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Meat spoilage: A comprehensive Review of Causes, Mechanisms and Control Strategies

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Review Article

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Abstract

Meat is a fundamental component of the human diet, providing essential proteins, vitamins, and minerals necessary for health. However, it is highly perishable due to microbial contamination as well as its enzymatic, and chemical constituents that can lead to undesirable odors, flavors, and sliminess, rendering it unfit for consumption. Effective preservation techniques are essential to extend shelf life, maintain nutritional value, and prevent contamination and the resulting spoilage or poses risks to the consumer health due to contamination with foodborne pathogens. These strategies focus on inhibiting microbial growth and preserving the quality and texture of meat, contributing to food safety, waste reduction, and sustainability in the food industry.

Keyword: *Meat Spoilage, Spoilage Mechanism, Preservation, Economic Losses, Food Borne Pathogens.*

Introduction

Meat is a nutrient-rich food that provides essential proteins, vitamins, and fats, making it a primary choice for many people and its consumption has been steadily increasing worldwide due to its high nutritional value **(Heinz & Hautziner, 2007; Vigar *et al.*, 2019).** However, meat is highly perishable and prone to spoilage, which leads to biochemical changes affecting its color, texture, and flavor. These undesirable alterations made it unfit for human consumption **(Burkepile *et al.*, 2006; Sherratt *et al.*, 2006).**

Meat spoilage occurs due to microbial, chemical, and physical factors that degrade its quality **(Karanth *et al.*, 2023).** Although fresh meat of healthy animals is considered sterile, contamination can occur during processing due to non-healthy environmental conditions, using of polluted water, utensils, equipment. The microbiological quality of meat after slaughter depends on many factors such as handling, processing, distribution, and storage conditions. Contaminants from slaughter equipment, air, water, workers hands and soil can introduce spoilage bacteria, leading to chemical deterioration of meat components **(Holman *et al.*, 2018; Wambui *et al.*, 2018).** Various intrinsic and extrinsic factors, including oxygen availability, pH levels, temperature, and microbial competition, influence the rate of meat spoilage **(Fletcher *et al.*, 2018).**

Beyond economic losses, contamination of meat with food borne pathogens meat also poses health risks to consumers **(Onyibe *et al.*, 2021).** While spoiled food is generally rejected due to sensory changes that makes it unappealing for consumption **(Koutsoumanis, 2009).** The causes of meat losses including physical damage, microbial activity, chemical reactions, and biological infestations **(Gram *et al.*, 2002; Ray & Bhunia, 2013).**

In medieval times, people relied on traditional preservation techniques to prevent meat spoilage, benefiting from lower microbial activity due to less pollution. However, in the modern era, higher pollution levels have increased microbial load in the environment, accelerating spoilage rates. Consequently, a significant amount of meat approximately 302.4 million tons is wasted annually due to spoilage **(Knowles *et al.*, 2014).** Recent advancements in preservation methods have highlighted the economic impact of meat spoilage, emphasizing the need for effective strategies to reduce waste and enhance the economic efficiency of the meat industry.

Meat preservation is essential to maintaining its quality and prolonging shelf life. It involves various techniques designed to control internal and external factors that contribute to spoilage while preserving the meat's nutritional value, color, texture, and flavor **(Zhao *et al.*, 2021; Nwosu *et al.*, 2022).** Therefore, the aim of this review is to summarize the common causes of spoilage, public health hazard and methods of control.

Economic Losses Of Meat Spoilage

The growing global demand for meat has amplified concerns about food loss. Since the 1960s, annual per capita meat consumption has risen from 10 kg to 26 kg by 2000, and is projected to reach 37 kg by 2030 **(Heinz & Hautzinger, 2007).** However, this increasing consumption also leads to higher spoilage rates, through producing large quantities at the expense of applying good production practices. Meat spoilage results in substantial economic losses each year, with millions of tons wasted annually **(Gaafar *et al.*, 2019)**. Approximately 40% of the meat produced worldwide goes to waste, costing the food industry an estimated $218 billion **(Gunders, 2017)**. In the United States alone, more than 96 billion pounds of food are lost each year, with meat, poultry, and fish contributing to 8.5% of this loss. Additionally, approximately 3.5 billion kg of meat and poultry are wasted due to microbial spoilage at the consumer and food service levels, resulting in significant economic and environmental repercussions **(Kantor *et al.*, 1997)**.

