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ANTIBIOTIC RESISTANCE STRATEGIES FOR CONTAINMENT: MECHANISMS, DRIVERS AND ITS GLOBAL IMPACT

MAJED SALEH M ALJOHANI[1*], YASIR ABDULLAH M ALHARBI[1], NAIF SULAIMAN H ASR[1], AHMED ALI H ARABI[1], ABDALRHMAN SAAD N ALRHELY[1], AHMED ABDULLAH SHUOKR[1], WALEED MOHAMMED ALQAYIDI[1], NAIF HAMEED ALSAEDI[1], GHANEM ALI L ALMUTAIRI[2], WAHEEB MOHAMMED A AZONI[2]

[1]PHARMACY TECHNICIAN, ISLAMIC UNIVERSITY OF MADINAH, MADINAH, SAUDI ARABIA
[2]PHARMACIST, ISLAMIC UNIVERSITY OF MADINAH, MADINAH, SAUDI ARABIA

Abstract
The problem of antibiotic resistance is an acute challenge of modern medicine and population health. As a result, microorganisms are getting a mechanism that makes them able to overcome the effect of antibiotics thus compromising effective therapy, raise morbidity and mortality and also raise healthcare costs. The needless and inappropriate use and abuse of antibiotics in both human medicine and animal farming, as well as in aquaculture, has accelerated the outbreak and spread of resistant pathogens. All these include enzymatic inactivation, changes of the target-site, efflux pump function, and low membrane permeability, which contribute to the survival of bacteria in the antibiotic pressure. These determinants of resistance are often horizontally devolved, and this makes multidrug resistance a global issue. In addition, poor infection control measures in the healthcare facilities, as well as the pollution of the environment, contribute to the existence and the dissemination of resistant bacteria. The financial consequences of antibiotics resistance are also very drastic especially in the low- and income based economies where access to regulated healthcare services and diagnostic centers increase the load. Therefore, to overcome ABR, a complex multidimensional approach should be introduced, encompassing rigorous antibiotics management procedures, fast advancement of diagnostic tools, innovation of novel antimicrobial agents, pursuit of alternative therapeutic modalities (e.g., phage and peptide-based therapy), and tightening of One Health paradigm. Long-term public education, legislative changes, and cooperation at the global level are the only things without which the current trend will not be reversed, or the existing antibiotics will remain usable.

Keywords: Antibiotic resistance, antimicrobial resistance, multidrug resistance, bacterial infections, efflux pumps.

INTRODUCTION

The biggest modern medicine challenge is the antibiotic resistance. It occurs when microorganisms-bacteria, virus, fungi, and parasites acquire mechanisms that make antibiotics ineffective, and therefore, bear out bilateral implications on the outcomes of treatment on a wide range of infectious diseases and elevate the chances of longer sickness, higher mortality, and higher health costs. The spreading rate of the resistance inherently correlates with selective pressure of the pervasive and frequently irrational antibiotic utilization in humans and pets (Andreescu, 2023). Successive and excessive exposure to antibiotics would eliminate such vulnerable microbial strains, and benefit the proliferation of the resistant strains which would contain the genetic mutation or obtain the resistance genes by horizontal gene transfer. Such robust communities grow and eventually conquer microbial groups (Chavada et al., 2023; Nwobodo et al., 2022).
Anthropogenic evolution of antibiotic-resistant pathogens had hollowed out the pharmacological arsenal of infection control, and even assuming that the rates of antibiotic resistance will not accelerate in the future, there is the probability that, unless the situation with antibiotic resistance is addressed, the global population will face a scenario in which treatable commons infections may become untreatable (Vivas et al., 2019). In some places, the number of antibiotics sold to the community is more than in hospitals, indicating the role of human factors in the development of resistance, in particular, that of irrational and overuse of antibiotics (Sannathimmappa, 2025). The late detection of the etiological microorganisms and the sensitivity data in the health care settings promote the inappropriate use of broad-spectrum drugs and, in this way, again contribute to the resistance issue (Khalid et

al., 2023). Antibiotic resistance has implications to animal health, agriculture, and the environment, in addition to human health, which illustrates that there is a need of multidiscipline approach to combat this resistance.

Interrelated determinants belonging to humans, animals, and the environment influence antibiotic resistance, which has a multifactorial character (Wang et al., 2017). Ineffective use in clinical uses, especially over-prescriptions of antibiotics to viral illnesses, poor patient compliance with a course of treatment and general availability of antibiotics without requiring a prescription are important risk factors to the emergence and/or spread of resistance. Correspondingly, when antibiotics are used as growth promoters and as growth promoters in concentrated animal feeding operations, additional selective pressure is created through habitual use in animal husbandry. This veritable melange of activities in human gut, an environment that has nutrient abundance and a diversified microbiome, enables the outbreak of resistance genes and antibiotic resistant bacteria which present significant risk to human health (Karnwal et al., 2025).

