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Global Antimicrobial Stewardship, Surveillance, and Infection Prevention and Control Programs: Leveraging One Health, Nanotechnology, and Artificial Intelligence to Combat Antimicrobial Resistance in a Climate-Impacted World

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Abstract

Introduction: Antimicrobial resistance (AMR) remains a critical global health issue contributing to increased morbidity and mortality. Antimicrobial stewardship (AMS), surveillance, and infection prevention and control (IPC) programs have been established and implemented to mitigate this crisis. Alongside this, advancements in nanotechnology and artificial intelligence (AI) or machine learning have enhanced academic tone and readability in combating AMR. This study employed a comprehensive narrative review approach to provide detailed evidence of AMS programs initiated to address AMR across One-Health sectors (human, animal, plant, and environmental health). **Methods:** A comprehensive narrative review was conducted to assess the global implementation of AMS, surveillance, and IPC programs, nanotechnology, and AI aimed at curtailing the rising prevalence of AMR. We also focused on the impacts of these AMS programs across diverse populations and settings. Relevant literature published between January 1995 and June 2025 was extracted from PubMed, Google Scholar, and Scopus databases. **Results:** The findings of this review demonstrate that AMS, surveillance, and IPC programs have been successfully established and implemented in some hospitals, community pharmacies, academic institutions, communities, and animal health. These programs have significantly promoted the rational use of antimicrobials in the One Health sector, prevented infections, reduced the emergence of antibiotic-resistant bacteria, improved adherence to treatment guidelines, awareness and knowledge of AMR, and patient outcomes. Advancements in technology, including nanotechnology and AI/machine learning, have shown promise in enhancing AMS and surveillance programs aimed at combating AMR. However, there is a dearth of empirical data on AMS activities within the environmental and animal health sectors, pointing out a critical gap in the One Health approach to AMR mitigation. **Conclusions:** This review underscores the importance of developing and implementing AMS, surveillance, and IPC programs as effective strategies to combat AMR using a One Health approach. Consequently, the study found very little information regarding AMS activities in the animal and environmental health sectors despite global problems as climate change. Notably, this study emphasizes the importance of embracing nanotechnology and AI within the healthcare system as innovative tools to combat AMR. It further highlights the need to promote integrated AMS, IPC, and surveillance programs across the One Health continuum, leveraging all available strategies to effectively combat AMR.

Keywords

Antimicrobial Resistance, Antimicrobial Stewardship, Artificial Intelligence, Climate Change, Global, Infection Prevention Programs, Integrated AMS Programs, Integrated Surveillance Programs, Machine Learning, Nanotechnology, One Health, One Health Framework

1. Introduction

The discovery of antibiotics was a great milestone in the field of medicine because it led to the successful prevention and treatment of infections thereby reducing morbidity and mortality [1]-[5]. However, the development of drug-resistant microorganisms negated this gain, thereby affecting the management of infectious diseases [6]-[11]. Antimicrobial resistance (AMR) was first reported in the 1940s [12] [13]. This phenomenon occurs when microorganisms evolve and no longer respond to antimicrobial agents that were previously effective, rendering standard treatments ineffective [14]-[17]. The resistant pathogens have been reported across human, animal, agricultural, and environmental sectors [18]-[21]. Bacteria gain resistance to antibiotics through acquired and intrinsic pathways [16] [17]. In 2019, it was estimated that AMR was associated with close to 5 million human deaths [22]. It is further estimated that if AMR is not controlled, it will lead to the death of 10 million people annually across the globe by 2050 [22]-[24] with other studies predicting more deaths [25] [26]. Alongside this, AMR negatively affects the global economy because it is expensive to treat drug-resistant infections [15] [27]-[29]. Moreover, antimicrobial-resistant pathogens can cause infections that may be difficult or impossible to treat [15] [30]-[32], which affects the aims of antimicrobial therapy [17] [33] [34].

Many drivers have contributed to the development of AMR, including human, animal, agricultural, aquatic, and environmental causes, as well as climate change [35]-[45]. The inappropriate use of antimicrobials is a key driver in the emergence and spread of AMR, contributing significantly to the development of resistant pathogens and undermining the effectiveness of existing treatments [36] [39] [46]-[55]. The misuse and overuse of antibiotics have been reported in both human and animal health sectors [6] [56]-[62]. The overuse of antimicrobials is very high in low- and middle-income countries (LMICs) [63]-[73]. In Africa, studies have shown that AMR is a growing public health threat that demands urgent, coordinated action from all stakeholders, including governments, healthcare providers, researchers, and the public [74] [75]. An estimated 23.5 human deaths per 100,000 were recorded in sub-Saharan Africa in 2019 [76]. The challenges of AMR in Africa are particularly severe, likely due to weak surveillance systems that limit the availability of reliable data needed to inform effective policies and targeted intervention strategies [76] [77]. The absence or weakness of surveillance systems to monitor AMR in food-producing animals in LMICs has significantly contributed to the unregulated and often excessive use of antimicrobials [78]. Further, AMR has been driven by many factors including inadequate awareness, knowledge, attitudes, perceptions, and practices regarding antimicrobial use (AMU) and AMR among healthcare workers, animal health practitioners, environmental health practitioners, students, farmers, and the general public [79]-[88].

Poor understanding of AMR and the inappropriate use of antimicrobials are prevalent across the human, animal, and environmental health sectors. For instance, Essack *et al.* (2017) reported significant knowledge gaps and the frequent misuse of antibiotics among healthcare and animal health practitioners in sub-Saharan Africa [89]. Similarly, Kimera *et al.* (2020) found that farmers and livestock handlers often used antimicrobials without veterinary oversight, thereby exacerbating the emergence of resistant microbial strains [77]. Furthermore, inadequate diagnostic capacity and limited laboratory infrastructure have contributed to the development and spread of AMR [90]-[97]. It is also crucial to consider the complex sociological dimensions, such as sociocultural, socioeconomic status, political, and economic factors that drive inappropriate antibiotic use and fuel the spread of AMR in different settings [37] [98]-[100]. Alongside this, social disparities, poverty, low health literacy, and the influence of unregulated drug markets significantly hinder efforts to promote responsible antibiotic use, underscoring the urgency of a multifaceted response [98]. As the burden of AMR increases, so does the prescribing pressure on healthcare providers and animal health experts, who are faced with limited or diminishing treatment options, often resulting in the use of broader-spectrum or last-resort antimicrobials [101]-[104]. A surge in the development and distribution of falsified and substandard antimicrobials has also contributed to the emergence and spread of AMR [43] [105]-[109]. It is crucial to understand the mechanisms and consequences of AMR, which include increased healthcare costs, prolonged illness, higher mortality rates, a greater burden on health systems [28] [110], a negative impact on the economy [76] [111] [112], and increased morbidity and mortality across populations [14] [22] [113]-[116]. Hence, there has been a call by the World Health Organization (WHO), Food and Agriculture Organisation (FAO) and World Organisation for Animal Health (WOAH) that AMR should be tackled using a One Health approach [14] [117] [118].

AMR has been reported to be a global public health problem that requires a holistic, multi-sectoral, and One Health collaborative approach to address it [6] [15] [22] [119]-[127]. Additionally, it is a threat to the world's sustainable development, which is driven by many factors [33] [36] [50] [128]-[131]. Therefore, a "One Health" approach is recommended in addressing AMR because it affects humans, animals, the environment, and ecosystems [74] [132]-[135]. The One Health approach to tackling AMR is effective as it tackles the problems in all areas where antimicrobials are used [135]-[141]. The WHO reported that AMU in food-producing animals could lead to antimicrobial-resistant microorganisms that can be transmitted to humans via food or other transmission routes [142] [143]. Hence, the WHO has restricted the use of antimicrobials for growth promotion and prevention of diseases in food-producing animals [142]. AMR has been reported to be a global public health challenge that requires a collaborative global response [22] [144] and a reduction in antimicrobial use via effective monitoring mechanisms [145]. The emergence of antimicrobial-resistant pathogens brought about global public health challenges, including prolonged hospital admissions, difficulties in treating infections, increased health costs, and morbidity and mortality [15] [28]. Therefore, there is a need to strengthen AMR prevention activities, including heightened surveillance, antimicrobial stewardship (AMS) programs, and other strategies to monitor and address AMR and associated causative factors [146]-[152].

There are reports of antimicrobial overuse in food-producing animals and contamination of the environment resulting from the inappropriate use of antimicrobials [77]. The continuous overuse of antimicrobials in food-producing animals contributes to the development of AMR in food-producing animals [77] [153]. In poultry, there has been an increase in the use of antimicrobials for growth promotion, increasing egg production, preventing diseases and empirical treatment [154] [155]. This exposes the microorganisms resident in poultry, including normal flora and pathogenic agents to antimicrobials, leading to the development and spread of AMR [156] [157]. Additionally, most poultry antibiotics are administered through drinking water and chicken feed, thereby acting on the microorganisms in the gut of flocks [153] [158]. The problem in the poultry sector has been worsened by the inappropriate dispensing of antibiotics without prescriptions [159]. The overuse and misuse of antimicrobials in poultry, dairy, and piggery have also been reported among the key drivers of AMR [160]-[167].

AMR is a huge burden in most African countries and has been reported to have variabilities in prevalence due to differences in AMR testing capacities, data quality, and AMR estimates [168]. A study among African countries found that the use of antibiotics in food-producing animals was 100% in Zambia, Tanzania, Cameroon and Egypt, while in Nigeria, the use of antibiotics in food-producing animals was found to be 77.6% [77]. Tetracyclines, aminoglycosides, and penicillins were reported as the most used [77]. Besides, the overuse of tetracyclines and aminoglycosides in food-producing animals has been documented in many countries [42] [77] [153] [169]-[172]. Further, there were reports of MDR isolates that ranged from 20% to 100%, indicating a significant public health problem [31] [77]. MDR isolates are those that acquired non-susceptibility to at least one agent in three or more antimicrobial categories [173] [174]. In Cameroon, a study found that antibiotics such as oxytetracycline, chloramphenicol, and neomycin were overused and misused in poultry [175]. A study in Tunisia found Extended-Spectrum Beta-Lactamase (ESBL)-producing *E. coli* in food-producing animals, indicating a public health problem, as these genes may damage beta-lactam antibiotics [176]. ESBL-producing isolates have been reported in many countries [177]-[179]. The overuse of antimicrobials in animal husbandry has contributed to an increase in the emergence and spread of antibiotic-resistant *E. coli* [175] [176] [180]-[182]. In Tanzania, a study found that most *E. coli* isolates from commercial-layer and free-range chickens were resistant to most antibiotics used in poultry [183]. In LMICs, studies have reported AMR as a public health challenge that the inappropriate use of antibiotics has exacerbated [39] [48] [50] [66] [162] [184]-[187].

Healthcare-associated infections (HAIs) are a significant concern in the context of AMR, with common pathogens including virulent and high-risk bacterial strains such as "ESKAPE" pathogens (*Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa and Enterobacter species*) [30] [188] [189]. These infections are prevalent in intensive care units (ICUs), where patients are particularly vulnerable due to invasive procedures, immunocompromised, and extensive antibiotic use [188] [190]. By definition, HAIs are infections that patients acquire during the course of receiving medical treatment in a healthcare facility or shortly after discharge [191] [192]. These infections are not present or incubating at the time of admission and typically emerge 48 hours or more after hospitalization [193] [194]. HAIs can occur in various healthcare settings, including hospitals, outpatient clinics, nursing homes, and long-term care facilities, and they often result from invasive procedures, prolonged hospital stays, or lapses in infection prevention and control (IPC) [191] [194]. The occurrence of HAIs is a serious threat to healthcare safety and contributes to the overuse of antibiotics, increased costs, and the development and spread of AMR [188] [195]-[197]. Other pathogens that have developed resistance to antibiotics include *Mycobacterium tuberculosis* [198]-[208], *Staphylococcus aureus* (*S. aureus*), *Klebsiella pneumoniae*, *Salmonella* spp [15], *Acinetobacter* spp [16] [209]-[212], *Enterococcus* spp, *Pseudomonas aeruginosa*, *Enterobacter* spp [30] [212], *Streptococcus pneumoniae*, and *Escherichia coli* (*E. coli*), among other pathogens [22]. The most common cause of death among these antimicrobial-resistant pathogens includes *E. coli*, *S. aureus*, *Klebsiella pneumoniae*, *Streptococcus pneumoniae*, *Acinetobacter baumannii*, and *Pseudomonas aeruginosa*, accounting for a total of 929,000 human deaths [22].

The WHO released the 2024 Bacterial Priority Pathogens List (WHO BPPL), which is an important tool in the global fight against AMR [213] [214]. Building on the 2017 edition, the 2024 WHO BPPL updates and refines the prioritization of antibiotic-resistant bacterial pathogens to address the evolving challenges of AMR. The list categorizes these pathogens into critical, high, and medium-priority groups to inform research and development (R&D) and public health interventions [213]. The 2024 WHO BPPL covers 24 pathogens, spanning 15 families of antibiotic-resistant bacterial pathogens [213]. Notable among these are Gram-negative bacteria resistant to last-resort antibiotics, drug-resistant *Mycobacterium tuberculosis*, and other high-burden resistant pathogens such as Salmonella species, Shigella species, *Neisseria gonorrhoeae*, *Pseudomonas aeruginosa*, and *S. aureus* [213] [215]. Carbapenem-resistant *Klebsiella pneumoniae*, third-generation cephalosporin-resistant *E. coli*, and carbapenem-resistant *Acinetobacter baumannii* are in the top priority list and remain a problem globally as they contribute majorly to the burden of disease, morbidity, and mortality in all settings [216]. The inclusion of these pathogens in the list underscores their global impact in terms of burden, as well as issues related to transmissibility, treatability, and prevention options. It also reflects the R&D pipeline of new treatments and emerging AMR trends [213].

The WHO BPPL acts as a guide for prioritizing R&D and investment efforts in the fight against AMR, emphasizing the need for regionally tailored strategies to effectively combat drug resistance [213]. It targets developers of antibacterial medicines, academic and public research institutions, research funders, and public-private partnerships investing in AMR R&D, as well as policy-makers responsible for developing and implementing AMR policies and programs [213]. Further details on the rationale behind the list, the methodologies used to develop the list, and the key findings can be found in the accompanying report [213]. Furthermore, it is critical to discover, research, and develop new antibiotics to treat the WHO priority list of antibiotic-resistant bacteria alongside the priority research areas [217] [218].

Based on the Global Action Plan (GAP) and National Action Plans (NAPs) on AMR and other strategies, there is a need to address AMR in a holistic, One Health, and multidisciplinary approach [219]-[226]. Multidisciplinary teams comprising clinicians, pharmacists, veterinarians, environmental scientists, public health experts, and policymakers are essential for implementing effective AMS programs, as they bring together diverse expertise to design and operationalize integrated, One Health strategies that address the complex biological, behavioural, and socio-economic drivers of AMR across human, animal, plant, and environmental health sectors [14]. Additionally, addressing AMR requires the establishment and implementation of AMS programs using a One Health approach [146] [225] [227]-[233]. It requires designing programs that take into account the complex mechanism of development of AMR in both humans and animals and the complex interlink between behavioural and socio-economic determinants of AMR [227] [234] [235]. These multi-sectoral AMR mitigation programs need to be backed by strong policy frameworks, priority setting, R&D and human capacity development to tackle AMR across the One Health Spectrum [146] [236].

