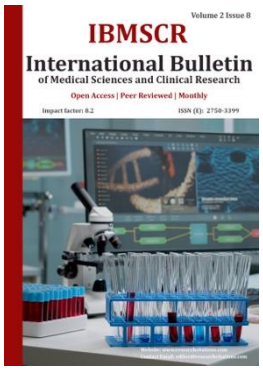

ANTIBIOTIC RESISTANCE: CAUSES, GLOBAL HEALTH IMPACTS, AND FUTURE STRATEGIES FOR PREVENTION AND TREATMENT

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Abstract

Antibiotic resistance is one of the most serious challenges facing modern healthcare. Incorrect and uncontrolled use of antibiotics, failure to complete the full course of treatment, self-medication, and excessive use of antibiotics in medicine and animal farming contribute to the development of resistant bacteria. As a result, common infections become more difficult to treat, hospital stays become longer, treatment costs increase, and the risk of severe complications rises. This article discusses the main causes of antibiotic resistance and its impact on human health and the global healthcare system. It also describes important future approaches, including the rational use of antibiotics, prevention of infections, development of new antibacterial drugs, vaccination, and alternative treatment methods. Effective control of antibiotic resistance requires close cooperation between healthcare professionals, patients, and health organizations.

Keywords: antibiotics, antibiotic resistance, bacteria, infection, antibacterial therapy, rational antibiotic use, prevention, global health, treatment strategies.

Relevance of the problem

Antibiotic resistance has become one of the most serious problems in modern medicine. Antibiotics that were once highly effective against bacterial infections are gradually losing their activity because many bacteria have developed mechanisms that allow them to survive treatment. This situation makes common infections more difficult to treat and increases the risk of complications, prolonged hospitalization, disability, and death. A large global analysis published in 2024 estimated that bacterial antimicrobial resistance was directly responsible for about 1.14 million deaths in 2021 and was associated with approximately 4.71 million deaths worldwide. If current trends continue, deaths directly attributable to antimicrobial resistance may rise substantially by 2050. [1]

The scale of the problem is also demonstrated by recent international surveillance. According to the World Health Organization, antibiotic resistance is now detected in many important bacterial pathogens responsible for bloodstream, urinary tract, gastrointestinal, and other common infections. Recent surveillance data from more than one hundred countries show that resistance is not limited to a particular region or health system. It is increasingly becoming a global problem affecting both high-income and low- and middle-income countries. At the same time, antibiotic consumption differs markedly between countries, reflecting both unnecessary use in some settings and inadequate access to appropriate treatment in others. [2,3]

One of the major reasons for the growing resistance problem is inappropriate antibiotic use. Antibiotics are still often prescribed for viral infections, used without microbiological confirmation, taken without medical supervision, or stopped before the prescribed course is

completed. In addition, the widespread use of broad-spectrum antibiotics creates strong selective pressure that allows resistant microorganisms to survive and spread. The problem is not limited to human medicine; antimicrobial use in livestock, agriculture, and food production also contributes to the circulation of resistant bacteria and resistance genes in the environment. [4,5]

Recent data from China demonstrate that antimicrobial resistance remains an important clinical challenge even in countries with well-established surveillance systems. National surveillance has shown persistent resistance among major hospital pathogens, including *Escherichia coli*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, and other Gram-negative bacteria. Particularly concerning is resistance to third-generation cephalosporins and carbapenems, because these antibiotics are often used to treat severe infections when first-line drugs are no longer effective. [6]

A similar situation has been described in India. Recent systematic analyses have reported high resistance among several WHO priority pathogens. Extended-spectrum beta-lactamase-producing organisms and carbapenem-resistant bacteria are increasingly identified in clinical practice. Resistance to commonly used penicillins, cephalosporins, fluoroquinolones, and other antibacterial agents reduces available treatment options and often forces physicians to use more expensive or more toxic drugs. These findings show that local and regional surveillance is necessary because resistance patterns may differ significantly between states and hospitals. [7]

Pakistan also faces a considerable antibiotic resistance burden. Recent studies indicate that over-prescription, self-medication, weak regulation of antibiotic sales, and insufficient antimicrobial stewardship remain important contributors. In addition, multidrug-resistant organisms have complicated the treatment of common bacterial diseases, including enteric infections. The experience of Pakistan illustrates how social, economic, and healthcare-system factors can interact and accelerate the development and spread of resistance. [8]

