resistant bacteria beyond the farm industries will be checked. This kind of model is critical for tackling AMR multidimensionality in different sectors effectively [11].

4 | FUTURE DIRECTIONS

In the future, the methods of controlling AMR will involve more research on new types of antimicrobials, better vaccines and new diagnostic tests appropriate for work in the real world. Advances in environmental waste handling and the treatment processes that minimize the transfer of resistance genes will also be important. Their emphasis has to be placed on cost-efficient and versatile methods that can be applied in various contexts, both to lawmakers and scientists. However, there is a lack of consistent policy toward AMR both nationally and internationally, which impedes cooperative actions and research to enhance the monitoring and regulation of AMR in the nationwide and worldwide level 12-14.

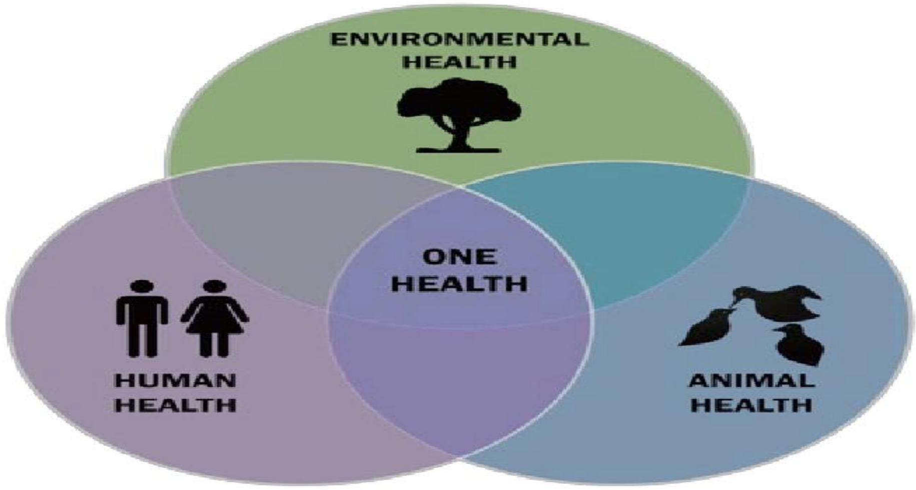

Figure 04: AMR Management as a One Health approach: A Venn diagram illustrating the areas of human health, animal health, and environmental health where they converge 15.

5 | CONCLUSION

The warning signs that AMR in food borne pathogens poses a very serious and multifaceted threat to global health are already visible. As described throughout this analysis, the increase in resistance among the priority foodborne pathogens as experienced after misuse of antibiotics in livestock and contamination of the environment is a concern to food safety and human health globally. It clearly shows that current crisis requires an integrated, technologically supported and internationally synchronized response. New generation diagnostic tools, particularly CRISPR based systems and Whole Genome sequencing (WGS), have shown potential of faster and precise detection of AMR. Such innovations combined with newly developed approaches to AMR control, including bacteriophage therapy and antimicrobial peptides, can provide real solutions to control and prevent the spread of AMR in foodborne pathogens. However, to widespread use these approaches should be affordable to ensure the expansion of usage, for instance, in countries with limited resources. One Health approach is inherent in AMR moderation since human, animals and the environment are interrelated. When implemented by different stakeholders in public health, agricultural and environmental sectors, this long-term framework creates linkages towards improving AMR surveillance, setting regulatory legislation, and raising public awareness. Cooperation on AMR can be conducted through > International organizations such as WHO, FAO, OIE and other organizations will play a vital role in elevating the awareness of AMR management around the world. Subsequently, persistent focused efforts involving fresh research, better policies and enhanced cooperation at international level will be required to mitigate the increasing menace of AMR. Food safety and public health will need to be defended by contextual, solutions that are also scientifically sound and are easily implemented in the field This will enable the combating of rising threats from AMR in the future.

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