AMS programs are essential tools in the fight against AMR, playing a crucial role in optimizing antibiotic use within both human and animal health [235] [237]-[239]. These programs work to reduce unnecessary antibiotic prescriptions, thereby alleviating the selective pressure that fuels the development and spread of resistance [233] [240]-[244]. By promoting adherence to evidence-based treatment guidelines, AMS programs ensure that the right drug is used at the correct dosage and for the appropriate duration, contributing significantly to the preservation of antibiotic effectiveness [70] [73] [245]-[248]. Alongside other antimicrobial stewardship efforts, healthcare facilities must adhere to evidence-based guidelines such as the World Health Organization's Access, Watch, and Reserve (AWaRe) classification of antibiotics [249]-[258]. This framework categorizes antibiotics based on their spectrum of activity, potential for resistance development, and importance in human medicine [255] [257]. By promoting the preferential use of Access group antibiotics for common infections, those with lower resistance potential, while reserving Watch and Reserve group antibiotics for specific, high-risk infections or infections caused by MDROs, the AWaRe classification supports rational antibiotic prescribing [252] [255] [259] [260]. Adherence to these guidelines not only reduces the emergence of AMR but also improves clinical outcomes, optimizes treatment efficacy, and preserves the effectiveness of last-resort antibiotics [261]. Additionally, AMS programs promote education and training of healthcare workers on AMU, AMR, and AMS [52] [262]-[266]. Therefore, more studies should be conducted to address any gaps that need improvement among healthcare workers [170] [184] [267]-[276], veterinary personnel [276]-[282], farmers [169] [283]-[291], students [79] [81] [85] [86] [292]-[298], and the general public [272] [299]-[305]. AMS programs should also be strengthened in antifungal and antiviral resistance due to increased resistance in fungi and viruses [306]-[315]. AMS programs must be integrated with IPC programs into strategies to combat AMR [316] [317].

The importance of AMS programs extends across the One Health spectrum, recognizing the interconnectedness of human, animal, and environmental health [146] [235] [239] [318]. Effective implementation of AMS programs requires collaboration and coordination among various stakeholders, including healthcare providers, veterinarians, farmers, policymakers, and public health officials [235]. Through this collaborative approach, AMS programs can holistically address antibiotic use, tackling AMR at its source and mitigating its spread across different sectors [235]. This evidence indicates the need for continuous education on AMU and AMR to promote AMS across the One Health sector [319].

Surveillance plays a critical role in combating AMR by enabling the early detection of resistance trends, guiding appropriate therapeutic decisions, and informing public health interventions [320] [321]. Effective AMR surveillance systems help in tracking the emergence and spread of resistant pathogens across human, animal, and environmental sectors, thus supporting the One Health approach to AMR containment [14]. Through continuous monitoring, surveillance data inform AMS programs, shape national and global treatment guidelines, and support the development of targeted infection prevention and control strategies [119] [322] [323]. Additionally, surveillance facilitates resource allocation and policy-making by providing evidence on resistance hotspots and priority pathogens. For instance, the Global Antimicrobial Resistance and Use Surveillance System (GLASS) has been instrumental in standardizing AMR data collection across countries and promoting coordinated global responses [324]-[331]. The GLASS, launched by the WHO in 2015, has been instrumental in establishing a standardized approach to the collection, analysis, and sharing of AMR and AMU data across participating countries [332]. By promoting harmonized surveillance methodologies and fostering the integration of AMR data from human health, animal health, and environmental sectors, GLASS enhances comparability of data at both national and international levels [76] [324]-[326] [329]-[333]. This coordinated system enables countries to identify resistance trends, prioritize public health actions, inform treatment guidelines, and support policy-making [325] [334] [335]. Furthermore, GLASS facilitates global collaboration by offering a platform for countries to share experiences, challenges, and best practices, thereby strengthening capacity for AMR response and promoting accountability in antimicrobial stewardship efforts worldwide [325]. Hence, it is critical that countries establish and strengthen sustainable AMR surveillance in their sentinel sites [336]. Without robust surveillance mechanisms, resistance may go unnoticed until it becomes widespread, limiting treatment options and increasing morbidity, mortality, and healthcare costs [76] [337] [338].

IPC plays a pivotal role in supporting AMS programs to mitigate the spread of AMR [317] [339]. Effective IPC measures such as hand hygiene, environmental cleaning, patient isolation, and surveillance of HAIs help reduce the incidence of infections, thereby decreasing the need for antimicrobial use and limiting the selection pressure that drives resistance [340]-[342]. By preventing the transmission of MDR organisms (MDROs) within healthcare facilities, IPC complements AMS strategies that promote the rational use of antimicrobials. Integrated IPC and AMS efforts are particularly essential in low- and middle-income countries, where overburdened healthcare systems and limited laboratory capacity can exacerbate the spread of resistant pathogens [33].

The synergy between IPC and AMS is increasingly recognized as a cornerstone of effective AMR containment [343]. The WHO recommends a One Health approach, emphasizing that coordinated efforts across IPC, AMS, and surveillance are vital to achieving sustainable AMR control [146] [239] [344]. Studies have shown that implementing IPC interventions alongside AMS programs significantly reduces the prevalence of resistant infections, such as methicillin-resistant *S. aureus* (MRSA) and carbapenem-resistant *Enterobacteriaceae* (CRE) [316] [345]. Institutional commitment to both IPC and AMS including adequate staffing, training, and resource allocation, is therefore essential to optimize AMU while minimizing the risk of AMR transmission within healthcare settings [263] [346]-[348].

Biosecurity is a fundamental component of AMS in animal health, playing a crucial role in preventing the emergence and spread of AMR [146] [349]. By minimizing the introduction and dissemination of infectious agents on farms through practices such as controlled animal movement, disinfection protocols, vector control, and farm zoning, biosecurity reduces the need for antimicrobial use [350]. A well-implemented biosecurity plan decreases the incidence of infectious diseases, thereby lowering the reliance on antibiotics as preventive or therapeutic tools [351]-[353]. This preventive approach aligns with the core principles of AMS, which advocate for the judicious and responsible use of antimicrobials in animal health practice [354].

In livestock systems, poor biosecurity is frequently linked to the overuse and misuse of antibiotics, particularly in intensive production environments where disease outbreaks can spread rapidly [349]. Strengthening farm-level biosecurity, therefore, not only supports animal health and productivity but also acts as a first line of defence against the development of AMR [355]. Global health bodies such as the WOAH (formerly OIE) emphasize integrating biosecurity measures into national AMS action plans as part of a One Health approach to combating AMR [356]. Moreover, education and training of farmers and veterinarians on the importance of biosecurity are vital for its effective implementation and sustainability in animal health systems [352] [357].

Evidence has shown that nanoparticles are emerging as promising tools in the fight against AMR and can play important roles in AMS [358]. Their unique properties offer innovative strategies to combat bacterial infections, particularly those caused by MDROs [359]-[361]. Additionally, nanoparticles can be designed to deliver antimicrobial agents directly to the site of infection, enhancing their effectiveness while minimizing off-target effects and reducing the overall dosage required. Therefore, this targeted delivery helps to preserve the effectiveness of antibiotics and reduces the selective pressure that leads to the development of AMR. Alongside this, nanoparticles themselves can possess intrinsic antimicrobial properties. For example, metal nanoparticles like silver and copper have demonstrated the ability to kill bacteria through various mechanisms, including disrupting bacterial cell membranes and interfering with essential cellular processes [362]. Utilizing nanoparticles with inherent antimicrobial activity can reduce the reliance on traditional antibiotics, an important aspect of AMS [363].

In addition to their direct antimicrobial effects, nanoparticles are also being explored for their potential to improve diagnostic methods for bacterial infections [364]-[367]. Rapid and accurate diagnosis is crucial for effective AMS, as it allows for timely and appropriate treatment decisions [368] [369]. Nanoparticles can be engineered to detect specific bacterial pathogens or markers of infection, enabling clinicians to quickly identify the causative agent and prescribe the most appropriate antibiotic, or avoid unnecessary antibiotic use altogether [365] [368] [369].

The advancement of technology has demonstrated the usefulness of artificial intelligence (AI) to address AMR and support AMS programs [370]-[372]. In predictive analytics, AI can be used to analyze large datasets to predict AMR patterns, identify high-risk patients, and forecast outbreaks. In surveillance and monitoring, AI-powered systems can be used to monitor antimicrobial use and resistance trends in real time, enabling swift interventions [373]. Regarding genomic analysis, AI can help analyze genomic data to identify AMR genes, track their spread, and develop targeted interventions. Additionally, AI systems can be used for the virtual screening of compounds and accelerate the discovery of new antimicrobials by virtually screening large libraries of compounds [370] [371] [374]. Evidence has demonstrated that AI models can be used to support AMS programs by optimizing antimicrobial use by analyzing the prescribing data to identify areas for improvement and provide personalized recommendations for optimization [371]. Additionally, AI-powered systems can provide healthcare professionals with real-time, evidence-based guidance on antimicrobial prescribing, thereby informing clinical decision support and improving AMS. AI-powered systems can help identify patients at high risk of AMR or adverse reactions, enabling targeted interventions to improve patient outcomes and antimicrobial use. In automated surveillance, AI can monitor antimicrobial use and resistance data, enabling early detection of issues and prompt interventions. Alongside this, AI-powered platforms can provide personalized education and training for healthcare professionals on AMR and AMS. Along the same line, AI-driven Chatbots and virtual assistants can help raise public awareness about AMR and promote responsible antimicrobial use. Finally, in Research and development, AI-powered systems can be used to accelerate the discovery of new antimicrobials and diagnostics by analysing large datasets and identifying patterns in a shorter period [371].

Therefore, this study employed a comprehensive narrative review approach to provide an in-depth overview of integrated AMS and IPC programs implemented to combat AMR across the One Health sector, highlighting the role of advanced technologies such as nanotechnology and AI.

2. Materials and Methods

This narrative review was conducted from May 2024 to June 2025. The literature search was done using Google Scholar, PubMed, and Scopus databases. This paper includes all publications that were published in English between January 1995 and June 2025. We conducted a narrative review to comprehensively include studies that have been published on AMR, AMS, IPC, One Health, and AI for all literature published between January 1995 and June 2025. This approach has been utilized in previous studies on AMR and AMS [65] [66] [125] [146] [306] [375]-[377]. This study utilized Boolean operators including AND/OR and key terms that included "antimicrobial resistance", "antimicrobials", "artificial intelligence", "universities", "animals", "animal health", "communities", "hospitals", "human health", "humans", "One Health", "antimicrobial use", "antimicrobial stewardship", "antimicrobial stewardship programs", "strategies", "collaboration", "AWaRe classification", "Global Action Plan", "infection prevention and control", "Nanoparticles", "Nanotechnology", "National Action Plan", "Programs", "surveillance", "Global", "Impact", "drivers", "laboratories", "surveillance", "climate change", and "combating antimicrobial resistance". The paper also includes publications that were only published in the English language. The review was conducted following the 2020 Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [378]. The literature search found 850 studies of which the screening and eligibility processes, removing of duplicates, excluded some studies to ensure that only 91 studies that were done in line with the inclusion criteria of this review. Two authors (SM and AFL) independently verified that the selected studies met the inclusion criteria in a blinded manner, while any discordances were resolved by the principal author (SM).

3. Results

The findings of this study revealed that AMS programs are very useful in combating AMR. Evidence indicates that AMS programs promote the appropriate use of antimicrobials and improve patient outcomes. Additionally, AMS programs reduce the overall use of antimicrobials, thereby reducing the emergence and spread of AMR. The advancement in technology has also demonstrated that AI has the potential to be used in AMS and strategies to reduce AMR. Additionally, AI can be used for accelerated drug development and the identification of pathogens. Finally, the use of a One Health approach to address AMR has been recommended and shown to be an inclusive method of addressing AMR (Table 1).

Table 1. Antimicrobial stewardship, surveillance, infection prevention and control programs, nanotechnology, and artificial intelligence in combating AMR.

Authors, year	Study design	Findings and conclusion
	Promoting Hospital AMS Programs to Combat AMR	
Awad Al-Omari *et al.*, 2020 [379]	The pre-post quasi-experimental study, Saudi Arabia	• Implementation of AMS programs at Habib Medical Group (HMG) healthcare facilities resulted in reduced antimicrobial use and cost, and lowered incidence of HAIs. • The implementation of the AMS program significantly reduced the consumption of broad-spectrum antibiotics, with average daily defined doses (DDDs) dropping from 320 to 233 per 1,000 patient days post-intervention. • Antimicrobial expenditures decreased by 28.45% in the first year of AMS implementation, leading to cumulative cost savings of over S.R. 6.2 million. • The incidence of healthcare-associated infections (HAIs) including C. difficile, ventilator-associated pneumonia (VAP), and central line-associated bloodstream infections (CLABSI) declined markedly after AMS was established. • A large-scale, multi-hospital pre-post study design demonstrated the real-world effectiveness of AMS interventions, reinforcing the value of AMS in improving clinical and economic outcomes in tertiary healthcare settings.
Fishman *et al.*, 2006 [380]	Randomized Controlled trial comparing the Hospital of the University of Pennsylvania's AMS program to usual practice	• Appropriate antimicrobial selection increased from 32% to 90%. • The cure rate increased from 55% to 91%. • The clinical failure rate decreased from 31% to 5%. • Prevalence of resistant pathogens decreased from 9% to 1%.
Valiquette *et al.*, 2007 [381]	Audit and feedback strategy focused on the appropriate use of second- and third-generation cephalosporins, ciprofloxacin, clindamycin, and macrolides in Canada	• Decreased total antimicrobial consumption by 23%. • Decreased targeted antimicrobial consumption by 54%. • The incidence of Clostridium difficile infection decreased by 60%.
Shively *et al.*, 2020 [382]	Prospective audit and feedback, Allegheny General Hospital, Pittsburgh	• An intense AMS program model, facilitated in the community hospital setting via telehealth, led to reduced broad-spectrum AMU, increased infectious disease consultations, and reduced antimicrobial expenditures. • Implementation of a telehealth-based AMS program in two community hospitals led to a 24.4% reduction in broad-spectrum AMU, measured in direct observe therapy (DOT) per 1,000 patient days ($P < .001$). • A high acceptance rate (88.9%) of stewardship recommendations indicated strong collaboration between infectious diseases physicians and local pharmacists, despite limited prior AMS program experience. • Infectious disease consultations increased by 40.2% during the intervention, suggesting enhanced clinical engagement in complex infection management.

