



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; Mar-

tins *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; WOA, 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 competi-

tiveness 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 (Mwonge 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.

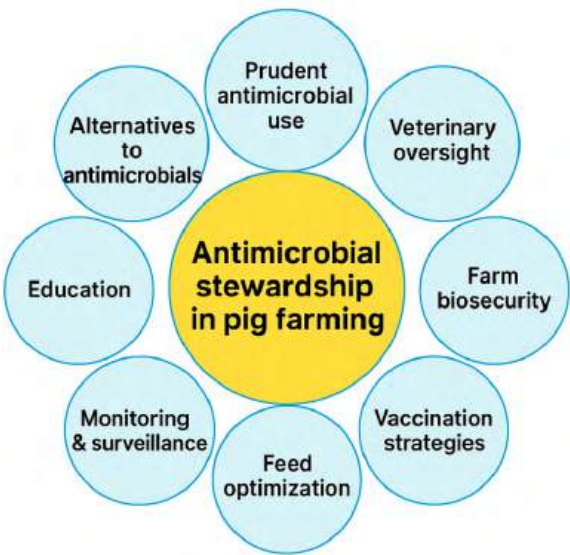


Figure 1. Key components of antimicrobial stewardship in pig farming.

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 frame-

works 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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References

- Alhassan, M. Y., Kabara, M. K., Ahmad, A. A., Abdulsalam, J., & Habib, H. I. (2025). Revisiting antibiotic stewardship: veterinary contributions to combating antimicrobial resistance globally. *Bulletin of the National Research Centre*, 49(1), 25. <https://doi.org/10.1186/s42269-025-01317-3>
- Cassini, A., Högberg, L. D., Plachouras, D., Quattrocchi, A., Hoxha, A., Simonsen, G. S.,...Cecchini, M. (2019). Attributable deaths and disability-adjusted life-years caused by infections with antibiotic-resistant bacteria in the EU and the European Economic Area in 2015: a population-level modelling analysis. *The Lancet Infectious Diseases*, 19(1), 56–66. [https://doi.org/10.1016/S1473-3099\(18\)30605-4](https://doi.org/10.1016/S1473-3099(18)30605-4)
- De Lange, C. F. M., Pluske, J., Gong, J. & Nyachoti, C. M. (2010). Strategic use of feed ingredients and feed additives to stimulate gut health and development in young pigs. *Livestock Science*, 134(1–3), 124–134. <https://doi.org/10.1016/j.livsci.2010.06.117>
- ECDC, EFSA, and EMA. (2017). Second joint report on the integrated analysis of the consumption of antimicrobial agents and occurrence of antimicrobial resistance in bacteria from humans and food-producing animals (JIACRA II). Retrieved from <https://www.efsa.europa.eu/en/efsa-journal/pub/4872> Accessed March 8, 2025.
- Emes, D., Naylor, N., Waage, J., & Knight, G. (2022). Quantifying the relationship between antibiotic use in food-producing animals and antibiotic resistance in humans. *Antibiotics*, 11(1), 66. <https://doi.org/10.3390/antibiotics11010066>
- ESVAC, (2023). European Surveillance of Veterinary Antimicrobial Consumption report. Retrieved from https://www.ema.europa.eu/en/documents/report/sales-veterinary-antimicrobial-agents-31-european-countries-2021-trends-2012-2021-eleventh_en.pdf Accessed July 25, 2025.
