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Beyond Antibiotics: One Health Education for Tackling Antimicrobial Resistance

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Abstract

Antimicrobial resistance (AMR) is recognized as one of the most urgent global health threats, demanding coordinated, multisectoral responses under the One Health framework. Among the multidisciplinary tasks aimed at collectively tackling the AMR crisis, surveillance, research and education stand as major priorities. Education is a strategic pillar of the World Health Organization Global Action Plan, yet a comprehensive synthesis of educational initiatives explicitly grounded in One Health remains limited. This review analyzes the educational landscape of AMR, focusing on formal and informal educational programs targeting students, professionals, and communities, and integrating human, animal, and environmental dimensions through a One Health approach. It also examines the pedagogical strategies used to promote AMR awareness, prevention, and responsible antimicrobial use. School-based programs (e.g., e-Bug, ISGlobal initiatives, Ambientech); public awareness and community education via national strategies such as PRAN; programs for university students; professional tranining, and continuing education (e.g., ESCMID, AMR EDUCare); and international online platforms including FAO e-learning programs and the One Health Workforce Academy were examined. Programs were analyzed according to target population, pedagogical approach, sectoral integration, and evaluation methods. Active and experiential methodologies, such as service-learning (e.g., Tiny Earth, MicroMundo) game-based learning, gamification, and interdisciplinary and systems thinking–based learning, consistently enhance knowledge acquisition, systems thinking skills, and awareness of cross-sectoral AMR transmission pathways. Despite all these initiatives, studies on knowledge, perceptions and attitudes about AMR point to clear errors and deficiencies. Key gaps, such as inconsistent curriculum integration, limited integration of environmental dimension and scarce rigorous impact evaluations, persist. Strengthening One Health-oriented AMR education requires policy-level curriculum inclusion, cross-sector collaboration, standardized competencies, and robust evaluation frameworks. Embedding education within national AMR strategies is essential to foster sustained behavioral change and preserve antimicrobial effectiveness across human, animal, and environmental systems.

Keywords: antimicrobial resistance; education; One Health; antibiotic stewardship; public health; health literacy

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1. Introduction

1.1. The Global AMR Crisis

Antimicrobial resistance (AMR) has emerged as one of the most significant threats to global public health in the 21st century. The World Health Organization (WHO) identifies AMR as one of the top ten global public health threats facing humanity, with projections estimating that antibiotic-resistant infections could cause 10 million deaths annually by 2050 if no effective interventions are implemented [1, 2]. In Spain alone, antibiotic resistance is responsible for approximately 4,000 deaths per year, while across Europe, this figure reaches 33,000 annual fatalities [3].

The emergence and spread of antibiotic resistance are driven by multiple interconnected factors, including inappropriate antibiotic use in human medicine, overuse in veterinary medicine and agriculture, and environmental contamination through pharmaceutical waste and hospital effluents [4,5]. This complex, multifaceted nature of AMR necessitates a comprehensive, integrated approach that transcends traditional sectoral boundaries.

1.2. The One Health Framework

The One Health approach provides a critical framework for addressing AMR by recognizing the intrinsic interconnections between human health, animal health, and environmental health [6, 7]. Defined by the American Veterinary Medical Association as 'the integrative effort of multiple disciplines working locally, nationally, and globally to attain optimal health for people, animals, and the environment,' One Health acknowledges that antibiotic use in any sector can impact the health of all others [8].

This holistic perspective is essential for developing effective strategies to combat AMR, as resistant bacteria and resistance genes can be transmitted between humans, animals, and the environment through various pathways including food chains, water systems, and direct contact [9,10]. The scientific evidence supporting a One Health approach to AMR is substantial.

Molecular epidemiological studies have demonstrated the transmission of antimicrobial-resistant bacteria and resistance genes among humans, animals, food products, and environmental reservoirs within the One Health framework. Several examples of these transmission dynamics are highlighted in this special issue "A One Health Approach to Antimicrobial Resistance". Resistant Staphylococcus spp. and Mammaliicoccus sciuri strains carrying antibiotic resistance genes were identified in both poultry and healthy humans, suggesting potential interspecies dissemination through direct contact and food production systems [11]. Similarly, resistant Escherichia coli strains isolated from free-living birds were found to harbor virulence and resistance traits associated with human infections, emphasizing the role of wild birds as environmental reservoirs and vectors of antimicrobial resistance [12]. In addition, the detection of antibiotic-resistant bacteria in street foods and wastewater environments further supports the role of contaminated food products and environmental compartments in the dissemination of antimicrobial resistance to human populations [13,14].

Complementing these findings, recent work on wildlife sentinels has shown that red foxes (Vulpes vulpes) in Western Romania can harbor antimicrobial-resistant bacterial strains, reinforcing their role as effective indicators of AMR circulation at the wildlife–human interface [15]. Environmental studies from aquatic ecosystems in agricultural regions, including areas with intensive pig farming in Spain, have further demonstrated the presence and genetic diversity of multidrug-resistant Enterobacteriaceae in surface waters and wastewater treatment plants, highlighting the contribution of livestock-associated contamination to environmental AMR reservoirs [16]. Broader One Health syntheses also emphasize the plasmid-mediated global spread of high-risk resistance determinants such as mcr genes conferring colistin resistance, illustrating how clinical, agricultural, and environmental compartments are interconnected through mobile genetic elements [17]. Similarly, large-scale reviews of dairy farm environments across Asia report consistent AMR patterns linked to antimicrobial use practices in livestock systems, reinforcing the agricultural contribution to environmental dissemination [18]. Collectively, these studies strengthen the concept that antimicrobial resistance is maintained and propagated through tightly linked human, animal, and environmental pathways, requiring integrated surveillance and mitigation strategies across all sectors.

1.3. The Role of Education

Education plays a central role in implementing the One Health approach to AMR. The WHO Global Action Plan on Antimicrobial Resistance identifies improved awareness through effective communication, education, and training as a fundamental pillar for combating resistance. Educating diverse stakeholders including students, healthcare professionals, veterinarians, farmers, policymakers, and the general public is essential for promoting responsible antibiotic use and implementing effective stewardship practices [1].

Despite the increasing number of educational initiatives addressing AMR, there is still a lack of comprehensive synthesis of programs explicitly grounded in the One Health approach. This review aims to provide an integrated overview of current levels of knowledge and awareness of AMR among students and the general public, as well as to systematically compile and analyze educational interventions on AMR developed within the One Health framework. Ultimately, this work seeks to inform and support researchers, educators, and policymakers in the design, implementation, and improvement of effective AMR education strategies.