		• The AMS program intervention resulted in significant cost savings, with estimated annualized reductions in antimicrobial expenditures totalling over $142,600.
Yusef *et al.*, 2021 [383]	A retrospective, ecological assessment in a tertiary teaching hospital over 6 years (January 2014 to December 2019), Jordan	• The introduced AMS interventions contributed to a reduction in the use of several broad-spectrum antibiotics and reversed the trends of increasing the use of other antibiotics. • AMS interventions were associated with a significant reduction in carbapenem-resistant Acinetobacter baumannii. • Significant reductions in the use of several broad-spectrum antibiotics were observed following AMS program implementation, including imipenem/cilastatin, vancomycin, colistin, and third-generation cephalosporins ($P < 0.001$ for most). • Trends of increasing use for certain antibiotics, such as piperacillin/tazobactam, were halted after the AMS program introduction, indicating effective intervention in prescribing behaviour. • AMS program implementation significantly reduced carbapenem-resistant Acinetobacter baumannii (CRAb) levels ($P = 0.0237$), demonstrating impact beyond prescribing metrics. • Changes in antibiotic usage slope post-intervention—for agents like ertapenem and ciprofloxacin—reflect sustained improvements in AMS over time.
Apisarnthanarak *et al.*, 2006 [384]	Prospective cohort; pre-AMS vs prospective cohort; post-AMS, Thailand	• After the intervention, there was a 24% reduction in the rate of antibiotic prescriptions (640 vs. 400 prescriptions/1000 admissions) • The incidence of inappropriate antibiotic use was significantly reduced—$p = 0.001$ (42% vs. 20%) • Significant reductions in the incidence of infections due to methicillin-resistant, S. aureus (48% vs. 33.5%), ESBL-producing *E. coli*—$p = 0.001$ (33% vs. 21%), ESBL-producing Klebsiella pneumoniae (30% vs. 20%), and third-generation cephalosporin-resistant Acinetobacter baumannii (27% vs. 19%) were also observed. Total cost savings were US$32,231 during the study period.
Boyles *et al.*, 2013 [385]	Retrospective cohort control arm; prospective cohort intervention arm, Cape Town, South Africa	• There was a 19.6% decrease in volume with a cost reduction of 35% of the pharmacy's antibiotic budget. • There was a concomitant increase in laboratory tests driven by requests for procalcitonin. • There was no difference in inpatient mortality or 30-day readmission rate during the control and intervention periods.
Alabi *et al.*, 2022 [386]	A bundle of three interventions including local treatment guidelines, staff training, and regular AMS ward rounds were implemented, Liberia	• Following the implementation of AMS ward rounds, adherence to local guidelines significantly improved across several parameters: the selection of antimicrobial agents increased from 34.5% to 61.0% ($P < 0.0005$), correct dosage from 15.2% to 36.5% ($P < 0.0005$), and appropriate duration from 13.2% to 31.0% ($P < 0.0005$). • Microbiological samples were sent for 79.7% of patients (247/310), and clinical improvement by Day 3 was observed in 92.3% of patients (286/310). • Additionally, the use of ceftriaxone was significantly reduced from 51.3% to 14.2% ($P < 0.0005$).
Arenz *et al.*, 2024 [387]	Retrospective data were collected from 2017 to 2021 at the LMU University Hospital in Munich, Germany	• Guideline adherence improved during P2 (distribution of guideline pocket cards) across all infectious disease categories. Although adherence to guidelines declined after three years in P3 (reassessment after 3 years), it remained higher than in P1 (pre-intervention period). • Distribution of guideline pocket cards significantly improved adherence to treatment protocols for infections like pneumonia and cystitis, rising from

		47% to 58.6% (P = 0.005). • Daily AMS ward rounds further enhanced guideline adherence, increasing it to 72.5% in the final period (P < 0.001), even during weekends and night shifts. • Sustained adherence to AMS specialist recommendations was high (91.3%), demonstrating strong provider engagement and trust in stewardship guidance. • Antibiotic prescribing shifted toward increased use of narrow-spectrum agents, accompanied by reduced use of fluoroquinolones and cephalosporins, aligning with stewardship goals. • AMS ward rounds led to a significant additional increase in adherence (P1 to P2: 47% to 58.6%, P = 0.005; P2 to P3: 58.6% to 57.3%, P = 0.750; P3 to P4: 57.3% to 72.5%, P < 0.001). • Notably, adherence improved significantly not only during weekdays but also on weekends and night shifts. Compliance with AMS specialist recommendations was exceptionally high (91.3%). • Furthermore, there was a marked increase in the use of narrow-spectrum antibiotics and a reduction in the application of fluoroquinolones and cephalosporins.
Raja Dahar *et al.*, 2024 [388]	A comparative study design, Pakistan	• A reduction in the misuse of antibiotics, leading to better clinical outcomes for patients. • Identified eight specific drug-related problems associated with improper antibiotic use, including excessive duration of therapy and failure to follow culture sensitivity reports. • Significant cost savings due to reduced unnecessary therapy and shorter hospital stays. • The rates of AMR were lower in tertiary care hospitals with effective AMS programs compared to smaller hospitals. • AMS programs are essential for improving patient outcomes, reducing healthcare costs, and minimizing the risk of AMR.
Baur *et al.*, 2017 [389]	Systematic review and meta-analysis	• Implementation of AMS programs led to a significant reduction in AMR and HAIs. • AMS programmes in hospitals significantly reduce the incidence of infections and colonisation with MDR organisms, including a 51% reduction in MDR Gram-negative bacteria, 48% in ESBL-producers, 37% in MRSA, and 32% in Clostridioides difficile infections. • The effectiveness of AMS is enhanced when combined with IPC measures, particularly hand hygiene interventions underscoring the synergistic role of AMS and IPC in combating AMR in hospital settings.
Davey *et al.*, 2017 [390]	Systematic review	• Hospital-based AMS programs significantly reduced unnecessary antibiotic use without compromising patient outcomes. • High-certainty evidence supports that AMS interventions significantly improve compliance with antibiotic prescribing policies and reduce treatment duration by nearly 2 days, without increasing patient mortality, demonstrating their safety and effectiveness in hospital settings. • AMS programs likely reduce hospital length of stay by approximately 1.1 days and show strong potential to lower unnecessary antibiotic use, with 70% of real-world interventions implemented hospital-wide. • Enablement strategies, particularly when combined with feedback, significantly enhanced the effectiveness of AMS interventions, even in programs that used restrictive components highlighting the importance of behaviour change techniques.

		• Although AMS interventions showed variable microbial impact, limited evidence suggested potential reductions in Clostridioides difficile and resistant Gram-negative and Gram-positive infections, underscoring the need for more robust microbial outcome data. • Future AMS efforts should focus on optimizing intervention design using behavioural science, evaluating unintended consequences such as treatment delays or breakdown in communication, and tailoring strategies to overcome implementation barriers in diverse hospital settings.
Karanika *et al.*, 2016 [3]	Systematic review and meta-analysis	• AMS programs were associated with decreased antibiotic consumption and lower infection rates from resistant pathogens. • AMS programs significantly reduced total antimicrobial consumption by 19.1%, with even greater reductions observed in ICU settings (39.5%), along with decreased use of restricted and broad-spectrum antibiotics, and a 33.9% reduction in overall antimicrobial costs. • Implementation of AMS led to reduced hospital length of stay (−8.9%) and lowered infection rates from key resistant pathogens such as MRSA, imipenem-resistant *P. aeruginosa*, and ESBL-producing *Klebsiella* spp., without increasing mortality or infection-related adverse outcomes. • These findings highlight AMS as an effective hospital-based intervention to curb AMR while improving clinical efficiency and reducing healthcare costs, particularly in high-risk settings like ICUs.
Schuts *et al.*, 2016 [391]	Systematic review and meta-analysis	• Proper AMS programs reduce the length of stay, AMU, and AMR while improving clinical outcomes. • Implementation of AMS objectives such as guideline-adherent empirical therapy, de-escalation, IV-to-oral switch, and use of restricted antibiotics, was significantly associated with reduced mortality and improved treatment outcomes (e.g., 35% mortality reduction with guideline-adherent therapy and 56% with de-escalation). • Despite moderate to high heterogeneity and generally low-quality evidence across studies, several AMS strategies consistently showed measurable positive impacts, guiding for prioritizing interventions in hospital settings. • Limited or no evidence was found for some AMS objectives (e.g., therapy discontinuation based on lack of infection evidence, renal dosing adjustments), and none were reported for long-term care facilities, highlighting areas for further research and implementation.
Pulcini *et al.*, 2019 [392]	Qualitative study, A Consensus Approach	• A comprehensive literature review yielded seven core elements and 29 checklist items relevant to hospital AMS programmes based on 48 references. • A consensus process involving 15 experts from 13 countries across six continents confirmed the relevance of all seven core elements and 29 items (including one newly proposed), with ≥80% agreement and 20 items rephrased for clarity. • The finalized elements are applicable across both high- and LMICs, providing a foundational framework for national AMS guideline development and hospital-level implementation worldwide. • Healthcare professionals recognize the importance of AMS programs but need more institutional support and training.
Howard *et al.*, 2015 [393]	An International Cross-Sectional Survey	• AMS programs are critical for global AMR strategies and require multidisciplinary coordination and policy support. • Among 660 hospitals from 67 countries, 58% had AMS programs, but only 52% of countries had national AMS standards; implementation barriers included lack of funding, personnel, IT infrastructure, and prescriber

		resistance. • Most hospitals with AMS programs engaged in activities like antimicrobial restriction (81%), AMS rounds (64%), usage reporting (85%), and staff education (89%), though only 20% used comprehensive electronic prescribing. • Among hospitals that reviewed their AMS programs, high percentages reported reductions in inappropriate prescribing (96%), broad-spectrum antibiotic use (86%), costs (80%), HAIs (71%), and AMR (58%). • Findings highlight both the potential benefits and variability of AMS implementation worldwide, underscoring the need for standardized evaluation frameworks and global stewardship strategies.
Nathwani *et al.*, 2019 [394]	A systematic review	• Hospital AMS programs have significant value with beneficial clinical and economic impacts. • National AMS programs contribute to rational antibiotic use and better clinical governance in healthcare settings.
Laxminarayan *et al.*, 2013 [395]	Global review and policy analysis	• AMS programs are essential to combat global AMR trends and must be integrated into national health strategies. • AMR is a complex, global challenge driven by human behaviour across all levels of society, with consequences that impact every individual worldwide. • Despite extensive knowledge and documentation of AMR causes and solutions, coordinated political action both nationally and globally, remains insufficient. • Antibiotics are essential for modern medicine, enabling safe surgery, cancer chemotherapy, organ transplants, and neonatal care; their loss threatens major medical advancements. • Without immediate and coordinated global action, the world risks severe medical, social, and economic setbacks, underscoring the urgency of implementing comprehensive AMS strategies.
Rajput, 2023 [396]	A Narrative Review	• AMS programs are essential in combating AMR by promoting rational antibiotic use, improving patient outcomes, and reducing healthcare costs. • Despite challenges such as limited resources, lack of awareness, and resistance to change, AMS programs can be strengthened through the integration of technologies like clinical decision support systems, real-time surveillance, and tailored interventions across diverse healthcare settings. • Adopting a One Health approach, enhancing education and training, and fostering global collaboration and research are key strategies for ensuring the long-term sustainability and effectiveness of stewardship efforts in mitigating AMR.
Cassim *et al.*, 2024 [397]	A Pre-implementation Study, South Africa	• Most healthcare professionals (97%) acknowledged AMR as a problem in South African hospitals, with 81% expressing willingness to engage in AMS initiatives, reflecting readiness for AMS implementation. • The situational analysis highlighted existing AMS strengths, including the presence of AMS committees and access to supportive information and technology systems at facilities. • Despite infrastructure, actual AMS activity levels and healthcare professional participation were low, indicating the need for strategies to improve engagement and operationalize AMS plans. • Conducting a pre-implementation phase allowed for the identification of systemic gaps, providing a critical baseline for future evaluation and improvement of AMS program effectiveness.
Mudenda *et al.*, 2025 [268]	A Cross-Sectional Mixed Methods Study, Zambia	• Educational interventions, such as AMS training, significantly improved knowledge on AMU, AMR, and AMR surveillance, with a 16% increase in

		knowledge scores observed post-training. • Laboratories demonstrated strengths in basic microbiology infrastructure, including the presence of physical labs and essential equipment like safety cabinets, autoclaves, and incubators. • Major challenges included shortages of trained microbiology staff, lack of reagents, and inadequate training in bacteriology and AMR testing, limiting their capacity for effective surveillance. • To enhance AMR surveillance, laboratories require continued AMS education, mentorship, capacity building, and resource support to address these gaps.
Nyoloka *et al.*, 2024 [398]	Cross-sectional studies using the Global Point Prevalence Survey (GPPS), Malawi	• A pharmacist-led partnership between Malawi and Wales significantly strengthened AMS activities in two tertiary referral hospitals through a collaborative and sustainable approach. • The first Global Point Prevalence Survey (GPPS) conducted in Malawi revealed a high reliance on ceftriaxone, emphasizing the need for improved antibiotic prescribing practices. • A train-the-trainer educational model successfully empowered pharmacists, who subsequently trained 120 multidisciplinary professionals and disseminated a practical AMS toolkit for bedside use. • This model demonstrated measurable progress and is scalable, offering a replicable framework to support Malawi's National Action Plan on AMR and similar efforts in other resource-limited settings.
Mudenda *et al.*, 2025 [242]	Cross-Sectional Studies using the WHO PPS, Zambia	• A multifaceted AMS intervention in three tertiary hospitals in Zambia led to a 10% reduction in overall antibiotic use, decreasing from 81% in 2022 to 71% in 2023. • Use of ceftriaxone, the most commonly prescribed antibiotic declined significantly, from 48% in 2022 to 38% in 2023, indicating improved prescribing practices. • Adherence to Standard Treatment Guidelines (STGs) improved modestly, rising from 42% to 45%, reflecting better alignment with national treatment protocols. • The average number of antibiotics prescribed per patient decreased, from 1.38 in 2022 to 1.21 in 2023, showing progress toward more rational antibiotic use.
Promoting Community Pharmacy AMS Programs to Combat AMR		
AlAhmad *et al.*, 2023 [399]	A Cross-Sectional Study in the Emirate of Abu Dhabi, United Arab Emirates (UAE)	• Participating in AMS programs helped community pharmacists to implement AMS activities in their practice. • Among 55 pharmacy teams, the majority had implemented at least one component of each AMS outpatient core element commitment and action (94.5%), education and expertise (81.8%), and tracking and reporting (67.3%). • Pharmacy teams scored highest in action (81.8%) and commitment (76.4%), while tracking and reporting remained the weakest area (43.6%), indicating the need for improvement in monitoring practices. • Participation in formal AMS programs significantly increased the likelihood of implementing AMS activities among pharmacists ($p = 0.048$), highlighting the importance of targeted training. • The findings underscore the pivotal role of community pharmacies in outpatient AMS and the positive influence of structured AMS education on stewardship performance.
Mohammed *et al.*, 2024 [400]	A pre-and post-intervention study	• Significant increase in AMS knowledge and attitudes post-intervention. • Improved selection of the most appropriate antibiotic therapy

