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Antimicrobial resistance in livestock: current trends, challenges and future directions

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Summary

Antimicrobial resistance (AMR) is a critical global threat to human, animal and environmental health and has received increasing attention from stakeholders worldwide. The overuse and misuse of antimicrobials in both human and veterinary medicine have significantly accelerated the emergence and spread of antimicrobial-resistant microorganisms. On the veterinary side, significant efforts have been undertaken in livestock to reduce antimicrobial use (AMU) and minimise the spread of AMR.

The aim of this review was to provide an overview of current trends in AMU and AMR in food-producing animals, to identify the main constraints and mitigation strategies related to AMR, and to highlight future directions and key research gaps. A global reduction in the total quantity of antimicrobials intended for use in animals has been reported, with prospects for a continued downward trend. A positive correlation between the use of certain classes of antimicrobials and bacterial resistance in specific pathogens of importance to both animal and human health has been observed. Integrated surveillance programmes for AMU and AMR have played a crucial role in generating these AMR data and in guiding the formulation of recommendations.

For this article, the Hazard Analysis and Critical Control Point framework was used as an approach to structure and customise some examples of on-farm intervention strategies aimed at both reducing AMU and minimising AMR. The article outlines future challenges in mitigating AMR in animal production that must be addressed to preserve the efficacy and longevity of existing antimicrobials, while supporting sustainable animal production practices.

Keywords

Antimicrobial resistance – Antimicrobials – Antimicrobial use – Food-producing animals – Hazard Analysis and Critical Control Point – One Health – Sustainable animal production – Veterinary.

Required citation

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Copyright

Introduction

Antimicrobials are naturally occurring, semi-synthetic or synthetic substances that kill or inhibit the growth of microorganisms [1]. These molecules are considered among the most significant medical discoveries of the 20th century due to their profound impact on human and animal health [2]. However, the overuse and misuse of antimicrobials in both human and veterinary medicine have significantly accelerated the emergence and spread of antimicrobial resistance (AMR) on a global scale [3]. A comprehensive global study estimated that in 2019, AMR bacteria were associated with 4.95 million deaths, including 1.27 million deaths directly attributable to antimicrobial-resistant bacteria [4]. It is projected that between 2025 and 2050, AMR could be associated with more than 169 million deaths globally [5]. The link between AMR in humans and the use of antimicrobials in animals is a major concern within the scientific community [2]. Several studies have estimated that approximately 73% of all antimicrobials sold globally are used in food-producing animals [6,7]. More recent analyses, however, have revised this estimate downward, indicating that the actual proportion is likely closer to 50–55% [8,9]. Indeed, when considering population biomass-corrected consumption, antimicrobial use (AMU) in food-producing animals is now slightly lower than in humans in some regions/countries; however, this pattern varies across countries [10,11]. Based on total tonnage estimates, and excluding biomass-corrected metrics, global veterinary antimicrobial usage was estimated at 99,502 tonnes in 2020, and if current trends persist, this figure is projected to increase by 8.0%, reaching 107,472 tonnes, by 2030 [10]. In the same year, AMU in cattle, chicken and pig farming was estimated at 76,060 tonnes, of which 40,697 tonnes (53.5%) were attributed to cattle, 31,120 tonnes (40.9%) to pigs and 4,243 tonnes (5.6%) to chickens [12]. However, these projections could vary by +14.2% to −56.8%, depending on changes in livestock biomass and the implementation of measures aimed at reducing AMU [8].

Significant efforts have been undertaken in livestock to reduce AMU and minimise the emergence of antimicrobial-resistant bacteria and AMR genes [1]. These initiatives aim to preserve the efficacy and longevity of existing antimicrobials, especially given the widely held view that the likelihood of developing and commercialising new antimicrobials for use in farm animals is low. However, an initiative recently launched by the Ineos Oxford Institute for Antimicrobial Research is focused on developing new animal-specific antimicrobials with the aim of reducing the use of human antimicrobials in farm animals [13]. The overarching goal of this review is to provide an overview of current trends in AMU and AMR in food-producing animals, to identify the main constraints and mitigation strategies related to AMR, and to highlight future directions and key research gaps. These insights aim to support sustainable animal production practices within the framework of the One Health approach. Given the limited knowledge on AMU and AMR in aquaculture species and the under-representation of this sector in AMR surveillance programmes, aquaculture production was not included within the scope of this article.

Antimicrobial use in animal production

Objectives of antimicrobial use in food-producing animals and strategic considerations

In food-producing animals, antimicrobials can be used for therapeutic purposes, metaphylaxis (disease control) and prophylaxis (disease prevention) and as growth promoters [14]. These uses may vary across regions and countries, depending on the regulations in force and their implementation in practice. Treatment involves administering antimicrobials to clinically ill animals, typically following a veterinary diagnosis of a bacterial infection. In some countries, identifying the specific bacterial strain and its antimicrobial susceptibility profile is necessary to guide effective treatment, particularly when using critically important antimicrobials [15,16]. From a responsible AMU perspective, the World Organisation for Animal Health (WOAH) recommends that antimicrobials classified by the World Health Organization (WHO) as highest priority critically important antimicrobials (HPCIAs) (e.g. fluoroquinolones, third- and fourth-generation cephalosporins, colistin [polymyxin E] and phosphonic acid derivatives [e.g. fosfomycin]) should not be used as first-line treatments in food-producing animals unless clearly justified [17]. Prophylactic use involves administering antimicrobials to healthy animals exposed to a high risk of infection (e.g. piglets during the post-weaning period, dairy cows at dry-off) [18,19]. It is noteworthy that the prophylactic use of antimicrobials in farm animals has been banned in European Union (EU) countries since Regulation (EU) 2019/6 came into effect on 28 January 2022 [20]. This regulation explicitly prohibits the preventive use of antimicrobials in groups of animals, except in exceptional cases and with strict veterinary justification [16]. This practice is also restricted in some other countries, particularly when it involves antimicrobials considered critically important for human medicine [15]. It should be stressed here that WOAH recommends that antimicrobials classified by WHO as HPCIAs should not be used for the prevention of infections in individual animals or animal groups [17]. On the other hand, it cannot be excluded that in certain animal production systems, such as swine, antimicrobials may still exert a growth-promoting effect under prophylactic use, due to heterogeneous exposure among animals within the same pen, particularly when administered via feed or drinking water [21].

Use for control or metaphylaxis involves administering the antimicrobial to a group of animals after a clinical disease has been identified in part of the group, with the aim of treating the clinically ill animals and preventing the spread of the disease to animals in close contact with them and at risk of infection, including those that may already be subclinically infected [16,22]. This practice is particularly common in poultry and swine production, as well as in beef cattle (in cattle upon arrival at the feedlot). In this context, efforts in swine production to separate clinically ill animals from healthy ones where possible – thereby limiting treatment to those that truly require it – are strongly encouraged, as they contribute significantly to reducing the overall AMU on farms [16]. Lastly, growth promotion involves the use of subtherapeutic doses of antimicrobials added to feed to enhance zootechnical performance, particularly by increasing average daily gain and improving feed efficiency [23,24], and, in some cases, to compensate for suboptimal husbandry practices or inadequate farm management [16]. It is hypothesised that these low doses modulate the intestinal microbiota by reducing the load of pathogenic bacteria, mitigating the effects of subclinical infections on animal performance and preserving the integrity of the intestinal mucosa by limiting the impact of microbial metabolites [23,24]. International guidelines recommend banning the use of HPCIAs for human medicine as growth promotants; however, some countries still permit their use for this purpose. Indeed, WOAH’s 9th Animal Antimicrobial Use (ANIMUSE) annual report reveals that 22% of reporting Members continue to permit the use of antimicrobial growth promoters (AGPs), most without any prior risk analysis [25]. Notably, some countries even authorise the use of antibiotics classified by WHO as HPCIAs, such as colistin (polymyxin E) and enrofloxacin (fluoroquinolones), for growth promotion purposes in farm animals [25]. The most critical issue with using AGPs in animal production is their documented contribution to the selection and dissemination of antimicrobial-resistant bacteria [26]. Numerous studies have reported a significant association between the use of antimicrobials at subtherapeutic concentrations and increased levels of AMR [27-29], reinforcing the urgency of globally phasing out the use of AGPs in food-producing animals, particularly HPCIAs (e.g. polymyxins, quinolones). In addition, the economic benefit of AGPs has become increasingly questionable, particularly in the context of modern, optimised livestock production systems [30]. In fact, several economic evaluations have shown that when effective husbandry and biosecurity measures are in place, the zootechnical performance gains associated with the use of AGPs are often marginal and may not justify the long-term risks to both animal and public health associated with AMR dissemination [31,32].

