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ESKAPE Pathogens and Their Mitigation Strategies in Meat Products

Importance of Meat in Nutrition and India's Status in Global Meat Production

Meat is a nutrient-dense food that plays a vital role in human nutrition. It is a rich source of high-quality proteins containing all essential amino acids required for growth, tissue repair, and immune function. Additionally, meat provides important micronutrients such as iron (especially heme iron), zinc, selenium, and B-complex vitamins, including vitamin B12, which are either absent or poorly bioavailable in plant-based diets. These nutrients are crucial for combating anaemia, supporting cognitive development, and ensuring overall health, particularly in vulnerable populations such as children, pregnant women, and the elderly.

In the context of India, meat consumption is relatively lower compared to global averages due to dietary preferences, cultural and religious factors. However, the country has a significant role in global meat production. India ranks among the top producers of meat in the world, with major contributions coming from buffalo meat (carabeef), poultry, and goat meat. According to FAO and Ministry of Fisheries, Animal Husbandry & Dairying data:

- India is **the largest exporter of buffalo meat** (carabeef), primarily catering to markets in Southeast Asia, the Middle East, and Africa.
- The country is among the **top five producers of chicken meat**, with rapidly growing poultry production due to increasing demand from urban populations.
- India also has one of the **largest populations of small ruminants**, making it a key global producer of goat meat (chevon).

The meat sector in India not only supports nutritional security but also plays a crucial role in rural livelihood, employment, and international trade. With increasing awareness of protein-rich diets and changing consumer habits, the domestic demand for safe and quality meat is steadily rising. This underscores the need for stringent food safety measures and sustainable practices, especially considering emerging public health threats like antimicrobial resistance associated with meat-borne pathogens.

The acronym **ESKAPE** stands for *Enterococcus faecium*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Enterobacter species*. These pathogens are collectively termed “ESKAPE” because they have the remarkable ability to “escape” the effects of antimicrobial agents and are responsible for the majority of nosocomial (hospital-acquired) infections worldwide. Clinically, these bacteria are known for:

- **Multidrug resistance (MDR):** Many ESKAPE strains exhibit resistance to multiple classes of antibiotics, including β -lactams, aminoglycosides, and fluoroquinolones.
- **Virulence factors:** They possess various mechanisms to invade host tissues, evade immune responses, and form biofilms.
- **Treatment challenges:** Infections caused by ESKAPE pathogens are difficult to treat and are associated with high morbidity, mortality, and healthcare costs.

Their prominence in clinical settings has made them a primary focus for global antimicrobial resistance surveillance and containment strategies.

Relevance to the Meat Industry — Contamination During Slaughter, Processing, and Handling

Although ESKAPE pathogens are traditionally linked with healthcare environments, increasing evidence suggests their **presence in the food chain**, particularly in **meat and meat products**. Contamination in the meat industry can occur through several pathways:

- **During slaughter:** Poor hygienic practices can allow gut-derived organisms like *Enterococcus faecium* or *Klebsiella pneumoniae* to contaminate carcasses.
- **From workers and surfaces:** *Staphylococcus aureus* can be transferred from the skin or nasal passages of meat

handlers, while *Acinetobacter* and *Pseudomonas* are often introduced from processing surfaces and equipment.

- **Environmental contamination:** Improper cleaning of processing areas, tools, and storage units allows for biofilm formation and persistence of resistant organisms.

As meat is a highly perishable commodity, the presence of these pathogens not only reduces shelf life but also poses serious health risks if such meat is undercooked or mishandled.

Rising Concern Due to Antimicrobial Resistance (AMR) and Public Health Implications

The **emergence of antimicrobial resistance (AMR)** among foodborne pathogens, particularly the ESKAPE group, represents a major global health threat. In the context of meat:

- **Antibiotic use in livestock**—for disease prevention, growth promotion, or metaphylaxis—contributes to the selection pressure favouring resistant strains.
- **Transmission to humans** may occur through:
 - Consumption of contaminated or undercooked meat.
 - Cross-contamination in kitchens.
 - Environmental routes during meat processing or waste disposal.

Public health implications include:

- **Limited treatment options** for foodborne infections.
- **Increased burden on healthcare systems** due to resistant infections.
- **Potential transfer of resistance genes** from animal-origin bacteria to human commensals or pathogens via horizontal gene transfer.

Thus, the convergence of ESKAPE pathogens,

meat contamination, and AMR emphasizes the urgent need for an integrated "One Health" approach—bridging human, animal, and environmental health sectors—to ensure food safety and combat resistance at its source.

The presence of ESKAPE pathogens in meat products is a growing concern due to their ability to survive common processing conditions and their potential to transfer antimicrobial resistance genes through the food chain. These pathogens can enter the meat supply at various stages—ranging from slaughter to post-processing—and contaminate a wide range of meat products, posing significant food safety risks.