It is the combination of these human and veterinary activities along with the movement of resistant bacteria and resistance genes through a variety of ecological niches that has driven antibiotic resistance to the center of world health issues. The ease at which bacteria can obtain and share resistance through horizontal gene transfer three conjugation, transduction and transformation increases the rapidity and the spread of resistance acquisition. Moreover, the environmental aspect has become even more noticeable, and it is observed that the release of antibiotics and resistant living beings by wastewater treatment, agricultural runoff, and industrial discharge develops the selective pressures that promote the prevalence of resistance genes in environmental bacteria (Wunderlich et al., 2017). This reservoir of environmental resistance may easily be transferred to the human pathogens (Miller et al., 2016).

Mechanisms of Antibiotic Resistance

Antibiotic resistance has already become the x-factor that cannot be ignored because of the complex processes of interaction between bacteria and the action of antimicrobial agents (Devi et al., 2024). The resistance mechanisms caused by the antibiotics may be roughly divided into a few major approaches: inactivation of antibiotics by enzymes, modifications of the antibiotic binding site, decreased uptake, and efflux pump activation. Enzymatic inactivation incorporates the manufacture of bacterial enzymes that change or deactivate the antibiotic particle at the chemical level, bringing it to idleness (El-Saadony et al., 2025).

Target site modification involves changes in the structures or proteins of bacteria, which antibiotics target; thus, the binding efficiency of the drug cannot be high and, therefore, exerts its inhibitory effect (Blom, 2015). Less accumulation may be achieved B blockage of antibiotic antibiotics into the bacterial cell or C enhanced elimination of the antibiotic out of the cell. To cope with the pressure of antibiotics, bacteria have developed lots of adaptive methods (M et al., 2018). Resistance determinants are often carried on mobile genetic elements including plasmids, transposons and integrons that enhance their horizontal transfer amongst bacteria allowing a rapid spread of resistance genes through a heterogeneous bacterial population (Dermott et al., 2003). The active resistance of drug resistance is attained through efflux of the antibiotic, alteration of the focus of the antibiotic as well as production of the modifying enzymes which specifically hits and kills antibiotics (Wright, 2005).

The long-term implications of gaining insights into molecular mechanisms of antibiotic resistance are the design of new fronts to fight resistant infections and the maintenance of antimicrobial drug effects (Ahmed et al., 2024).

Genetic Mechanisms

The antibiotic resistance is a multifactorial issue that appears due to the different genetic mechanisms, one of them being chromosomal mutation and horizontal gene transfer. The fast spread of the resistant determinants in a group of bacteria takes place by horizontal gene transfer. The genetic contents like bacteriophages, integrons, transposons, plasmids, etc. that can occur simultaneously, due to their inherent mobility, confer simultaneous resistance to several classes of antibiotics (McCallum et al., 2009).

The resistance genes or the genes that specify the antibiotics targets directly are mutated resulting into chromosomal alterations. A mutation in encoded ribosomal RNA and other protein-coding genes can also alter drug binding (Parmanik et al., 2022).

Enzymatic inactivation is another resistant strain of bacteria. Examples of enzymes that cleave the beta-lactam ring of penicillins or cephalosporins are the enzymes Beta-lactamases, and examples of enzymes that alter the structure of the antibiotics, disallowing attachment to the ribosome are the aminoglycoside-modifying enzymes composed of aminoglycoside acetyltransferases, aminoglycoside phosphotransferases, and aminoglycoside adenylyltransferases. Chloramphenicol acetyltransferases are enzymes that attach an acetyl group to chloramphenicol and in the process, make drug unusable to block protein synthesis (Ashraf et al., 2023).

The other method of resistance is reduced intracellular accumulation of antimicrobials. The reduction of membrane permeability by mutations or sometimes the deletion (or mutation) of porin proteins can also limit antibiotic uptake, whereas in other cases, antibiotics can be actively pumped out of the cell through efflux pumps, to prevent intracellular levels of the antibiotic rising above the sub-inhibitory threshold. Such mechanisms sometimes turn out to synergize in a way that drastically decreases the active concentration of drugs in the bacteria cell (Golkar et al., 2018; McPhee et al., 2009).

Table 1: Major Mechanisms of Antibiotic Resistance in Bacteria

Mechanism	Description	Examples	References
Enzymatic Inactivation	Bacteria produce enzymes that degrade or modify antibiotics.	β-lactamases hydrolyze β-lactam rings; aminoglycoside-modifying enzymes add acetyl, phosphate, or adenyl groups.	El-Saadony et al., 2025; Ashraf et al., 2023; Yarahmadi et al., 2025
Target Site Modification	Alteration in antibiotic binding sites reduces efficacy.	rRNA methylation (macrolide resistance); DNA gyrase mutations (quinolone resistance).	Blom, 2015; Parmanik et al., 2022; Kapoor et al., 2017
Efflux Pumps	Transport proteins eject antibiotics from bacterial cells.	MexAB-OprM (Pseudomonas); NorA (Staphylococcus aureus).	Wright, 2005; Costa et al., 2013; Golkar et al., 2018
Reduced Permeability	Mutation or loss of porins reduces drug entry.	OmpF/OmpC mutations in Enterobacteriaceae.	McPhee et al., 2009; M et al., 2018
Biofilm Formation	Bacteria form protective layers that resist antibiotic penetration.	*P. aeruginosa* in cystic fibrosis lung infections.	Urban-Chmiel et al., 2022