Undoubtedly, ensuring animal health and welfare requires that animals receive antimicrobials when necessary, under the guidance of a veterinarian through proper diagnosis and prescription, and ideally supported by laboratory testing. To achieve this goal effectively, it is essential to ensure that Veterinary Services are accessible to livestock producers, particularly in terms of reasonable geographic proximity [33]. On the other hand, in many low- and middle-income countries (LMICs), antimicrobials intended for use in animals can still be purchased over the counter [34]. In this context, it is essential that these countries establish and enforce regulations requiring a veterinary prescription for the use of medically important antimicrobials. On the other hand, prophylactic and control use of antimicrobials in farm animals should also only be undertaken under the guidance of the Veterinary Services and not considered routine applications. The use of medically important antimicrobials as AGPs should be eliminated due to their well-documented role in driving AMR and compromising the effectiveness of the current therapeutic arsenal. It is noteworthy that in some countries, such as Canada and the United States of America (USA), although medically important antimicrobials are no longer labelled for growth promotion, certain antimicrobials not used in human medicine – such as ionophores and flavophospholipols (also known as bambermycin or moenomycin) – continue to be added to animal feed [35]. These compounds are used partly to control coccidiosis (in the case of ionophores) but also to promote growth in food-producing animals, particularly broiler chickens and beef cattle. However, because ionophores (e.g. lasalocid, maduramicin, salinomycin, monensin, narasin, semduramicin) are classified as antimicrobials in Canada and in the USA, their use disqualifies products from being labelled as ‘Raised Without Antibiotics’ or ‘No Antibiotics Ever’ [35,36]. Nonetheless, the potential for the development of bacterial resistance following the use of ionophores and flavophospholipols, as well as the possibility of co-selection for resistance to clinically important antimicrobials [37] – particularly under conditions of concomitant *in vivo* administration – warrants further investigation in future studies. Moreover, the environmental impact of ionophore antibiotics, as emerging environmental pollutants, should also be more thoroughly explored [38], as has been the case with heavy metals (copper/zinc), which are used in some countries as feed additives for farm animals [39]. In parallel, the development of effective and competitive alternatives to ionophores, particularly given their classification by WOAH as Veterinary Highly Important Antimicrobial Agents (Table I), as well as to other synthetic anticoccidials (e.g. robenidine, decoquinate and diclazuril) should be supported as part of a sustainable livestock production model [36].

Surveillance initiatives and evolving trends in antimicrobial use in food-producing animals

Monitoring the quantity of antimicrobials intended for use in animal production provides valuable insights in addition to the total volume used, such as the specific molecules administered based on their importance in both veterinary and human medicine, the identification of high-use sectors and the effectiveness of policies implemented to improve AMC in livestock. Moreover, data on AMU/sales in food-producing animals are essential for guiding policy-makers in the development of evidence-based strategies to combat AMR [40]. Such data support the identification of high-risk practices, facilitate robust risk assessments and help prioritise targeted regulatory and policy interventions, while also enabling the monitoring of progress following their implementation [40]. These data on AMU/sales in farm animals also help inform consumers about production systems that rely on reduced AMU and may influence their purchasing decisions, especially regarding imported food products from countries with less prudent AMU practices [6]. In this context, in February 2023, the EU adopted Regulation (EU) 2023/905, which prohibits the import of animal-derived products from third countries where farm animals have been administered antimicrobials for growth promotion or yield enhancement [41].

To support AMU surveillance efforts in animal production, several national and regional monitoring programmes have been established, mainly in high-income countries. These include the Canadian Integrated Program for Antimicrobial Resistance Surveillance (CIPARS), the Food And Drug Administration (FDA)'s Center for Veterinary Medicine in the USA, the European Surveillance of Veterinary Antimicrobial Consumption coordinated by the European Medicines Agency, the Danish Integrated Antimicrobial Resistance Monitoring and Research Programme (DANMAP), the Japanese Veterinary Antimicrobial Resistance Monitoring System (JVARM) and NethMap/MARAN in the Netherlands [6,42,43]. Notably, in 2025, the 27 Member States of the EU, along with Iceland and Norway, jointly published the first European Sales and Use of Antimicrobials for Veterinary Medicine annual report [44]. This inaugural report, covering data from 2023, marked the beginning of a new and regular surveillance initiative aimed at producing yearly updates on veterinary antimicrobial sales and use across Europe [44]. In contrast, in LMICs, where populations are growing and undergoing economic development, comparable initiatives and programmes for monitoring AMU and AMR should be actively encouraged and supported through both scientific collaboration and sustained financial investment [45,46]. It is noteworthy that the monitoring of AMU in farm animals remains largely unharmonised across countries, resulting in data that are often not directly comparable [2]. Indeed, surveillance approaches vary widely: some countries rely on veterinary prescription or invoice data, others on import data or antimicrobial sales data reported by pharmaceutical companies, while a few collect farm-level usage data directly [40]. This variability poses challenges for cross-country comparisons and global assessments of trends. To standardise global data collection on AMU/sales in animal production while supporting LMICs in reporting their data, WOAH has, since 2015, gathered voluntary information from up to 157 countries on the use of antimicrobial agents in animals [10,47]. In September 2022, to enhance the effectiveness of these efforts, WOAH launched the online ANIMUSE global database, a digital platform designed to streamline data collection [48]. This database enables national Veterinary Services not only to collect, monitor and report data more efficiently and accurately, but also to visualise, analyse and utilise the data for surveillance purposes, thereby supporting the implementation of national action plans on AMR. Additionally, it provides Members with the option to choose the confidentiality level of their validated data: confidential, semi-public or fully public [48]. However, for scientific assessment, without country-level disclosure of AMU data, it remains challenging to compare trends between AMU and AMR at national and international levels, or to assess the impact of regulations and policies that are implemented at the national level.

A large proportion of antimicrobials marketed worldwide – historically estimated at approximately 73% and more recently declining to 50–55% – are intended for use in food-producing animals [49]. The use of antimicrobials in farm animals has substantially contributed to the intensification of animal production systems. By facilitating the prevention and control of infectious diseases, antimicrobials have helped optimise zootechnical performance and support the expansion of livestock production to meet the growing global demand for animal-based proteins, thereby contributing to food security goals [50].

In 2017, global sales of antimicrobials for farm animals were estimated at 93,309 tonnes, with projections indicating an 11.5% increase to reach 104,079 tonnes by 2030 [6]. However, updated estimates from 2020 suggest that global usage in farm animals had already risen to 99,502 tonnes, now expected to increase by 8.0% to 107,472 tonnes by 2030 [10]. This upward revision in projected AMC in farm animals by 2030, compared to earlier forecasts based on 2017 data, is largely attributed to revised estimates indicating higher usage in regions such as Asia/Oceania and the Americas [10]. According to a recent WOAH report covering the period 2020–2022, the total quantity of antimicrobial agents intended for use in animals ranged from 70,648 to 74,035 tonnes, based on submissions from 107 participating countries [25].

During this period, a global reduction of 5% in milligrams of antimicrobials per kilogram of estimated animal biomass was reported, with Europe showing the most significant decrease at 23% [25]. In fact, in 2021, for the first time in the EU, AMC in food-producing animals was reported to be lower than in humans. Specifically, the EU/European Economic Area population-weighted mean AMC – expressed in milligrams of active substance per kilogram of estimated biomass – was 125.0 mg/kg in humans (28 countries, range: 44.3–160.1) compared to 92.6 mg/kg in livestock (29 countries, range: 2.5–296.5) [51]. A notable achievement in reducing the use of medically important antimicrobials in livestock is illustrated by EU/European Economic Area data: the population-weighted mean consumption of third- and fourth-generation cephalosporins was 5.1 mg/kg of estimated biomass in humans, compared to just 0.2 mg/kg in food-producing animals. Similarly, the mean consumption of fluoroquinolones and other quinolones was 6.3 mg/kg in humans versus 2.9 mg/kg in food-producing animals [51]. Furthermore, the EU has set an ambitious target to reduce AMC in food-producing animals by 50% by 2030 compared to 2018 levels, in line with recommendations from the European Council and as outlined in the European Commission's Farm-to-Fork Strategy [51]. A similar trend was observed in the USA, where the FDA's Center for Veterinary Medicine, in its 2023 report on antimicrobials sold or distributed for use in food-producing animals, reported a 2% decrease in the sales and distribution of medically important antimicrobials approved for use in these animals between 2022 and 2023 [52]. From 2022 to 2023, antimicrobials sold for use in farm animals in Canada followed patterns comparable to those reported in the USA, with a 3% reduction when normalised to mg/kg of biomass [53]. On the other hand, the most recent NethMap/MARAN report documented a 4.5% increase in the sales of antimicrobial veterinary medicinal products in the Netherlands in 2023, reaching a total of 117 tonnes compared to 2022 [43]. However, a substantial overall reduction of 76.4% in sales of such products was achieved between 2009 and 2023, with 2009 serving as the baseline reference year established by the Dutch government [43]. It should be stressed here that certain regulatory decisions have had a significant impact on reducing AMU in animals. For instance, when the Ministry of Agriculture of China banned the use of colistin as a growth promoter in animal feed, a measure that came into effect in April 2017, it likely led to the withdrawal of more than 8,000 tonnes of colistin from the Chinese veterinary sector [54]. Furthermore, a recent study projected that, under a business-as-usual scenario, antibiotic use quantity in farm animals could reach approximately 143,481 tonnes by 2040 [8]. This estimate, however, could vary significantly – from a 14.2% increase to a 56.8% decrease – depending on several key factors, including changes in livestock biomass, national and international AMU regulations, the level of country-specific commitment to reducing AMU, the development of competitive alternatives to antimicrobials, economic incentives, the strengthening of biosecurity measures on farms, societal pressure and demands from food retailers for antibiotic-free production practices [8].