A significant portion of these losses is due to discoloration caused by meat spoilage, which affects consumer perception and reduces marketability. (**Sherbeck *et al.*, 1995**) reported that between 2% and 20% of meat is either discounted or discarded due to spoilage-related discoloration. Additionally, the U.S. beef industry faces an annual loss of $1 billion as a result of meat spoilage discoloration **(Smith *et al.*, 2000).**

Public Health Hazard

Food borne diseases resulting from the consumption of Contaminated meat that carry harmful substances, toxins, or pathogenic microorganisms. Contamination can occur at any stage, starting from animal transportation to the market **(Elbehiry *et al.*, 2023).** Symptoms of foodborne illness include diarrhea, dehydration, vomiting, nausea, and headaches. Factors such as microbial presence, food sources, and improper storage conditions contribute to the survival and multiplication of harmful bacteria, increasing the risk of food poisoning **(Nwachukwu *et al.*, 2024).**

Foodborne diseases fall into three categories: intoxication, infection, and toxic-infection. Intoxication occurs when a person consumes food containing toxins **(Emakpor *et al.*, 2024)**. Food infection results from ingesting food containing food borne pathogens that attach to the gastrointestinal tract and grow **(Akpoghelie *et al.*, 2024).** Toxic-infection occurs when food containing microorganisms produces toxins inside the body. Vulnerable groups include immunocompromised patients, pregnant women, the elderly, and infants **(Bintsis, 2017)**.

Causes Of Meat Spoilage

Food spoilage is a complex metabolic process influenced by various biological and environmental factors that contribute to the degradation of food quality (**Karanth *et al.*, 2023**). Meat spoilage begins at the production stage and continues throughout the supply chain. The transportation of livestock from farms to slaughterhouses involves several steps, including loading and handling. Inadequate handling and excessive stress during slaughter can cause injuries, negatively impacting meat quality and accelerating spoilage **(Gallo *et al*., 2018).**

The causes of meat spoilage can be categorized into two main stages: pre-slaughter and post-slaughter deterioration. Animals subjected to stress before slaughter suffer from reduction in muscle glycogen levels, which alters the pH of the meat due to glycogen breakdown **(Gallo *et al*., 2018).** Prolonged stress leads to dark, firm, and dry (DFD) meat with a higher pH and reducing its shelf life. In contrast, short-term stress results in pale, soft, and exudative (PSE) meat, where the pH drops to around 6.2 which is an optimal level for protein degradation and bacterial growth.

Microbial activity is a primary factor in meat spoilage, as bacteria, yeast, and molds colonize meat surfaces. The growth of these microorganisms is influenced by intrinsic and extrinsic factors. Intrinsic factors include moisture content, pH, oxidation-reduction potential, available nutrients, physical barriers, and natural antimicrobial compounds. Meanwhile, extrinsic factors involve storage temperature, gaseous environment, relative humidity, and the type and count of microorganisms present **(Alegbeleye *et al*., 2022; Igual & Martínez-Monzo, 2022).** Additionally, microbial contamination plays a crucial role in spoilage, particularly in high-protein foods with high water activity **(Mancini & Hunt, 2005; Ramanathan *et al*., 2021).**

Besides microbial spoilage, chemical and enzymatic reactions contribute significantly to meat deterioration. Lipid oxidation occurs when unsaturated fats react with oxygen, forming peroxides and secondary compounds that result in rancid flavors and odors **(Nychas *et al*., 2008)**. Additionally, myoglobin oxidation causes color changes, turning fresh meat from bright red to brown or greenish hues, making it less appealing to consumers **(Borch *et al*., 1996).** Enzymatic degradation also plays a role, as post-mortem enzymatic activity continues to break down proteins (proteolysis) and fats (lipolysis), altering the texture and creating an environment conducive to bacterial growth **(Dave & Ghaly, 2011).**