	among community pharmacists, Malaysia	post-intervention. • Before the seminar, only 59% of participants correctly understood the concept of AMR reversibility, which significantly increased to 85.9% after the seminar ($p = 0.002$). • The average AMS knowledge score improved from 5/10 to 8/10 following the intervention ($p < 0.05$). • Additionally, there was a notable improvement in pharmacists' ability to select appropriate antibiotic therapies, particularly for urinary tract infections, with correct responses increasing from 78% to 90%.
Saleh, Farha and El-Hajji, 2021 [272]	A descriptive cross-sectional study design among community pharmacists, Jordan	• Community pharmacists have a good knowledge of antibiotics and a positive perception regarding AMS programs. • Pharmacists had great support for involvement in AMS programs. • Further, they advocated for incorporating AMS programs within the community pharmacy level.
Bishop *et al.*, 2019 [401]	A narrative overview strategy on AMS and the role of the community pharmacist	• Community pharmacists have expanded their role in patient care and public health issues such as outpatient AMS. • Support for dynamic ways and training to support AMS activities.
Mufwambi *et al.*, 2024 [402]	A Cross-sectional Study among Community Pharmacists, Zambia	• Community Pharmacists had a high level of awareness regarding AMS, but the practices were poor. • The strategies for AMS showed good practices. • This was shown to influence their provision of patient care in community pharmacies. • A need exists for the provision of educational intervention activities to promote the rational use of antibiotics in community pharmacies and AMS. • There is a need to design and implement AMS programs in all community pharmacies in Zambia. • Highlights the need for ongoing professional development to enhance AMS practices among community pharmacists.
Akande-Sholabi, Oyesiji and Adebisi, 2023 [403]	A cross-sectional survey conducted among 126 community pharmacists in Ibadan, Nigeria	• Most of the community pharmacists possess adequate knowledge of antibiotics and AMR; nonetheless, a significant portion of them exhibit poor antibiotic dispensing practices and AMS. • Most of the community pharmacists supported the dispensing of antimicrobials upon official prescriptions. • Community pharmacists had poor antibiotic dispensing practices.
Azevedo *et al.*, 2013 [404]	Pre-And Post AMS interventional teaching, Portugal	• Significant increases in knowledge were observed after the implementation of the teaching activity. • Knowledge of the correct use of antibiotics for bacterial diseases rather than viral diseases rose from 43% to 76% in the post-test ($p < 0.01$). • Knowledge of the risk of bacterial resistance to antibiotics from their incorrect use rose from 48% to 74% in the post-test ($p < 0.05$).
Hayat *et al.*, 2019 [405]	A multicenter cross-sectional study was conducted in the capital cities of three different provinces of China between March 2019 and July 2019	• The perceptions of pharmacists regarding AMS programs were positive. • However, gaps in knowledge about some aspects of antibiotics and participation in AMS programs were found. • The development of regional community-based AMS programs is urgently required.
Kafle *et al.*, 2010 [406]	A pre-post comparison of intervention implemented at the community level in purposively selected Bhaktapur District of Kathmandu Valley, Nepal	• There was a significant increase in correct knowledge of the action of antibiotics and excellent knowledge of the methods of administration of antibiotics in households after the intervention. • Similarly, there was a significant increase in knowledge of cough as a disease and a significant decrease in the use of cough medicines after intervention.

Lee and Bradley 2023 [407]	A Cross-Sectional Study, United States	• Among 61 surveyed community pharmacists, few met the CDC's outpatient AMS core elements—commitment (27.9%), action (24.6%), tracking and reporting (14.8%), and education and expertise (as low as 9.8% for patient education). • While 67.9% of pharmacists acknowledged the importance of AMS and 88.5% expressed willingness to participate, structured implementation remains low. • Key challenges included limited time, staffing, training, and technological support, along with prescriber resistance, patient pushback, and lack of leadership or financial incentives. • Findings emphasize the need for targeted investments, policy guidance, and capacity-building to unlock the AMS potential in community pharmacy settings.
Dlungele and Mathibe, 2023 [408]	Scoping Review	• AMS programs are a key strategy of the WHO global action plan to combat AMR, yet evidence from private healthcare settings in Africa remains limited. • Only a few studies exclusively from South Africa reported successful implementation of AMS programs in private healthcare, highlighting a significant research and reporting gap across the continent. • Effective interventions in these settings include locally driven prescription audits and pharmacist-led initiatives, demonstrating practical approaches to AMS. • To strengthen the fight against AMR, private healthcare settings in Africa must adopt evidence-based AMS programs and actively report on antibiotic use and outcomes.
Saha *et al.*, 2021 [409]	A Nationwide Cross-Sectional Study, Australia	• Most community pharmacists were aware of AMS but reported limited training (76.5%) and access to AMS guidelines (93.6%), highlighting the need for targeted education and resource support. • Community pharmacists (CPs) frequently performed clinical checks before dispensing antimicrobials, including counselling (97.0%) and reviewing allergies or drug interactions (93.8%), demonstrating readiness to contribute to AMS. • Collaboration with general practitioners (GPs) was limited, with only 41.8% contacting GPs about suboptimal prescriptions, largely due to perceived GP resistance to pharmacist input. • There was strong support for policy changes to enable AMS, including improved GP-CP collaboration (92.4%), restricted antimicrobial access (74.4%), and reduced repeat dispensing (74.2%).
Gebretekle *et al.*, 2020 [410]	A single-centre prospective quasi-experimental study	• A pharmacist-led, laboratory-supported AMS intervention significantly reduced antibiotic consumption, treatment duration, and in-hospital mortality, demonstrating the feasibility and impact of such interventions in a low-resource setting. • During the intervention phase, 96% of AMS team recommendations were accepted, with 54% involving discontinuation of unnecessary antibiotics—highlighting strong clinician receptiveness. • Cessation of the audit-feedback intervention led to a 51.6% increase in antimicrobial use, longer hospital stays, and doubled in-hospital mortality, underscoring the need for continuous AMS efforts. • Sustainable AMS impact requires institutional support and leadership commitment, especially in LMICs where resource constraints and syndromic treatment practices are prevalent.
Promoting AMS Programs in Academic Institutions to Combat AMR		

Dambrino and Green, 2022 [411].	Multinational (the paper discusses differences between low/ middle-income countries and high-income countries, but does not specify the exact countries where the studies were conducted)	• University students are a unique and promising target population for AMS efforts, as they are in a transformative life stage where they are learning to independently care for themselves. • Introducing AMS education during this transitional period could lead university students to adopt positive antibiotic-use behaviours that they will carry throughout their lives. Widespread adoption of AMS in college and university settings could have a broader positive impact on public health, both for present and future generations.
Tulloch *et al.*, 2019 [412].	Cross-sectional interventional study in the USA	• Medical students found the team-based learning (TBL) components of the AMS course, including readiness assurance testing, application activities, and team dynamics, to be effective. • The pre-class webcasts used for preparation were found to be ineffective by the students. • The study provides insights that can inform future implementations of TBL-based AMS education for medical students. • This study offered a first glimpse into the attitudes of pre-clinical medical students toward TBL as a strategy for introducing AMS. • It can serve as a roadmap for educators contemplating the implementation of a similar program at their institution and as a launching pad for research on the effects of this type of intervention on physician prescribing habits.
Majumder *et al.*, 2020 [413]	Narrative Literature Review	• AMS programs improve rational antibiotic use, reduce AMR, decrease complications of antibiotic use, and improve patient outcomes. • Many health professional students lack confidence and competence in antibiotic prescribing, highlighting the need to integrate AMS teaching into undergraduate curricula. • Proper undergraduate education on rational antibiotic use would enable future health professionals to enter clinical practice as competent, rational prescribers.
Beck *et al.*, 2018 [414].	Scooping Review	• Incorporate AMS content into the medical school curriculum. • Evaluate the status and effectiveness of AMS curricula. • Research the long-term outcomes of AMS training. • AMS-related content in the medical school curriculum is recommended.
Chahine *et al.*, 2015 [415].	Review article	• AMS programs are typically led by infectious disease physicians and pharmacists, to optimize patient outcomes, reducing AMR, decreasing adverse events, and controlling costs. • There is a shortage of formally trained pharmacists to serve as AMS coordinators. • The paper proposes a model to engage pharmacy students and residents/fellows in AMS programs, but further research is needed to assess the impact.
Augie *et al.*, 2021 [416]	A scoping review of 13 studies on medical school curricula teaching rational AMU.	• Didactic lectures and web-based learning were common instructional methods. Programs ranged from 75 minutes to 100 hours, implemented between the second and fourth years. • Emphasized the need for follow-up studies to assess long-term retention of AMS principles. • The 13 reviewed studies showed varied educational strategies including didactic lectures and web-based learning used to teach AMS, AMR prevention, and IPC to medical students. • Only six studies reported learning outcomes using tools like baseline/post-instruction assessments or short exams, highlighting a lack of standardization in measuring AMS education effectiveness. • Educational interventions were introduced as early as the second year of

		medical study and lasted between 75 minutes to 100 hours, reflecting flexibility in integrating AMS content across curricula. • While AMS education is widespread, further research is necessary to assess knowledge retention and application in clinical practice after students graduate from university, to ensure sustainability in AMR reduction efforts.
Lee and Bradley, 2021 [417]	Implementation of a peer educational tool (origami fortune teller) to promote AMS among university students	• The tool showed positive trends in increasing AMS knowledge among both health and non-health students, highlighting the effectiveness of peer education in this context. • A novel origami fortune teller was designed as an interactive tool to teach university students core antibiotic principles such as proper indications, resistance, and non-pharmacological strategies. • Peer educators facilitated engagement with students at a wellness fair, using real-life case scenarios embedded in the tool to enhance understanding of AMS. • Pre- and post-assessment scores demonstrated a significant increase in student understanding after using the tool (from 69.5% to 96.6%, $p \leq 0.05$), indicating its educational effectiveness. • The tool effectively promoted awareness of AMU and AMR in the general university population, highlighting its potential for wider public health education.
Shahpawee *et al.*, 2020 [418]	Cross-sectional survey of 130 university students in Brunei Darussalam	• 69% had previously used antibiotics, mostly from healthcare providers. 51% demonstrated good knowledge of antibiotic use and resistance, but misconceptions about treating viral illnesses and resistance mechanisms were prevalent. Recommended increasing awareness to correct misconceptions. • While 51% of students demonstrated good knowledge of antibiotics and AMR, a significant 76% incorrectly believed that AMR results from the body becoming resistant to antibiotics. • A total of 41% of respondents wrongly believed antibiotics are effective against viral illnesses like colds and flu, highlighting persistent misconceptions. • Only 14% of students had poor overall knowledge, indicating potential for targeted educational interventions to address specific gaps. • These findings underscore the importance of incorporating AMS principles into health education curricula to correct misconceptions and promote rational antibiotic use among future prescribers.
Dambrino and Green, 2022 [411]	Review article	• University students are a key AMS target group: As emerging adults developing lifelong health behaviours, undergraduate students represent a strategic population for AMS education to promote responsible antibiotic use. • Potential for long-term impact: AMS initiatives during this transitional life stage can shape positive, sustained antibiotic use practices, influencing not only personal health but also public health outcomes for future generations. • The gap in current research: Despite the clear opportunity, there is limited research evaluating AMS programs or interventions within university health systems. • AMS is vital in youth education: Implementing AMS efforts in college settings can drive early behavioural change, making it a critical avenue for tackling AMR through public health and educational strategies.
Mudenda *et al.*, 2023 [293]	Cross-sectional study among non-healthcare students at the University of	• Identified gaps in knowledge and practices related to antimicrobial use and resistance, emphasizing the need for targeted educational interventions among non-healthcare students to promote prudent antimicrobial use.

	Zambia	• Over half of university students demonstrated only moderate knowledge, attitudes, and practices (KAP) regarding AMU and AMR, with a high prevalence (76.7%) of antibiotic self-medication. • Male students and those in non-health-related fields (e.g., Social Sciences) had significantly poorer knowledge and attitudes towards AMR compared to females and students in technical fields like Engineering and Mining. • Students in advanced academic years (4th and 5th) had more positive attitudes towards responsible AMU and AMR than younger peers, indicating experience may enhance awareness. • Expanding AMS awareness through targeted workshops, short courses, and campaigns in all university disciplines is essential to improve antibiotic use behaviour and reduce AMR risks in the wider community.
Dyar *et al.*, 2018 [419]	Cross-sectional study assessing knowledge, attitudes, and behaviours of human and animal health students toward antibiotic use and resistance in the UK	• Highlighted the need for improved education on antibiotic use and resistance across both human and animal health disciplines to foster better AMS practices. • While 95% of healthcare students acknowledged AMR as a serious future concern, only 69% recognized that their professional use of antibiotics could contribute to the problem. • Only 20% of students felt adequately prepared with knowledge of antibiotic use for their future roles, highlighting a critical gap in AMS-related education. • Despite recognizing the significance of AMR, misconceptions about antibiotic use remain among students across disciplines, including medicine, pharmacy, veterinary, and dentistry. • Targeted AMS training using behavioural insights methods is necessary to address misconceptions and strengthen responsible antibiotic use among the next generation of healthcare professionals.
MacDougall *et al.*, 2017 [420]	Pre- and post-workshop survey	• Completion of the AMS curriculum significantly improved students' ability to describe the roles of different health professions in antimicrobial use (from 34% to 82%) and enhanced team communication skills (from 75% to 94%). • Students' ability to describe collaborative approaches to appropriate antimicrobial use rose significantly after the training (from 49% to 92%). • The AMS curriculum, which included online modules and small-group workshops, received high favorability ratings from students—85% for the module and 93% for the workshops. • Introducing AMS education early in medical and pharmacy training significantly improves students' knowledge, attitudes, and readiness for collaborative antimicrobial decision-making in future practice.
	Establishing and Promoting Community AMS Programs to Combat AMR	
Mitchell *et al.*, 2022 [421]	A knowledge-exchange cluster of six LMIC-based projects	• AMR in LMICs is driven by complex social and systemic behaviours, making behaviour change strategies essential for safeguarding antimicrobial effectiveness. • Community Engagement (CE) offers a context-specific approach to promote antimicrobial behaviour change, empowering communities to create locally meaningful solutions. • Existing CE interventions focus largely on human health and demand-side factors, underscoring the need to expand CE to include environmental and animal health dimensions within a One Health framework. • Though CE is challenging to evaluate and scale due to its contextual nature, synthesizing insights across diverse interventions can help clarify its broader potential in addressing AMR globally.