Antimicrobial resistance in food-producing animals

Overview of the current situation

There is broad scientific consensus that the overuse and misuse of antimicrobials in both human and veterinary medicine have significantly accelerated the emergence and spread of antimicrobial-resistant microorganisms on a global scale, posing a serious threat to the continued effectiveness of these critical drugs [3,55]. How the livestock sector contributes to the spread of AMR continues to be studied, with results pointing to the misuse of antimicrobials in farm animals as accelerating the selection, persistence and transmission of antimicrobial-resistant bacteria in animals [45,56]. These bacteria can spread between animals and humans through direct contact, as well as via contaminated food and water and shared environments [57].

The association between AMU in food-producing animals and the selection of antimicrobial-resistant bacteria remains complex and often inconclusive. Indeed, while several studies have reported reductions in AMR following decreased AMU in farm animals [54,58,59], other investigations have yielded contrasting results [60-62]. Even when comparing organic and conventional livestock production systems, findings on the prevalence of AMR are sometimes contradictory and highlight considerable variation depending on specific contextual factors [63]. However, the most comprehensive data on the relationship between AMU and AMR in animals originate primarily from national surveillance programmes conducted over extended periods – often several years or even decades. These long-term systems provide robust trend analyses, with notable examples including CIPARS (Canada), DANMAP (Denmark), JVARM (Japan), the National Antimicrobial Resistance Monitoring System (USA) [64], the European Union Summary Report on Antimicrobial Resistance in Zoonotic and Indicator Bacteria from Humans, Animals and Food [65] and the inter-agency report on the integrated analysis of AMC and AMR occurrence in bacteria from humans and food-producing animals in the EU [51].

It is worth mentioning that in 2022, the Food and Agriculture Organization of the United Nations (FAO) launched the International FAO Antimicrobial Resistance Monitoring (InFARM) IT platform to collect data on AMR in animals and antimicrobials intended for use on plants/crops [1]. In October 2015, WHO launched the Global Antimicrobial Resistance and Use Surveillance System (GLASS) to initially collect data on AMR and

AMU in humans [66]. Since 2018, WHO has progressively expanded this system, including through the development of the GLASS Emerging Antimicrobial Resistance Reporting component, to also integrate AMR signals arising from surveillance in animals, the food chain and the environment, in alignment with the One Health framework [67]. Establishing effective communication between databases managed by WOAH (ANIMUSE), WHO (GLASS) and FAO (InFARM) provides a major advantage, as it facilitates data interpretation and supports the development of evidence-based recommendations to address the issue of AMR at the human–animal–environment interface. In this context, WOAH, in collaboration with FAO and WHO, is developing the Tripartite Integrated System for Surveillance on Antimicrobial Resistance and Use (TISSA) [68]. The TISSA platform represents an important first step towards a fully integrated system for AMR and AMU surveillance. Recently, the FAO InFARM and WOAH ANIMUSE databases have supported the development of an integrated AMR surveillance system (the Global Integrated Surveillance System for AMR, or GISSA) [69].

For instance, through the analysis of data generated by the CIPARS programme, it was observed that the Canadian poultry industry-led interventions, which ceased the prophylactic use of ceftiofur – in hatching and day-old chicks – resulted in a significant reduction in the prevalence of ceftiofur/ceftriaxone-resistant *Salmonella* and *Escherichia coli* strains from chickens on farms, from the grocery store (retail) and in humans (for *Salmonella*) [70-73] (Fig. 1). In its most recent report (2023), the DANMAP programme documented a substantial increase in the use of aminoglycosides – primarily neomycin and apramycin – in weaner pigs, rising by 145%, from 16.87 defined animal daily doses per 1,000 animals per day (DAPD) in 2021 to 41.39 DAPD in 2023 [74]. This increase in aminoglycoside use was correlated with a sharp rise in neomycin resistance among haemolytic *E. coli* strains from pigs, from 25.6% in 2021 to 52.3% in 2023 [74]. In parallel, a notable increase in gentamicin resistance was observed in haemolytic *E. coli* strains, coinciding with the increased administration of apramycin in weaners [74]. These concerning trends appear to be associated with the increased reliance on aminoglycosides following the ban on zinc oxide in veterinary medicinal products, which came into effect across Europe on 26 June 2022, due to environmental safety concerns [74]. In the EU, data from 2019 to 2021 confirmed an association between the use of certain groups of antimicrobials and the occurrence of AMR in bacteria isolated from the sampled food-producing animals [51]. Notably, significant positive associations between the consumption of third- and fourth-generation cephalosporins in food-producing animals and the prevalence of extended-spectrum β-lactamase-producing and/or AmpC β-lactamase-producing *E. coli* were observed across the periods of 2018–2019, 2019–2020 and 2020–2021 [51]. Similarly, fluoroquinolone and other quinolone use in poultry showed a direct correlation with fluoroquinolone resistance in *Campylobacter jejuni* isolated from poultry, while fluoroquinolone use in pigs was significantly associated with resistance in *Campylobacter coli* [51]. Additionally, aminopenicillin use in farm animals was significantly correlated with ampicillin resistance in *E. coli*. Macrolide use in pigs was associated with macrolide resistance in *C. coli* [51]. Finally, significant positive associations were found between the estimated consumption of tetracyclines in poultry and resistance in both *E. coli* and *C. jejuni*, as well as between tetracycline consumption in pigs and resistance in *E. coli* and *C. coli* isolated from pigs [51]. On the other hand, the most recent NethMap/MARAN report highlighted a high level of resistance to tetracycline (33%) among *Salmonella* isolates from broiler meat. This finding could be attributed to the observed 3.5% increase in tetracycline sales for use in farm animals in 2023 compared to 2022 [43].

Estimates suggest that LMICs account for the majority of AMU in animals [46]. However, in many of these countries, initiatives and studies that systematically collect data on AMU in farm animals and assess its relationship with the emergence and evolution of AMR in bacteria of animal origin remain limited [75]. It is therefore important to underscore that not all LMICs fall into the same category, as several have made significant efforts to reduce AMU in animals. Notable examples include Thailand [46], while other countries – including some large meat exporters – face challenges in systematically capturing data on AMU and AMR in animal production [76].

In LMICs, the scarcity, in some regions, of reliable data has resulted in limited research reporting on AMR in animals [7,75,77]. Indeed, Ikhimiukor *et al*. (2023) compiled data from 191 studies that reported phenotypic AMR in farm animals across 38 countries in Africa, the Middle East, Asia, and South and Central America [77]. Using multiple antibiotic resistance (MAR) indices, the study highlighted alarmingly high levels of multidrug resistance in bacteria isolated from food-producing animals in these regions [77]. Hotspots of AMR were identified in several countries, with notably high median MAR indices reported in Malaysia (0.69), the Philippines (0.62), Pakistan (0.579) and Zambia (0.567) [77]. Comparably high MAR indices were also observed in *Campylobacter* spp. (0.84) from retail markets in the Philippines and in *E. coli* (0.81) from chicken farms in Nigeria, highlighting significant levels of AMR in these settings [77]. This same trend was previously reported by Van Boeckel *et al*. (2019), who identified regional hotspots of multidrug resistance (resistance levels exceeding 50% [P50 > 0.4]) in South and Northeast India, Northeast China, Northern

Pakistan, Iran, Turkey, the southern coast of Brazil, Egypt, the Red River Delta in Vietnam and the areas surrounding Mexico City and Johannesburg [7].

Constraints and mitigation strategies for antimicrobial resistance

Building on progress made in human medicine, there is increasing interest in quantifying the burden of animal diseases and AMR in animal production, as it is increasingly recognised as a critical step to inform evidence-based decision-making and to mobilise the necessary resources for managing these threats from a sustainable livestock production perspective [78-80]. In this context, according to projections by the World Bank, under a high-impact AMR scenario, global economic output could be 3.2% lower by 2030 [81]. The economic consequences are expected to be particularly severe in LMICs, where livestock production losses may reach up to 11%, further exacerbating food insecurity, potentially forcing population displacement and hindering economic development [81]. Several initiatives have been implemented in animal production to reduce AMU and AMR; however, the assessment of the economic impact of these interventions remains very limited in the animal sector compared to what has been done in human medicine [82].

Determining the true costs of the most promising interventions to reduce AMR in farm animal production is essential. However, due to the scarcity of such data, or its limited availability for only a few interventions within specific livestock sectors [83,84], there is a risk that policy-makers may misinterpret economic evaluations and use them to justify disinvestment rather than to support investment [82]. Even though it is challenging to determine the true cost, most AMR-related interventions in farm animals not only contribute to reducing AMU, but also mitigate infectious pressure, while enhancing animal welfare and improving production performance [85,86]. The rationale underlying the design and prioritisation of interventions in AMU on farms is often unclear.

To address this challenge, the present review adapted the principles of prerequisite programmes and the Hazard Analysis and Critical Control Point (HACCP) framework – widely utilised in food-processing facilities – as an approach to structure and customise some examples of on-farm intervention strategies aimed at both reducing AMU and minimising AMR [87] (Table II; Fig. 2). Each on-farm intervention should be designed using a risk analysis approach [88], taking into account, for example, the specific characteristics of the livestock farming – such as the animal species involved, the presence of multiple species on site, the farm's location and the producer's financial resources. It is worth noting that competent authorities may be able to provide support for each strategy with appropriate regulatory measures (Table II) while taking into account the principles of AMR governance through a collaborative process involving public and private stakeholders, aligned with AMR priorities at both global and national levels [1]. This approach also aligns with the core principles of antimicrobial stewardship (AMS) in veterinary medicine, which describe the multifaceted strategies needed to preserve antimicrobial efficacy and minimise the emergence of AMR [1,89]. The AMS concept was recently defined by Carson, Muloi and Page (2025) as a ‘commitment to preserving antimicrobial effectiveness by i) creating and sustaining conditions where antimicrobials are not needed, and ii) where use is necessary, optimising use to ensure maximum effectiveness and minimum resistance selection; within a culture of continuous improvement’ [90].