This review analyzes the educational landscape of AMR, focusing on formal and informal educational programs targeting students, professionals, and communities, and integrating human, animal, and environmental dimensions through a One Health approach. It also examines the pedagogical strategies used to promote AMR awareness, prevention, and responsible antimicrobial use.

2. Methodological Approach of the Review

This comprehensive review is based on an analysis of peer-reviewed literature, reports from international organizations, and descriptions of educational interventions focused on AMR and One Health. Programs were included if they met at least one of the following criteria: i) explicitly referenced the One Health approach; ii) addressed AMR across more than one sector (human, animal, or environment); iii) promoted interdisciplinary education or collaboration related to antimicrobial use and resistance.

Educational initiatives targeting diverse populations were considered, including healthcare professionals, veterinary professionals, farmers, policymakers, students, and the general public. Both formal (academic curricula, professional training) and informal (community campaigns, online courses) educational formats were included. The review synthesizes information from multiple sources to provide a comprehensive overview of the current landscape of One Health-oriented AMR education.

3. Political and Technical Context of the One Health Approach

3.1. Key Political and Technical Milestones (2015-2025)

The evolution of the One Health approach in the context of AMR has been marked by important political and technical milestones that have shaped global and national responses to antimicrobial resistance.

2015: WHO Global Action Plan on AMR

The WHO Global Action Plan on AMR represented the first global framework explicitly promoting One Health for AMR. This landmark document established five strategic objectives that integrate human, animal, and environmental sectors: i) improving awareness and understanding of AMR; ii) strengthening knowledge through surveillance and research; iii) reducing infection incidence; iv) optimizing antimicrobial use; v) ensuring sustainable investment in AMR responses. The plan emphasized the critical importance of education and awareness-raising across all sectors.

2017: Expansion of Quadripartite Collaboration

In 2017, the collaboration between the Food and Agriculture Organization (FAO), World Health Organization (WHO), and World Organisation for Animal Health (WOAH, formerly OIE) was formalized as a tripartite partnership to coordinate global efforts against AMR. This collaboration was later expanded to include the United Nations Environment Programme (UNEP), forming the Quadripartite, with increased emphasis on integrating the environment into One Health frameworks. This expansion recognized that environmental contamination and ecological factors play crucial roles in the emergence, persistence, and spread of antimicrobial resistance.

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2019: EU One Health Action Plan against AMR

The European Union adopted a comprehensive One Health Action Plan against AMR, representing a strong regional strategy with regulatory and surveillance measures. This plan served as a model for other regions, demonstrating how coordinated policy frameworks can address AMR across human health, animal health, food production, and environmental sectors simultaneously. The EU plan included specific provisions for education and training of healthcare professionals, veterinarians, and the public.

2020-2021: Advances in Surveillance and Technical Standards

WOAH released updated recommendations on animal AMR surveillance and veterinary practices, providing technical standards to support national programs. Simultaneously, significant technical advances enabled detection of antibiotic resistance genes (ARGs) in environmental and non-traditional sources through expansion of genomic and metagenomic surveillance capabilities. These technological developments allowed for more comprehensive monitoring of resistance dissemination across the One Health continuum and provided evidence for educational programs about environmental dimensions of AMR.

2023-2025: Consolidation and Implementation

FAO and WOAH released technical guidance on integrated surveillance and prudent use of antimicrobials, establishing standards to support national programs. Many countries revised their national One Health AMR action plans to include environmental and genomic surveillance components, reflecting the maturation of One Health approaches. Educational initiatives increasingly incorporated these expanded perspectives, addressing the full spectrum of AMR transmission pathways and intervention points.

3.2. Educational Implications of One Health Policies

Implementing AMR requires fundamental changes in education and training across multiple disciplines, as it is widely recognised in the scientific literature [19]. Healthcare professionals need to understand not only the clinical mechanisms of resistance, but also the environmental and agricultural drivers that contribute to its emergence and spread. In the same way, veterinarians must be aware of the implications of antimicrobial use in animals for human health, while farmers and agricultural workers require specific training on responsible antibiotic use and its environmental consequences. Environmental scientists also play a key role, as they must understand how antibiotic residues and resistance genes circulate within ecosystems and ultimately affect human and animal health systems [5].

From an educational perspective, this implies the need for truly interdisciplinary curricula that integrate human, animal and environmental health under a systems-thinking framework [20]. For the general public and students, One Health education is essential to foster health literacy and promote behavioural change. This includes appropriate antibiotic use, adherence to vaccination programmes, infection prevention practices, and environmental stewardship. Such competencies are consistently highlighted as crucial in global One Health frameworks, which emphasise the importance of cross-sectoral education to effectively combat AMR [21]. Overall, the literature supports the idea that addressing AMR requires not only scientific and policy coordination, but also a profound transformation in how health-related knowledge is taught and understood across society.

3.3. Educational landscape of AMR

Traditionally, AMR was not taught in relation to infectious diseases but rather addressed to understand evolutionary mechanisms. AMR has been used as a context to develop and assess students' knowledge of natural selection, mutations, and evolution [22]. For instance, it has been used in virtual simulations to explore concepts related to natural selection and the generation of AMR [23]. Animations have also been used to help students overcome the notion that mutations originate in response to the environment and to antibiotics [25].

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Currently, collaborative educational initiatives have been implemented, such as service-learning projects and open schooling experiences [26, 27, 28], which connect secondary and university students with experts in AMR. These approaches aim to strengthen students' understanding of the topic through real-world, interdisciplinary contexts.

Despite these efforts, many studies still address AMR in a limited way. Even when health education is included, it tends to focus mainly on antibiotic use, without fully incorporating broader factors such as environmental and animal health or the One Health perspective. A systematic review of 144 studies in medicine, pharmacy, nursing, dentistry, and veterinary undergraduate students concluded that teaching about antimicrobials is often superficial and called for a deeper integration of ecological and One Health dimensions [29]. A review published in 2021 analyzed initiatives aimed at addressing AMR among different audiences from a One Health perspective. Nevertheless, the primary emphasis was not on the One Health approach itself, but rather on the misuse of antibiotics in humans [30].

Some authors have begun to introduce more holistic perspectives by incorporating the One Health approach into AMR education. For example, open schooling initiatives have included specific One Health modules, which students found particularly engaging because they addressed the impact of AMR on animals, plants, and the environment—dimensions that were previously unfamiliar to them [28]. Nevertheless, these studies did not systematically assess how much students actually learned about the One Health concept itself. Despite this limitation, such initiatives reflect a growing tendency to integrate the One Health perspective into educational strategies. In the following section, "Educational Programs and Resources," these emerging approaches will be explored in greater detail.

