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Antimicrobial resistance in dairy systems: A comprehensive review

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Abstract
Antimicrobial resistance (AMR) has emerged as one of the most pressing global threats to animal and public health. Dairy production systems represent a significant interface where antimicrobial use, bacterial adaptation, and environmental dissemination converge. Antimicrobials are widely used in dairy cattle for therapeutic, prophylactic, and metaphylactic purposes, particularly for mastitis, reproductive disorders, and calf diseases. Continuous exposure of microorganisms to these agents has accelerated the selection and spread of antimicrobial-resistant bacteria and resistance genes. This review critically examines the occurrence, drivers, and mechanisms of AMR in dairy systems, explores its implications for animal productivity, food safety, and public health, and discusses current and emerging strategies for surveillance, antimicrobial stewardship, and sustainable disease control. Adoption of a One Health approach is emphasized as essential for addressing AMR in dairy production.

Keywords: Antimicrobial resistance, dairy cattle, mastitis, antimicrobial use, one health, food safety

1. Introduction

The intensification of dairy farming over recent decades has significantly improved milk production efficiency but has simultaneously increased disease pressure within herds. To mitigate disease-associated economic losses, antimicrobials have become indispensable tools in dairy herd health management. However, excessive and inappropriate antimicrobial use (AMU) has contributed to the rapid emergence of antimicrobial resistance (AMR), threatening the effectiveness of available drugs.

AMR is defined as the ability of microorganisms to survive or proliferate in the presence of antimicrobial concentrations that would normally inhibit or kill susceptible strains. In dairy systems, resistant bacteria can originate from animal infections, commensal flora, or environmental reservoirs and can be transmitted to humans through direct contact, food consumption, or environmental pathways. The global recognition of AMR as a One Health issue underscores the interconnectedness of animal agriculture, human medicine, and ecosystems.

2. Antimicrobial Use in Dairy Systems

2.1 Purposes and Patterns of Use

Antimicrobials in dairy cattle are primarily used for:

- **Therapeutic treatment:** Clinical mastitis, metritis, respiratory infections, lameness, and calf diseases
- **Prophylactic use:** Dry cow therapy to prevent intramammary infections
- **Metaphylactic use:** Group treatment when disease risk is high

Among these, mastitis accounts for the largest proportion of antimicrobial consumption in dairy herds. Blanket dry cow therapy, though effective in controlling mastitis, has historically contributed to substantial antimicrobial exposure.

Table 1: Common antimicrobials used in dairy cattle and their primary indications

Antimicrobial class	Common drugs used in dairy cattle	Primary indication	Remarks related to AMR
β-lactams	Penicillin, Amoxicillin, Ceftiofur	Mastitis, metritis	High resistance reported in *Staphylococcus* spp.
Tetracyclines	Oxytetracycline	Respiratory and systemic infections	Widely used; high resistance in *E. coli*
Aminoglycosides	Gentamicin, Neomycin	Severe mastitis, septicemia	Residue concerns; MDR emergence
Macrolides	Erythromycin, Tylosin	Respiratory infections	Limited use but increasing resistance
Sulfonamides	Sulfamethoxazole	Calf diarrhea	Resistance common in enteric bacteria
Fluoroquinolones	Enrofloxacin	Severe infections	Critically important for human medicine

2.2 Factors Influencing Antimicrobial Use
Antimicrobial usage patterns vary widely depending on herd size, management system, availability of veterinary services, regulatory frameworks, and farmer awareness. In low- and middle-income countries, antimicrobials are often accessible without prescription, leading to misuse, incorrect dosing, and failure to observe withdrawal periods.

3. Prevalence of Antimicrobial Resistance in Dairy Systems
3.1 AMR in Mastitis Pathogens
Mastitis pathogens such as *Staphylococcus aureus*, *Streptococcus agalactiae*, *Escherichia coli*, and *Klebsiella* spp. have demonstrated increasing resistance to commonly used antimicrobials. Resistance to β-lactams, tetracyclines, sulfonamides, and aminoglycosides is frequently reported. Methicillin-resistant *Staphylococcus aureus* (MRSA) strains in dairy cattle are of particular concern due to their zoonotic potential.

3.2 AMR in Commensal and Environmental Bacteria
Beyond clinical pathogens, commensal bacteria in the gastrointestinal tract of cattle serve as reservoirs of antimicrobial resistance genes (ARGs). These bacteria can transfer resistance determinants to pathogenic organisms through horizontal gene transfer. Manure, slurry, and wastewater from dairy farms further disseminate resistant bacteria and ARGs into soil and water systems.