Future directions and key research gaps

Addressing future challenges in mitigating AMR in animal production, with the overarching goal of preserving the efficacy and longevity of existing antimicrobials, will require coordinated action across several key domains. These include the continuous improvement of responsible and prudent use of antimicrobials, the development of rapid diagnostic tools for bacterial identification and antimicrobial susceptibility profiling of bacteria from farm animals, the early detection of bacterial infections at the farm level, reducing the need for antimicrobials through the development of effective, accessible and affordable vaccines, antimicrobial alternatives and new therapeutic antimicrobials, minimisation of environmental contamination with antimicrobials/residues and antimicrobial-resistant bacteria, and the implementation of integrated surveillance and monitoring systems to collect epidemiological and microbiological data on AMU and AMR (Fig. 2).

Enhancing and sustaining the responsible and prudent use of antimicrobials in food-producing animals through evidence-based strategies and strengthened regulatory frameworks: Despite the considerable global efforts to reduce AMU in animal production, it remains essential to sustain and intensify AMS. This includes, for example, reducing the need for antimicrobials by the implementation of global strategic initiatives, such as FAO’s Reduce the Need for Antimicrobials on Farms for Sustainable Agrifood Systems Transformation programme [91], reinforcing biosecurity protocols and practices [92], banning the use of medically important antimicrobials as growth promoters and ensuring uses for disease prevention and control are prudent and responsible. Achieving these goals requires increased awareness among all relevant stakeholders, particularly livestock producers [93] (Table II; Fig. 2), strong commitment from each country, and the development and enforcement of appropriate regulatory frameworks [49,94]. Several studies have reported positive outcomes of on-farm educational programmes designed to improve AMS practices among livestock farmers and veterinarians, contributing to a reduction in AMU in animal production systems [95,96]. On the other hand, the use of antimicrobials in animal feed, although widespread in several animal species, remains challenging for the following reasons: i) heterogeneity of antimicrobial exposure, particularly among diseased animals (e.g. sick animals may not eat), and ii) limited scientific literature addressing the interactions between antimicrobials and various feed ingredients, which may affect antimicrobial bioavailability [97]. These aspects warrant further investigation.

Many antimicrobials in use today in farm animals were originally approved between the 1950s and 1980s, and their dosage regimens have largely remained unreviewed since their initial approval. To ensure prudent and responsible use, pharmacokinetic and pharmacodynamic parameters should be optimised for each antimicrobial and for each animal species [98,99]. Finally, regarding the involvement of veterinarians within the One Health approach to mitigate AMR, it is essential to effectively communicate the efforts made by the veterinary sector to other key stakeholders (e.g. physicians, pharmacists, environmental scientists and public health professionals). This would help to better emphasise these contributions and strengthen interdisciplinary collaboration, thereby supporting a collective and coordinated effort to address AMR.

Promoting the development of rapid affordable diagnostic tools for bacterial identification and antimicrobial susceptibility profiling: Veterinary medicine has experienced a significant delay compared to human medicine in the development of rapid diagnostic tests for identifying bacteria in various clinical samples and determining their AMR profiles. Yet these tools are essential for enabling veterinarians to make timely, evidence-based treatment decisions (particularly choosing the effective antimicrobial) supported by reliable laboratory data. A total of 18 diagnostic kits for 12 animal diseases have been registered with WOAH to support rapid decision-making regarding the health status of animals on farms [100]. Although matrix-assisted laser desorption ionisation time-of-flight mass spectrometry (MALDI-TOF MS) technology has been available on the market and widely used in clinical microbiology since 2010 [101], its adoption in veterinary diagnostic laboratories remains limited, primarily due to its high cost and the large size of such systems, which pose significant constraints for their implementation in routine laboratory settings [102]. Indeed, compared to traditional biochemical identification methods, MALDI-TOF MS offers several advantages, including simple sample preparation, speed, accuracy and low cost per sample [101,102].

A recent study conducted across 241 veterinary clinical microbiology laboratories in 34 European countries highlighted the variability in diagnostic practices [103]. Turnaround times for bacterial culture and identification ranged from 1–2 days (77.8%) to 3–5 days (20%) and 6–8 days (1.6%). The most commonly used tools for bacterial identification were individual biochemical tests (77%) and Analytical Profile Index kits or similar systems (56.2%), followed by polymerase chain reaction (PCR, 46.6%) and MALDI-TOF MS (43.3%) [103]. This study revealed significant variability among veterinary laboratories in high-income countries regarding methods used for bacterial culture, isolation and identification, underscoring the need for access to standardised guidelines to harmonise these practices [103]. It is noteworthy that MALDI-TOF MS as well as Fourier transform infrared spectroscopy have been used, either alone or in combination with machine learning approaches, for the detection of AMR in different bacterial species [104-106]. On the other hand, fast, robust and affordable antimicrobial susceptibility testing (AST) is essential in the veterinary field to support timely decision-making. However, conventional growth-based AST requires multiple cultivation steps, including enrichment cultures (e.g. from faecal samples), plate culturing to obtain pure isolates, and subsequent AST on liquid (broth microdilution) or solid media (disk diffusion) using various antimicrobial concentrations [107]. Nevertheless, these AST methods are further limited by long turnaround times (48–72 hours) and significant hands-on time, requiring well-trained microbiology laboratory technologists to both perform the tests and interpret the results accurately. These limitations ultimately delay the delivery of laboratory findings to veterinarians in the field [108]. In 2024, Reszetnik *et al*. published a review compiling scientific literature and regulatory submissions describing over 90 technologies designed to deliver phenotypic AST results in a shorter time frame than conventional methods [109]. Nevertheless, several recent studies have highlighted discrepancies in result interpretation when applying either Clinical and Laboratory Standards Institute or European Committee on Antimicrobial Susceptibility Testing clinical breakpoints to various pathogen–antimicrobial combinations, reinforcing the need for a globally harmonised AST system [103]. Nucleic acid amplification tests (NAATs) (e.g. PCR, qPCR) have been proposed to address these challenges. However, most current NAAT methods are limited by their ability to detect only a narrow range of AMR genes [109].

On the other hand, the recent advancements in rapid and affordable DNA sequencing technologies have revolutionised diagnostic microbiology and microbial AMR surveillance [110]. Genomic approaches, particularly whole-genome sequencing (WGS), are increasingly used in veterinary medicine to detect bacteria and their AMR profiles [111,112]. A concordance of 91.7% between AST results obtained via standard broth microdilution and predictions based on WGS data was reported, highlighting the relevance and potential of this technique [113]. Since WGS generates a massive volume of fragmented data, advanced bioinformatics software is required to interpret the results, and personnel trained in bioinformatic analysis are essential [107]. The existence of a single, comprehensive database of all known resistance genes and mutations would greatly facilitate analyses. Further, there is growing interest in applying machine learning and deep learning approaches to predict AMR [114]. For instance, ARGNet utilises deep neural networks to detect antimicrobial resistance genes (ARGs) of varying lengths and classify them into 36 distinct AMR categories [115]. Most studies indicate that integrating WGS and AST data into machine learning models enhances predictive performance and offers valuable clinical decision support [116]. Veterinary medicine could also greatly benefit from these advancements. However, despite the decreasing cost of WGS, several challenges (e.g. limited access to a skilled workforce and supporting infrastructure, restricted availability of sequencing platforms and reagents, insufficient access to sequence repositories) continue to hinder its effective implementation in many LMICs [117]. Some promising initiatives have emerged in some LMICs, such as the SeqAfrica project, which has established a regional network and operational framework that has substantially strengthened WGS and bioinformatics capacity in sub-Saharan Africa, with a particular focus on AMR across all One Health sectors [118]. This initiative, however, continues to face persistent challenges, including bottlenecks in reagent and consumable procurement, difficulties in workforce retention and a strong reliance on donor funding [118]. In addition, technical challenges persist regarding the long-term storage of data and the protection of genomic information [119]. These issues are further exacerbated by recent policy shifts in several high-income countries, which have resulted in reduced funding for research initiatives.

Enhancing early detection of bacterial infections on farms: The adoption of advanced technologies enabling real-time data analysis for early disease diagnosis may represent the future of livestock health management [120]. In addition to training producers and farm workers to recognise early signs of illness specific to each animal species present on the farm, and to properly collect and preserve samples for veterinary and/or laboratory diagnostics, the use of point-of-care diagnostic devices for livestock is gaining interest [121,122]. These devices enable rapid, on-site detection of diseases and pathogens without the need for centralised laboratory infrastructure. Recent advancements have led to the development of point-of-care devices targeting significant diseases (e.g. African swine fever, porcine reproductive and respiratory syndrome, rinderpest, foot and mouth disease, bluetongue, avian and swine influenza), thereby supporting animal health [121]. Other technological tools, such as behaviour monitoring systems (e.g. physical and spatial behaviour tracking and physiological monitoring, particularly of body temperature), can help distinguish between healthy and affected animals at various stages of disease progression. These data can be analysed using artificial intelligence, enabling machine learning models to detect and correlate patterns between animal behaviour and disease status [120]. These advanced technologies are not intended to replace the expertise of veterinarians, farmers or animal health technicians, but rather should support them by enabling earlier and more accurate diagnosis of bacterial diseases in farm animals. This, in turn, can help reduce AMU, enhance animal welfare and promote the sustainability of livestock production systems [120].