In the same line, the minimum core curriculum established by the new Spanish educational legislation includes topics related to health, infectious diseases, antibiotics, and ecosystems. However, AMR is not explicitly identified as a specific curricular concept, and the One Health approach does not appear as an official curricular framework at the national level [32]. Nevertheless, each Autonomous Community further develops and specifies these contents. For instance, in the Autonomous Community of La Rioja, a specific section has been incorporated in the third year of Compulsory Secondary Education that directly addresses antibiotics, entitled 'Reflection on Self-Medication and the Appropriate Use of Antibiotics,' as well as indirect references through applied learning in Upper Secondary Education (Baccalaureate) This represents clear legislative progress in this area, as Robredo & Torres (2021) reported that antibiotics were not mentioned at any point in the secondary education curriculum [31]. The new local legislation also incorporates the 'One Health' approach, linking human, animal, and environmental health, as well as zoonoses and the emergence of new diseases."

4. Educational Programs and Resources

4.1. School-Based Programs (K-12 Education)

School-based programs target students from primary through secondary education, providing age-appropriate content that builds foundational knowledge about microbes, infections, and antimicrobial resistance.

4.1.1. e-Bug

Website: https://www.e-bug.eu/

e-Bug is an extensive international educational program developed through European collaboration, with support from public health agencies including the European Centre for Disease Prevention and Control (ECDC). The program provides comprehensive, evidence-based resources for teaching microbes, infection transmission, infection prevention, and responsible antibiotic use.

Program Structure and Content

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e-Bug offers appropriate age materials for different educational stages, from primary education through secondary and higher education. For younger students (ages 5-11), resources focus on hand hygiene, how infections spread, and the basics of vaccination, using engaging activities like glow-germ demonstrations and interactive games. Secondary-level materials (ages 11-15) introduce more sophisticated concepts including antibiotic mechanisms, resistance development, and the distinction between bacterial and viral infections, a critical knowledge gap that contributes to inappropriate antibiotic use.

The program includes lesson plans, student worksheets, PowerPoint presentations, and practical laboratory activities. Notably, e-Bug incorporates hands-on microbiology experiments that allow students to culture bacteria, test antibiotic susceptibility, and observe resistance development firsthand. These experiential learning opportunities are particularly effective for conveying the reality of AMR.

One Health Integration

Recent updates to e-Bug have strengthened its One Health components. Materials now explicitly address antibiotic use in agriculture and its consequences for human health, environmental contamination from pharmaceutical waste, and zoonotic disease transmission. Case studies illustrate real-world One Health scenarios, such as ESBL-producing *E. coli* transmission through contaminated food products or carbapenem-resistant bacteria in hospital wastewater affecting downstream environments. Evaluation studies have documented significant improvements in students' knowledge and attitudes toward antibiotic use following e-Bug implementation, demonstrating the program's effectiveness.

4.1.2. ISGlobal Programs (Barcelona Institute for Global Health)

Website: https://www.isglobal.org/en/antimicrobial-resistance

The Barcelona Institute for Global Health (ISGlobal) has developed several notable educational initiatives addressing antibiotic resistance from a One Health perspective.

Micro-Combat

Micro-Combat represents an innovative serious game approach to teaching antibiotic resistance. This card game, which received the 2018 award from the Spanish Agency of Medicines and Health Products for best awareness initiative on antibiotic resistance, engages players in the roles of healthcare professionals and researchers working to prevent bacterial infections. The educational value of Micro-Combat lies in its ability to make abstract concepts tangible through gameplay. Players directly experience how antibiotic overuse accelerates resistance development, how prevention strategies reduce the need for antibiotics, and how research investment is essential for developing new therapeutic options. The game is designed for ages 10 and above, making it suitable for secondary education contexts as well as public engagement activities.

Awareness Week Activities

During World Antimicrobial Awareness Week (WAAW), ISGlobal organizes educational installations and activities that illustrate bacterial growth and resistance development. These installations employ visual demonstrations, such as agar plate cultures showing resistant versus susceptible bacterial colonies, to make microbiological concepts accessible to general audiences. The activities explicitly connect human, animal, and environmental health under the One Health framework, helping participants understand how resistance emerges and spreads across different settings.

Educational Lectures

ISGlobal researchers deliver educational talks in schools and community settings. These presentations cover the biological mechanisms of antibiotic resistance, the public health implications of AMR, and individual and collective actions to mitigate the problem. The lectures are tailored to different audiences, from primary school students to healthcare professionals, and emphasize the One Health interconnections between different sectors.

'Superheroes Against Superbugs'

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Website: https://educaixa.org/microsites/IS_GLobal/Superheroes_contra_superbacterias/

EducaCaixa, the educational platform of the 'la Caixa' Banking Foundation, collaborated with ISGlobal to develop 'Superhéroes contra superbacterias' (Superheroes Against Superbugs), an interactive digital resource that explains antibiotic mechanisms, bacterial mutations, and the research process for discovering new antibiotics. This resource is particularly notable for its engaging multimedia approach, combining animations, interactive activities, and real-world case studies.

The resource is structured around several key learning modules. The first module explores the historical discovery of penicillin by Alexander Fleming, contextualizing antibiotics as one of medicine's greatest achievements while foreshadowing the emergence of resistance. Subsequent modules delve into how antibiotics work at the molecular level, targeting bacterial cell walls, protein synthesis, or DNA replication. A critical component explains bacterial mutation and horizontal gene transfer as mechanisms driving resistance evolution. The final modules focus on current research efforts to develop new antibiotics and alternative therapies, emphasizing the importance of continued innovation. Throughout the resource, students are presented with interactive challenges that reinforce key concepts. The resource aligns with Spanish secondary education curriculum standards in biology and health sciences, making it readily integrable into classroom instruction.

4.1.3. Ambientech: One Health Educational Platform

Website: https://ambientech.org/one-health

Ambientech is a Spanish non-profit organization comprising scientists and STEAM educators that develops interactive educational resources focused on science, health, and environment for secondary education, vocational training, and the general public.

'One Health: Una sola salud' Resource

The flagship One Health resource from Ambientech provides a comprehensive introduction to the interconnections between human, animal, and environmental health. Designed for secondary education and vocational training students, the resource employs animations and gamified activities to explain how diseases can transmit between animals and humans (zoonoses) and the factors that promote or prevent such transmission. The resource includes detailed case studies of two significant zoonoses: Lyme disease and hydatidosis (echinococcosis). For each disease, students learn about the pathogen's life cycle, animal reservoirs, transmission routes to humans, clinical manifestations, and prevention strategies. These case studies effectively illustrate One Health principles by demonstrating how wildlife management, domestic animal care, and human behavior collectively influence disease risk.