Sources and Drivers of Antibiotic Resistance

The development of antibiotic resistance is a complex event that can be determined by a variety of factors that do not exist in isolation, including the use of antibiotics, horizontal gene spread, and selective pressure. Overuse of antibiotics in medical and agricultural practice has developed an atmosphere that favors proliferation of resistant bacterial strains. The horizontal gene transfer is the means through which bacteria populations acquire resistance characteristics; plasmids, transposons and bacteriophages are mobile vectors due to which genetic content exchanges between the bacterial lineages occurs (Zhai et al., 2023). The main mechanism through which resistance-conferring genes spread among the population of bacteria is via the plasmid-mediated transfer (Landers et al., 2012). All such transferable components tend to contain resistance genes thus enabling development and spread of multidrug resistance.

Inefficient use and misuse of antibiotics are some of the leading antibiotic resistance factors in human medicine. Prescribing habits which are inappropriate (like prescribing an agent against viral pathogen or choosing broad spectrum agents when narrow spectrum drug would have been adequate) create selective pressures that promote the evolution of resistance (Begum et al., 2021). The demand of antibiotics by the patient, despite their unnecessary medical usage, and their failure to serve as effective treatment of viral infections also contribute to the selective pressure. Besides, poor infection-control measures, such as poor hand hygiene and poor isolation of patients with resistant infections, support infection with resistant microorganisms in healthcare facilities (Yao et al., 2025).

Rash antibiotic use, accompanied by its overuse and misuse, is the key driver of the growing antimicrobial-resistance epidemic (Ramachandran et al., 2019). Misuse goes as far as self-medication whereby the patients acquire and use antibiotics without any professional monitoring and advice. Such practices are characteristically combined with a delay in the dose, termination of the treatment early, and inadequate treatment duration, putting bacteria in the environment of sub-therapeutic concentrations of antibiotics that can favor survival and proliferation of resistant ones (Jadimurthy et al., 2022; Simeis & Serra, 2021).

Common use of antibiotics in animal farming and fish farming also plays a significant role in resistance emergence and transmission (Abebe & Alemayehu, 2023; Reverter et al., 2014). Even without clinical signs of infection, antibiotics are routinely added to animals feeding to foster growth and prevent disease (Rossi et al., 2020). The practice also implements resistant microorganisms in the GI tracts of animals, which enables the food chain and direct contact to humans (Verraes et al., 2013). The overuse associated with its deployment in the field of agriculture (especially when used in prophylactic settings) contributes to the issue significantly (Nair et al., 2018). It is worth noting that the clinical resistance is now increased, and environmental reservoir of resistance genes gets further fueled by the Taking the case of antibiotics, their non medical use in agriculture increases both cases not only in the clinical side of things, but also though the byproducts that leaks into the environment (Pawlowski et al., 2017).

The presence of antibiotics toxic to the environment due to human or animal activity places a selective force that in turn encourages the occurrence of resistance genes and their dissemination (Yu & Zhao, 2019). The spread of resistance genes in aquaculture conditions where the agents are used in therapeutic and preventive strategies promotes the manifestation of resistant diseases in the aquatic globe (Valladão et al., 2015). The presence of antibacterial resistants in animal products poses one more threat to human health (Silbergeld et al., 2008).

Antibiotic resistance dissemination is also affected by environmental factors. Even without having direct contact with antibiotics, the gene of resistance may remain in the water and soil (Economou & Gousia, 2015). Aquatic systems are polluted by industrial, domestic, and agricultural wastewater and thus increases the environmental resistome (McEwen & Collignon, 2018). There is a possibility that wastewater treatment plant offices do not effectively filter antibiotics along with antibiotic resistant organisms which is released into the environment. These resistant pathogens are then carried by wind, water and soil vectors to people (Abebe & Alemayehu, 2023).

Continuous antibiotic residues in the environment, even those in low concentration easily offer new sources of antibiotic selection pressure which maintains stability of resistance. In aquaculture about 80 % of antimicrobials applied to aquaculture stay in the environment and have significant activity, expanding the ecological niche of the resistant microorganisms (Rossi et al., 2020). Global movements as well as trade have further enhanced spread of antimicrobial resistance (Wang et al., 2017).