Okonkwo *et al.*, 2025 [422]	A Cross-Sectional Qualitative Study	• Community AMS practices in Southeast Queensland were found to be ambiguous and fragmented, indicating early-stage development compared to more established hospital-based AMS systems. • Thematic analysis revealed the need for clearer governance, system integration, and role clarity to support the effective implementation of AMS in community settings. • Applying the Elements of Medicines Stewardship (EMS) framework is essential for guiding the development and implementation of structured, multidisciplinary AMS strategies in the community. • This study underscores the importance of community-specific policies and multidisciplinary collaboration, which are vital to improving patient outcomes and addressing AMR sustainably outside hospital settings.
Engaging and Promoting Laboratory AMS Programs to Combat AMR		
Bouza *et al.*, 2018 [423]	A review study	• Laboratories play a vital role in AMS programs by: • Speeding up the laboratory workup of samples of particular significance; • Rapid reporting of positive and negative test results: Microbiology red phone; • Rapidly searching for certain pathogens; • Rapid antimicrobial susceptibility testing; • A systematic search for conflictive pathogens; • Rapid detection of resistance. • Alliance with clinical pharmacy and the stewardship committee to influence prescription: checklists. • Statistics for clinicians and epidemiologists: the stewardship committee • Periodic meetings with groups of physicians and nurses.
Perez *et al.*, 2024 [424]	An evidence-based intervention	• Rapid diagnostic integration with AMS significantly reduced time to optimal (from 80.9 h to 23.2 h) and effective antibiotic therapy (from 89.7 h to 32 h), enhancing early targeted treatment of resistant infections. • Hospital length of stay and ICU stay were markedly shortened (from 23.3 to 15.3 days and 16 to 10.7 days, respectively), indicating improved patient outcomes and more efficient resource use. • The intervention was associated with a notable reduction in 30-day all-cause mortality (from 21% to 8.9%) and remained an independent predictor of survival. • Cost-effectiveness was evident, with a reduction of $26,298 per inpatient survivor and an estimated $2.4 million in annual hospital savings.
Perez *et al.*, 2013 [425]	An evidence-based intervention	• Integration of matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS) and rapid antimicrobial susceptibility testing with AMS significantly reduced hospital length of stay (from 11.9 to 9.3 days; P = .01). • Multivariate analysis showed the AMS intervention (HR 1.38) and timely active therapy at 48 hours (HR 2.9) were independently associated with shorter hospital stays, emphasizing the importance of early targeted treatment. • Mean hospital costs per patient were significantly reduced by over $19,000 ($45,709 to $26,162; P = .009), demonstrating the economic benefit of integrating rapid diagnostics with stewardship. • The findings highlight the clinical and financial advantages of embedding rapid microbial identification within AMS programs, with potential to scale across diverse patient care settings.
Barlam *et al.*, 2016 [230]	Review Article	• Emphasized the importance of integrating clinical microbiology laboratories into AMS programs.

		• Highlighted that rapid diagnostic testing and timely communication of results are crucial for effective stewardship and improved patient outcomes.
MacVane, 2017 [426]	Review Article	• Discussed the role of rapid molecular diagnostics in AMS. • Concluded that these diagnostics significantly reduce time to pathogen identification and susceptibility results, leading to more targeted therapy and reduced inappropriate antibiotic use. • AMS programs aim to optimize the appropriate use of existing antimicrobial agents to improve outcomes for patients with MDR gram-negative infections, curb the spread of resistance, and lower hospital costs.
Messacar *et al.*, 2017 [427]	Review Article	• Explored diagnostic stewardship as a strategy to combat AMR. Found that appropriate use of laboratory testing can optimize antibiotic prescribing, reduce unnecessary antibiotic use, and improve patient outcomes. • Diagnostic stewardship ensures the selection and use of appropriate tests tailored to the clinical setting and guides testing toward the right patients. • AMS translates rapid diagnostic results into timely and appropriate clinical actions, ultimately improving patient outcomes.
Doern *et al.*, 2019 [428]	Review Article	• Reviewed the impact of rapid diagnostic testing in clinical microbiology on AMS. • The study concluded that rapid tests enhance the ability to quickly identify pathogens and resistance markers, thereby supporting timely and appropriate antimicrobial therapy.
Banerjee *et al.*, 2015 [429]	Prospective Randomized Controlled Trial	• Assessed the impact of rapid multiplex PCR (rmPCR) on the management of bloodstream infections. • The study found that rapid testing combined with AMS intervention reduced time to effective therapy and hospital length of stay. • Rapid multiplex PCR (rmPCR) significantly reduced the time to microorganism identification (1.3 vs. 22.3 hours) and enabled quicker antimicrobial adjustments. • Combining rmPCR with AMS led to decreased use of broad-spectrum antibiotics, increased use of narrow-spectrum β-lactams, and reduced treatment of contaminants. • The rmPCR/AS approach resulted in the fastest antimicrobial de-escalation and escalation decisions, demonstrating the added value of stewardship in optimizing therapy.
Huang *et al.*, 2013 [430]	Quasi-Experimental Study	• Investigated the effect of rapid organism identification on clinical outcomes in patients with bloodstream infections. • The study concluded that rapid identification, when coupled with AMS, improved time to effective therapy and reduced mortality. • Implementation of matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) with AMS significantly reduced time to organism identification (55.9 vs. 84.0 hours) and improved both times to effective (20.4 vs. 30.1 hours) and optimal antibiotic therapy (47.3 vs. 90.3 hours). • Clinical outcomes such as mortality, ICU stay, and recurrent bacteremia were lower in the intervention group, suggesting the potential benefits of the combined approach. • Acceptance of AMS recommendations showed a trend toward reduced mortality, highlighting the value of integrating stewardship with rapid diagnostics.
Establishing and Promoting Animal Health AMS Programs to Combat AMR		
Lloyd and Page,	Review study	• AMS programs have lagged in animal health compared to human health but

2018 [431]		their implementation is required to address AMR.
Allerton and Russell, 2023 [432]	Review study	• Veterinary AMS is essential to the One Health movement, promoting awareness of AMR among prescribers. • The reviewed educational resources cover key AMS themes, such as AMR mechanisms and rational antimicrobial use, while providing strategies to effectively communicate this knowledge to pet owners and farmers.
Espinosa-Gongora *et al.*, 2021 [237]	Cross-sectional study	• The findings also highlight gaps in veterinary curricula that, if addressed, could enhance AMS education. • Key areas for improvement include better integration of clinical rotations with pre-clinical theory, more effective training in antimicrobial best practices, and greater incorporation of international and national antimicrobial use guidelines to strengthen knowledge of drug classes across species and disease.
Hardefeldt *et al.*, 2022 [433]	Implementation trial in 135 general veterinary practices	• AMS interventions led to a 50% reduction in antimicrobial prescribing rates over four years, with significant decreases in the use of high-importance antimicrobials. • AMS interventions were implemented across a large network of general veterinary practices. • These interventions led to a reduction in overall antimicrobial use. • There was a notable shift toward using antimicrobials classified as low importance. • The most significant impact was observed in clinics with previously high prescribing rates.
Redding *et al.*, 2023 [434]	Cross-sectional qualitative study	• Veterinary technicians are knowledgeable about antimicrobials but often lack a full understanding of AMR and AMS concepts. • They can identify antimicrobial misuse and already contribute through client education and communication with veterinarians. • There is strong interest among technicians to participate in AMS programs. • Barriers include hierarchical practice structures, time constraints, and limited AMS-specific training. • Targeted education and systemic changes are needed to enable meaningful involvement of veterinary technicians in AMS efforts.
Walker *et al.*, 2022 [435]	Pre-post-intervention study in a companion animal practice	• Implementation of PROTECT-ME guidelines changed prescribing behaviours, notably reducing cefovecin use in cats and metronidazole use in dogs. However, overall prescription rates increased over time. • Discussions around AMS are more likely to influence the choice of antimicrobial prescribed rather than the decision to prescribe or not. • AMS interventions may be more effective when focused on promoting appropriate antimicrobial selection rather than solely aiming to reduce prescription frequency.
Lagana, Taylor, Scallan Walter, 2023 [436]	Cross-sectional qualitative study	• Veterinarians recognize the importance of AMS and understand its principles, but face practical barriers to consistently applying judicious antimicrobial use. • Technological tools are viewed as beneficial for AMS, provided they assist with prescribing decisions and deliver concise, reliable stewardship guidance. • Successful AMS tools must integrate seamlessly into existing clinical workflows, ensuring ease of use without disrupting practice efficiency. • There is a need for centralized access to antimicrobial use data, regional AMR patterns, and communication aids to support AMS in companion animal practice.
Robbins *et al.*, 2024	A Retrospective Study	• Fluoroquinolones were the most frequently prescribed WHO critically

[437]		important antimicrobials (CIAs) in both dogs and cats, with limited use of highest-priority classes like carbapenems and polymyxins. • Adherence to antimicrobial use guidelines was suboptimal (57.8%), mainly due to lack of culture and susceptibility (C/S) testing and unnecessary use of higher-tier antibiotics. • Although C/S testing increased post-AMS guideline implementation, overall guideline adherence remained low, with no observed change in infection confirmation, culture positivity, or resistance patterns. • These findings indicate the need to strengthen AMS programs in animal health.
Craig *et al.*, 2023 [438]	A systematic literature review describing behavior-change interventions	• The lack of studies describing the animal health sector precluded a meta-analysis. • Employing interventions such as veterinarian guidance on husbandry, biosecurity, or AMU, educational programs, AMU evaluation and feedback, and initiatives to implement infection prevention and control methods resulted in a significant overall reduction in AMU ($p < 0.05$). • Therefore, there is a need to instigate effective and efficient AMS programs in animal health to reduce and curb AMR.
Hardefeldt *et al.*, 2018 [439]	Qualitative semi-structured interviews	• Programs for AMS have not yet been extensively adopted in veterinary practice. • The cost of microbiological testing, client expectations and practice competition, a lack of AMS governance structures, and limited access to AMS resources, education, and training were the main obstacles. • Concern for how veterinary antibiotic usage contributes to the emergence of AMR in humans, pride in the services rendered, and readiness to modify prescribing procedures were the enablers. • The study provides insights that can inform the development and implementation of AMS programs in veterinary practices by identifying key factors influencing veterinarians' prescribing behaviour.
Mutua *et al.*, 2020 [440]	A desk review of the literature to identify practices of animal health and drug use in India	• AMS programs in livestock have not yet been established, and there is a lack of awareness of AMR. • Measures like the National Health Policy, the National Action Plan on AMR, and the National Program for Containment of AMR demonstrate a commitment to tackling the issue of AMR in the nation. • Incentives to increase their adoption should be investigated, as should involving stakeholders in a "theory of change" exercise through interventions that address AMR from the standpoint of animal health. • Interventions that address AMR from the animal health perspective should be promoted, and incentives to increase their adoption explored.
Shano *et al.*, 2024 [441]	A qualitative study using the Capability, Opportunity, and Motivation for Behavior (COM-B) model, conducted via semi-structured interviews with registered veterinarians in Bangladesh	• It is strongly advised that behavioural theories be incorporated into the development of AMS treatments meant to maximize the prescription of antibiotics in veterinary practice. • Under "Capability", veterinarians' prescription behaviour is influenced by elements like their understanding of AMR, their capacity to manage complicated medical problems, and their ability to recognize the right kind of antibiotic, its administration routes, and any possible adverse effects. • Under "Opportunity", the absence of laboratory testing facilities, inadequate farm biosecurity, farm location and management, agricultural conditions, climate change impacts, animal clinical histories, and social influence from various actors all had an impact on veterinarians' prescribing behaviour. • The study recommends integrating identified influencing factors into current or new AMS interventions to better address antimicrobial

		over-prescription. • The Behavior Change Wheel is proposed as a guiding framework for designing AMS strategies that enhance capability, opportunity, and motivation among prescribers.
Virhia *et al.*, 2024 [442]	In-depth interviews with animal and human health providers in rural northern Tanzania	• Coordinated AMS programs that take into account complex problems and local knowledge can lessen the burden of AMR. • Globally, there has been emphasis on the need for health workers to increase their understanding of AMR and AMS. Many healthcare professionals attribute AMR to the acts of others, even if they acknowledge that these are frequently motivated by a lack of options. • Addressing the blame narrative that pervades the AMR discourse, raising awareness of the obstacles to optimal AMS, and lowering the structural factors limiting providers' daily practices requires the participation of the larger AMR community in discussions of the challenges that have been identified. • Implement structured, context-specific AMR communication campaigns that are co-designed with target audiences and guided by communication and behaviour change theories to enhance public awareness and understanding. • Utilize a logic model framework, such as the SNAP-AMR Logic Model, to plan, implement, and evaluate communication interventions by clearly mapping resources, activities, outputs, and desired outcomes. • Promote the adaptation and use of validated communication models like Supporting the National Action Plan for AMR (SNAP-AMR) in countries with similar socio-cultural and economic contexts to support national AMR action plans and maximize campaign effectiveness.
Pinto Ferreira *et al.*, 2022 [240]	Overview of AMS on a global scale, FAO	• •To improve the management of the AMR phenomenon, AMS must be used more extensively. • Programs that strengthen governance, raise awareness, establish and improve AMR surveillance, and apply best practices for AMR in agrifood systems are all necessary to improve AMS. • •The idea of AMS in animal health is difficult to understand globally since it may be seen as abstract. In any event, it is crucial to emphasize that antimicrobials are shared resources that we must all protect as doing so will eventually result in a better and more sustainable future. • Widespread implementation of AMS is essential to control AMR, especially in agrifood systems where misuse affects human, animal, plant, and environmental health. • The FAO supports AMS efforts by strengthening governance, raising awareness, enhancing AMR surveillance, and promoting best practices in low- and middle-income countries. • Global initiatives such as the FAO's InFARM platform, campaigns to reduce antimicrobial use, and promotion of Codex AMR standards are critical for advancing responsible antimicrobial use and achieving sustainable development goals.
Abdelfattah *et al.*, [443]	Questionnaire survey of Antimicrobial Drug Use and Stewardship Practices in Adult Cows on California Dairies.	• The majority of dairy producers (96.8%) were aware that all uses of medically important antimicrobial medicines require a prescription. • Approximately 49% of respondents agreed or strongly agreed that antimicrobial medicines use in livestock does not cause problems in humans; • 45.6% of respondents included a veterinarian in their decision regarding which injectable antimicrobial medicines to purchase;

		• 48.8% of dairy producers included a veterinarian in their decision regarding which antimicrobial medicines were used to treat sick cows; • The survey documents antimicrobial use and stewardship practices in CA's dairy industry and focuses on areas for future research and education; • The results served as a roadmap for future extension and outreach efforts to advance AMS in California dairies.
Establishing and Strengthening Surveillance Systems and Activities to Combat AMR		
Pezzani *et al.*, 2020 [444]	A modified 3D combined approach matrix	• AMR surveillance provides critical data to inform and tailor AMS strategies, including empirical treatment choices and policy formulation. • Effective surveillance ensures AMS efforts extend beyond acute care to long-term care, outpatient, and veterinary settings, promoting a One Health approach. • Without robust AMR surveillance, AMS policies may be misdirected, risking increased MDR and adverse clinical outcomes.
van Kessel *et al.*, 2025 [445]	A systematic scoping review	• Data linkage in AMR surveillance enables a more comprehensive analysis of resistance patterns and dynamics, supporting hypothesis generation and targeted AMS interventions. • Linked AMR surveillance data provide actionable insights that influence clinical practice, guideline development, and future public health policies. • These studies highlight the importance of methodological improvements, better data access, and governance to strengthen AMR surveillance and its impact on AMS programmes.
Aboushady *et al.*, 2023 [334]	Retrospective review (Policy review and implementation analysis)	• AMR surveillance provides accurate, real-time data to guide evidence-based decision-making, improve clinical practices, shape national policies, and optimize empirical treatment protocols. • Surveillance systems strengthen laboratory infrastructure through standard operating procedures (SOPs), quality management systems, and harmonized antimicrobial susceptibility testing (AST), leading to better diagnosis and reduced misuse of antibiotics. • Robust surveillance allows AMS programmes to identify resistance trends, detect emerging threats, and evaluate the impact of interventions, thereby enabling targeted stewardship strategies and rational antimicrobial use. • Integrated surveillance systems across human, animal, and environmental health sectors enhance AMR response and pandemic preparedness, especially through regional data sharing and outbreak detection. • Surveillance data inform national health planning by identifying laboratory capacity gaps, guiding resource distribution, and training healthcare professionals in diagnostics, data interpretation, and reporting.
Do *et al.*, 2023 [446]	A Scoping Review	• The review identified six key themes affecting AMR surveillance systems: surveillance capacity, data infrastructure, policy, representativeness, stakeholder engagement, and sustainability. • Data infrastructure was the most frequently cited challenge (75%), indicating a critical need for investment in digital tools and reporting systems. • Stakeholder engagement emerged as the most common success factor (65.2%) in the effective implementation and use of surveillance systems. • Surveillance systems in low- and middle-income countries require further development and refinement to become representative, sustainable and aligned with global AMR surveillance objectives.
Aenishaenslin *et al.*, 2021 [447]	A Conceptual Framework	• Adopting a One Health approach in AMR and AMU surveillance is essential to effectively address health threats at the human-animal-environment interface.