Antimicrobial resistance is also an increasing concern in Middle Eastern countries. A recent systematic review from Saudi Arabia showed that resistant bacterial infections are becoming more common and are associated with increased treatment difficulties and healthcare costs. Rapid population movement, intensive healthcare use, widespread antibiotic exposure, and differences in prescribing practice may further contribute to resistance in the region. These findings support the need for stronger infection control and national antimicrobial stewardship programmes. [9]

The burden is particularly serious in many African countries, where limited laboratory capacity and incomplete surveillance may hide the true scale of the problem. A large regional analysis showed that bacterial antimicrobial resistance contributes substantially to mortality across the African continent. In several countries, inadequate access to diagnostic testing, uncontrolled antibiotic availability, poor infection prevention, limited sanitation, and antibiotic use in animals create favourable conditions for resistant bacteria to spread. [10,11]

Recent research from Egypt and Nigeria also supports the importance of a One Health approach. Antibiotic resistance genes and multidrug-resistant bacteria can circulate between humans, animals, food products, wastewater, and the wider environment. Therefore, controlling resistance only within hospitals is not sufficient. Effective prevention requires

coordinated action involving healthcare professionals, veterinarians, agricultural specialists, public health authorities, laboratories, and environmental services. [12,13]

High-income countries are not protected from this problem. Surveillance in Europe, the United Kingdom, and Australia continues to identify increasing or persistently high resistance in several important pathogens. European data show growing concern about carbapenem-resistant *Klebsiella pneumoniae* and other multidrug-resistant Gram-negative organisms. Recent national surveillance in England and Australia has also documented increases in some resistant bloodstream infections and critical resistance patterns despite established stewardship programmes. These findings confirm that antibiotic resistance is a dynamic problem that requires continuous monitoring even in countries with advanced healthcare systems. [14–16]

The increasing global spread of antibiotic-resistant bacteria threatens many achievements of modern medicine. Surgical procedures, organ transplantation, cancer chemotherapy, intensive care, neonatal medicine, and treatment of severe bacterial infections all depend on effective antibiotics. When these drugs no longer work, even routine medical procedures may become more dangerous. For this reason, the development of new antibiotics alone cannot solve the problem. Prevention of infections, vaccination, rapid microbiological diagnostics, rational prescribing, antimicrobial stewardship, surveillance, improved sanitation, and responsible use of antibiotics in agriculture must all be combined. [1,3,14]

Thus, antibiotic resistance should be considered not only a microbiological problem but also a major public health, clinical, economic, and social challenge. The evidence from different regions of the world shows that no country can solve this problem independently. International cooperation, stronger national surveillance, careful antibiotic prescribing, public education, investment in new treatment options, and implementation of the One Health strategy are essential to preserve the effectiveness of antibiotics for future generations. [2,4,10,17].

Aim of the study: to analyze the main causes and mechanisms of antibiotic resistance, assess its impact on global public health, and review current and future strategies for the prevention and treatment of antibiotic-resistant infections.

Materials and methods

This study was conducted as a review of the scientific literature. Recent publications were analyzed to evaluate the main causes of antibiotic resistance, its spread, its impact on human health, and current approaches to its prevention and treatment.

Scientific information was searched in the PubMed, Scopus, Web of Science, and Google Scholar databases. The following keywords were used during the search: “antibiotic resistance,” “antimicrobial resistance,” “antibiotic stewardship,” “multidrug-resistant bacteria,” “antimicrobial resistance in Central Asia,” and “antibiotic resistance in Uzbekistan.”

The analysis mainly included scientific articles, systematic reviews, international reports, and clinical recommendations published between 2020 and 2026. Data from the World Health Organization, international epidemiological organizations, and studies carried out in different countries were compared and summarized.

To adapt the analysis to the conditions of Uzbekistan, available information on antibiotic use, detection of antibiotic-resistant microorganisms, infection control, and rational antibiotic prescribing in the country was also reviewed. Data from other Central Asian countries were additionally considered for comparative analysis.

The collected information was evaluated using descriptive and comparative methods. The main causes of antibiotic resistance, risk factors, clinical consequences, and current and future strategies for prevention and treatment were grouped and analyzed separately.