Poor infection control in hospitals drives nosocomial resistance

Hospitals comprise one of the major sources of antibiotic-resistant bacteria, due to concentrations patients, widespread use of antibiotics, and many possibilities of induction of cross-transmission. The problem of nosocomial infections (nosocomial infection is the infection acquired in hospital) due to the resistance organisms is a major threat to patient safety. In hospital settings, direct contact between care providers, patients, contaminated surfaces, and air transportation of pathogen infected particles are the most popular ways of spreading antimicrobial-resistant pathogens. Substandard practices of infection control such as ineffective hand hygiene, inappropriate application of personal protection items, and the inability to isolate patients with resistant infections assist in the transmission of these microorganisms as well. Overcrowding along with the poor maintenance of basic hygiene standards and inadequate infection control measures then compound the situation of antibiotic-resistant bacteria spread (Nasher et al., 2018, Zaib et al., 2019).

Epidemiology and Global Burden

Antibiotic resistance epidemiology is very complex, pathogen-specific and depends on geographical location and the type of antibiotic of interest. Antibiotic resistance is a global affair since it flows in borders of nations as antibiotic-resistant species of bacteria move swiftly across Europe, Asia, and America (Li et al., 2015). Antibiotic resistance is usually highest in low- and middle-income states due to weak legislation on antibiotic consumption and improper policies on infection control regularly performed (Afari-Asiedu et al., 2020).

In such settings, inappropriate antibiotics use is further complicated by the high prevalence of fake and inferior products, procedures that enhance a rapid evolution of resistance determinants, as well as their spread (Hoellein et al., 2022). Its economic costs are enormous as it increases healthcare costs, prolonged length of stay in the hospital, morbidity and mortality rates (Pulingam et al., 2021). Treatment with ineffective antimicrobial agents may also increase, morbidity, and mortality rates caused by infections, requiring protracted periods of hospitalization and leading to enhanced prices (Ahmed et al., 2021).

Clinically, resistance makes the treatment of infectious diseases more complicated and expensive; more toxic and more costly antibiotics may be needed, but their effectiveness at the same time may decrease. This has led to the realization of the necessity to initiate concerted, worldwide action, which should deal with the complexities of the factors of resistance and reduce the effects of the resistance (public-health and economic) (Marinho et al., 2016). Otherwise, the ongoing growth process of antimicrobial resistance will continue to undermine the positive trends in medicine, making common infections incurable and causing chronic global health to turn back (Munita & Arias, 2016).

Global increase in antibiotics resistance is a daunting challenge to the prevention and management of infectious diseases. The emergence of resistance pathogens is linked to the use of antibiotics across the world, infection-control process, and non-local travel (Posada-Perlaza et al., 2019). Unless specific prevention measures are introduced, the issue of antibiotic resistance is ready to spike the morbidity, mortality, and healthcare expenditures as never before (Hoellein et al., 2022). In its turn, improper use of antibiotics in the global context has led to the spread of antibiotic-resistant microorganisms, which is an increasingly threatening issue to the human population and modern medical practice (Wang et al., 2020).

This complex of phenomena has promoted the existence of a significant increase in the prevalence of antibiotic-resistant infections worldwide (Oliveira et al., 2024). Antimicrobial resistance has become one of the key issues faced on a global level, jeopardizing the practicality of antibiotics and other antimicrobial disorders, which are also essential to the treatment of infectious diseases (Aslam et al., 2021).

Table 2: Sources and Drivers of Antibiotic Resistance

Source	Driver	Implications	References
Human Medicine	Overprescription, self-medication, poor compliance	Selection of resistant strains in the community and hospitals	Ramachandran et al., 2019; Jadimurthy et al., 2022

Agriculture	Use of antibiotics for growth promotion and prophylaxis	Transfer of resistance genes to humans through food or environment	Verraes et al., 2013; Nair et al., 2018; Rossi et al., 2020
Environmental	Wastewater discharge, industrial pollution	Spread of ARGs in water and soil ecosystems	Kotwani et al., 2021; Wunderlich et al., 2017
Hospitals	Nosocomial transmission due to poor infection control	Outbreaks of multi-drug resistant organisms (MDROs)	Nasher et al., 2018; Zaib et al., 2019
Global Travel & Trade	International dissemination of resistant strains	Globalization of resistance, harder containment	Wang et al., 2017; Posada-Perlaza et al., 2019

Some species of bacteria like methicillin-resistant *Staphylococcus aureus*, vancomycin-resistant *Enterococcus*, and carbapenem-resistant Enterobacteriaceae are considered particularly notorious owing to the elevated levels of resistance, and their ability to cause severe infections. The swift spread of the carbapenem-resistant Enterobacteriaceae across the world is also an acute issue with carbapenems often used as a measure of last resort against multidrug-resistant infectious agents. Infections by these very resistant organisms are refractory to commonly available therapeutic modalities often resulting in compromised morbidity, mortality and heightened healthcare expenditure (Lee et al., 2013). Taken together, these organisms, also known as the ESKAPE pathogens (including *Enterococcus faecium, Staphylococcus aureus, Klebsiella pneumoniae, Acinetobacter baumannii, Pseudomonas aeruginosa* and *Enterobacter* species) exhibit an amazing ability to share and transfer resistance determinants and high-risk clones around the globe (Miller & Arias, 2024).