		• There is currently a lack of standardized guidelines and metrics for evaluating the integration of One Health in AMR/AMU surveillance systems. • The Integrated Surveillance System Evaluation (ISSE) framework provides a structured approach for assessing One Health integration across five key components: integration capacity, information generation, actionable knowledge, decision-making influence, and outcome impact. • The ISSE framework enables stakeholders to refine and improve AMR surveillance systems globally, ensuring that evaluation efforts support continuous learning and effective decision-making in line with One Health principles.
Agunos *et al.*, 2021 [448]	Methodology development study	• This study developed a structured methodology for integrating AMU and AMR data across multiple food animal species at the farm level, using the Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS) framework. • Integration involved six key steps, including descriptive analysis, result synthesis, outcome selection, use of AMU indicators, analytical modelling, and data visualization. • Standardized metrics such as mg/Population Correction Unit (PCU) and AMR adjusted for animal biomass were incorporated to enable cross-species comparisons and inform stewardship strategies. • The integrated approach supports enhanced surveillance and AMU stewardship by providing a more comprehensive understanding of the relationships between AMU and AMR trends within and across species.
Roles of Infection Prevention and Control Measures to Combat AMR		
Lacotte *et al.*, 2020 [449]	Narrative literature review and expert survey analysis; Europe	• Identified IPC as a cost-effective intervention against AMR, highlighting the need for prioritizing IPC research and implementation. • IPC programs are essential to reducing healthcare-associated infections (HAIs), which directly lowers the need for antibiotics and helps prevent the emergence and spread of resistant pathogens—making IPC a foundational pillar in AMR containment and AMS implementation. • Understanding and addressing barriers such as socio-economic factors, behavioural practices, overcrowding, and infrastructure gaps is crucial for effective IPC implementation, which in turn strengthens AMS outcomes and overall infection control.
Magill *et al.*, 2014 [450]	Point-prevalence survey of HAIs, USA	• Highlighted the burden of healthcare-associated infections and the importance of IPC and AMS programs in reducing infection rates and improving patient safety. • A multistate survey found that 4% of hospitalized patients had at least one HAI, with pneumonia and surgical-site infections being the most common. • Clostridium difficile was the leading pathogen, responsible for 12.1% of HAIs, underscoring the need for focused AMS and infection control efforts. • Only 25.6% of HAIs were device-associated, suggesting the need to broaden surveillance and prevention efforts beyond traditional device-related infections. • Public health strategies should expand to include a wider range of HAIs while maintaining efforts to reduce C. difficile and other high-burden infections through AMS and infection prevention programs.
Allegranzi *et al.*, 2016 [451]	Implementation study; Multiple countries	• Demonstrated that multimodal IPC strategies, including AMS components, led to significant reductions in healthcare-associated infections.
Karanika *et al.*, 2016 [452]	Meta-analysis; Global	• Concluded that AMS programs are more effective in reducing AMR when combined with IPC measures, reinforcing the need for integrated approaches.

Gentilotti *et al.*, 2020 [453]	A before-after intervention cohort study in Tanzania	• Following the multidisciplinary AMS intervention, there was a significant increase in the use of antibiotic prophylaxis (98% vs 2%, $p < 0.001$), and surgical quality improved with a higher proportion of caesarean sections performed by qualified personnel (40% vs 28%, $p = 0.001$), and the adoption of best practices such as Pfannenstiel incisions and intradermic sutures. • The intervention led to a marked reduction in post-caesarean SSIs (17% post vs 48% pre-intervention, $p < 0.001$), alongside a lower prevalence of gram-positive bacteria and methicillin-resistant Staphylococcus aureus in post-intervention samples. • The intervention also resulted in a shift in microbiological patterns, with a reduced prevalence of Gram-positive pathogens and methicillin-resistant Staphylococcus aureus (MRSA). • These findings support the effectiveness of hospital-based AMS and IPC strategies, especially in reducing AMR and infection burden in resource-limited settings.
Utilizing Artificial Intelligence to Combat AMR		
Liu *et al.*, 2024 [454]	Narrative Review	• Al technology constitutes can be used to predict novel antibiotic compounds, while image-based can help identify resistant bacteria. • Al can also predict potential resistance sites and related enzymatic functions, laying the groundwork for designing better antibiotics. • More antibiotics or antimicrobials are expected to make it through the drug development pipeline and enter the market. • AI could help build systematic models to rapidly diagnose diseases and automatically recommend more personalized treatments for patients in clinical practice.
Branda and Scarpa, 2024 [370]	Perspective Approach	• The use of machine learning algorithms to analyze genomic sequences can help to quickly identify specific mutations associated with AMR. • AI-based decision support systems can guide clinicians in choosing the most appropriate antibiotics, reducing inappropriate use and minimizing the risk of AMR development e.g. implementation of a CDSS can help to analyze real-time patient data and microbiological information in order to suggest the most effective therapies while taking into account clinical history and local patterns of resistance. • AI can help to personalize antibiotic regimens by analyzing large amounts of patient data, including genetic information, aiding in the prediction of individual responses to different antibiotics. • A multidisciplinary approach that integrates AI with other emerging technologies, could be effective in the mitigation of AMR, preserving the efficacy of antibiotics for future generations.
Tran, Nguyen, & Pham, 2022 [455]	Perspective Approach	• Application of AI deploying data to support AMS programs would prevent many MDR bacterial infections, lowering antibiotic use and eventually limiting the prevalence and spread of AMR. • AI models can learn new structural patterns to identify new agents with new mechanisms of action, allowing us to regain the upper hand over bacteria. • AI algorithms are gradually assisting physicians to quickly identify resistant strains through either standard Kirby-Bauer Diffusion disk or whole-genome sequencing antimicrobial susceptibility testing (AST). • AI models have optimized the in vitro combination of meropenem and polymyxin B against the carbapenem-resistant Acinetobacter baumannii. • A multidisciplinary approach of combining clinical medicine with AI would be the solution to the threat and burden of the global crisis AMR.

Lau *et al.*, 2021 [456]	Mini-review, Malaysia	• AI offers efficient ways to predict and detect AMR in bacteria. Additionally, combining machine learning algorithms with laboratory testing can markedly speed up the discovery of new antimicrobials. • Numerous machine-learning models for identifying AMR have been developed and rigorously validated. • These models often deliver highly accurate results, surpassing traditional methods that depend on sequence comparison within databases.
Zagajewski *et al.*, 2023 [457]	Experimental study design with a proof-of-concept methodological approach. United Kingdom	• The models achieved 80% single-cell accuracy in distinguishing untreated and treated susceptible *E. coli* cells across four antibiotics. For ciprofloxacin, the models identified significant differences ($p < 0.001$) between bacterial populations impacted by treatment, with phenotypic effects correlating with clinical susceptibility at 10 mg/L over 30 minutes. • Testing six *E. coli* strains with varying ciprofloxacin resistance levels revealed that single-cell phenotyping could match the information provided by growth-based antimicrobial susceptibility testing (AST) assays, but within just 30 minutes.
Olatunji *et al.*, 2024 [458]	Review methodology, United States of America	• AI has the potential to enhance the detection of AMR genes and aid in identifying antibiotic targets, as well as bactericidal and bacteriostatic molecules suitable for antibiotic development. • AI models are now capable of identifying ARGs from short next-generation sequencing raw reads or fully assembled genes. However, ARGs detected using AI still require validation through experimental, non-computational methods. • This therefore means that AI can be used as a tool and guided by domain experts to help address the problem of AMR.
Tsoukalas, Albertson, & Tagkopoulos [459]	The study employed a data-driven, probabilistic modelling approach using a Partially Observable Markov Decision Process (POMDP), in the United States.	• The study showed that a data-driven POMDP model improved sepsis management by recommending optimal antibiotic administration policies, resulting in favourable outcomes for 49% of cases compared to 37% with alternative approaches ($P = 1.3e{-13}$). • Patients under the optimal policy experienced significantly more transitions to better or stable states (605 vs. 344 patients, $P = 8.6e{-25}$) and fewer transitions to worse states (33.7% vs. 51.2%, $P = 4.6e{-117}$). • Mortality prediction achieved an AUC of 0.7 with up to 82% accuracy, while length-of-stay prediction had AUCs between 0.69 and 0.73 with similar accuracy. • These findings highlight the potential of this probabilistic framework to enhance clinical decision-making in sepsis treatment and pave the way for its application in other medical conditions with sufficient training data.
Giske *et al.*, 2024 [460]	Validation study design, Sweden	• The study assessed the performance of GPT-4 and a customized EUCAST-GPT agent in detecting beta-lactamase resistance mechanisms in Gram-negative bacteria, using routine diagnostics and microbiologists as references. • GPT models achieved high sensitivity for ESBL (95.4%), AmpC (96.9%), and carbapenemase (100%) detection, but lower specificity for ESBL (69.23%) and AmpC (86.3%), potentially leading to increased testing and costs. • Microbiologists demonstrated higher overall accuracy, with 94.4% concordance across 862 phenotypic categories, and provided concise reasoning compared to GPT agents. • While GPT-4 showed promise, its unspecific flagging and lack of regulatory approval highlight the need for further validation before clinical use.
Abavisani *et al.*, 2024 [461]	Comprehensive review approach, Iran	• According to this review, AI-powered Chatbots demonstrate significant potential in combating AMR by enhancing patient engagement, improving

		diagnostic accuracy, and promoting efficient healthcare delivery. • Recent advances in large language models (LLMs), such as ChatGPT, have shown exceptional capabilities in understanding complex medical queries and delivering tailored responses. LLMs, based on transformer networks, process and analyze vast amounts of sequential data using self-attention mechanisms, enabling faster and more accurate predictions than traditional models. • While generative AI models like ChatGPT have limitations, such as restricted access to medical data, their ability to simulate human interaction and pass medical licensing exams show their potential as valuable tools in managing infectious diseases and supporting the fight against AMR.
Harandi *et al.*, 2025 [462]	A systematic review	• AI, particularly machine learning models, plays a crucial role in AMS by optimizing empirical antibiotic selection, predicting resistance patterns, and improving treatment appropriateness. • These technologies support timely and precise adjustments to antibiotic regimens, helping reduce mortality and improve patient outcomes. • AI aids in personalized antibiotic dosing, such as for vancomycin, enhancing therapeutic efficacy while minimizing resistance development.
Tran-The *et al.*, 2024 [463]	A Retrospective Cohort Study	• AI models in AMS can significantly enhance decision-making by identifying more cases requiring targeted interventions, such as discontinuation, IV to PO switch, and de-escalation compared to conventional strategies. • These models not only improve the efficiency of AMS programs by prioritizing high-impact cases but also provide explainable insights that align with clinical reasoning. • Therefore, AI supports more precise, data-driven antimicrobial use, contributing to the fight against AMR.
	Utilizing Nanotechnology to Combat AMR	
Hajipour *et al.*, 2012 [464]	Review article	• Nanoparticles like silver, zinc oxide, and titanium dioxide exhibit antimicrobial properties through membrane disruption and oxidative stress. • They offer broad-spectrum activity and a lower risk of resistance development.
Gurunathan *et al.*, 2014 [465]	Experimental (*in vitro*) study	• Silver nanoparticles demonstrated enhanced antibacterial and antibiofilm activity against Gram-positive and Gram-negative bacteria, making them potential alternatives to antibiotics.
Hetta *et al.*, 2021 [466]	A Comprehensive Review	• Nanotechnology can enhance AMS by improving the targeted delivery and efficacy of antibiotics, thereby reducing unnecessary exposure and minimizing AMR development. • Nanoantibiotics can penetrate biofilms and treat resistant bacterial infections more effectively than conventional antibiotics, supporting better infection control. • Additionally, their synergistic effects with existing antimicrobials offer a strategy to restore the potency of older drugs and limit the emergence of MDR pathogens.
Rai *et al.*, 2012 [467]	Review article	• Silver and copper nanoparticles show effective antimicrobial action and can be integrated into surfaces, textiles, and medical devices to reduce microbial load.
Pelgrift & Friedman, 2013 [468]	Review article	• Emphasized the potential of nanoparticle-based drug delivery systems to enhance the efficacy of antibiotics and reduce off-target effects.
Zhou *et al.*, 2018 [469]	Experimental study	• Developed liposomal and polymeric nanoparticles for targeted antibiotic delivery, which improved drug stability and reduced dosage requirements.
Baptista *et al.*, 2018 [470])	Experimental study	• Demonstrated that silver nanoparticles can potentiate antibiotic action against MDR bacteria, including MRSA and *Pseudomonas* spp.

		• Nanoparticles can support AMS and combat AMR by enabling targeted drug delivery and disrupting bacterial functions such as cell wall integrity, efflux mechanisms, and essential metabolic pathways, thereby enhancing treatment efficacy and reducing the need for broad-spectrum antibiotics.
Lara *et al.*, 2010 [471]	Experimental study	• Silver nanoparticles demonstrate potent anti-HIV activity by primarily targeting the early stages of viral replication. They inhibit viral entry by binding to gp120, thereby blocking CD4-dependent fusion and infectivity, and also affect post-entry stages, making them effective against both cell-free and cell-associated HIV strains. • Given their broad-spectrum activity and low risk of inducing resistance, silver nanoparticles hold promise as a novel preventive agent against diverse HIV-1 strains.
Durán *et al.*, 2016 [472]	Review article	• Advocated for the integration of green-synthesized nanoparticles in infection control, citing lower toxicity and sustainable production methods. • Silver nanoparticles offer a promising strategy to address AMR and support AMS by exerting broad-spectrum antibacterial effects through mechanisms such as membrane disruption, DNA interaction, and reactive oxygen species generation, although the exact mode of action and potential for resistance development remains under investigation.
Rai *et al.*, 2012 [467]	Review article	• Silver and copper nanoparticles show effective antimicrobial action and can be integrated into surfaces, textiles, and medical devices to reduce microbial load.
Pelgrift & Friedman, 2013 [468]	Review article	• Emphasized the potential of nanoparticle-based drug delivery systems to enhance the efficacy of antibiotics and reduce off-target effects.

4. Discussion

This comprehensive narrative review was undertaken to provide detailed AMS programs instigated to address AMR across the One Health sector. The study found that AMS, surveillance, IPC programs, nanotechnology and the use of AI are critical in addressing AMR in a One Health approach. Therefore, effective implementation of AMS, surveillance, and IPC programs in healthcare facilities, farms, communities, universities/colleges and schools is essential to combat AMR from a One Health perspective.