Results and discussion

1. Current Pattern of Antibiotic Resistance

The review of recent studies shows that antibiotic resistance continues to increase in both hospitals and the community. The problem is especially serious among Gram-negative bacteria such as *Escherichia coli*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, and *Pseudomonas aeruginosa*. These bacteria can cause urinary tract infections, pneumonia, bloodstream infections, wound infections, and sepsis. When they become resistant to several antibiotics at the same time, treatment becomes more difficult and the choice of effective drugs becomes limited. [18,19]

The World Health Organization updated its Bacterial Priority Pathogens List in 2024. This list includes 24 pathogens belonging to 15 groups of antibiotic-resistant bacteria. Carbapenem-resistant *Acinetobacter baumannii*, carbapenem-resistant Enterobacterales, third-generation cephalosporin-resistant Enterobacterales, and rifampicin-resistant *Mycobacterium tuberculosis* were placed in the critical priority group. These pathogens were given the highest priority because they are difficult to treat and are associated with serious infections and high mortality. [18]

2. Antibiotic Resistance in Central Asia

Recent studies show that antimicrobial resistance is also an important problem in Central Asia. A recent regional review covering Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan showed that AMR surveillance is still not equally developed across the region. In some studies, up to 70% of Enterobacterales were resistant to third-generation cephalosporins, while resistance to macrolides among *Staphylococcus* species reached up to 58%. [19]

The situation is made more difficult by differences in laboratory capacity, antibiotic prescribing practice, public knowledge, and national surveillance systems. In some areas, microbiological testing is not performed before antibiotic treatment is started. This can lead to the repeated use of broad-spectrum antibiotics and can increase the selection of resistant microorganisms. [19,20]

A systematic review of antimicrobial resistance surveillance in post-Soviet countries also showed that AMR data are still incomplete in many countries of the region. The authors emphasized the need for standard laboratory methods, regular reporting of resistance data, and stronger national surveillance systems. [20]

3. Antibiotic Resistance in Uzbekistan

The most important recent national data come from the antimicrobial resistance surveillance project carried out in Uzbekistan between 2019 and 2022. The project included four health-care facilities and the National Antimicrobial Resistance Center. In total, 2063 patients were included, and 299 positive blood cultures with clinically important bacterial pathogens were identified. [21]

Among the main microorganisms were *Staphylococcus aureus*, *Escherichia coli*, and *Klebsiella pneumoniae*. High levels of resistance were found, including multidrug resistance in *K. pneumoniae* and methicillin resistance in *S. aureus*. These findings confirm that antibiotic-resistant bloodstream infections are already an important clinical problem in Uzbekistan. [21]

The same surveillance project also showed practical difficulties in microbiological diagnosis. Delays in antimicrobial susceptibility testing, problems with laboratory supplies, and errors in blood culture sampling were reported. At the same time, the project improved cooperation between clinicians and laboratory specialists and supported the development of the National AMR Center. [21]

These findings suggest that further development of microbiology laboratories is one of the most important steps for Uzbekistan. Faster identification of bacteria and their antibiotic sensitivity would allow physicians to choose a more appropriate drug and avoid unnecessary use of broad-spectrum antibiotics.

4. Importance of Microbiological Diagnosis

Microbiological diagnosis is very important in the management of bacterial infections. The choice of an antibiotic only on the basis of symptoms may sometimes be necessary at the beginning of treatment, especially in severe infections. However, when possible, biological samples should be collected before antibiotic therapy is started.

Culture methods and antimicrobial susceptibility testing can show which microorganism caused the infection and which antibiotics are still effective. This allows the physician to change empirical treatment to more targeted therapy.

Modern rapid diagnostic methods can further reduce the time needed to identify pathogens and resistance mechanisms. Molecular tests can detect bacterial pathogens and some resistance genes much faster than traditional culture methods. Studies show that rapid diagnostic tests can shorten the time to correct antibiotic treatment, especially in bloodstream and respiratory infections. [22]

For Uzbekistan, wider access to rapid microbiological diagnosis may help reduce unnecessary antibiotic exposure and improve the treatment of serious bacterial infections.

5. Hospital-acquired infections

Hospital-acquired infections remain one of the main areas where antibiotic resistance causes serious problems. Patients in intensive care units, surgical departments, neonatal units, and oncology wards often have a higher risk of infection because they may have catheters, mechanical ventilation, surgical wounds, or weakened immunity.

Resistant *K. pneumoniae*, *A. baumannii*, *P. aeruginosa*, *E. coli*, and *S. aureus* are especially important in hospital settings. These bacteria can spread between patients and may survive for long periods in the hospital environment.

When an infection is caused by a multidrug-resistant bacterium, the first antibiotic may not work. As a result, the treatment must be changed, hospitalization may become longer, and the risk of complications may increase. [18,20]

Strict hand hygiene, correct use of medical devices, isolation of patients when needed, regular environmental cleaning, and microbiological monitoring can reduce the spread of resistant bacteria inside hospitals.

6. Antimicrobial stewardship

Antimicrobial stewardship is one of the main strategies for reducing antibiotic resistance. Its main principle is simple: antibiotics should be used only when they are needed, and the most appropriate drug, dose, route, and duration should be selected.