Advancing the development of novel vaccine approaches, antimicrobial alternatives and new therapeutic antimicrobials in farm animals: It was reported in several studies that use of vaccines in food-producing animals substantially decreased AMU and reduced the risk of antimicrobial-resistant bacteria emergence [123]. An expert ranking conducted across six European countries identified vaccines as the most practical and effective alternative to the use of antimicrobials in pig production [124]. Given its pivotal role in animal production, vaccination plays a key role in maintaining livestock health, improving animal welfare, enhancing food safety and reducing the risk of some zoonotic disease transmission to humans [125]. Consequently, prioritising the development of vaccines that are not only effective but also accessible and affordable is critical for sustainable animal production. Reflecting this importance, the focus of the Animal Health Forum at the 92nd WOAH General Session in May 2025 was ‘Veterinary Vaccines and Vaccination: From Science to Action – Reflections for Change’ [126]. This forum, along with other reports, emphasised the critical role of research and emerging technologies (e.g. microencapsulation, autogenous vaccines, multi-pathogen formulations, novel oral delivery systems, innovative adjuvants, nucleic acid-based vaccines, reverse vaccinology) in advancing vaccination strategies in farm animals [127]. These innovations aim not only to prevent infectious diseases in livestock but also to support improved AMS. It should be stressed here that despite their demonstrated benefits, veterinary vaccines remain underutilised, particularly in LMICs, due to a range of challenges [126]. These include limited investment in vaccine development, gaps in farmers’ perception of vaccination value, insufficient production capacity, regulatory hurdles, purchase cost, procurement difficulties and logistical constraints related to cold-chain requirements (e.g. storage, transport and handling) [126].

Several studies have been conducted in food-producing animals to develop alternatives capable of replacing the use of antimicrobials – initially as growth promoters, particularly in countries where AGPs are still permitted, and later to reduce their prophylactic and therapeutic use. This approach aims to minimise the selection pressure for antimicrobial-resistant bacteria at the farm level and throughout the food chain [128]. Antimicrobial alternatives are typically natural or organic compounds that can be administered through feed or drinking water. They promote animal growth and health, primarily by acting on the gastrointestinal tract. These alternatives include prebiotics, probiotics, synbiotics, paraprobiotics, organic acids, phytobiotic products, egg yolk antibodies, enzymes, bacteriophages, antimicrobial peptides and bacteriocins [128-130]. Some emerging alternative strategies (e.g. antivirulence, quorum sensing inhibitors or quorum quenching enzymes and two-component inhibitors, silver nanoparticles, antibiotic adjuvants, CRISPR-Cas9 gene-editing technology, antisense-based antibiotics, acoustic pulse therapy [bovine mastitis], photodynamic therapy [bovine mastitis]) were proposed to control bacterial pathogens in human and veterinary medicine [128,131-133]. Several studies have demonstrated the beneficial effects of some of these alternatives in farm animals, including immune modulation, enhanced digestion, improved nutrient availability and absorption, antimicrobial and antioxidant activities, improved gut integrity and intestinal barrier function, and modulation of the host gut microbiota [134]. These compounds can also serve as nutrients for the host and contribute to overall intestinal health. However, several knowledge gaps remain, particularly regarding their precise mechanisms of action, variability in efficacy, potential safety concerns, the lack of comprehensive toxicological evaluations and limited data on cost-effectiveness [134]. Furthermore, interactions between these alternatives and with other dietary components are still poorly understood. While such alternatives may support animals during critical production phases (e.g. piglet weaning, peak egg laying), their antimicrobial activity remains significantly lower than that of conventional antimicrobials currently in use.

Identifying novel antibacterial compounds remains a top global health priority in human medicine, particularly those effective against Gram-negative bacteria classified by WHO as critical threats [135]. However, in veterinary medicine, the discovery of new antimicrobials has not received the attention it deserves [136]. With the exception of the ionophore class, which is specific to veterinary medicine, most antimicrobial classes used in animals are shared with human medicine. There are only a few exceptions, including certain compounds that belong to major antimicrobial classes but are exclusively marketed for veterinary use (e.g. cefquinome, gamithromycin, tulathromycin, tilmicosin, tylosin and avilamycin) [17]. Therefore, the development of novel veterinary-specific antimicrobials [13], particularly oral antimicrobial agents with high bioavailability and minimal impact on the gut microbiota, or long-acting parenteral formulations capable of achieving bacteriological cure with a single dose [137], should be strongly encouraged to reduce the reliance of veterinary medicine on human-use antimicrobials. In fact, according to the FDA, among the 41 antimicrobials (including ionophores) that were approved for use in food-producing animals in the USA as of 2020, 30 were categorised as being medically important for humans [138].

Promoting strategic measures to limit environmental contamination by antimicrobials/residues and antimicrobial-resistant bacteria: The majority of antimicrobials administered to farm animals are poorly absorbed in the gastrointestinal tract [137]. As a result, a substantial proportion is excreted unchanged or as active metabolites, contributing to the presence of antimicrobial residues in the environment, particularly following the use of manure and slurry as fertiliser on agricultural land. In addition to antimicrobial compounds and their metabolites, animal waste often contains antimicrobial-susceptible bacteria, antimicrobial-resistant bacteria and ARGs, providing all the necessary elements to maintain selective pressure on environmental bacterial populations [139]. Despite the critical role of the environment as a reservoir for antimicrobial-resistant bacteria and ARGs, few innovative treatment technologies have been developed and implemented to remove these hazards from animal waste [140]. Certain approaches, such as thermophilic composting of manure and anaerobic digestion of slurry and manure, as well as the best practices for land application of animal waste, have been described to mitigate the environmental dissemination of antimicrobial-resistant bacteria and ARGs following the use of animal excreta as fertiliser [140]. It is therefore essential to give greater attention to this environmental dimension, particularly the treatment of animal waste, while considering economic feasibility and regulatory constraints.

Advancing the implementation of integrated surveillance and monitoring systems to collect epidemiological and microbiological data on AMU and AMR: In addition to WOAH’s ANIMUSE platform, and to further support countries in collecting, collating and analysing AMU (plants/crops) and AMR data (animals and food), FAO developed InFARM, a global information system that strengthens surveillance and monitoring at national, regional and global levels [1]. It also helps visualise and interpret trends in AMR to guide decision-making and facilitates the sharing of information across national and international platforms [1]. Some integrated monitoring programmes have been established in high-income countries; however, a major gap – collecting data on AMR from animal pathogens – has only progressively begun to be addressed, with limited implementation of these programmes in other regions. Examples include CIPARS in Canada, DANMAP in Denmark, JVARM in Japan, NethMap in the

Netherlands, Swedres-Svarm in Sweden and FINRES-Vet in Finland [42,43,141,142]. These AMU and AMR surveillance programmes, although often limited to a few bacteria (e.g. *E. coli*, *Salmonella*, *Campylobacter*), play a key role in guiding policy. By providing evidence-based data, they support informed decision-making and the development of recommendations to promote the prudent and responsible use of antimicrobials across sectors. While the implementation of such programmes can be costly, their scope can be adapted to each country's available resources, and naturally this requires the engagement of all relevant stakeholders, as well as strong political commitment.

Conclusions

AMR is a global threat that compromises the effective treatment of bacterial infections in both humans and animals. It poses significant challenges to animal health, public health, environment health and food security, particularly in the context of increasing efforts around the world towards national food autonomy. The use of antimicrobials in human and veterinary medicine is widely recognised as a major driver of antimicrobial-resistant bacteria emergence and dissemination. Despite notable progress in food-producing animals over the past two decades, including improved husbandry practices, enhanced biosecurity, increased stakeholder awareness, substantial reductions in AMU in several regions, particularly in the EU, and the use of vaccines and antimicrobial alternatives, the persistence of antimicrobial-resistant bacteria and ARGs in the gut microbiota of farm animals remains a critical concern. In the context of sustainable livestock production and in order to reduce selection pressure and preserve antimicrobial efficacy, future efforts should prioritise: i) the promotion and sustained implementation of responsible and prudent AMU in farm animals through evidence-based approaches and robust regulatory frameworks; ii) the development of rapid, cost-effective diagnostic tools for bacterial identification and AST, alongside improved access to WGS platforms and sequence repositories; iii) the implementation of early bacterial infection detection systems at the farm level, supported by artificial intelligence-based decision-making tools; iv) the advancement of novel vaccines approaches, antimicrobial alternatives and new veterinary-specific antimicrobials; v) the promotion of strategic measures to limit environmental contamination by antimicrobials/residues, antimicrobial-resistant bacteria and ARGs; and vi) implementation of integrated surveillance and monitoring systems for AMU and AMR adapted to the realities and available resources of each country. These current and future efforts will enable the livestock sector to play a pivotal role in reducing AMU and AMR within the One Health framework.