MDRO Gram-negative bacteria also complicate circular infection, such as pneumonia and urinary tract infection (Dadgostar, 2019). The increased instances of multidrug-resistant strains have burdened the health care system and reduced the effectiveness of the antimicrobial treatment. In that respect, the proliferation of multidrug-resistant so-called ESKAPE organisms stands out as one of the most challenging aspects of the current infection disease management (Gill et al., 2014). The growth of the issues related to antimicrobial resistance coupled with the shrinking antimicrobial pipeline will pose a looming crisis to the health of the masses (Miller & Arias, 2024).

Mitigation Strategies

The multi-faceted approach involving preventive activities aimed at reducing antibiotic usage, strengthening infection control, and developing a new toolset of new antibacterial drugs is required to overcome antibiotic resistance (Lee et al., 2013). Based on this kind of strategy, the identification of novel antimicrobials (in the form of drugs, vaccines, and alternative treatments) is essential in combatting resistant pathogens. Similar steps toward improved infection prevention and control in the health care facilities are needed to slow down the spread of the multidrug-resistant bacteria (Wang et al., 2020). Also, research now gives priority to alternatives to the traditional antibiotics: bacteriophage therapy and immunotherapy. Clinical practice antibiotic stewardship is a critical element in the quest to ensure that there is wise use of antibiotics. The access of speedy diagnostic tests which can identify resistant microbes and help deliver effective antimicrobial treatment is also essential to ensure the best patient outcomes (Zhou et al., 2023).

The adverse effects of antibiotic resistance have gone beyond the personal clinical outcomes to have significant influence on the cost of healthcare and their utilization. In the economic sense, the issue involves high expenditures of medicine, lack of productivity and hindrances of national growth. The problem of modern times lies in the fact that the converging trends of antimicrobial resistance and the ongoing reduction of the size of the antimicrobial development pipeline present an increasing risk to the health of the population. Increased costs of resistant-infection management have a great burden on the healthcare systems rendering them unable to allocate resources to other three essential services. Consequences of antibiotic resistance to the economy are, thus, far-reaching in terms of the consequences to the provision of health care, national economies, as well as other modes of international stability. In particular, in the United States, more than 2.8 million infections and 35,000 deaths are annually due to multidrug-resistant bacteria, and an estimated 55 billion dollars are added to healthcare costs and productivity; this is alongside more than 50 million infections and 10,000 deaths due to multidrug-resistant fungi (Mercer et al., 2020).

Diagnostic Challenges

The insufficient fast and precise diagnostic tests are a serious hindrance to the successful control of the antibiotic resistance, in that, it is not always possible to tell when the correct antimicrobial therapy should be implemented. The use of broad-spectrum antibiotics by clinicians in absence of rapid diagnostics contributes to further resistance (Elbehiry et al., 2022). It is necessary to develop and introduce new diagnostics that will provide opportunities to identify resistant bacteria and select appropriate antibiotic therapy as soon as possible to optimize patient outcomes. Besides, lack of point-of-care diagnostics in resource-limited settings further complicates the issue related to antibiotics resistance, as they slow down the progress of the cure and promote the expansion of resistant organisms. The practical use of advanced technology in molecular diagnostics could offer clinicians actionable data to facilitate the use of targeted antimicrobial therapy with better clinical outcomes and reduced healthcare costs. In the absence of proper and effective diagnostics, the choice of relevant antibiotics is frequently made late, which leads to the high morbidity rates, mortality, and expenditure of health care funds. Lack of fast and precise diagnostic tools is an essential complication in the competent control over antibiotic resistance so that the necessary path is holding up the introduction of suitable antimicrobial medicine. In the research I used, the authors described the effects of physical activity on male fertility and mentioned it is possible to increase sperm count through exercise (Eubank et al., 2020).

Existing procedures used to diagnose antibiotic resistance are frequently limited by slow speed, accuracy and availabilities, which are barriers to effective decision making. The results of antibiotic susceptibility testing are performed using methods based on traditional cultures and need several days before the initiation of adequate therapy can proceed (Zhang et al., 2020). Besides, most of the diagnostic tests in use today are too insensitive to pick low level of resistance, or recognize emerging resistance mechanisms. Inappropriate use of antibiotics that may occur due to the delays connected with using the traditional methods of culture may favor further development and transmission of resistance (Eubank et al., 2020). The existing approaches are not perfect (Dietvorst et al., 2020).