Pedagogical Approach

Ambientech resources are distinguished by their active learning methodology. Interactive modules require students to make decisions, solve problems, and explore consequences, rather than passively receiving information. Gamification elements, such as points, badges, and progress tracking, enhance engagement and motivation. The platform's comprehensive glossary serves as an additional learning support tool. All Ambientech resources are freely accessible online, removing financial barriers to adoption. The organization also provides teacher guides and professional development opportunities to support effective classroom implementation.

4.1.4. Tiny Earth: Crowdsourcing Antibiotic Discovery

Website: https://tinyearth.wisc.edu/

Tiny Earth is an innovative educational network engaging students in authentic antibiotic discovery research. Operating across 45 U.S. states and 15 countries, the program engages students in collecting soil samples from their local environments and screening bacterial isolates for antibiotic production capabilities. This 'crowdsourcing' approach serves dual purposes: advancing antibiotic discovery research while providing students with genuine research experiences. From a One Health perspective, Tiny Earth is particularly valuable for illustrating environmental reservoirs of antibiotic-producing organisms and the ecological origins of antimicrobial compounds. Students gain hands-

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on experience with microbiological techniques, experimental design, and data analysis while contributing to addressing the global shortage of novel antibiotics. The program has been successfully implemented in general biology, microbiology, and cell/molecular biology courses at various educational levels.

4.1.5. MicroMundo

MicroMundo is an educational and scientific project inspired by Tiny Earth that brings together universities and secondary/high school students to address AMR. The project is based on citizen science and service-learning. University students work with and mentor younger students to collect soil samples and isolate microorganisms that may produce new antibiotics. In this way, participants learn microbiology through hands-on activities while also contributing to real scientific research. Besides its scientific goals, MicroMundo promotes awareness of the One Health concept, which connects human, animal, and environmental health, and encourages responsible antibiotic use. Over the past several years, many universities across Spain and Portugal have participated in the initiative, involving thousands of students in the collaborative search for new antibiotics and helping to increase interest in science and research [33].

4.1.6. PRAN School-Based Initiatives

Website: https://resistenciaantibioticos.es/es

Spain's national action plan against antibiotic resistance (PRAN), coordinated by the Spanish Agency of Medicines and Health Products (AEMPS), collaborates with the Ministry of Education to integrate AMR education into school curricula. Teacher training workshops equip educators with knowledge and resources to teach antibiotic resistance effectively. Student materials, aligned with curriculum standards, cover topics including infection prevention, appropriate antibiotic use, the consequences of resistance, and One Health interconnections.

4.1.7. DivulSuperbac

The DivulSuperBac project was developed as an educational outreach initiative aimed at raising awareness on AMR and “superbugs” among pre-university students. The project engaged university students, particularly those in health-related degrees, through a Service-Learning approach that integrated academic learning with community service. The educational tool consisted of a travelling exhibition of 14 infographics called DivulSuperBac. The exhibition and related activities take place in secondary schools. Infographics are structured visual tools created to communicate complex scientific concepts in a clear, accessible, and engaging manner. They combine concise textual information with images, charts, and graphical elements to enhance understanding and retention of key messages related to AMR, disease control, and responsible antibiotic use; one out of the 14 infographics deals with the One Health approach [26]. The infographics were originally developed at the University of Valencia, Spain, and the project is currently expanding to different universities and countries: Italy (Palermo), Poland (Opole), Germany (Mainz), Morocco (Fez), and Spain (Ourense, La Rioja) [34].

4.1.8. Local, informal education

Activities for children such us the musical hall “The Mould that Changed the World” [35], the educational theatre “The drugs don’t work” [36], forum theatre on antibiotic use in Myanmar [37], school-based educational intervention on rational antibiotic use [38], debate activities [39] or peer-to-peer education about prudent antibiotic use in schools [40].

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4.2. Public Awareness and Community Education

Community programs translate complex scientific concepts into accessible messages for non-specialized audiences, targeting the general public through campaigns, events, and community-based initiatives.

4.2.1. PRAN Public Campaigns

Website: https://resistenciaantibioticos.es/es

PRAN has launched several public campaigns, including "¡Corre sin resistencias! (Run Without Resistance)", consisting in running races and walks. Campaign materials include posters, videos, social media content, and informational brochures distributed through healthcare facilities, schools, and community centers. Educational materials explicitly adopt a One Health framework, addressing antibiotic use in human medicine, veterinary medicine, and agriculture. Resources for healthcare professionals include clinical guidelines, continuing education modules, and stewardship toolkits. Materials for farmers and veterinarians focus on appropriate antimicrobial use in food-producing animals and the importance of infection prevention.

4.2.2. OAZIS Health - AMR and One Health for Community Educators

Website: https://oazis.rw/learn/courses/amr-and-one-health-for-community-educators/

OAZIS Health is an African-based e-learning platform, headquartered in Rwanda, focused on capacity building in public health and community health education. It offers the online course 'AMR and One Health for Community Educators', which addresses antimicrobial resistance from a community-oriented One Health perspective. It introduces fundamental concepts of antimicrobial resistance, including causes, transmission pathways, and prevention strategies, emphasizing interconnections between human health, animal health, and the environment. The target audience includes community educators, health promoters, local leaders, and professionals involved in non-governmental or community-based health initiatives. Primarily oriented toward low- and middle-income country settings, focusing on awareness-raising and behavior change at the community level.

4.2.3. Local, Informal Education

Activities such as educational theatre and public discussions on antimicrobial resistance [36], forum theatre approach for public engagement in Myanmar [37], caregiver and children training sessions on rational antibiotic use [38].

4.2.4. Online multidisciplinary course "The Problem of Antibiotic Resistance" for teachers, students and citizens. The course includes videos and materials from different disciplines, such as microbiology, chemistry, and philosophy, helping participants understand the complexity of the problem from a One Health perspective [41].

4.3. University students Programs

Some of the programs mentioned in sections 4.1. and 4.2. are also suitable for university students. In other initiatives, such as Tiny Earth, MicroMundo, or DivulSuperbac, university students themselves act as disseminators of information, teaching and raising awareness among students at lower educational levels. The following are some specific activities designed for university students:

- Laboratory activity on fitness of antibiotic-resistant bacteria in the environment. This activity allows undergraduate students to investigate how antibiotic-resistant and sensitive bacteria survive under different environmental conditions. Students collect water samples from their communities and analyze bacterial fitness in the presence or absence of antibiotics. The activity promotes critical thinking, laboratory skills, and awareness of environmental antimicrobial resistance [42].