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Résistance aux antimicrobiens chez les animaux d'élevage : tendances actuelles, défis et perspectives d'avenir

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Résumé

La résistance aux antimicrobiens (RAM) constitue une menace mondiale majeure pour la santé humaine, animale et environnementale et fait l'objet d'une attention croissante de la part des acteurs concernés à l'échelle internationale. L'usage excessif et inapproprié des antimicrobiens en médecine humaine comme en médecine vétérinaire a considérablement accéléré l'émergence et la propagation de micro-organismes résistants aux antimicrobiens. Dans le domaine vétérinaire, des efforts importants ont été entrepris dans les élevages afin de réduire l'utilisation des antimicrobiens (UAM) et de limiter la diffusion de la RAM.

L'objectif de cette revue était de fournir une vue d'ensemble des tendances actuelles de l'UAM et de la RAM chez les animaux destinés à la production alimentaire, d'identifier les principales contraintes ainsi que les stratégies d'atténuation liées à la RAM, et de mettre en évidence les orientations futures et les principales lacunes en matière de recherche. Une réduction mondiale de la quantité totale d'antimicrobiens destinés à un usage animal a été rapportée, avec des perspectives de poursuite de cette tendance à la baisse. Une corrélation positive entre l'utilisation de certaines classes d'antimicrobiens et la résistance bactérienne chez certains agents pathogènes importants pour la santé animale et humaine a été observée. Les programmes intégrés de surveillance de l'UAM et de la RAM ont joué un rôle essentiel dans la production de ces données relatives à la RAM et dans l'élaboration de recommandations.

Pour cet article, le système d'analyse des dangers et des points critiques pour leur maîtrise (HACCP – *Hazard Analysis and Critical Control Point framework*) a été utilisé comme approche permettant de structurer et d'adapter certains exemples de stratégies d'intervention en élevage visant à la fois à réduire l'UAM et à limiter la RAM. L'article présente les défis futurs liés à l'atténuation de la RAM dans les productions animales, qui devront être relevés afin de préserver l'efficacité et la pérennité des antimicrobiens existants, tout en soutenant des pratiques durables de production animale.

Mots-clés

Analyse des dangers et des points critiques pour leur maîtrise – Animaux destinés à la production alimentaire – Antimicrobiens – Production animale durable – Résistance aux antimicrobiens – Une seule santé – Utilisation des antimicrobiens – Vétérinaire.

Resistencia a los antimicrobianos en el ganado: tendencias actuales, desafíos y perspectivas futuras

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Resumen

La resistencia a los antimicrobianos (RAM) constituye una grave amenaza mundial para la salud humana, animal y medioambiental y ha suscitado una atención creciente por parte de los actores implicados en todo el mundo. El uso excesivo e inadecuado de los antimicrobianos tanto en medicina humana como en medicina veterinaria ha acelerado considerablemente la aparición y propagación de microorganismos resistentes a los antimicrobianos. En el ámbito veterinario, se han llevado a cabo importantes esfuerzos en la ganadería para reducir el uso de antimicrobianos (UAM) y minimizar la propagación de la RAM.

El objetivo de esta revisión fue ofrecer una visión general de las tendencias actuales del UAM y de la RAM en los animales destinados a la producción de alimentos, identificar las principales limitaciones y estrategias de mitigación relacionadas con la RAM, y destacar las futuras líneas de actuación y las principales lagunas de investigación. Se ha notificado una reducción global de la cantidad total de antimicrobianos destinados al uso en animales, con perspectivas de que esta tendencia descendente continúe. Se ha observado una correlación positiva entre el uso de determinadas clases de antimicrobianos y la resistencia bacteriana en ciertos patógenos de importancia tanto para la salud animal como la salud humana. Los programas integrados de vigilancia del UAM y de la RAM han desempeñado un papel fundamental en la generación de estos datos sobre la RAM y en la formulación de recomendaciones.

En este artículo, se utilizó el marco del Análisis de Peligros y Puntos Críticos de Control como enfoque para estructurar y adaptar algunos ejemplos de estrategias de intervención en las explotaciones ganaderas destinadas tanto a reducir el UAM como a minimizar la RAM. El artículo expone los retos futuros para mitigar la RAM en la producción animal, que deberán abordarse con el fin de preservar la eficacia y la durabilidad de los antimicrobianos existentes, al tiempo que se apoyan prácticas sostenibles de producción animal.

Palabras clave

Análisis de Peligros y Puntos Críticos de Control – Animales destinados a la producción de alimentos – Antimicrobianos – Producción animal sostenible – Resistencia a los antimicrobianos – Una sola salud – Uso de antimicrobianos – Veterinaria.

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Table I

WOAH List of antimicrobial agents of veterinary importance in livestock [17]

Category	**Antimicrobial classes**
Veterinary Critically Important Antimicrobial Agents	Aminocyclitol (spectinomycin) Aminoglycosides Amphenicols Cephalosporins (3rd and 4th generation) Diaminopyrimidines Macrolides Penicillins Quinolones (2nd generation) Sulfonamides Sulfonamides + diaminopyrimidines Tetracyclines
Veterinary Highly Important Antimicrobial Agents	Ansamycin – rifamycins Cephalosporins (1st and 2nd generation) Ionophores Lincosamides Phosphonic acid derivatives Pleuromutilins Polypeptides (e.g. bacitracin, colistin) Quinolones (1st generation)
Veterinary Important Antimicrobial Agents	Aminocoumarin Arsenicals Bicyclomycin Fusidane (fusidic acid*) Orthosomycins Quinoxalines Streptogramins Thiostrepton

* Used in horses for the topical treatment of ophthalmic infections, and in dogs and cats for the topical treatment of ophthalmic and skin infections. Horses are considered livestock.

Table II

Examples of on-farm intervention strategies structured according to the adapted prerequisite programmes and the Hazard Analysis and Critical Control Point (HACCP) approach to reduce infectious disease pressure, antimicrobial use and antimicrobial resistance

Strategies	Prerequisite programmes	Interventions	Considerations/challenges
Improve animal husbandry practices	Premises (farm, barn)	– The site should be selected based on air flow orientation, accessibility for vehicles, flood risk, distance from other farms, and use of durable and easy-to-clean materials – As applicable to the farmed species, maintaining temperature in accordance with the animals' physiological stage, ensuring appropriate stocking density, regulating light cycles, providing adequate ventilation and ensuring the quality of feed and water – Farm cleaning and sanitation – Use codes of practice (international – e.g. WOAH's *Terrestrial Code* and *Aquatic Code* – and national/regional if available)	– Financial resources of the producer – Maintaining suitable conditions is challenging in aging or poorly maintained animal housing facilities – The regulatory framework in the country – The level of technical training or education of the producer
Establish and continuously improve/review biosecurity measures	Vehicles used for transportation of animals and feed, as well as the procedures for procurement, receipt, and storage of feed on farms and of feed ingredients intended for on-farm feed mills	– Vehicles must be appropriate for their intended use – Feed transport vehicles should be free from any risk of cross-contamination with residues from previous loads – Vehicles for animal transport, whether for purchase or for sale, must ensure animal welfare and minimise stress during handling and transport – Having on-farm silos dedicated to medicated feed (for bulk feed), as well as a designated storage area for feed and chemical products (e.g. antimicrobials, disinfectants, etc.) that is not accessible to animals and rodents – Specifications, requirements and adherence to these requirements for receiving feed and newly introduced animals aim to limit microbial contamination on the farm – Clear biosecurity requirements and compliance with the requirements for employees and visitors (such as feed and animal transporters, veterinarians, etc.)	– Producers' financial capacity and the availability and quality of transportation services adapted to animal species – Alignment of animal transportation systems with the country's climatic conditions – Transport conditions may vary depending on whether the producer uses its own vehicle or contracts external transport services – Producer requirements (e.g. a letter of guarantee) for feed transport providers and livestock suppliers to mitigate potential microbiological and chemical contamination – Local/regional/national and international regulatory requirement
Establish and continuously improve/review biosecurity measures	Equipment and materials used inside the building	– Materials (e.g. feeders and drinkers) should be appropriate for the type of production and constructed in a way that facilitates cleaning and maintenance – Regular washing and disinfection of coveralls and boots. Where applicable, provision of	– Financial resources of the producer – The level of the producer's awareness and adherence to cross-contamination prevention principles

Strategies	Prerequisite programmes	Interventions	Considerations/challenges
		washing and disinfection stations at the entrance and exit of production buildings – Where applicable, equipment designated for specific areas – such as farrowing rooms – should be used exclusively in those zones and not transferred to other sections to avoid cross-contamination	
Establish and continuously improve/review biosecurity measures	Sanitation and pest control	– Sanitary downtime (e.g. poultry house) with an approved cleaning and disinfection programme, including the use of approved chemical products – Where applicable, measures to prevent the entry of insects, rodents, birds or other vermin onto the farm (e.g. screens, traps and other control devices) – Carcass disposal programme and animal waste (manure, slurry) treatment strategy prior to land application	– Quality of training for producers and employees – Producers' financial resources and access to affordable, qualified labour – Availability and affordability of approved chemical products (e.g. disinfectants) – Availability, compliance and enforcement of relevant regulations
Training and awareness raising for the various stakeholders in animal production	Personnel	– Development of training programmes targeting the reduction of infection pressure, including the implementation of on-farm biosecurity measures, and the promotion of responsible and prudent AMU among key stakeholders, including farmers, veterinarians, animal health workers and feed mill operators – Peer-to-peer learning, through which successful practices are shared among producers (e.g. the FAO Farmer School Community) – Development of guidelines and codes of practice adapted to the production context (e.g. treatment protocols, diagnostic flowcharts), based on established frameworks (e.g. WOAH's *Terrestrial Code*, Chapter 6.10. Responsible and prudent use of antimicrobial agents in veterinary medicine) – Strengthening of the integration of microbial infection prevention and AMU/AMR education into veterinary and agricultural curricula, as well as the implementation of effective antimicrobial stewardship programmes	– The commitment of different stakeholders to reducing microbial contamination and AMU along the food chain – Availability of financial and human resources – Availability and enforcement of regulations mandating training programmes and ensuring participant attendance