4.1. Overview of Antimicrobial Stewardship Programs

Antimicrobial stewardship (AMS) programs are coordinated programs that promote the appropriate use of antimicrobials, leading to improved patient outcomes, reduced microbial resistance, and decreased spread of infections caused by MDR organisms [245] [248] [413] [473] [474]. These programs constitute a coherent set of actions that have been established to ensure the optimal use of antibiotics and improve patient outcomes [246]. It is essential to take into consideration the One Health approach (humans, animals, plants, and the environment) when developing AMS strategies to address AMR [235]. AMS programs have demonstrated effectiveness in reducing the occurrence of AMR and HAIs, as well as being cost-saving through addressing inappropriate antimicrobial usage in healthcare settings [379]. AMS Programs promote AMS principles, such as antimicrobial optimization and IPC measures, and these programs help to reduce the emergence and spread of resistant pathogens within healthcare settings [316] [340]. Additionally, AMS programs are key in facilitating surveillance efforts to monitor AMR patterns, identify emerging resistance trends, and implement targeted interventions to address resistance hotspots [248].

AMS programs in hospitals play a pivotal role in combating AMR from a One Health perspective, integrating efforts across human health, animal health, and environmental sectors [475]. AMS as an integral component of health systems is a cooperative, diverse, and multidisciplinary strategy which engages different stakeholders such as healthcare leaders, scientists, microbiologists, infectious disease specialists, physicians, nurses, farmers, veterinarians, public health practitioners, environmental health practitioners, IT experts, and clinical pharmacists to improve patient treatment outcomes and safety through curtailing the development of resistant pathogens [73] [476]. These programs are designed to optimize antimicrobial use, promote judicious prescribing practices, and enhance patient outcomes while mitigating the emergence and spread of resistant pathogens [248]. To successfully implement AMS and IPC programs, there is a need for continued education and training on these strategies to address AMR [263]. Finally, continuous monitoring and evaluation of the implementation and impact of AMS programs in hospitals is very critical [232] [233] [393] [477].

4.2. Hospital-Based Antimicrobial Stewardship Programs to Combat Antimicrobial Resistance

Hospital AMS Programs strive to enhance the rational utilization of antimicrobial agents through a range of interventions [391] [394] [397] [478]-[483]. These interventions include implementing clinical guidelines for appropriate antimicrobial prescribing, promoting the use of narrow-spectrum antibiotics over broad-spectrum ones whenever possible, and encouraging de-escalation or discontinuation of antimicrobial therapy when it is no longer necessary [68] [231] [250]. Through advocating for rational use of antimicrobials, these initiatives aid in minimizing the selection pressure for resistant pathogens, thereby lowering the likelihood of AMR emergence and spread [379] [484]-[487].

In this review, AMS programs were found to be critical in promoting the rational use of antimicrobials in hospitals. This review further found that the implementation of AMS programs in hospitals led to improved awareness, knowledge, attitudes, and practices concerning AMR among healthcare workers. A study in Zambia found that after the instigation of AMS activities, healthcare workers who were involved implementation of AMS activities had good knowledge, attitudes, and practices regarding AMR and AMS [269]. Therefore, AMS programs provide education and training for healthcare workers concerning the appropriate use of antimicrobials to improve patient outcomes and combat AMR [234] [244] [262] [265] [271] [477] [488]-[490].

AMS programs contribute significantly to improving patient outcomes by ensuring that antimicrobial therapy is customized to individual patient needs [491]

[492]. Additionally, AMS programs promote the appropriate use of antimicrobial agents at the right doses and durations; these programs help optimize treatment efficacy while minimizing the risk of adverse effects such as antibiotic-associated infections and the emergence of drug-resistant pathogens [493]. Hence, healthcare workers must adhere to the treatment guidelines when prescribing, dispensing, administering, and monitoring the use the use antimicrobials [253] [257] [261] [494] [495]. As a result, patients receiving care in hospitals with robust AMS programs are more likely to experience better clinical outcomes, reduced treatment failures, and shorter hospital stays [246]. Alongside this, successful AMS programs must be implemented by a team of multidisciplinary healthcare workers [344] [496]-[499]. Current evidence indicates that pharmacist-led AMS interventions have been very crucial to combat AMR [409] [410] [485] [500] [501]. Therefore, healthcare workers have a huge role to play in instigating AMS programs and combating AMR.

4.3. Implementing AMS in Communities and Universities to Combat Antimicrobial Resistance

AMS programs in communities play a vital role in addressing AMR by promoting responsible AMU, raising awareness about AMR, and fostering collaboration among diverse stakeholders [400]. By engaging healthcare providers, patients, caregivers, and community members, these programs contribute to the preservation of antimicrobial effectiveness and the protection of public health. Embracing a One Health approach to AMS in communities is essential for mitigating the threat of AMR and ensuring the sustainable use of antimicrobial agents across human, animal, and environmental domains [421] [502] [503].

In this review, studies have demonstrated the effectiveness of community-based AMS interventions, showing that structured educational initiatives significantly improve knowledge, attitudes, and practices regarding antibiotic use [404]. Furthermore, a multicenter study conducted in three major provinces in China revealed that while pharmacists held generally positive perceptions of AMS programs, gaps in knowledge and limited participation were prevalent [405]. This suggests that despite their willingness to support stewardship initiatives, pharmacists require targeted training and structured AMS frameworks to maximize their impact. Thus, further highlighting the urgent need for regional, community-based AMS programs that integrate pharmacists as key stakeholders, ensuring they are adequately equipped to contribute to AMS efforts [400] [504]. However, AMS interventions have proven effective in correcting misconceptions and modifying antibiotic use behaviours, as revealed by a study conducted in Bhaktapur District, Nepal [406]. Additionally, there was a notable increase in public understanding of respiratory illnesses such as coughs, leading to a significant reduction in the use of unnecessary cough medicines post-intervention [406]. These findings emphasize that AMS programs tailored to community-specific needs can effectively curb inappropriate self-medication practices and promote more rational antibiotic use.

The implementation of AMS programs in universities is a valuable strategy to enhance students' awareness and knowledge of AMR [411]. Effective AMS programs within universities have been shown to successfully improve students' understanding of antimicrobials, the growing threat of AMR, and the core principles of AMS [411] [484] [488]. This is particularly important because university students, especially those in health-related fields, are future healthcare professionals who will play a critical role in combating AMR. By targeting this population with tailored educational interventions, universities can foster responsible antibiotic prescribing practices and promote a culture of AMS early in their professional development. Therefore, this review found that effective implementation of AMS programs in universities contributes to an improvement in awareness and knowledge of antimicrobials, AMU, AMR, and AMS among students.

4.4. The Role of Laboratories in Antimicrobial Stewardship Programs to Combat Antimicrobial Resistance

Laboratories play a crucial role in addressing AMR and are integral to antimicrobial stewardship (AMS) programs [75]. They provide essential services such as rapid pathogen identification and antimicrobial susceptibility testing, which are vital for tailoring specific therapies and improving patient outcomes. The integration of microbiology laboratories into AMS programs enhances the effectiveness of these programs by ensuring timely and accurate data, which is critical for informed decision-making in clinical settings [505]. Microbiology laboratories facilitate the early identification of pathogens and conduct antimicrobial susceptibility tests, which are crucial for directing targeted therapy and reducing inappropriate antibiotic use [505]. Rapid reporting of test results allows for timely adjustments in treatment plans, thereby improving the delivery of care and reducing the consequences of antimicrobial use [505]. Laboratories are a major component of AMS programs, providing data that help in the formulation of effective treatment strategies and the prevention of unnecessary antibiotic prescriptions [506]. Effective communication between laboratory staff and clinicians is essential to achieve the goals of AMS, ensuring that the data provided by laboratories are utilized effectively [506].

The laboratory plays a critical role in detecting and reporting MDR pathogens, which informs targeted antimicrobial therapy [507]. In Lebanon, the first case of carbapenem-resistant Enterobacteriaceae (CRE) was reported by the CML at the American University of Beirut Medical Center (AUBMC) in 2008, showcasing the importance of laboratory-based AMR surveillance [507]. Early identification of resistant strains enables timely intervention and improves patient outcomes [507]. Variation in laboratory capabilities affects the accuracy of bacterial identification and antimicrobial susceptibility testing (AST), leading to potential misdiagnosis and inappropriate antibiotic use [507]. Ensuring standardized laboratory practices and training can enhance diagnostic accuracy and AMS effectiveness [508]. The laboratory implements strict protocols for specimen collection and processing to minimize contamination and reduce unnecessary antibiotic prescriptions [508]. The adoption of new rapid diagnostic technologies can improve diagnostic efficiency while balancing healthcare costs [508].

Data sharing between private and public laboratories is essential for tracking resistance trends and guiding public health policies [509].

Effective LIS enhances data collection and analysis, improving AMR surveillance and clinical decision-making [510]. Reliable resistance data support the development of AMS policies and public health strategies [510].

Clinical microbiology laboratories play a critical role in antimicrobial stewardship by integrating rapid diagnostics, biomarker utilization, and antibiogram development to guide appropriate antimicrobial use [511] [512]. Rapid diagnostic tests play a crucial role in AMS by enabling the timely and accurate identification of pathogens, allowing for targeted antimicrobial selection [513]-[515]. Additionally, rapid diagnostic tests have the potential to enhance antimicrobial use by enabling timely pathogen identification, guiding targeted therapy, and reducing unnecessary antibiotic prescriptions [516]. By reducing reliance on broad-spectrum antibiotics, these tests help improve patient outcomes and minimize the development of AMR [513]. Biomarkers have been increasingly incorporated into diagnostic algorithms to differentiate infections that necessitate antimicrobial treatment, helping to reduce unnecessary prescriptions [511]. Additionally, laboratories compile aggregate antimicrobial susceptibility data to develop antibiograms, providing valuable insights into local resistance patterns and informing empirical therapy decisions [511] [517] [518]. By leveraging these tools, laboratories enhance AMS efforts, ultimately improving patient outcomes and mitigating the spread of AMR [511].

4.5. Implementing Antimicrobial Stewardship Programs in Animal Health to Combat Antimicrobial Resistance

Antimicrobials are widely used in animals for prophylaxis, growth promotion, and treatment of infections. The overuse and misuse of antimicrobials in animals may lead to the development and spread of antimicrobial-resistant infections. Consequently, the resistant pathogens may be transmitted to humans. Therefore, AMS programs must be extended to the animal health sector to promote the rational use of antimicrobials. However, it is noted that AMS programs have lagged in implementation in veterinary medicine compared to human health [431]. AMS programs are widely implemented in human hospitals worldwide and have been shown to improve clinical outcomes for patients while limiting the emergence and spread of AMR [241] [242] [246] [264] [484]. However, AMS in veterinary medicine is not as well defined as it is in the human sector; therefore, there has been a need for improved AMS in veterinary practices. In human medicine, the term AMS programme generally refers to specific programmes or interventions to monitor and direct AMU at the hospital and community level [486] [519] [520]. Further, in large human hospitals, this avenue encompasses multidisciplinary teams which include clinicians, microbiologists, pharmacists, nurses and doctors

[235]. Lastly, medical strategies for AMS are unlikely to be directly applicable to veterinary medicine because of differences in the availability of human and financial resources for the diagnosis and treatment of individual animals, geographical spread, and limited tools supporting AMS in the veterinary sector [240] [521]. Efforts have been made by other researchers to develop AMS programs in the veterinary sector [522]. Therefore, in veterinary medicine, the term AMS usually encompasses numerous elements directed towards improved AMU. The first step towards improving AMS in veterinary medicine is to develop NAPs that deliberately target Veterinary medicine. Other programs that will aid in the progression of AMS in veterinary medicine include the development of treatment guidelines, AMS guidelines for veterinary and veterinary paraprofessionals, the creation of regional laboratories and encouraging the use of alternatives to antimicrobials.

Based on the provided evidence, AMS activities in animal health promote the rational use of antimicrobials [240] [432]. There is a strong need to implement sustainable AMS programs in animal health, thereby addressing AMR from a One Health perspective [146] [235] [432] [502].

4.6. The Application of Nanotechnology in Combating Antimicrobial Resistance

Nanotechnology offers innovative solutions to combat AMR, a growing global health threat that affects humans, animals, and the environment in the One Health approach [358] [468] [523]-[528]. By manipulating materials at the nanoscale, scientists have developed nanoparticles (NPs) with potent antimicrobial properties that can target drug-resistant bacteria more effectively than conventional antibiotics [526]. Silver, gold, and zinc oxide nanoparticles, among others, have demonstrated broad-spectrum antimicrobial activity by disrupting microbial cell membranes, generating reactive oxygen species, and interfering with essential cellular processes [362] [464] [529]. Similar evidence has shown that silver, gold, zinc oxide, and copper nanoparticles exhibit antimicrobial effects via membrane disruption and interference with cellular processes [530]. Their multi-targeted modes of action reduce the likelihood of resistance development, making them promising tools in AMR control strategies [531]. Alongside this, nanotechnology can be used for rapid diagnosis and hence treatment of infections to prevent resistance [368] [369]. Their role to treat antimicrobial-resistant and MDR-infections makes nanomaterials very significant weapons in the fight against AMR [368] [466]. The targeted delivery role of nanomaterials makes them very effective to treat infectious diseases and resistant pathogens [524] [532].

Currently, different classes of nanomaterials including metallic, polymeric, and lipid-based nanoparticles, have demonstrated promising antimicrobial properties through various mechanisms of action [363]. These mechanisms primarily involve disruption of microbial cell membranes, induction of oxidative stress via the generation of reactive oxygen species (ROS), interference with intracellular components, and inhibition of biofilm formation [363].

In the One Health context, nanotechnology-based interventions can be integrated across human and veterinary medicine, agriculture, and environmental health. For instance, nano-formulations of antibiotics can improve drug delivery in both humans and livestock, enhancing therapeutic efficacy while minimizing the dose and duration of antibiotic use [465]. In agriculture, nanoparticle-based disinfectants and coatings on animal feed or farm equipment can reduce the spread of resistant pathogens. Additionally, nanomaterials can be employed in environmental monitoring systems to detect antimicrobial residues and resistance genes in water or soil, providing early warning systems for AMR hotspots [533]-[536].

Incorporating nanotechnology into AMS programs aligns with the One Health vision by promoting innovative, cross-sectoral interventions that address AMR at its source. Consequently, for successful implementation, rigorous assessment of nanoparticle toxicity, environmental impact, and regulatory frameworks is essential. Future research should prioritize eco-safe nanomaterials and scalable applications, ensuring that nanotechnology enhances stewardship without introducing new risks. As part of an integrated strategy, nanotechnology holds the potential to revolutionize how we detect, prevent, and treat infections in a world increasingly threatened by antimicrobial resistance.

4.7. The Application of Artificial Intelligence in Antimicrobial Stewardship to Combat Antimicrobial Resistance

Innovative AI models offer valuable insights into the development of novel antimicrobials, repurposing of existing medications, and combination therapies through molecular structure analysis [373] [537]. Alongside this, machine learning algorithms are useful in the rational design of antimicrobial peptides [538] [539]. AI-driven clinical decision support systems provide real-time guidance to healthcare professionals, which helps optimise antibiotic prescribing practices. Additionally, this review has highlighted AI's potential to enhance AMR surveillance, analyse resistance trends, and facilitate early outbreak detection, ultimately informing data-driven public health strategies.