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- Role-playing exercise on beta-lactam antibiotics and resistance. This kinesthetic activity helps students understand how antibiotics work and how bacteria develop resistance. Students physically represent molecules and cellular structures, making abstract microbiological concepts easier to visualize and remember. The exercise encourages active participation and long-term retention of knowledge [43].
- Bacterial Survivor interactive game. This classroom game demonstrates how bacterial mutations and natural selection contribute to antibiotic resistance. Students participate in a fast-paced activity that challenges misconceptions about bacterial evolution and resistance mechanisms. It is especially effective in large biology or microbiology classes [44].
- PARE Project (Prevalence of Antibiotic Resistance in the Environment) engages university students in environmental surveillance research. Students collect soil samples and test them for antibiotic-resistant bacteria using standardized microbiological methods. The project combines authentic scientific research with global collaboration and contributes to real antimicrobial resistance monitoring efforts [45].
- AntibioGame® serious game for medical students. This educational game uses clinical scenarios to train medical students in responsible antibiotic prescription practices. Through role-playing and problem-solving activities, students improve their clinical decision-making skills and their understanding of antimicrobial stewardship in primary healthcare settings [46].

4.4. Professional Training and Continuing Education

Healthcare professionals play a central role in antimicrobial stewardship, infection prevention and control, and patient education. Strengthening their understanding of AMR during training is therefore essential to improve prescribing practices, adherence to infection control protocols, and public awareness [47, 48]. Professional training programs target healthcare workers, veterinarians, and other professionals with direct responsibilities in antimicrobial management, providing specialized knowledge and practical skills for their specific sectors.

In Spain, healthcare professionals such as physicians, pharmacists, nurses, and veterinarians are legally required to be registered with their corresponding professional regulatory bodies (colegios profesionales) in order to practice their profession. Membership involves the payment of professional fees and guarantees adherence to ethical, legal, and professional standards established by these organizations. Beyond their regulatory role, professional colleges play an important function in continuing professional development by offering accredited training programs, scientific updates, and educational activities in areas of major public health concern, including AMR and antimicrobial stewardship.

These professional organizations contribute significantly to the dissemination of knowledge and best practices regarding the prudent use of antibiotics. Continuing education initiatives promoted by professional colleges frequently include courses, workshops, seminars, and online training focused on rational antibiotic prescribing, infection prevention, and the reduction of antimicrobial resistance. This lifelong learning approach is particularly relevant because healthcare professionals are key actors in combating AMR through appropriate prescription practices, patient education, and interdisciplinary collaboration.

Furthermore, the involvement of professional regulatory bodies helps standardize competencies related to antimicrobial stewardship across healthcare disciplines. In Spain, this coordinated educational structure strengthens national and regional strategies aimed at addressing AMR, ensuring that healthcare professionals remain updated on evolving scientific evidence, clinical guidelines, and public health recommendations. Such institutional support reinforces the integration of AMR education not only during undergraduate training but also throughout professional practice, which is considered essential for an effective and sustainable One Health response to AMR.

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4.3.1. Antimicrobial Stewardship Programs (ASP)

Antimicrobial Stewardship Programs (ASP) are coordinated institutional interventions designed to measure and improve the appropriate use of antimicrobials. Their primary goals are to enhance patient outcomes, reduce microbial resistance, decrease healthcare costs, and minimize adverse drug events.

To ensure a successful and sustainable framework, the Centers for Disease Control and Prevention (CDC) outline seven essential pillars for hospital ASPs: i) Hospital Leadership Commitment: Dedicating necessary human, financial, and technological resources; ii) Accountability: Appointing a single leader (often an infectious diseases physician) responsible for program outcomes; iii) Pharmacy Expertise: Appointing a co-leader pharmacist specialized in infectious diseases to manage dosing and selection; iv) Action: Implementing specific interventions, such as systemic "antibiotic timeouts" or pre-authorization for restricted drugs; v) Tracking: Monitoring prescribing patterns, local resistance rates, and overall antimicrobial consumption; vi) Reporting: Regularly sharing use and resistance data with doctors, nurses, and hospital leadership; vii) Education: Providing continuous training to healthcare workers regarding optimal prescribing practices.

While initially developed for high-acuity hospital settings, ASP principles apply across the entire healthcare spectrum: i) Acute Care Hospitals: Focus on severe infections, critical care dosing, and reducing healthcare-associated infections, ii) Long-Term Care Facilities: Tailored to elderly populations, heavily focusing on preventing the overtreatment of asymptomatic bacteriuria; iii) Outpatient & Primary Care: Target public education and reduce unnecessary antibiotic prescriptions for viral upper respiratory tract infections.

ASPs guide clinicians to evaluate every prescription against five fundamental criteria: i) Right Drug: Selecting the most narrow-spectrum agent effective against the suspected or confirmed pathogen; ii) Right Dose: Tailoring the dosage to patient-specific factors like weight, age, organ function (especially kidney health), and site of infection; iii) Right Duration: Limiting the therapy to the shortest effective timeframe proven by clinical guidelines to avoid driving resistance; iv) Right Route: Preferring oral medications whenever clinically feasible, or executing an early intravenous-to-oral switch; v) De-escalation: Reviewing microbiological culture results at 48–72 hours to transition from broad-spectrum empiric therapy to targeted narrow-spectrum drugs.

4.3.2. European Society of Clinical Microbiology and Infectious Diseases (ESCMID)

Website: https://www.escmid.org/education/education-ondemand/academy/an-introduction-to-antimicrobial-resistance/

Online course including integrated modules on antimicrobial resistance, surveillance systems, policy frameworks, and selected One Health considerations. The One Health approach is limited but relevant, with emphasis on clinical and public health aspects. The target audience includes professionals in microbiology, medicine, and public health.

4.3.3. AMR EDUCare (European Project)

Website: https://www.amreducare.eu/

Online educational materials and modular training courses organized by EU4Health Programme, coordinated by the Spanish Agency of Medicines and Medical Devices (AEMPS) with participation of 14 European partner organizations. Primarily it is centered on optimizing antimicrobial prescribing and clinical practices, with a limited but relevant One Health dimension. The target audience includes healthcare professionals in antimicrobial resistance, focusing on prudent antibiotic use, educational strategies, and competencies aimed at improving clinical practice.

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4.3.4. PRAN–UCM Course: 'One Health and Antimicrobial Resistance'

Website: https://resistenciaantibioticos.es/es/lineas-de-accion/formacion/cursos/one-health-y-la-resistencia-los-antibioticos

The course 'One Health and Antimicrobial Resistance' is organized by Spanish National Action Plan on Antimicrobial Resistance (PRAN) in collaboration with Universidad Complutense de Madrid (UCM), as part of UCM Summer Courses. This course represents a model of collaboration between health authorities and academic institutions for continuing professional education. Topics covered include current AMR situation from a One Health perspective, scientific and social challenges related to AMR, and control strategies and educational actions.