Strategies	**HACCP principles**	**Interventions**	**Considerations/challenges**
Farm-level microbiological and epidemiological profiling	HACCP principle 1: Hazard analysis	– Identify endemic and high-risk pathogens on the farm or in the area surrounding the farm – Assess the vulnerability of the target animal species based on age, stocking density, physiological stage and other environmental factors (light cycle, humidity, etc.) – Characterise the farm's location in relation to neighbouring farms and nearby industrial or agricultural zones – Document the history of microbial infections on the farm, confirmed by veterinary diagnosis, as well as in the surrounding region – Review, where available, laboratory-confirmed diagnostic records from farm-derived samples, including AMR profiles of isolated bacteria – Review, where available, the history of AMU, including the antimicrobial classes used, annual volumes, routes of administration, duration of treatment and laboratory results obtained following AMU – Consider the regional and national animal health status, particularly with respect to endemic and emerging infectious diseases – Identify past episodes of microbial contamination associated with breaches or failures in biosecurity measures – Evaluate the level of implementation of the above prerequisite programmes, including herd/flock management practices, biosecurity measures, personnel training and pest control	– Level of producer engagement in managing microbial contamination and promoting the responsible use of antimicrobials – Availability of financial and human resources – Producer and farm employee training – Access to veterinarians or other relevant sources (e.g. national or international reference and surveillance databases) for data analysis – Cost and access to diagnostic laboratories – Data availability and quality – Producer concerns regarding data confidentiality and liability
Non-antimicrobial approaches for disease prevention and control (e.g. keeping animals healthy)	HACCP principle 2: Determine the critical control points*	**Vaccination:** – Identify endemic and high-risk pathogens on the farm or in the area surrounding the farm or the risk of introduction on the farm – Assess the potential consequences of not vaccinating animals (cost–benefit–consequence assessment), considering the herd's disease history, previous veterinary diagnoses and laboratory test results – Establish a vaccination programme appropriate for the specific animal species, age and physiological status	– Vaccine availability, efficacy, access and cost – Vaccine storage conditions, including maintenance of the cold chain when required, until vaccine administration – Vaccination coverage – Producer and farm employee training

Strategies	**HACCP principles**	**Interventions**	**Considerations/challenges**
Non-antimicrobial approaches for disease prevention and control (e.g. keeping animals healthy)	HACCP principle 2: Determine the critical control points*	**Antimicrobial alternatives:** – Identify key pathogens linked to high morbidity and mortality rates, particularly those not addressed by the current vaccination programme – Choose the most appropriate alternative(s), whether singly or in combination, according to the particular conditions of the farm – options include probiotics, prebiotics, organic acids, plant extracts, etc.	– Cost and efficacy of antimicrobial alternatives – Availability of antimicrobial alternatives on the market – Impact on animal performance (e.g. effects on feed or water palatability, potentially influencing intake and growth) – Regulatory and market acceptance
AMU for the treatment, prevention and control of disease in farm animals	HACCP principle 2: Determine the critical control points*	– Identify the critical phases of the on-farm production cycle and determine whether a biological hazard identified under Principle 1 is present and was not effectively controlled by the vaccination programme and/or the antimicrobial alternatives – Administer the antimicrobial in accordance with antimicrobial stewardship principles or the established treatment guidelines, where available for the specific region and animal species	– Quality and availability of training for producers and employees – Access to Veterinary Services (cost and availability) – Access to and availability of approved antimicrobials on the market – Self-medication and use of falsified products
Compliance with good practices in the use of vaccines, antimicrobial alternatives and antimicrobials	HACCP principle 3: Establish critical limits	– Establish thresholds for morbidity, mortality, significant compromise of animal welfare, or marked declines in production performance that are considered unacceptable and warrant the use of vaccines, antimicrobial alternatives or antimicrobials, or a change in one of these approaches – Identify prevalences of resistance to which there would be a concern with treatment/prevention/control efficacy – to guide subsequent continued AMU, modification or replacement of the antimicrobials used – Respect withdrawal times** for antimicrobials, and where applicable for vaccines and alternative products, to ensure residue-related safety of animal-derived food products	– Quality of training for producers and employees – Access to Veterinary Services (cost and availability) – Quality and availability of laboratory data related to the antimicrobial susceptibility of pathogenic bacteria at the farm level
Tracking effectiveness	HACCP principle 4: Establish monitoring procedures	– Monitoring of product***/vaccine use (e.g. product, dose, route, duration, indication) – Monitoring of morbidity, mortality and clinical signs – Monitoring of production performance indicators (e.g. growth rate, feed efficiency, egg production) – Monitoring of AMR following AMU	– Quality of training for producers and employees – Producer's commitment, financial capacity and access to a qualified workforce – Cost and access to Veterinary Services and diagnostic laboratories

Strategies	**HACCP principles**	**Interventions**	**Considerations/challenges**
		– Monitoring of adverse events – Monitoring of compliance with veterinary prescriptions and withdrawal periods – Monitoring of storage conditions for different products (e.g. cold chain for vaccines, expiration dates, etc.)	
Tracking effectiveness	HACCP principle 4: Establish monitoring procedures	– Re-training of personnel when improper handling or administration is detected – Re-evaluation of the diagnosis/situations by a veterinarian – Immediate review and adjustment of administration protocols when inappropriate use by the farmer is identified – Adjustment or discontinuation of the products/vaccines when no measurable health or performance benefit is observed – Determination of the antimicrobial susceptibility profile of the target bacteria (laboratory analysis) – Replacement of compromised products/vaccines (e.g. cold-chain failure, expired products) – Integration of additional interventions (e.g. biosecurity, nutrition, management)	– Cost and access to Veterinary Services – Level of producer engagement (awareness, compliance) in the responsible use of antimicrobials – Cost and access to diagnostic tools and laboratories
	HACCP principle 5: Establish corrective actions		
Regular assessment of on-farm non-antimicrobial approaches, AMU and AMR trends	HACCP principle 6: Establish verification procedures	– Veterinarians shall be responsible for verifying products/vaccines administration practices (e.g. dose, duration), ensuring producer and employee training, and monitoring adherence to established veterinary protocols – Auditing of veterinary prescriptions by veterinary regulatory bodies – Cross-checking of product/vaccine use records with purchase and inventory data – Verification of product/vaccine quality and supplier compliance – Review of compliance with withdrawal times, where applicable – Verification of cold-chain management (storage temperature, expiration dates), where applicable – Verification of expected *versus* observed health or performance outcomes – Analysis of microbiological test results (e.g. antibiograms), identification of trends over time, and comparison with regional or national reference and surveillance data	– Training of producers and their engagement/compliance with more prudent AMU (e.g. antimicrobial more targeted to the pathogen) – Availability of financial and human resources – Access to veterinarians or other relevant sources (e.g. national or international reference and surveillance databases) for data analysis – Cost and access to diagnostic laboratories – Availability and enforcement of regulations for corrective actions, where applicable – Genomic data sharing and collaboration among diverse stakeholders and laboratories

Strategies	HACCP principles	Interventions	Considerations/challenges
	HACCP principle 7: Establish record-keeping and documentation procedures	– Maintain detailed records of on-farm disease history confirmed by veterinary diagnosis – Document veterinary prescriptions and treatment justifications – Maintain detailed records of on-farm product/vaccine use (e.g. dose, duration, indication, route, treated animal groups) – Products/vaccines purchase, inventory and usage records – Records of withdrawal periods and compliance verification – Records of adverse reactions or products/vaccines failures – Laboratory reports on AMR surveillance results and trends over time – Records of any corrective actions taken following therapeutic failure or non-compliant AMU as well as preventive measures, such as vaccination programmes and the use of alternatives to antimicrobials – Records of staff training – Ensure that all records are retained for the required period in accordance with current regulations	– Training of producers and their engagement in addressing AMU and reducing AMR – Availability of financial and human resources – Availability and enforcement of regulations regarding AMU/vaccines, where applicable

* A critical control point (CCP) in the food industry is a step at which control measures can be applied to prevent, eliminate or reduce a food safety hazard to an acceptable level. In the context of this article, decisions regarding vaccination and/or the use of adaptive alternatives, or the administration of antimicrobials on the farm are considered critical control points.

