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Review Paper

Antimicrobial stewardship for sustainable meat production in pig farming from One Health perspectives

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ABSTRACT

The widespread use of antimicrobials in pig farming has played a key role in improving animal health, reducing mortality, and ensuring productivity. However, inappropriate or excessive antimicrobial use contributes to the global challenge of antimicrobial resistance (AMR), posing risks to both public health and the sustainability of meat production. The increasing global concern over AMR has positioned livestock farming at the centre of sustainability debates. Pig farming, as one of the most intensive livestock production systems, plays a critical role in shaping antimicrobial use (AMU) patterns and in mitigating risks associated with AMR. This paper explores antimicrobial stewardship (AMS) in pig farming from regulatory, practical, and sustainability perspectives. It also highlights strategies that link AMS with sustainable meat production, including biosecurity measures, vaccination, and feed optimization. Drawing on regulatory frameworks, farm-level strategies, and the One Health approach, the study emphasizes the importance of aligning industry practices with global sustainability goals. The analysis highlights how AMS contributes to sustainable meat production and food system resilience.

1. Introduction

Antimicrobial resistance (AMR) poses an unprecedented global health and economic challenge, threatening human, animal, and environmental health (*Alhassan et al.*, 2025). The profound consequences of AMR on human health are well established (*Cassini et al.*, 2019; *Salehi et al.*, 2022), while in contrast, precise data quantifying the direct effects of AMR on animal health remain limited (*Emes et al.*, 2022). Even so, the veterinary field recognizes AMR's detrimental role in increased disease burden, higher mortality, and decreased productivity *(White & Hughes*, 2019; *Palma et al.*, 2020; *Martins et al.*, 2024), emphasizing the urgency of coordinated strategies to address this growing challenge.

Antimicrobial stewardship (AMS) refers to coordinated interventions designed to improve and measure the appropriate use of antimicrobials. Its primary objectives are to optimize therapeutic efficacy, reduce the emergence of AMR, and ensure animal welfare and food safety (*Guardabassi & Prescott*, 2015) through a coordinated set of actions. The need for AMS arises from the widespread antimicrobial use (AMU) in livestock production, often as growth promoters or for disease prevention, which has contributed significantly to the development of AMR (*Van Boeckel et al.*, 2015).

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In pig farming, AMU is particularly high due to intensive production systems that expose animals to increased disease pressure. The European Medicines Agency (EMA) has repeatedly emphasized that pigs are among the top consumers of veterinary antimicrobials within the European Union (EU) (*EMA*, 2020). The consequences extend beyond animal health, as resistant pathogens and resistance genes may spread to humans and the environment, threatening public health and ecosystems (*Ferri et al*., 2017). Acknowledging this reservoir, veterinarians are key actors in the One Health framework for AMS (*McEwen & Collignon*, 2018). AMS is closely aligned with the One Health concept, which recognizes the interdependence of human, animal, and environmental health. Thus, addressing AMR requires multisectoral cooperation, with livestock farming serving as a critical intervention point (*OIE*, 2019). Moreover, since many antimicrobial classes are shared between human and veterinary medicine, their use in animals can increase AMR in pathogens relevant to public health *(Marshall & Levy, 2011; Thanner et al*., 2016). Pig farming in Southeast Europe, particularly in countries where pork is a dominant component of the diet, presents both a challenge and an opportunity: while AMU remains relatively high, regulatory alignment with EU standards offers a pathway toward sustainable and responsible production.

This paper examines AMS in pig farming by analyzing regulatory frameworks, practical implementation strategies, and sustainability outcomes. By doing so, it highlights the central role of AMS in transitioning toward sustainable meat production systems. The present paper builds upon our earlier published work (*Kovačević et al.,* 2026), expanding the discussion toward sustainable meat production and regional implementation of AMS principles in pig farming through a One Health perspective.

2. Policy environment supporting sustainable antimicrobial use

EU has established a robust regulatory framework to ensure the prudent use of antimicrobials in animals, primarily through the EU Regulations 2019/4 (*Regulation, 2019/4,* 2019) and 2019/6 (*Regulation, 2019/6,* 2019), which replaced Directive 2001/82/EC (*Regulation, 1831/2003/EC,* 2003). These acts define clear obligations for veterinarians, producers, and pharmaceutical companies, including strict control of prophylactic use and a complete ban on growth promotion. A detailed overview of these EU regulatory foundations has been presented previously (*Kovačević et al*., 2026), providing the groundwork for the present discussion focused on their sustainability and implementation aspects. Beyond their legal intent, these measures reflect a broader policy shift toward integrating AMS into the EU's sustainability and *One Health* agenda (*WHO*, 2017).

At the international level, the World Health Organization (WHO), Food and Agriculture Organization (FAO), and World Organisation for Animal Health (WOAH, formerly OIE) provide guidance through the Global Action Plan on AMR (*WHO*, 2015). These frameworks emphasize the importance of monitoring, reporting, and reducing AMU in livestock, while fostering innovation in disease prevention strategies. In the regional context, Southeast European countries aspiring to EU accession have adopted harmonized regulations. National strategies now include restrictions on antimicrobial prophylaxis, requirements for veterinary prescriptions, and obligations for AMU reporting. These measures reflect a convergence with EU standards but also expose challenges in enforcement, particularly at the farm level where compliance depends on farmer awareness and veterinary capacity. They promote responsible prescription practices and encourage alternative strategies such as improved biosecurity, vaccination, and precision livestock farming to reduce antimicrobial dependence without affecting productivity (Lhermie et al., 2017). EMA, the European Food Safety Authority (EFSA), and the European Centre for Disease Prevention and Control (ECDC) jointly monitored AMU and resistance through the European Surveillance of Veterinary Antimicrobial Consumption (ESVAC) program, providing data for evidence-based policymaking and benchmarking across Member States (*EMA*, 2022). Within the *Farm to Fork Strategy* and the EU *One Health Action Plan*, AMS is recognized as a core element of sustainable agricultural policy rather than an isolated veterinary issue (*WHO*, 2015; *OECD*, 2022).