4.4. Online Courses and MOOCs (Open Access)

Massive Open Online Courses (MOOCs) and e-learning platforms have democratized access to AMR and One Health education, reaching global audiences across diverse sectors and geographic regions with free or low-cost comprehensive training.

4.4.1. Coursera: Antimicrobial Resistance – Theory and Methods

Website: https://www.coursera.org/learn/antimicrobial-resistance#modules

This online course provides theoretical foundations and methodological tools for understanding AMR. The objective is to equip learners with basic analytical and conceptual tools to study AMR, including cross-sectoral surveillance approaches. It includes a dedicated module on One Health and integrated surveillance systems linking human, animal, and environmental health. A certificate is available with paid option.

4.4.2. FAO eLearning Academy on Antimicrobial Resistance

Website: https://elearning.fao.org/course/view.php?id=783

The Food and Agriculture Organization of the United Nations (FAO) offers several free online courses: “Understanding Antimicrobial Resistance in Food and Agriculture” (an introduction to AMR addressing human, animal, and environmental dimensions); 'Raising Awareness on the Responsible Use of Antibiotics in Livestock' (focused on animal production systems and prudent antimicrobial use); “FAO Progressive Management Pathway for AMR” (a One Health-oriented management framework supporting policy development and implementation); “FAO One Health Course” (self-paced online course introducing the One Health approach and its application to emerging infectious diseases, AMR, climate change, and food systems). These courses are designed for professionals, policymakers, and educators, with content available in multiple languages including Spanish and English.

4.4.3. AMR Training Portal – The Global Health Network (TGHN)

Website: https://amr.tghn.org/training/

The AMR Training Portal of The Global Health Network offers a collection of free online courses addressing multiple aspects of antimicrobial resistance, including introduction to AMR, surveillance systems, responsible use of antibiotics, and One Health and AMR. Courses are available in multiple languages, and selected modules explicitly integrate a multisectoral One Health perspective.

4.4.4. One Health Workforce Academy (OHWA): Antimicrobial Resistance in One Health

Website: https://onehealthworkforceacademies.org/training/antimicrobial-resistance-2/

The One Health Workforce Academy (OHWA) offers educational materials, applied learning activities, knowledge assessments and online training courses on antimicrobial resistance explicitly framed within a One Health approach. The program includes modules covering antimicrobial agents,

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mechanisms of resistance, rational use of antibiotics, public health impact, and surveillance across human, animal, and environmental sectors. There are introductory and advanced levels available.

4.4.5. International Society for Companion Animal Infectious Diseases (ISCAID)

Website: https://www.iscaid.org/

The International Society for Companion Animal Infectious Diseases runs the CAAMS (Companion Animal Antimicrobial Stewards) committee. They host international webinars, workshops, and case-study sessions tailored specifically to resolving everyday clinical prescribing dilemmas in dog and cat veterinary practices.

4.4.6. World Small Animal Veterinary Association Academy

Website: https://wsava.org/wsava-academy/

The World Small Animal Veterinary Association offers online modules and hybrid courses (often in collaboration with the World Organisation for Animal Health - WOAH) focused on why ASP matters in pets and how to apply global prescribing guidelines in private practice.

4.4.7. WHO–FAO–WOAH Online Course on Zoonotic Disease Outbreak Response

Website: https://www.who.int/news/item/31-10-2023-fao--who--and-woah-launch-new-online-course-on-joint-response-to-zoonotic-disease-outbreaks

Joint online training developed by World Health Organization, Food and Agriculture Organization of the United Nations, and World Organisation for Animal Health focused on coordinated One Health responses to zoonotic outbreaks.

4.4.8. European School for Advanced Veterinary Studies (ESAVS)

Website: https://esavs.org/?utm_source=chatgpt.com

Postgraduate veterinary education programs integrating AMS and responsible antimicrobial use into specialties such as internal medicine, dermatology, and critical care.

4.5. International Organizations and Resource Repositories

International health organizations provide comprehensive educational resources, policy guidance, and technical materials that serve as valuable references for educators developing local or national educational programs.

4.5.1. World Health Organization (WHO) Educational Resources

Website: https://openwho.org/ |

It provides comprehensive educational resources on AMR for diverse audiences. These include webinars, training modules, policy briefs, and communication materials available in multiple languages. Resources emphasize the One Health approach and cover topics such as antimicrobial stewardship in healthcare and agriculture, surveillance systems, infection prevention and control, and regulatory frameworks. These international resources serve as valuable references for educators developing local or national educational programs. They provide scientifically rigorous information reflecting current global consensus on AMR challenges and solutions.

4.5.2. Food and Agriculture Organization (FAO) Educational Resources

Website: https://elearning.fao.org/

The Food and Agriculture Organization of the United Nations provides extensive educational resources focused on AMR within the context of food systems, livestock production, and agriculture. Through its eLearning platform, it offers self-paced courses, training materials, technical guides, and awareness-raising resources aimed at professionals, policymakers, farmers, and educators. These

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materials emphasize the reduction of antimicrobial use in animal production, the promotion of responsible practices, and the strengthening of surveillance systems in food and agriculture sectors.

A key feature of FAO's resources is their alignment with the One Health approach, integrating human, animal, and environmental health perspectives. This makes them particularly valuable for designing interdisciplinary educational interventions and for supporting capacity building in low- and middle-income countries.

4.5.3. World Organization for Animal Health (WOAH) One Health Resources

International One Health guidance, operational tools, workforce development materials, and multisectoral AMR resources from the human, animal, and environment interface.

4.5.4. Tripartite One Health Zoonoses Guide (WHO–FAO–WOAH)

Collaborative guidance document supporting countries in implementing One Health approaches for zoonoses, food safety, and antimicrobial resistance management.

4.5.5. The Fleming Fund Program

This UK aid program developed a comprehensive online curriculum on AMR in partnership with the Open University. It features a dedicated Veterinary Services learning pathway that covers everything from epidemiological surveillance of resistant bacteria on farms to correct clinical sampling techniques.