** Withdrawal times currently consider only chemical residues of antimicrobials and do not account for AMR safety.

*** Products, in this table, refer to antimicrobial alternatives or antimicrobials.

AMR:	antimicrobial resistance
AMU:	antimicrobial use
FAO:	Food and Agriculture Organization of the United Nations
HACCP:	Hazard Analysis Critical Control Point
WOAH:	World Organisation for Animal Health

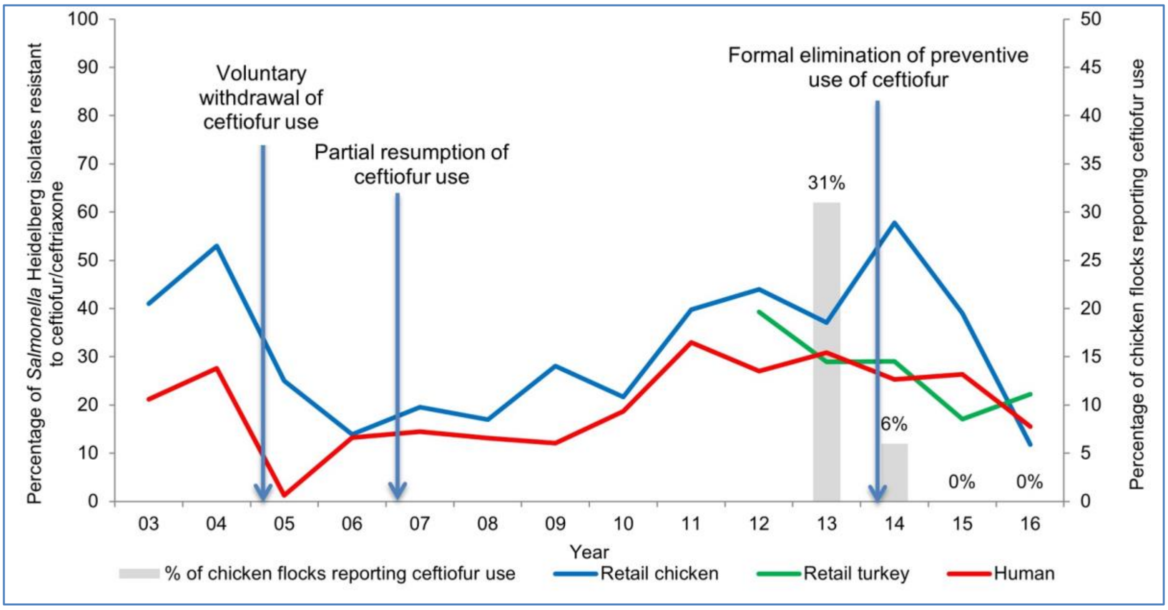

Figure 1

Percentage of ceftiofur/ceftriaxone-resistant *Salmonella* Heidelberg from retail poultry and humans, and ceftiofur use in broiler chicken flocks in Canada [73]

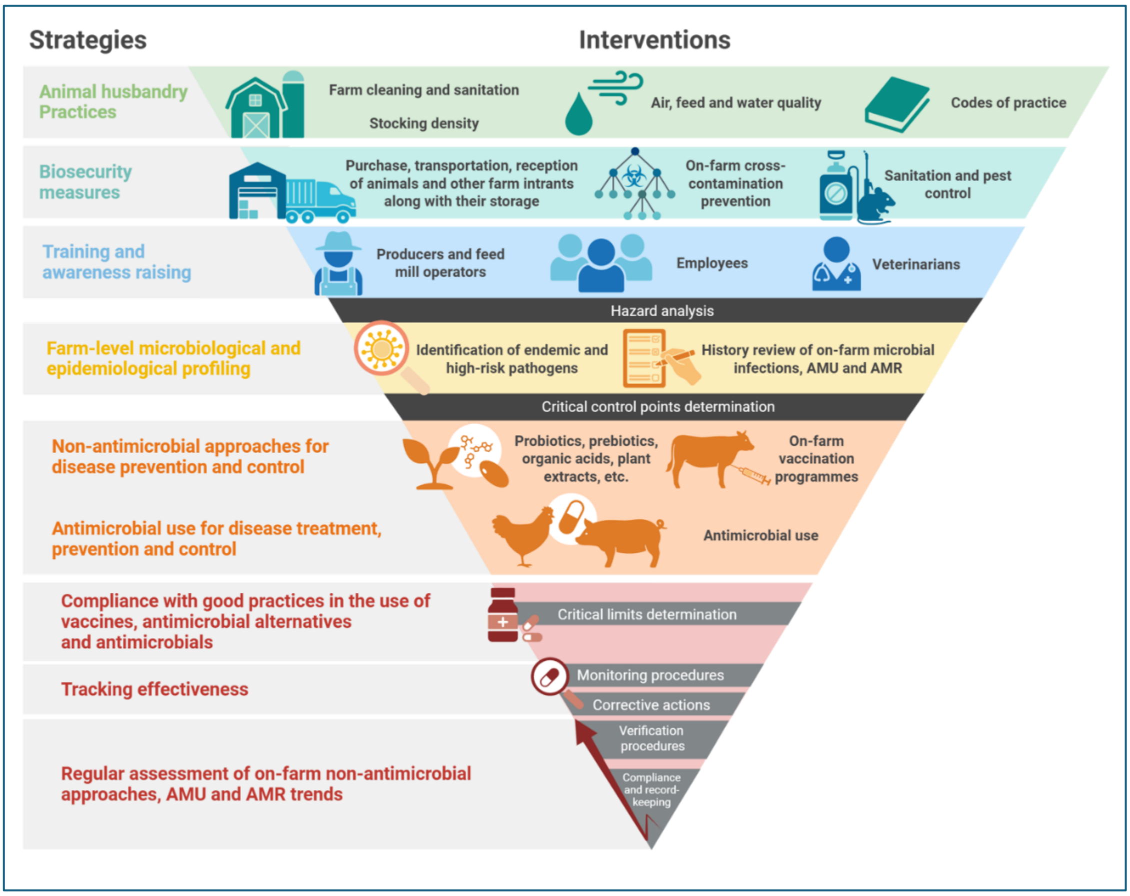

Figure 2

Examples of on-farm intervention strategies structured according to the adapted prerequisite programme principles and the Hazard Analysis Critical Control Point approach to reduce infectious disease pressure, antimicrobial use and antimicrobial resistance

AMR: antimicrobial resistance
AMU: antimicrobial use

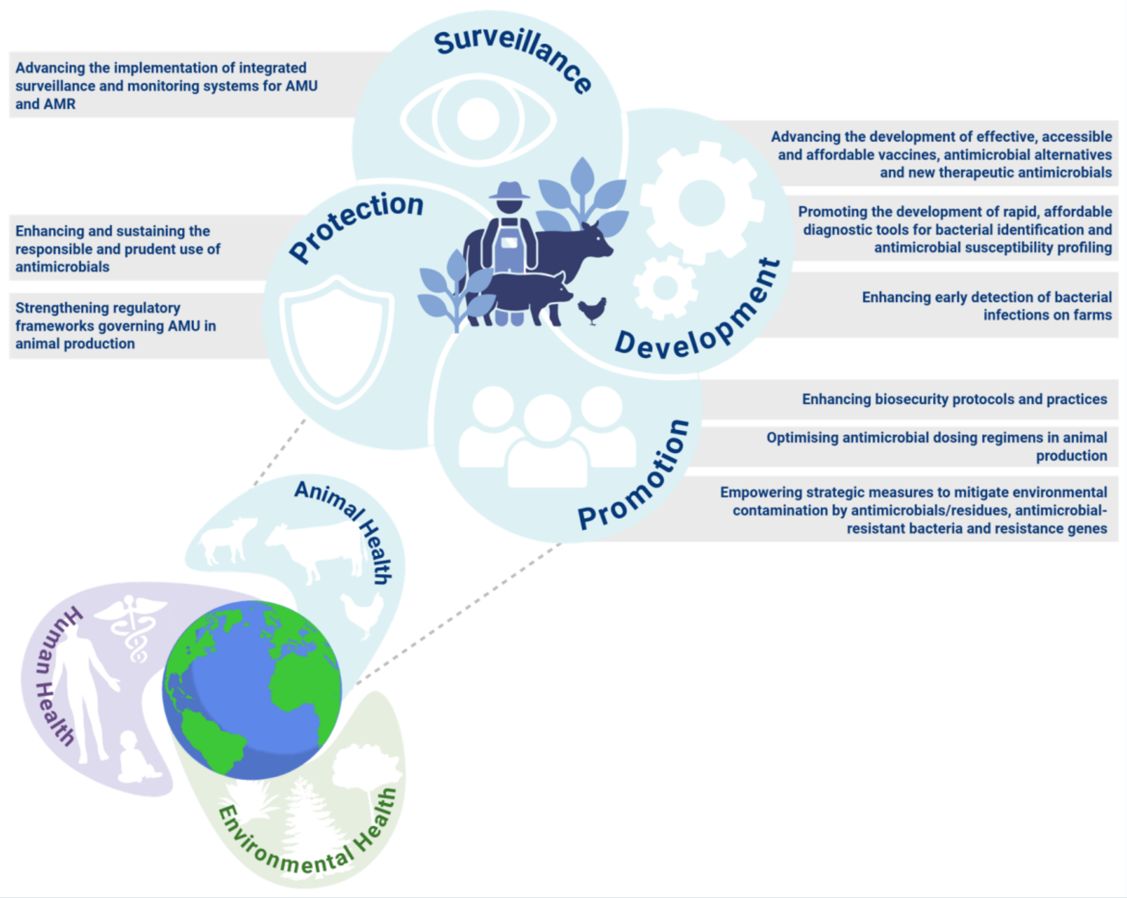

Figure 3

Future directions for livestock stakeholders in One Health approach to promote prudent and responsible antimicrobial use in animal production and minimise the selection for antimicrobial-resistant bacteria

AMR: antimicrobial resistance
AMU: antimicrobial use