Sources of Contamination

1. Animal Gut Flora

Certain ESKAPE pathogens, such as *Enterococcus faecium* and *Klebsiella pneumoniae*, naturally inhabit the gastrointestinal tract of livestock. During slaughter, improper evisceration or accidental gut rupture can lead to the contamination of carcasses with faecal matter containing these pathogens. Without adequate hygienic interventions, these bacteria can persist and multiply in meat products.

2. Skin and Nasal Flora of Handlers

Staphylococcus aureus is a common commensal organism found on the skin, nose, and throat of humans. Food handlers, especially in slaughterhouses, meat processing units, and retail settings, can act as vectors for contamination through unwashed hands, sneezing, or skin contact. In particular, methicillin-resistant *S. aureus* (MRSA) strains have been isolated from meat products, highlighting the occupational risk and food safety implications.

3. Environmental Contaminants in Processing Units

Environmental organisms such as *Acinetobacter baumannii* and *Pseudomonas*

aeruginosa are opportunistic bacteria that thrive on wet surfaces, poorly cleaned equipment, and chilled environments. These pathogens are capable of forming resilient biofilms on stainless steel, plastic, and conveyor belts, leading to persistent contamination of meat products. Their presence is often associated with post-processing contamination, especially in ready-to-eat (RTE) meat items.

Public Health Impact of ESKAPE Pathogens in Meat Products

The contamination of meat products with ESKAPE pathogens has significant public health consequences due to their virulence, ability to evade treatment, and potential to act as reservoirs of antimicrobial resistance (AMR). These pathogens not only cause foodborne illnesses but also contribute to the larger crisis of antibiotic resistance through the food chain.

Mechanisms of Resistance and Virulence

ESKAPE pathogens exhibit a wide array of genetic and biochemical mechanisms that contribute to their pathogenicity and resistance, including:

- **Enzymatic degradation of antibiotics:** e.g., β -lactamases and carbapenemases in *Klebsiella pneumoniae* and *Enterobacter spp.*, rendering β -lactam antibiotics ineffective.
- **Efflux pumps:** Found in *Pseudomonas aeruginosa* and *Acinetobacter baumannii*, these actively expel antibiotics from the bacterial cell.
- **Biofilm formation:** A key survival mechanism seen in *Staphylococcus aureus*, *Pseudomonas*, and *Acinetobacter*, enabling persistence on meat surfaces and processing equipment, and reducing susceptibility to sanitizers and antibiotics.

- **Alteration of target sites:** e.g., mutation in penicillin-binding proteins (PBPs) in methicillin-resistant *S. aureus* (MRSA).
 - **Virulence factors:** Including toxins, adhesins, and enzymes that allow these pathogens to invade host tissues and evade immune responses.
- These features make infections caused by ESKAPE pathogens more severe, harder to treat, and often associated with longer hospital stays and higher mortality rates.

Outbreaks Linked to Contaminated Meat

While healthcare settings remain the primary concern for ESKAPE pathogens, there is growing documentation of foodborne outbreaks and sporadic infections related to contaminated meat products:

- **Methicillin-resistant *Staphylococcus aureus* (MRSA)** has been isolated from retail meat in several countries, including India, and linked to skin infections and bacteremia in humans.
 - *Enterococcus faecium*, often carrying vancomycin-resistance genes (VRE), has been detected in poultry and pork, posing risks especially to immunocompromised individuals.
 - *Klebsiella pneumoniae* and *Enterobacter spp.* have been associated with gastrointestinal infections and, in some cases, extraintestinal infections following consumption of contaminated meat.
- Such outbreaks are particularly concerning when the pathogen is multidrug-resistant, limiting treatment options and increasing the burden on healthcare infrastructure.

Transfer of Resistance Genes Through the Food Chain

One of the most alarming aspects of ESKAPE pathogens in meat is their ability to act as **vectors for horizontal gene transfer (HGT)** of resistance elements

through:

- **Plasmids and transposons:** Mobile genetic elements that allow sharing of resistance genes like *blaKPC*, *mecA* and *vanA*, across bacterial species.
 - **Consumption of contaminated meat:** May introduce resistant bacteria into the human gut microbiota, where gene exchange with native flora can occur.
 - **Environmental contamination:** Manure and slaughterhouse waste containing resistant bacteria can contaminate water and soil, facilitating indirect transmission to humans.
- The presence of ESKAPE pathogens in meat thus contributes to the **dissemination of AMR beyond the clinical setting**, complicating both public health response and global efforts to curb antimicrobial resistance.

4. Mitigation Strategies for ESKAPE Pathogens in Meat Products

Controlling the presence and spread of ESKAPE pathogens in the meat production continuum requires a holistic, multi-tiered strategy encompassing pre-harvest, harvest, processing, and post-processing stages. Below are key interventions categorized across the meat production chain:

A. Pre-harvest Interventions

1. Good Animal Husbandry Practices

Optimal housing, clean water supply, balanced nutrition, and biosecurity measures reduce animal stress and disease susceptibility, lowering the need for antibiotic use. Ensuring sanitary conditions on farms helps minimize the carriage and shedding of ESKAPE pathogens in livestock.