- EMA—European Medicines Agency, (2019). Categorisation of antibiotics in the European Union. Answer to the request from the European Commission for updating the scientific advice on the impact on public health and animal health of the use of antibiotics in animals. Retrieved from <https://www.ema.europa.eu/en/news/categorisation-antibiotics-used-animals-promotes-responsible-use-protect-public-and-animal-health> Accessed July 25, 2025.
- EMA—European Medicines Agency, (2022). Sales of veterinary antimicrobial agents in 31 European countries in 2021: Trends from 2010 to 2021. Retrieved from https://www.ema.europa.eu/en/documents/report/sales-veterinary-antimicrobial-agents-31-european-countries-2021-trends-2010-2021-twelfth-esvac-report_en.pdf Accessed July 25, 2025.
- Ferri, M., Ranucci, E., Romagnoli, P., & Giaccone, V. (2017). Antimicrobial resistance: A global emerging threat to public health systems. *Critical reviews in food science and nutrition*, 57(13), 2857–2876. <https://doi.org/10.1080/10408398.2015.1077192>
- Gozdzielewska, L., King, C., Flowers, P., Mellor, D., Dunlop, P. & Price, L. (2020). Scoping review of approaches for improving antimicrobial stewardship in livestock farmers and veterinarians. *Preventive Veterinary Medicine*, 180, 105025. <https://doi.org/10.1016/j.prevetmed.2020.105025>
- Guardabassi, L., & Prescott, J. F. (2015). Antimicrobial stewardship in small animal veterinary practice: from theory to practice. *Veterinary Clinics: Small Animal Practice*, 45(2), 361–376. <https://doi.org/10.1016/j.cvs.2014.11.005>
- Hardefeldt, L.Y., Gilkerson, J. R., Billman-Jacobe, H., Stevenson, M. A., Thursky, K., Bailey, K. E. & Browning, G. F. (2018). Barriers to and enablers of implementing antimicrobial stewardship programs in veterinary practices. *Journal of Veterinary Internal Medicine*, 32(3), pp.1092–1099. <https://doi.org/10.1111/jvim.15083>
- Hibbard, R., Mendelson, M., Page, S. W., Ferreira, J. P., Pulcini, C., Paul, M. C., & Faverjon, C. (2024). Antimicrobial stewardship: a definition with a One Health perspective. *npj Antimicrobials and Resistance*, 2(1), 15. <https://doi.org/10.1038/s44259-024-00031-w>
- James, R., Hardefeldt, L. Y., Ierano, C., Charani, E., Dowson, L., Elkins, S., & Thursky, K. (2025). Antimicrobial stewardship from a One Health perspective. *Nature Reviews Microbiology*, 1-17. <https://doi.org/10.1038/s41579-025-01233-3>
- Kovačević, Z., Krivokapić, M., Tomanić, D., & Mugoša, S. (2026). Antimicrobial stewardship in pig production: regulatory frameworks and strategic implementation. *Veterinarski Arhiv*, 96, 155-163. <https://doi.org/10.24099/vet.arhiv.2987>