Recent innovations in rapid diagnostics (e.g., PCR, CRISPR-based tools)

The effectiveness of recent innovations in the field of rapid diagnostics is linked to the fact that in less than ten years, they have transformed the management and rapid detection of antibiotic resistance, offering clinicians real-life information that prompts action (Endimiani et al., 2020). The techniques present a promise to identify resistance genes with direct clinical samples so as to identify resisting bacteria quickly. The development of nucleic acids amplification tests, microfluidics, and biosensors is transforming the process of antibiotic resistance detection and control by supplying the clinician with results that can be acted upon within a reasonable timeframe (Shin et al., 2019). Direct detection of resistance genes via rapidly developed tests PCR-based tests and microarray technologies are rapid (can yield results in a couple of hours), allowing the explicit detection of resistance genes in clinical samples (Trotter et al., 2019).

Matrix-assisted laser desorption/ionization, time-of-flight mass spectrometry has become an effective method of addressing the need to quickly identify bacteria and determine their resistance to antibiotics (Roca et al., 2015). Microfluidic platforms can provide a high-throughput and high-profile antibiotic sensitivity at a single-cell resolution (Avesar et al., 2017; Zhang et al., 2020). These approaches provide the possibility of detection of resistance genes directly in clinical samples, which allows identifying resistance bacteria very quickly (Salam et al., 2023). Microfluidic-nanotechnological integration has allowed creating sensitive and specific biosensing systems to detect antibiotic resistance (Avesar et al., 2017; Zhang et al., 2020).

Strategies to Combat Antibiotic Resistance

The war against antibiotic resistance must be based on a multidimensional approach that would include strategies that will minimize the usage of antibiotics, create new antibiotics, and reduce the prevalence of infections through infection control strategies. Antibiotics should be used wisely to ensure that there is less selective pressure to result in emergence of and transmission by resistant strains (Tenover, 2006). As a way of curbing transmission of resistant bacteria, it will be essential to improve hygienic measures and sanitation within healthcare environments and communities. Continued investigation into the process of antibiotic resistance and the creation of novel therapeutic compounds is of great importance in ensuring that one can outsmart the constantly mutating problem of antibiotic resistance. It is a top priority developing new antimicrobial compounds that cannot be subjected to the current methods of resistance (Elshobary et al., 2025).

Stewardship and Rational Use

Antibiotic stewardship programs should be implemented in healthcare facilities in order to encourage the rational use of this type of medication and decrease inappropriate prescription of the drugs (Avesar et al., 2017). Through such programs, it may become possible to ensure that antibiotics are used only when essential, in the right amount and within the right duration. It is also essential to promote antibiotic stewardship in agriculture and aquaculture since the problem of antibiotics abuse poses a substantial risk to the emergence and transmission of resistance (Raman, 2017). Moreover, through campaigns, people can be made to understand the topic on being responsible with the use of antibiotics and not attempting self medication. Antibiotic adjuvants are an alternative and complementary measure to the emergence of new antibiotics and optimization of the existing ones (Zhou et al., 2023).

Infection Prevention and Control

The use of strong infection prevention and control interventions within the healthcare facilities are essential in restricting the spread of the resistant organisms and the occurrence of healthcare-acquired infections. Such interventions are hand hygiene, cleaning of the environment and isolation of those patients who have resistant infection (Uchil et al., 2014). Prevention of transmission of resistant bacteria also requires sanitation and hygiene practices to be improved safely in communities by making them find access to clean water, and effective waste disposal solutions (Collignon & McEwen, 2019).

New Antibiotics Development

Over the past few decades, the pace of development of the new medications against antibiotics has decreased because of a range of economic, regulatory, and scientific factors. These issues and motivation to produce new types of antibiotics are essential to maintain an efficient way of treatment of resistant infections (Ahmed et al., 2024; Gupta & Sharma, 2022).

But discovery of new targets of antibacterial agents and the new generation of antibiotics are necessary to overcome the resistance mechanisms and provide effective antinociceptive forms of resistant infection. Public interest is on investigating the new directions of therapy, i.e., phage therapy and antimicrobial peptides to address the problem of antibiotic-resistance infections (Citarasu, 2009; Zia & Alkheraije, 2023). Phage therapy The idea of using viruses to attack and kill bacteria and discovering a replacement to antibiotics is based on phage therapy. Advances in Antibiotics have been one of the major challenges of the fish farmer in the aquaculture business; this is because of the overuse and the emergence of drug-resistant bacterial pathogens (Raman, 2017).

Discovery of new antimicrobial agents capable of breaking the current resistance is also important to fight the rising problem of antibiotic resistance (Khan et al., 2024). Some of the alternative approaches to traditional antibiotics, which become of interest, are such as phage therapy, antimicrobial peptides or CRISPR-based antimicrobials (Alam et al., 2019). Bacteriophages (phages), viruses that kill and destroy bacteria, have proved as a good specific remedy against bacterial infections, especially in cases where the bacterial infection is by multidrug-resistant organisms. The other prospect of discovering innovative remedies is the use of antimicrobial peptides, short sequences of the amino acids that show broad-spectrum antimicrobial activity (Theuretzbacher & Piddock, 2019).