2. Probiotic and Competitive Exclusion Agents

Probiotics, such as *Lactobacillus* and *Bacillus* species, when administered through feed or water, competitively inhibit colonization by pathogenic bacteria in the gastrointestinal tract. Competitive exclusion cultures establish beneficial flora that

outcompete ESKAPE organisms for nutrients and attachment sites.

3. Prudent Use of Antibiotics and Alternatives

Restricting non-therapeutic antibiotic use in animals is critical. Alternatives include:

- **Phytobiotics** (plant-based bioactive compounds such as garlic, turmeric, neem) that possess antimicrobial and immunomodulatory effects.
- **Bacteriophages**, which are viruses that specifically target and lyse bacterial pathogens without disturbing beneficial flora.
- **Organic acids, enzymes, and essential oils** as feed additives with growth-promoting and pathogen-reducing potential.

B. Slaughterhouse and Processing Hygiene

1. HACCP and GMP Implementation

Hazard Analysis and Critical Control Points (HACCP) and Good Manufacturing Practices (GMP) frameworks help in identifying contamination risks and ensuring preventive measures at every critical point in meat processing—from stunning to packaging. Strict adherence minimizes pathogen introduction and cross-contamination.

2. Rapid Detection Methods

Early detection of contamination is vital. Advanced diagnostics like:

- **Polymerase Chain Reaction (PCR)** for quick gene-level identification.
- **Matrix-Assisted Laser Desorption/Ionization-Time of Flight (MALDI-TOF)** for precise bacterial profiling.
- **Biosensors** for real-time detection on surfaces or in meat matrices.

These help implement timely corrective actions and reduce product recalls.

3. Sanitation of Contact Surfaces

Regular cleaning and disinfection of equipment,

tools, and workspaces using:

- **Thermal treatments** (hot water/steam),
- **Chemical disinfectants** (chlorine, peracetic acid),
- **UV-C radiation**, which effectively inactivates microbial DNA without leaving chemical residues.

These measures disrupt biofilm formation and reduce surface contamination by ESKAPE pathogens.

C. Novel and Emerging Technologies

1. Bacteriophage Therapy

Highly specific and effective against multidrug-resistant bacteria, bacteriophages can be applied to meat surfaces or incorporated into sprays or dips to reduce *Staphylococcus aureus*, *Klebsiella*, and *Pseudomonas* counts without affecting meat quality.

2. Natural Antimicrobials

Natural compounds like **essential oils** (e.g., oregano, thyme, clove) and **plant extracts** (e.g., green tea, tulsi) possess broad-spectrum antimicrobial activities. They can be applied as marinades, dips, or incorporated in edible coatings to inhibit pathogen growth.

3. Cold Plasma, Ozonation, High-Pressure Processing (HPP)

These **non-thermal technologies** help in:

- **Cold plasma:** Disrupting microbial cell membranes using ionized gas.
- **Ozone:** A powerful oxidizing agent that kills pathogens without residues.
- **HPP:** Uses extremely high pressure (400–600 MPa) to inactivate microorganisms while preserving nutritional and sensory qualities.

These methods ensure minimal thermal degradation of meat while achieving microbial safety.

4. Antimicrobial Packaging

Smart packaging materials are being developed to enhance shelf life and prevent post-processing

contamination. These include films infused with:

- **Nano-silver particles** with strong antibacterial effects,
- **Antimicrobial peptides**, and
- **Enzymes** like lysozyme or nisin to inhibit specific bacterial targets.

D. Regulatory and Surveillance Measures

1. WHO, FAO, and Codex Guidelines on AMR in Foods

International agencies have framed clear guidelines and action plans for:

- Reducing AMR in food production,
- Monitoring antimicrobial use in animals,
- Implementing risk-based surveillance of meat products.

The **Codex Alimentarius** includes standards for meat hygiene, maximum residue limits, and guidelines for responsible antibiotic use in livestock.

2. National Surveillance Programs

India has made progress through:

- **FSSAI's food safety audits and risk assessments**,
- **NCDC's AMR surveillance initiatives**,
- **ICAR's coordinated research on AMR in livestock and poultry sectors**.

These programs monitor ESKAPE pathogens in animal-source foods and assess their resistance profiles.

3. One Health Approach in Meat Supply Chains

A comprehensive strategy that integrates animal, human, and environmental health sectors is key to tackling ESKAPE-related threats. The **One Health** approach promotes:

- Interdisciplinary collaboration,
- Shared surveillance databases,
- Coordinated interventions from farm to fork.

Conclusion

The presence of ESKAPE pathogens in meat products poses a serious public health challenge due to their high virulence, multidrug resistance, and ability to spread resistance genes through the food chain. Effective mitigation requires a comprehensive farm-to-fork approach involving good animal husbandry, responsible antibiotic use, stringent slaughter and processing hygiene, advanced detection and decontamination technologies, and adherence to national and international regulatory frameworks. By integrating these strategies under the One Health approach, it is possible to curb the risks associated with ESKAPE pathogens, ensure the microbiological safety of meat, and protect both consumer health and the sustainability of the meat industry.