- Lhermie, G., Gröhn, Y. T., & Raboisson, D. (2017). Addressing antimicrobial resistance: an overview of priority actions to prevent suboptimal antimicrobial use in food-animal production. *Frontiers in microbiology*, 7, 2114. <https://doi.org/10.3389/fmicb.2016.02114>
- Marshall, B. M., & Levy, S. B. (2011). Food animals and antimicrobials: impacts on human health. *Clinical Microbiology Reviews*, 24(4), 718–733. <https://doi.org/10.1128/CMR.00002-11>
- Martins, S. B., Afonso, J. S., Fastl, C., Huntington, B., & Rushton, J. (2024). The burden of antimicrobial resistance in livestock: A framework to estimate its impact within the Global Burden of Animal Diseases programme. *One Health*, 19, 100917. <https://doi.org/10.1016/j.onehlt.2024.100917>
- McEwen, S. A., & Collignon, P. J. (2018). Antimicrobial resistance: a one health perspective. *Microbiology Spectrum*, 6, 521–547. <https://doi.org/10.1128/microbiolspec.ARBA-0009-2017>
- Muwonge, A., Nanteza, A., Tumwine, G., Baluka, S. A., Erume, J., & Dione, M. (2025). Drivers of antimicrobial resistance in pig production systems of Uganda. *Communications Earth & Environment*, 6, 506. <https://doi.org/10.1038/s43247-025-02506-8>
- Nhara, R. B., Marume, U., & Nantapo, C. W. T. (2024). Potential of organic acids, essential oils and their blends in pig diets as alternatives to antibiotic growth promoters. *Animals*, 14(5), 762. <https://doi.org/10.3390/ani14050762>
- OIE, (2019). Critically important antimicrobial agents for veterinary medicine. World Organisation for Animal Health. Retrieved from <https://www.oie.int> Accessed June 20, 2025.
- Palma, E., Tilocca, B., & Roncada, P. (2020). Antimicrobial resistance in veterinary medicine: An overview. *International Journal of Molecular Sciences*, 21(6), 1914. <https://doi.org/10.3390/ijms21061914>
- Postma, M., Speksnijder, D., Jaarsma, A., Verheij, T. J., Wagenaar, J., & Dewulf, J. (2016). Opinions of veterinarians on antimicrobial use in farm animals in Flanders and the Netherlands. *Veterinary Record*, 179, 68–68. <https://doi.org/10.1136/vr.103618>
- Regulation (EU) 2019/4, (2019). Regulation (EU) 2019/4 of the European Parliament and of the Council of 11 December 2018 on the manufacture, placing on the market and use of medicated feed. Official Journal of the European Union. 2019;L4:1–23. Accessed July 25, 2025.
- Regulation (EU) 2019/6, (2019). Regulation (EU) 2019/6 of the European Parliament and of the Council of 11 December 2018 on veterinary medicinal products and repealing Directive 2001/82/EC. Official Journal of the European Union. 2019;L4:43–167. Accessed July 25, 2025.
- Regulation (EC) No 1831/2003, (2003). Regulation (EC) No 1831/2003 of the European Parliament and of the Council of 22 September 2003 on additives for use in animal nutrition. Retrieved from <https://eur-lex.europa.eu/eli/reg/2003/1831/oj/eng> Accessed July 25, 2025.
- Robinson, T. P., Wertheim, H. F., Kakkar, M., Kariuki, S., Bu, D., & Price, L. B. (2016). Animal production and antimicrobial resistance in the clinic. *The Lancet*, 387(10014), e1–e3. [https://doi.org/10.1016/S0140-6736\(15\)00730-8](https://doi.org/10.1016/S0140-6736(15)00730-8)
- Salehi, B., Abu-Darwish, M., Tarawneh, A., Cabral, C., Gadetskaya, A., Salgueiro, L.,...Sharifi-Rad, M. (2022). Antimicrobial resistance collaborators global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. *Lancet*, 399, 629–655. [https://doi.org/10.1016/S0140-6736\(21\)02724-0](https://doi.org/10.1016/S0140-6736(21)02724-0)
- Thanner, S., Drissner, D., & Walsh, F. (2016). Antimicrobial resistance in agriculture. *MBio*, 7(2), e02227-15. <https://doi.org/10.1128/mBio.02227-15>
- Time, M. S., & Veggeland, F. (2020). Adapting to a global health challenge: managing antimicrobial resistance in the Nordics. *Politics and Governance*, 8(4), 53–64. <https://doi.org/10.1128/mBio.02227-15>
- Van Boeckel, T. P., Brower, C., Gilbert, M., Grenfell, B. T., Levin, S. A., Robinson, T. P.,...Laxminarayan, R. (2015). Global trends in antimicrobial use in food animals. *Proceedings of the National Academy of Sciences*, 112(18), 5649–5654. <https://doi.org/10.1073/pnas.1503141112>
- White, A., & Hughes, J. M. (2019). Critical importance of a one health approach to antimicrobial resistance. *EcoHealth*, 16(3), 404–409. <https://doi.org/10.1007/s10393-019-01415-5>
- WHO, (2015). World Health Organization Global Action Plan on Antimicrobial Resistance. Geneva. Retrieved from <https://www.who.int/publications/i/item/9789241509763> Accessed July 25, 2025.
- WHO, (2017). Guidelines on use of medically important antimicrobials in food-producing animals. Retrieved from <https://www.who.int/publications/i/item/9789241550130> Accessed July 25, 2025.
- WOAH, (2022). Strategy on antimicrobial resistance and prudent use of antimicrobials. Retrieved from <https://www.woah.org/app/uploads/2021/03/en-amr-strategy-2022-final-single-pages.pdf> Accessed January 14, 2025.
- Xu, Y., Lahaye, L., He, Z., Zhang, J., Yang, C. & Piao, X. (2020). Micro-encapsulated essential oils and organic acids combination improves intestinal barrier function, inflammatory responses and microbiota of weaned piglets challenged with enterotoxigenic Escherichia coli F4 (K88+). *Animal Nutrition*, 6(3), 269–277. <https://doi.org/10.1016/j.aninu.2020.04.004>

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