3. Translating policy into sustainable farm practices

Effective AMS in livestock depends on translating policy into farm-level action through practical, science-based management. AMS should be seen not as a regulatory burden but as a pathway to

greater productivity, animal welfare, and sustainability. Veterinarians play a central role by guiding diagnostics-based prescribing and ensuring responsible use of critically important antimicrobials (*WHO*, 2017; *EMA*, 2019). In particular, third- and fourth-generation cephalosporins, fluoroquinolones, and colistin are tightly restricted in animals to safeguard their effectiveness for people (*ECDC, EFSA and EMA*, 2017). Farms that implement all-in/all-out systems, maintain strict sanitation, and adopt vaccination strategies consistently report lower AMU levels. Beside vaccination programs, alternatives to antimicrobials, such as prebiotics, probiotics, and feed additives (organic acids and essential oils), are alternatives that improve gut health and resilience (*De Lange et al*., 2010; *Xu et al*., 2020; *Nhara et al*., 2024). Educational campaigns and incentive schemes have proven effective in improving compliance with AMS programs (*Hardefeldt et al*., 2018; *Gozdzielewska et al*., 2020). Ultimately, on-farm AMS implementation embodies the One Health vision, linking responsible veterinary practice with environmental protection and public health objectives.

4. Antimicrobial stewardship in a sustainability context: One Health and regional perspectives

AMS contributes directly to sustainable meat production by aligning animal health management with environmental and public health goals. By reducing AMU, AMS decreases the risk of resistant pathogens entering the food chain, protects ecosystems from antimicrobial residues, and ensures the long-term efficacy of essential medicines. Actually, successful AMS in veterinary medicine has shown reduced AMU without harming productivity. Denmark and the Netherlands stand out, implementing policies focused on veterinary training, regulation, and surveillance (*Robinson et al.*, 2016). Denmark's "Yellow Card" system, introduced in 2010, set usage thresholds and achieved a 27% drop in livestock antibiotic consumption *(Time & Veggeland*, 2020; *WOAH*, 2022). Figure 1 provides an overview of the main elements of AMS in pig farming, highlighting the interaction between management practices, AMU, and sustainability outcomes.

In Southeast Europe, where pork production is a cornerstone of the agricultural economy, AMS also has socio-economic significance. Aligning local practices with EU frameworks enhances competitiveness in international markets while supporting national food security. Importantly, AMS is integral to the One Health approach, which integrates the interests of veterinary, human health, and environmental sectors (*Hibbard et al*., 2024). According to James et al. (2025), the key drivers of effective AMS include strong governance, education, access to diagnostics, and digital surveillance all of which require context-specific adaptation across different production systems. Recent evidence from Uganda further illustrates that farm-level factors such as hygiene and the intensity of production directly influence the spread of resistance, with pigs in semi-intensive systems being more than twice as likely to harbor resistant bacteria compared to those in free-range settings (*Muwonge et al.*, 2025).

AMS should also be viewed in relation to the Sustainable Development Goals (SDGs) which promotes reduced AMU, supports SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land) (*Alhassan et al*., 2025). Thus, AMS is not only a veterinary or regulatory concern but a broader sustainability imperative.

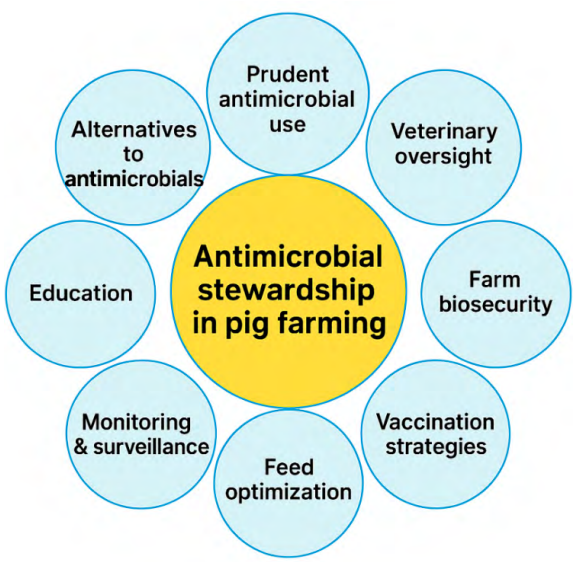

Figure 1. Key components of antimicrobial stewardship in pig farming.

5. Conclusion

AMS is no longer optional but an essential component for sustainable meat production. While regulatory frameworks establish necessary restrictions and monitoring requirements, real progress depends on farm-level implementation supported by veterinary oversight, farmer engagement, and preventive

health strategies. The One Health perspective further underlines the interconnectedness of AMS with human health and environmental protection. In the regional context of Southeast Europe, aligning pig production practices with EU regulatory frameworks presents both a challenge and an opportunity for ensuring sustainable, competitive, and resilient food systems. The path forward requires cross-sectoral collaboration, continuous surveillance, and global commitment to responsible AMU.

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