3.3 Multidrug Resistance
Multidrug-resistant (MDR) bacteria, resistant to three or more antimicrobial classes, are increasingly isolated from dairy cattle and milk. MDR infections complicate treatment, prolong disease duration, increase costs, and elevate the risk of therapeutic failure.

Table 2: Major antimicrobial-resistant bacteria reported in dairy systems

Bacterial species	Source	Common resistance reported	Public health relevance
Staphylococcus aureus	Milk, udder	Penicillin, methicillin	Zoonotic; MRSA risk
Escherichia coli	Milk, feces, environment	Tetracycline, ampicillin	Foodborne illness
Klebsiella spp.	Bedding, milk	β-lactams	Environmental persistence
Streptococcus spp.	Milk	Macrolides, tetracycline	Mastitis persistence
Salmonella spp.	Feces, milk	Multidrug resistance	High zoonotic risk

4. Mechanisms of Antimicrobial Resistance
4.1 Genetic Mechanisms
AMR arises through:
- Chromosomal mutations altering antimicrobial targets
- Horizontal gene transfer via plasmids, transposons, and integrons

Genes encoding β-lactamases, efflux pumps, and altered ribosomal targets are commonly detected in dairy-associated bacteria.

4.2 Role of the Dairy Farm Environment
The dairy farm environment acts as a critical reservoir for resistance. Continuous exposure of bacteria to sub-therapeutic antimicrobial concentrations in feed, bedding, and manure enhances selection pressure and persistence of resistant populations.

5. Transmission Pathways and Public Health Implications
Resistant bacteria and ARGs can reach humans through:
- Consumption of raw or improperly processed milk
- Direct contact with animals or farm workers
- Environmental contamination of water and crops

This poses serious food safety and occupational health risks. The potential transfer of resistance from animal to human pathogens compromises the effectiveness of critically important antimicrobials in human medicine.

6. Surveillance of AMR in Dairy Systems
6.1 Current Surveillance Approaches
Surveillance strategies include:
- Antimicrobial susceptibility testing of clinical isolates
- Monitoring antimicrobial sales and usage data
- Molecular detection of ARGs using genomic tools

However, surveillance remains fragmented in many regions, particularly in developing countries.

6.2 Challenges in Surveillance
Key challenges include lack of standardized methodologies, insufficient laboratory capacity, and limited integration of animal, human, and environmental data.

7. Antimicrobial Stewardship in Dairy Production
7.1 Principles of Stewardship
Antimicrobial stewardship aims to:
- Optimize antimicrobial selection, dose, and duration
- Reduce unnecessary antimicrobial use
- Preserve antimicrobial efficacy

Selective dry cow therapy, culture-based mastitis treatment, and veterinary-guided prescribing are effective stewardship practices.

7.2 Alternatives to Antimicrobials
Non-antibiotic strategies include:
- Improved hygiene and biosecurity

- Vaccination programs
- Genetic selection for disease resistance
- Use of probiotics, prebiotics, and phytotherapeutics

These approaches reduce disease incidence and antimicrobial dependency.

8. Policy, Education, and One Health Approach

Regulatory frameworks restricting non-prescription antimicrobial sales and banning antimicrobial growth promoters have shown positive impacts in several countries. Farmer education and extension services play a vital role in translating policy into practice.

The One Health approach integrates veterinary, medical, and environmental disciplines to address AMR holistically. Coordinated surveillance, shared data, and cross-sectoral collaboration are essential for long-term success.

9. Future Research Directions

Future priorities include:

- Understanding resistome dynamics in dairy ecosystems
- Development of rapid on-farm diagnostics
- Evaluation of alternative therapeutics
- Socio-economic studies on antimicrobial use behavior

10. Conclusion

Antimicrobial resistance in dairy systems is a complex and escalating problem driven by antimicrobial use practices, environmental dissemination, and microbial adaptability. Its consequences extend beyond animal health to food safety and public health. Sustainable mitigation requires integrated surveillance, robust antimicrobial stewardship, policy enforcement, and adoption of a One Health framework. Protecting the efficacy of antimicrobials in dairy production is essential for ensuring sustainable livestock systems and global health security.

11. Conflict of Interest

Not available.

12. Financial Support

Not available.

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