Alternative Strategies

The necessity to find other methods of combating bacterial diseases when the antibiotic resistance occurs caused an idea to develop alternative techniques (Khalid et al., 2023). Among them are phage therapy (killing an organism through viruses), antimicrobial peptides, which interfere with the bacterial membranes, and CRISPR-Cas which allows specific targeting and destruction of a resistance gene (Murugaiyan et al., 2022). Due to the emergence of antibiotic resistance, alternative strategies have gained popularity in fighting bacterial infections such as antivirulence therapy and phage therapy (Hauser et al., 2016). A wide variety of non-antibiotic therapy is in development to switch to a post-antibiotic condition (Wang et al., 2020).

Bacteriophages are viruses which attack and destroy the bacteria and thus are used as phage therapy in treating bacterial infection. Broad-spectrum antimicrobial activity is related to the use of antimicrobial peptides as a type of molecule that has the ability to dis alter bacterial membranes and impair bacterial growth (Hassan et al., 2022). The intake of probiotics, i.e. microorganisms live and beneficial to the host, may rectify the microbiota balance in the gastrointestinal tract and improve the immune reaction of the host against bacterial infections (Valenzuela-Gutierrrez et al., 2021).

Vaccines

Immunization may also be essential to decrease dependency on antibiotics by creating prevention of the initial infection with bacteria. The action of vaccines is the activation of the immune system in a host that creates antibodies which are able to neutralize or destroy the bacteria within the host so preventing infection or minimizing its effects. The use of vaccines has also become one of the central coping mechanisms of the problem of antibiotic dependence since preventing bacterial illnesses strives to reduce them to a bare minimum (Rabetafika et al., 2023). Commercial vaccines, however, may be prohibitively costly, and they are not easily adopted by fish producers, additionally, their application may only be effective against particular types of paths (Reverter et al., 2014).

Antibiotic resistance can be killed with CRISPR-Cas systems, namely a line of defense used by bacteria and can be exploited to provide specific editing of genes (Malone et al., 2020). The novel methods that can be used to employ nanotechnology to kill disease-causing organisms are new ways to deliver antimicrobial agent in the cells of bacteria, evade resistance procedures, and get improvement in effectiveness of treatment. Another scientific solution to the problem of resistance lies in combination therapy, which implies the application of two or more antimicrobial substances, the mechanisms of action of which are different, to combating infections (Murugaiyan et al., 2022).

Also, silver nanoparticles have shown an antimicrobial effect and the ability to increase the effectiveness of aminoglycosides in treating antibiotic-resistant bacteria (Dove et al., 2023).

Global Policies and One Health Approach

One of the health strategies aims at solving the problem of antibiotic resistance in a complex approach that considers the unity of the health of people, animals, and the environment (Ajayi et al., 2024).

One Health concept takes into consideration the mutual linkages of the health of humanity, animals, and the environment and possible cross transmission of antibiotic resistance amongst these realms (Urban-Chmiel et al., 2022). Responsible use of antibiotics, as well as education of the population about the danger of antibiotic resistance, can be popularized with the help of public awareness and educational campaigns (Tang et al., 2023). Ensuring the rational use of antibiotics in animal farming, such as a decrease in the prophylactic application of antibiotics to animals, is also important in avoiding the development and transmission of resistance (Tang et al., 2023).

Table 3: Strategies to Combat Antibiotic Resistance

Strategy	Action	Expected Benefit	References
Antibiotic Stewardship	Rational prescribing, dosage control, public awareness	Reduces misuse and preserves drug efficacy	Avesar et al., 2017; Zhou et al., 2023
Surveillance & Diagnostics	Monitoring resistance patterns and rapid detection	Enables targeted therapy and containment	Eubank et al., 2020; Shin et al., 2019
Development of New Antibiotics	Incentivize R&D, explore novel targets	Overcome current resistance mechanisms	Ahmed et al., 2024; Khan et al., 2024
Alternative Therapies	Phage therapy, antimicrobial peptides, probiotics	Bypass traditional resistance pathways	Hauser et al., 2016; Hassan et al., 2022
One Health Approach	Integrate human, animal, and environmental health interventions	Holistic control of AMR emergence and spread	Ajayi et al., 2024; Urban-Chmiel et al., 2022

The WHO has already elaborated a Global Action Plan on Antimicrobial Resistance, defining the measures to address the resistance, i.e. enhance surveillance, encourage the appropriate use of antibiotics, and increase research and antimicrobial development (Wierup et al., 2021). There are a number of international projects like the Global Antimicrobial Resistance Surveillance System, which were developed to monitor diffusion of resistance and guide the public health interventions.