5. Pedagogical Approaches and Best Practices

5.1. Active and Experiential Learning

The most effective RAM educational programs employ active learning strategies that engage students as active participants rather than passive recipients of information. Active learning methodologies have demonstrated significant benefits in STEM disciplines compared to traditional approaches. A meta-analysis of 225 studies revealed that active learning methods consistently achieve better educational outcomes in STEM disciplines [49] The methodologies employed in RAM educational programs are as follows:

5.1.1. Service-Learning (SL)

SL is considered a comprehensive pedagogical approach that combines academic learning with community service, promoting both personal development and civic responsibility [50]. It is an experiential methodology that unites learning and community service in a single project with an academic and civic foundation [51]. This method not only aims for students to acquire theoretical knowledge but also actively involves them in solving community problems, which contributes to their development as responsible and engaged citizens. Service-learning (SL) fosters a cycle of care and empowerment in young people, allowing them to practice democratic citizenship skills from primary to secondary school [502]. This approach not only benefits students in terms of personal and academic development but also strengthens their connection to the community, as evidenced by the fact that young people who participate in service-learning experiences tend to demonstrate greater community engagement in the future [53]. Furthermore, research suggests that opportunities to reflect on these experiences are crucial, as they allow students to link theoretical learning with real-world practice [54]. On the other hand, SL has been observed to be an effective bridge between theory and practice, especially in teacher training, as it provides educators not only with pedagogical skills but also with a deeper understanding of the social realities their future students face [55]. This approach reflects the importance of interdisciplinary training and experiential learning, which are crucial for preparing students for real-world challenges [56]. Implementing service-learning programs across different disciplines has proven effective in improving student motivation and

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academic performance [57]. Ultimately, service-learning emerges as a decisive educational strategy for developing an active and engaged citizenry capable of addressing contemporary challenges.

Programs such as e-Bug, Tiny Earth, and MicroMundo utilize hands-on activities and laboratory experiments to make abstract concepts tangible. Research in science education consistently demonstrates that experiential learning approaches lead to deeper understanding, better retention, and a greater ability to apply knowledge to real-world situations. Laboratory activities where students culture bacteria, perform antibiotic susceptibility tests, and observe the selection of resistance provide direct evidence of the mechanisms of antimicrobial resistance (AMR).

5.1.2. Game-Based Learning

Game-based learning (GBL) is based on engagement and motivation theories, highlighting the role of enjoyment and deep learning [58] and increased motivation [59]. GBL employs complete, often stand-alone, games designed to achieve specific learning objectives. In science education, digital game-based learning is the most common and is linked to better content understanding, greater scientific achievement, and faster task completion [60]. Simulation games like Micro-Combat allow students to experience the challenges of decision-making in managing antibiotic use and resistance. These active approaches are particularly effective for developing systems thinking and understanding the complexity of One Health challenges.

5.1.3. Gamification

Gamification integrates game elements into existing curriculum structures to increase engagement. Gamification elements, such as progress tracking, points, and achievement badges, foster intrinsic motivation and encourage continued engagement with educational content [59]. Resources from EducaCaixa and Ambientech demonstrate how interactive animations, interactive diagrams, and game mechanics can make learning about microscopic processes and epidemiological concepts more accessible and engaging.

5.1.4. Interdisciplinary and Systems Thinking–Based Learning (ST)

The One Health approach to AMR inherently requires interdisciplinary thinking. Science educators have highlighted both the importance and the difficulty of developing ST to address complex health challenges such as AMR. Effective educational strategies are needed to support this development to integrate multiple perspectives when interpreting health-related systems.

In this sense, recent research examining modelling activities with 56 pre-service teachers found that such approaches can foster ST development in the context of AMR. Participants engaged in written explanations and group activities designed to promote the identification of system components and relationships, the proposal of actions, and the adoption of an “inside the system” perspective. After completing the sequence, most srudents incorporated a One Health vision in their explanations, increasingly recognised complex cause-effect relationships and showed more sophisticated retrospective reasoning when analysing AMR. Notably, multimodal representations used during intermediate activities appeared particularly effective in supporting this type of reasoning. The study concludes that the use of diverse representational formats can facilitate systems thinking development and improve understanding of complex health systems [61].

This systems perspective contrasts with traditional, compartmentalized approaches to health education and is essential for developing the holistic understanding needed to address global challenges such as AMR. The integration of agricultural, environmental, clinical, social, economic, and political dimensions within One Health education reflects this interdisciplinary framework.

Programs can foster systems thinking through activities such as multimodal representations, concept maps, causal loop diagrams, or role-playing that simulates the interactions among different stakeholders in the AMR system.

5.2. Real-Wordl and Contex-Based Learning

Effective AMR education connects abstract concepts to learners' lived experiences and local contexts. Context-based science education has been shown to improve student engagement, motivation, and the meaningful understanding of scientific concepts by linking learning to real-world situations and socio-scientific issues [62, 63]. In the context of AMR education, this approach is particularly relevant because antimicrobial resistance constitutes a complex socio-scientific issue that directly affects public health, food systems, and environmental sustainability [64].

Programs that use local disease examples, regional resistance patterns, or culturally relevant scenarios increase relevance and engagement. The case-study approach employed by Ambientech and e-Bug, using diseases familiar to target audiences, exemplifies this principle. Emphasizing the personal and societal implications of AMR, such as the potential for common infections to become untreatable or the economic burden of resistance, helps learners understand why the topic matters and supports informed decision-making regarding antibiotic use.

5.3. Behavior Change Focus

Beyond knowledge transmission, effective AMR education should aim to influence attitudes and behaviors. Educational interventions addressing antimicrobial resistance increasingly draw on behavior change theories, particularly the Theory of Planned Behavior [65]. and Social Cognitive Theory [66]. which emphasize the importance of attitudes, perceived norms, self-efficacy, and behavioral intentions in promoting responsible health practices.

Programs should explicitly address common misconceptions, such as the belief that antibiotics are effective against viral infections, normalize appropriate health-seeking behaviors, and empower learners to take action through proper antibiotic use, infection prevention, and advocacy for policy changes. Research shows that public understanding of antimicrobial resistance remains limited and is frequently associated with misconceptions regarding antibiotic use [67].

6. Current Challenges and Gaps

6.1. Curriculum Integration

The WHO has repeatedly emphasized education as a central component of global strategies to combat antimicrobial resistance, highlighting the need to incorporate AMR and One Health concepts into formal educational systems [1]. Recommendations include incorporating AMR and One Health topics into national and state science standards, developing standardized assessment items that include AMR content, and providing curriculum mapping guidance to help educators identify natural integration points within existing courses.

In Spain, recent local educational legislation has incorporated antibiotics and the One Health approach into secondary education curricula, including topics related to self-medication, zoonoses, and environmental health, as already discussed in section 3.2.

6.2. Teacher Training and Resources

Teachers require both content knowledge about AMR and One Health and pedagogical skills for teaching these topics effectively. Many educators report insufficient preparation to teach AMR, particularly the molecular biology, epidemiology, and interdisciplinary aspects. Professional development programs specifically focused on AMR education remain limited [68].

Addressing this gap requires systematic professional development opportunities, including workshops, online courses, and continuing education programs for in-service teachers [69]. Partnerships between educational institutions and research organizations like ISGlobal can provide teachers with access to current scientific knowledge and resources. Pre-service teacher education programs should also incorporate AMR and One Health content. The One Health Joint Plan of Action

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also highlights workforce development and interdisciplinary education as key priorities for strengthening global responses to AMR and other interconnected health threats [70].