The findings from this narrative review the important role that AI can play in addressing AMR across the One Health sector. AI has shown promise in various aspects of AMS programs, such as the prediction of novel antibiotic compounds, the identification of AMR, and the analysis of potential resistance sites [540] [541]. Liu *et al.* (2024) explain how AI can enhance antibiotic discovery by predicting enzymatic functions related to resistance, which could facilitate the development of more effective antibiotics [454]. AI-driven diagnostic models have the potential to rapidly identify resistant strains and recommend personalized treatments, which can also improve clinical outcomes.

Machine learning algorithms are proving to be effective and useful in analysing genomic sequences to detect mutations associated with antibiotic resistance [542]. This is very useful in predicting the emergence of AMR and thus suggests the appropriate treatment [542] [543]. Branda and Scarpa emphasize the role of AI-based decision support systems in guiding clinicians to select the most appropriate antibiotics, thus minimizing the risk of resistance development [370]. The integration of AI into clinical decision-making, especially through computerized decision support systems (CDSS), allows for real-time analysis of patient data and microbiological information, ensuring more precise and effective antimicrobial treatments [544] [545].

The potential of AI in AMS programs extends to preventing MDR bacterial infections. Tran, Nguyen, and Pham (2022) discussed how AI models can identify new structural patterns for antibiotic agents, optimizing antimicrobial combinations against resistant pathogens [455]. Their findings suggest that AI-assisted AST, using both traditional Kirby-Bauer diffusion methods and whole-genome sequencing, is enhancing the ability to quickly and accurately identify resistant strains [373] [545]. The multidisciplinary approach of combining AI with clinical medicine could be instrumental in controlling the global AMR crisis.

Lau *et al.* [177] reinforce the importance of AI in predicting and detecting AMR, especially when integrated with machine learning algorithms [456]. These models have been rigorously validated, often surpassing traditional sequence-comparison methods in accuracy. Similarly, an experimental study by Zagajewski *et al.* (2023) and Ji *et al.* (2021) demonstrated that AI-driven single-cell phenotyping achieved 80% accuracy in distinguishing untreated and treated *E. coli* cells across multiple antibiotics [457] [546]. Their findings indicate that AI-based methods can provide rapid and reliable alternatives to conventional growth-based AST assays, potentially reducing the time required for resistance detection to just 30 minutes.

In the realm of antibiotic resistance gene (ARG) detection, AI has emerged as a powerful tool. A study by Olatunji *et al.* (2024) explained AI's ability to identify ARGs from next-generation sequencing data [458]. This ability offers a promising approach that can be used for detecting resistance mechanisms in bacteria. However, they also stress that AI predictions must be validated through experimental methods so as to ensure reliability before implementation in clinical settings.

Recent advancements in AI, coupled with growing computational capabilities, have accelerated the integration of AI into various biomedical applications [547]. Further validating AI's potential in AMR detection, Giske *et al.* (2024) assessed the performance of GPT-4 and a specialized EUCAST-GPT agent in identifying beta-lactamase resistance mechanisms in Gram-negative bacteria [460]. While these AI models exhibited high sensitivity in detecting resistance, their lower specificity suggested a potential for increased testing and costs. The study highlights the need for further validation and regulatory approval before AI tools can be fully integrated into clinical microbiology.

On the part of the emerging role of AI-powered Chatbots and large language models (LLMs) in AMR mitigation. Studies have found that these technologies are enhancing patient engagement, improving diagnostic accuracy, and streamlining healthcare delivery. Advances in generative AI, such as ChatGPT, have demonstrated their ability to process vast amounts of medical data and provide informed responses, despite limitations related to medical data access and regulatory concerns [548] [549]. AI Chatbots indeed have the potential to complement AMS efforts by promoting appropriate antibiotic use and improving patient outcomes. If this potential should be fully realized, there is a need for rigorous clinical trials, interdisciplinary collaboration, regulatory clarity, and tailored algorithmic improvements to ensure their safe and effective integration into clinical practice [550]. Therefore, combating AMR requires leveraging AI and machine learning as potential weapons for AMS that must be further investigated [551] [552].

4.8. Implementing Infection Prevention and Control and Biosecurity in Antimicrobial Stewardship and Combating Antimicrobial Resistance

Infection prevention and control (IPC) plays a critical yet often underemphasized role in strengthening AMS efforts within the broader One Health approach to combat. Effective IPC practices such as hand hygiene, sanitation, environmental cleaning, and biosecurity measures reduce the transmission of resistant pathogens in healthcare settings, veterinary practices, and community environments, thereby lowering the need for antimicrobial use [553]-[557]. By minimizing infections at the source, IPC not only complements AMS by decreasing inappropriate antimicrobial prescriptions but also helps to preserve the efficacy of existing drugs. In human and animal health sectors alike, the integration of IPC into AMS programs supports a coordinated response to AMR, especially in low- and middle-income countries where resources are limited and cross-sectoral collaboration is vital [316] [558]-[560]. Furthermore, environmental IPC strategies such as waste management and water quality control contribute to mitigating the spread of resistant organisms between ecosystems, aligning with the core principles of One Health [561] [562]. Thus, embedding IPC within AMS frameworks across human, animal, and environmental health sectors enhances resilience against AMR and supports sustainable global health security.

4.9. Embracing a One-Health Approach to Combat Antimicrobial Resistance

AMR is a complex, global public health challenge that transcends human health and impacts animals, plants, and the environment [15] [125] [135] [563]-[568]. The One Health approach recognizing the interconnectedness of human, animal, and environmental health, provides a holistic framework for addressing AMR [146] [195] [226] [227] [569] [570]. This integrated perspective is essential given the multifactorial drivers of AMR, including the misuse of antibiotics in human medicine, overuse in livestock and aquaculture, and the release of antimicrobial agents into the environment through waste streams [55] [66] [195] [571]-[573]. The WHO, the WOAH, and the FAO have all emphasized the need for coordinated action across sectors to effectively manage AMR risks and protect global health [14] [354] [356] [574].

Implementing a One Health strategy involves strengthening surveillance systems, promoting AMS, and improving biosecurity across all sectors [227] [228] [575]-[579]. For instance, integrated AMR surveillance, such as that promoted by the Global Antimicrobial Resistance and Use Surveillance System (GLASS), can monitor trends in AMR and AMU across humans, animals, and the environment [326]-[329] [580]. Simultaneously, AMS programs should be adapted to specific contexts, ensuring responsible prescribing in human health, reducing prophylactic use in animals, and promoting infection prevention measures [235] [239] [240] [436] [581]. A successful example includes the Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS), which harmonizes AMU and AMR data from farm-level animal populations to inform policy and drive behaviour change [165] [577] [582]-[584]. Such multisectoral programs provide evidence-based guidance to regulate AMU and help curb the spread of AMR [335] [585].

Moreover, education, collaboration, and policy harmonization are critical components of the One Health approach [227] [565] [569] [586]-[590]. Cross-sectoral education programs targeting healthcare providers, veterinarians, farmers, and environmental scientists foster shared responsibility in combating AMR [237] [242] [265] [441] [591]-[594]. Collaborative governance structures, such as national AMR coordinating committees, play a vital role in ensuring policy alignment and resource mobilization across sectors [220] [223] [228] [595]-[598]. For low- and middle-income countries, international partnerships and capacity-building initiatives are crucial to implementing effective One Health AMR strategies [238]. Embracing One Health not only offers a sustainable pathway to manage AMR but also strengthens health systems resilience and contributes to achieving the Sustainable Development Goals (SDGs) related to health, food security, and clean water [599].

4.10. Other Alternatives to Combat Antimicrobial Resistance

Evidence has demonstrated the usefulness of alternatives to conventional antimicrobials to combat AMR [146] [530] [600]. Some of the strategies used to combat AMR using alternatives to antimicrobials are discussed below:

a. Plant-Derived and Traditional Medicines

Medicinal plants are rich reservoirs of antimicrobials and produce diverse secondary metabolites such as flavonoids, terpenoids, alkaloids, polyphenols, and saponins that inhibit microbial growth, disrupt cell walls, impede DNA replication, interfere with biofilm formation, and modulate virulence [601]-[607]. They often act via multiple targets, which makes it more difficult for pathogens to develop resistance. Studies show plant compounds can synergize with antibiotics, enhancing potency or restoring efficacy against resistant strains. African medicinal plants are emerging as promising alternatives against MDR pathogens, with structural diversity and cost-effective production [608]. *Desmodium styracifo-*

lium (used in Chinese medicine) demonstrates broad antibacterial and antifungal activities in vitro and in vivo [603]. More than 30% - 50% of current pharmaceuticals derive from plant metabolites, showing the deep potential of phytochemicals in novel drug discovery [609]. Despite the promise, plant-based antimicrobials face challenges including limited sourcing, variable pharmacokinetics, lack of molecular target insight, and scalability hurdles [610]. Consequently, addressing these challenges would make the plants a good source of antimicrobials which are critical for combating AMR.

b. Vaccines' Role in Preventing Antimicrobial Resistance

By preventing infections, vaccines reduce the need for antibiotic treatments, ultimately lowering the emergence and spread of resistant pathogens [600]. The WHO highlights vaccines as a key intervention in a multi-pronged AMR strategy, offering herd and individual-level protection [611] [612]. Consequently, most vaccines target viruses, but there's a critical need to develop bacterial vaccines for key AMR threats: carbapenem-resistant *Klebsiella pneumoniae*, MRSA, and third-generation cephalosporin-resistant *E. coli*, among others [600].

c. Other Non-Traditional Antimicrobial Alternatives

1. Bacteriophage Therapy

Bacteriophage therapy is viruses that kill bacteria and are currently being resurrected in the fight against resistant infections [613]. Bacteriophages are effective in managing infections caused by MDR pathogens [614] [615]. They can penetrate biofilms, target bacteria with high specificity, and evolve alongside bacterial adaptation. Additionally, it is essential to consider the importance and roles of probiotics and microbiota in combating AMR [616].

2. Antimicrobial Photodynamic Therapy (aPDT)

This involves activating photosensitizers using light to destroy microbes. Antimicrobial photodynamic therapy using methylene blue effectively inactivated 26 *E. coli* strains, regardless of their antibiotic resistance profiles in both planktonic and biofilm states, demonstrating its potential as an alternative strategy against MDR bacteria [617]. This therapy offers > 99.999% inactivation across a range of pathogens, including those in antibiotic-resistant biofilms [618].

3. Immunomodulators and Monoclonal Antibodies

Monoclonal antibodies are among the treatment therapies for bacterial infections and should also be investigated thoroughly [614] [619] [620]. Treatments such as bezlotoxumab (targeting *C. difficile* toxins) and AR-301 (for *S. aureus*) support anti-infective strategies beyond traditional antibiotics [621].

4. Integrated and One-Health Approaches

Combining plant-based medicines, vaccines, phages, nanotechnology, and immune-based therapies via a One-Health framework is critical. This strategy includes animal, human, and environmental health through integrated surveillance and policy action. In livestock, bacteriocins, antimicrobial peptides, and phages are emerging, along with improved living conditions and vaccination to reduce antibiotic use.

5. Addressing Climate Change Problems

Addressing climate change is increasingly recognized as a critical component in the global response to AMR [622]. Climate-related factors such as rising temperatures, extreme weather events, and altered precipitation patterns can influence the transmission, persistence, and spread of infectious diseases, thereby increasing the demand for antimicrobials and potentially accelerating the emergence and dissemination of resistant pathogens [623] [624]. Warmer climates enhance the survival of resistant bacteria in water, soil, and food systems, creating environmental reservoirs that contribute to the AMR burden [624]. Additionally, climate-induced disruptions to sanitation, hygiene, and healthcare services, especially in LMICs, can exacerbate inappropriate AMU [625]. Sustainable climate mitigation strategies such as improved water and waste management, responsible agricultural practices, and strengthened health systems are essential for reducing AMR drivers and environmental contamination [37] [626]-[628]. Integrating AMR containment within climate change and One Health frameworks is vital to building global health resilience and protecting future generations [629] [630].

4.11. Way Forward and Recommendations Based on This Review

Based on our observations, there is a critical need to promote integrated AMS, surveillance, and IPC programs to effectively address AMR across human, animal, plant, and environmental health domains. Despite growing recognition of the One Health approach, the implementation of AMS programs in the animal health sector remains limited and poorly documented, particularly in LMICs.

To close this gap, we strongly recommend the initiation and strengthening of AMS interventions within the animal health and environmental sectors. These efforts should include the development of evidence-based guidelines for antimicrobial use in veterinary medicine, capacity building for veterinary professionals, and improved regulatory oversight of antimicrobial sales and distribution.

It is also critical to promote the integration of AMS programs across all relevant sectors namely human health, animal health, agriculture, and environmental management to establish a unified and comprehensive One Health approach to combating AMR. A well-coordinated, multisectoral strategy enables more effective data sharing, harmonized surveillance systems, joint risk assessments, and the development of cohesive policies that reflect the interconnected nature of AMR. This cross-sectoral collaboration also enhances the efficient use of resources, supports early detection of resistant pathogens, and ensures that intervention strategies are context-specific and mutually reinforcing. Recent global efforts underscore that siloed approaches are insufficient; only through integrated, system-wide stewardship can we preserve the efficacy of existing antimicrobials and reduce the overall burden of AMR.

Overall, a unified and comprehensive approach is essential to safeguard the efficacy of antimicrobials and mitigate the long-term consequences of AMR on global health, food security, and ecosystems. These approaches to combat AMR must be implemented while leveraging on technology such as nanotechnology and AI.

5. Conclusions

This review highlights that the effective implementation of AMS, surveillance, and IPC/biosecurity programs across diverse One Health settings, including hospitals, universities, colleges, schools, communities, environmental systems, and the animal health sector, plays a pivotal role in promoting the rational use of antimicrobials. These interventions are strongly associated with improved clinical outcomes, reduced antimicrobial misuse, and a decreased burden of AMR. Furthermore, AMS programs have been shown to significantly enhance awareness and knowledge regarding AMU, AMR, and stewardship practices across the human, animal, and environmental health sectors, in line with the One Health approach.

Laboratories also play a critical role in supporting AMS efforts through the promotion of diagnostic stewardship. By ensuring timely and accurate identification of pathogens and their resistance profiles, laboratories enable targeted antimicrobial therapy, reduce empirical treatment, and minimize the unnecessary use of broad-spectrum agents. Strengthening laboratory capacity, particularly in LMICs, is essential for enabling real-time surveillance and informing evidence-based policy and clinical decisions.

In addition, the advancement of innovative technologies, including AI and nanotechnology, offers promising tools for addressing the complex challenges of AMR. AI can enhance AMR prediction, guide antimicrobial selection, and improve data analytics for surveillance systems. Nanotechnology is being explored for novel diagnostic tools, targeted drug delivery systems, and the development of antimicrobial agents with reduced resistance potential. Therefore, countries should actively invest in and leverage these emerging technologies as part of their broader AMR response strategies. We propose the initiation and strengthening of integrated One Health AMS programs, supported by robust diagnostics and advanced technologies, as a sustainable and holistic approach to effectively combat AMR on a global scale.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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