The global action plan reflects the necessity to reduce the development and transmission of antimicrobial resistance, and it is stated that special attention should be brought to interventions that include better sanitation, hygiene, as well as waste management practices (Tang et al., 2023). The utilization of the robust surveillance programs is necessary to follow the patterns of antibiotic utilization and resistance among the human and animal population which could inform the population health interventions (Oliveira et al., 2024).

Cross-national collaboration and exchange of data is important in monitoring the movement of the resistance and organizing international response to this challenge (Shinn & Bron, 2012). The identification of new diagnostic tools that allow to quickly detect resistant bacteria and make decisions about the treatment of patients is important to enhance patient outcomes and prevent the further diffusion of resistance. Better diagnostics is essential to diagnosing resistant bacteria and maximising treatment (Marinho et al., 2016). Closely related to this is the urgent need to maintain investments in research and development of new antimicrobial agents as well as alternative therapy in order to combat the menace of antibiotic resistance. Legislative measures such as EU Regulation 2019/6 have been taken to limit or prevent the use of antibiotics, even as a feed additive to livestock but also to treat and or prevent bacterial infections such as antibacterial in metaphylaxis (Urban-Chmiel et al., 2022).

To promote the education of health professionals, animal keepers, and the population, it is necessary to reinforce the dissemination of information in the South countries as well (Ayukekbong et al., 2017).

Problems and Prospects

The emergence of antibiotic resistance is a global problem that has to be controlled by international collaborations as well as major investments in research, monitoring, and public health policy. To have a sustainable pipeline of effective drugs through new antimicrobial agents, it is vital to consider regulatory barriers and incentive them to pursue the development (Sifri et al., 2019). Antimicrobial resistance has become a serious risk of harming the whole world, with possible consequences of spreading the diseases, causing serious infections, and vice-versa, leading to low mortality rates (Miteu et al., 2023). Multifaceted approaches that encompass the policy makers, public health departments, regulatory bodies, pharmaceutical firms and the scientific community are needed to successfully deal with antimicrobial resistance (Roca et al., 2015). Some of the factors that contribute to antibiotic resistance include mismatched use of antibiotics in healthcare, veterinary, and agricultural activities alongside the international travel and trade of antibiotic-resistant bacteria (Elshobary et al., 2025).

Integrated pest management procedures are important in reducing resistance build up rates and long term applicability of antiparasitic medications used in fisheries (Shinn & Bron, 2012). Effective and licensed treatments are in short supply and this has been one of the major constraints towards effective control of parasites in aquaculture (Shinn & Bron, 2012). Anti-parasitic drugs of different classes can be cycled within the farm cycle, which will allow avoiding the development of resistance and preserving the therapeutic effect (Shinn & Bron, 2012). It is imperative that new compounds or new formulations be identified to minimize or get rid of the use of broad-spectrum disinfectants that pose serious risks to the environment, like formaldehyde.

The effectiveness of treatments and the cases of resistance may be reduced with the usage of several antiparasitic compounds in a certain sequence (Shinn & Bron, 2012). Exhaustive risk assessment should also be done prior to carrying chemical treatments in order to determine how their use may be harmful to non-target organisms and the environment (Wunderlich et al., 2017). Recent studies have been revolved on new biocontrol interventions to control the use of antibiotics in the control of bacterial infections in aquaculture (Defoirdt et al., 2011). This entails an in-depth knowledge of parasite biology, interaction between the parasites and its host as well as environmental determinants that may affect the transmission and pathogenicity of the parasites (Shinn & Bron, 2012). The screening of the antiparasitic substances using plants also gain interest, which can substitute the usage of the harmful chemicals (Pandey, 2013).

CONCLUSION

Antibiotic resistance (ABR) is an intricate and quickly growing menace that hazards general wellbeing, food security, and growth in the world. It appears because of the use of antibiotics that is excessive and inappropriate in the field of human medicine, veterinary practice, agricultural and aquaculture sectors, and poor infection control procedures and environmental pollution. Mechanistically, complex strategies allowing bacteria to deal with and resist even the most active antibiotics have evolved such as enzymatic degradation, target site alterations, efflux pumps and horizontal genes transfer.

The consequences of unmitigated ABR are enormous, including the death of more patients and an extension of the length of their hospital stays to higher spending on healthcare and a faltering economy. It poses a risk to the effectiveness of big medical procedures such as surgery, chemotherapy, and transplantation of organs. Since the emergence of resistant infections, the pipeline of efficient antibiotics will keep declining because more people are worried that humanity will fall into the post-antibiotic era. In addition, the widespread education of the population, a more accurate approach to the use of antibiotics, collaboration across the borders are the keys to fighting resistant spread. Devoid of political will and inter disciplinary cooperation, the world will impose decades of medical gains. Emergent, scientific and fair measures are necessary to maintain effectiveness of the available treatment and achieve a healthy and more robust future.

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Author contributions

Original manuscript drafts are written by the first author and cross-ponding author supervisor. Each author helped write the manuscript, collected data, edited it, created tables, and got the go-ahead to submit it to a journal for publication.

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