6.3. Laboratory Access and Resources

Hands-on microbiology activities are highly effective for teaching AMR but require laboratory facilities, equipment, and materials that many schools lack, particularly in resource-limited settings. This creates inequities in access to high-quality AMR education.

Solutions include developing low-cost alternatives to traditional laboratory activities, such as simplified culturing techniques using household materials; creating virtual laboratory simulations; establishing partnerships with local universities or hospitals to provide laboratory access; and prioritizing resource allocation to support science laboratory infrastructure. In this line, it is worth highlighting the MicroMundo project, in which the materials used in secondary education centres are provided by universities, making it possible to carry out laboratory practices that would otherwise be unfeasible within the budget constraints of a secondary school [33].

6.4. Evaluation and Evidence Base

While many AMR educational programs exist, rigorous evaluation of their effectiveness remains limited. Few programs have published peer-reviewed assessments of knowledge gains, attitude changes, or behavioral impacts. Without robust evaluation data, it is difficult to identify which approaches are most effective and to justify continued investment in educational interventions.

Future research should employ rigorous study designs, including randomized controlled trials where feasible, to evaluate AMR educational interventions. Evaluation frameworks should assess not only immediate knowledge acquisition but also longer-term outcomes such as sustained behavior change and broader community impacts. Standardized assessment instruments would facilitate comparison across different programs and contexts.

6.5. Limited Integration of Environmental Dimension

Despite growing recognition of environmental factors in AMR transmission, many educational programs still provide limited coverage of this dimension. The role of environmental contamination, wastewater treatment, pharmaceutical residues, and ecological reservoirs of resistance genes often receives less attention than clinical and agricultural aspects. Strengthening the environmental component of One Health AMR education represents an important gap to address in future programs [61].

Several authors have warned that the environmental dimension continues to be the “neglected component” of the One Health framework despite its major role in the dissemination of resistance genes and antimicrobial residues [71].

7. Recommendations for Strengthening AMR Education

7.1. Policy and Curriculum

National education authorities should explicitly include AMR and One Health topics in science and health education curriculum standards. This inclusion should span multiple grade levels with age-appropriate progression from basic concepts of infection and hygiene in primary education to more sophisticated understanding of resistance mechanisms, epidemiology, and systems thinking in secondary and tertiary education.

Standardized assessments should include items related to AMR to signal the importance of this content and ensure accountability for teaching it. Curriculum developers should provide clear guidance on integrating AMR education within existing subject areas, including biology, health sciences, environmental science, and social studies. International organizations increasingly advocate the integration of sustainability and systems-thinking competencies into formal education as essential components for addressing complex global challenges such as AMR [72].

7.2. Teacher Support and Professional Development

Comprehensive professional development programs should equip teachers with both content knowledge and pedagogical strategies for effective AMR education. These programs should emphasize active learning approaches, One Health perspectives, and strategies for addressing common student misconceptions.

Professional development should be ongoing rather than one-time events, with opportunities for continued learning and peer collaboration. Online platforms and professional learning communities can facilitate sustained support. Pre-service teacher education programs should incorporate AMR and One Health content to ensure new teachers enter the profession prepared to teach these topics.

Developing systems thinking competencies among teachers is particularly important because understanding AMR requires the ability to interpret dynamic and interconnected biological, environmental, social, and political systems [61, 73].

7.3. Resource Development and Dissemination

Continued investment in developing high-quality, evidence-based educational resources is essential. Resources should be freely accessible, adaptable to local contexts, and available in multiple languages. Digital platforms like e-Bug and Ambientech exemplify accessible, comprehensive resources that can be widely disseminated.

Resource repositories should be well-curated and easily searchable, allowing educators to quickly find materials suitable for their specific needs. Quality assurance mechanisms should ensure that resources reflect current scientific understanding and adhere to pedagogical best practices.

7.4. Cross-Sectoral Collaboration

Effective AMR education requires collaboration between education, health, agriculture, and environment sectors. Partnerships should be established at national, regional, and local levels to coordinate messaging, share resources, and leverage diverse expertise. Examples include collaborations between schools and local health departments, universities and agricultural extension services, or research institutes like ISGlobal and educational foundations like EducaCaixa.

Professional organizations in medicine, veterinary science, agriculture, and education should prioritize AMR education in their activities, providing leadership and credibility to educational initiatives.

7.5. Research and Evaluation

A robust research agenda should investigate effective pedagogical approaches for teaching AMR and One Health concepts, identify common learning challenges and misconceptions, and evaluate the impact of educational interventions on knowledge, attitudes, and behaviors. Research findings should inform iterative improvement of educational programs. In this line the evaluation of the MicroMundo project was conducted in order to assess its contribution to improving knowledge about AMR, as well as to determine the optimal age of participants [74].

Mixed methods combining quantitative measures with qualitative insights can provide comprehensive understanding of program effectiveness. Evaluation frameworks should extend beyond immediate post-intervention assessments to examine longer-term outcomes and community-level impacts.

Research on science learning has shown that students often struggle to understand complex systems due to difficulties recognizing non-linear interactions, feedback mechanisms, and emergent behaviors.

7.6. Equity and Access

Educational equity requires ensuring that high-quality AMR education reaches all learners regardless of geographic location, socioeconomic status, or educational setting. This includes developing low-cost alternatives to resource-intensive activities, providing materials in multiple languages, and addressing digital divides that might limit access to online resources.

Special attention should be given to resource-limited settings where AMR burdens are often highest but educational resources most scarce. International development organizations and philanthropic entities can support AMR education initiatives in low- and middle-income countries.

8. Future Directions

Future educational programs should strengthen the integration of environmental sciences, promote policy-oriented education, and leverage digital technologies for broader reach. The development of standardized competencies and evaluation indicators for One Health AMR education could enhance comparability and impact across different programs and contexts.

Embedding One Health AMR education within national action plans and professional accreditation systems may contribute to sustainability. When AMR education becomes a requirement for professional licensure or certification, incentives align to ensure comprehensive coverage. The integration of emerging technologies, including mobile learning platforms, virtual reality for immersive laboratory experiences, and artificial intelligence for personalized learning pathways, holds promise for significantly expanding the reach and effectiveness of AMR education.

Finally, fostering international collaboration and knowledge exchange will be essential. Platforms for sharing educational resources, pedagogical innovations, and evaluation findings across countries and regions can accelerate progress and avoid duplication of efforts. The establishment of a global repository of One Health AMR educational resources, coupled with communities of practice for educators and program developers, could significantly advance the field.

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Abbreviations

The following abbreviations are used in this manuscript:

AMR	Antimicrobial resistance
ST	Systems Thinking

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