Hospital stewardship programmes may include regular review of antibiotic prescriptions, consultation with microbiologists, use of local resistance data, and correction of treatment after culture results become available.

This approach is particularly important in countries where broad-spectrum antibiotics are commonly used empirically. In Uzbekistan, local hospital guidelines based on the actual resistance patterns of each institution could improve antibiotic selection and reduce unnecessary use.

Antibiotic stewardship should not be viewed as a way to restrict treatment. Its main goal is to make antibiotic therapy more accurate and effective while preserving the activity of existing drugs for future patients. [19,21]

7. One health approach

Antibiotic resistance does not develop only in hospitals. Antibiotics are also used in veterinary medicine, livestock production, agriculture, and food production. Resistant bacteria and resistance genes can move between people, animals, food, water, and the environment.

For this reason, the One Health approach has become an important part of global AMR control. It combines human health, animal health, food safety, and environmental protection in one coordinated strategy. [23,24]

A recent review emphasized that reducing the demand for antibiotics requires better sanitation, clean water, infection control, universal access to health care, and more careful use of antimicrobials in agriculture. [23]

Another recent study showed that resistant bacteria and resistance genes can circulate between humans, animals, and the environment. Antibiotic use in livestock and agriculture may therefore contribute to resistance that later affects human health. [24]

For Uzbekistan, the One Health approach may be especially useful because antibiotic control should include not only hospitals and pharmacies, but also veterinary medicine, agriculture, food production, and wastewater monitoring.

8. Development of new antibiotics

The development of new antibacterial drugs is slower than the development of resistance. According to WHO, 97 antibacterial products were in clinical development at the end of 2023. However, only 32 antibiotics were being developed specifically against WHO priority bacterial pathogens. Of these, only 12 met at least one important innovation criterion. [25]

This means that the number of truly new antibiotics is still limited. Many new drugs belong to existing antibiotic classes or act through mechanisms that may already be affected by resistance.

WHO therefore continues to emphasize the need for new drugs against critical priority pathogens, especially carbapenem-resistant Gram-negative bacteria. [25]

The 2025 WHO pipeline review also concluded that the present antibacterial development pipeline remains insufficient to fully address the growing problem of drug-resistant infections. [26]

9. Bacteriophage therapy

Bacteriophage therapy is one of the most discussed alternative approaches to antibiotic-resistant infections. Bacteriophages are viruses that infect and destroy specific bacteria.

Recent reviews show that phages may be useful against multidrug-resistant bacteria, especially when standard antibiotic treatment is no longer effective. They may also have an

advantage because they can act against a specific bacterial pathogen without causing major damage to the normal bacterial flora. [27]

Another important direction is the combined use of bacteriophages and antibiotics. Some studies suggest that phages and antibiotics can work together and may improve bacterial killing in difficult Gram-negative infections. [28]

However, phage therapy is not yet a routine treatment method. Important limitations include narrow bacterial specificity, difficulty in selecting the correct phage, development of phage resistance, and the lack of standardized clinical protocols. [27,29]

Systematic reviews published in recent years show promising safety and effectiveness, but larger and better controlled clinical studies are still required before phage therapy can be widely recommended. [29]

10. Future directions

The results of this review show that antibiotic resistance cannot be controlled by one method alone. Several approaches must be used together.

The first step is to reduce unnecessary antibiotic use. The second is to improve laboratory diagnosis and antimicrobial susceptibility testing. The third is to strengthen infection prevention in hospitals. Public education is also important because self-medication and inappropriate antibiotic use can contribute to resistance.

National surveillance must be continued and expanded. Resistance patterns should be monitored regularly because they can change over time. These data should then be used to update clinical treatment guidelines.

For Uzbekistan, the development of the National AMR Center and participation in international surveillance systems provide a useful basis for further improvement. However, surveillance should be expanded to more hospitals and regions, and results should be regularly shared with clinicians. [21]

The future control of antibiotic resistance will also depend on research into new antibiotics, bacteriophages, rapid diagnostics, vaccines, antimicrobial peptides, and other alternative treatment methods. At the same time, the effectiveness of existing antibiotics must be protected through careful and rational use.

Overall, the evidence shows that antibiotic resistance is not only a microbiological problem. It is a clinical, public health, economic, agricultural, and environmental issue. A coordinated approach involving physicians, microbiologists, pharmacists, veterinarians, public health specialists, researchers, and the general population is therefore necessary to reduce its future impact. [23–29]

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