Moreover, the environmental conditions significantly influence meat spoilage. High temperatures accelerate microbial growth and enzymatic reactions, while excessive humidity promotes mold growth and surface spoilage. Exposure to oxygen further enhances oxidative processes and supports the proliferation of aerobic bacteria **(Jay *et al*., 2005).**

Mechanism of Meat Spoilage

Meat spoilage occurs through three primary mechanisms: bacterial activity, lipid oxidation, and autolytic enzymatic activity **(Ndudi *et al*., 2024).**

Bacterial Activity

Meat and meat products provide an excellent medium for microbial growth, including bacteria, yeasts, and molds, some of which are pathogenic **(Jay *et al*., 2005).** The intestinal tract and skin of animals are primary sources of these microorganisms. Their presence in meat is influenced by several factors, including pre-slaughter conditions, slaughtering and evisceration practices, animal age, temperature control during processing and distribution, storage methods, and packaging **(Shaltout *et al*., 2017; Saad *et al*., 2019).**

Common bacterial species in meat include Pseudomonas, Micrococcus, Streptococcus, Lactobacillus, Salmonella, Escherichia, Clostridium, *Staph. aureus* and *Bacillus*. Among them, Enterococcus is the most prevalent **(Hayes *et al*., 2003; Lin *et al*., 2004).** Yeast species such as Candida and Cryptococcus spp. **(Garcia-Lopez *et al*., 1998)** and mold species like Sporotrichum, Geotrichum, Cladosporium, and Penicillium also contribute to spoilage.

Storage conditions significantly impact microbial growth. Most bacteria are more active in cold environments, and enteric bacteria are frequently found in refrigerated products. Psychrotrophic bacteria such as Pseudomonas, Moraxella, Psychrobacter, and Acinetobacter spp. are commonly found in refrigerated meat, while salt-resistant microorganisms like lactic acid bacteria, Enterococci, and yeasts are present in raw, salted-cured products **(Cerveny *et al*., 2009).** The growth of Enterobacteriaceae and Pseudomonas is more prevalent in atmosphere-packed meat than in vacuum-packed meat, and their growth is favored at 5°C

(Garcia-Lopez *et al.*, 1998). Pseudomonas spp. grows rapidly at 2°C, altering meat's shelf life, while Salmonella proliferates above 7°C **(Sentence, 2010)**. The ideal pH range for bacterial growth in meat is 5.5-7.0 **(Russell *et al.*, 1996).**

Lipid Oxidation

Free radical production and lipid oxidation in meat lead to the degradation of fatty acids, causing off-flavors and deterioration **(Samitzis & Deligeorgis, 2010).** Af ter slaughtering, metabolic processes halt, leading to lipid oxidation due to oxygen exposure **(Gray & Pearson, 1994; Linares *et al.*, 2007).** Lipid oxidation progresses in three phases: initiation, propagation, and termination **(Fernández *et al.*, 1997).**

Initiation: Natural catalysts like heat, metal ions, and irradiation release free radicals, which react with oxygen to form peroxyl radicals.

Propagation: Peroxyl radicals interact with lipids, forming hydroperoxides and generating new free radicals **(Fraser & Sumar, 1998; Hultin, 1994).**

Termination: Free radicals combine to form stable, non-radical products **(Hultin, 1994).**

Lipid oxidation is influenced by antioxidants (e.g., vitamin E) and fatty acid composition. The breakdown of hydroperoxides releases aldehydes, acids, and ketones, leading to off-flavors and nutritional degradation **(Raharjo & Sofos, 1993; Shahidi, 1994; Fernández *et al.*, 1997).** Additionally, lipid oxidation is associated with carcinogenic and pathogenic effects **(Liu *et al.*, 1995).** Enzymatic lipid breakdown (lipolysis) is mediated by enzymes such as lipases, esterases, and phospholipases, which may originate from the meat itself or from psychrotrophic microorganisms **(Ghaly *et al.*, 2010).** Non-enzymatic lipid hydrolysis occurs through the oxidation of heme proteins such as hemoglobin, myoglobin, and cytochrome **(Kanner, 1994).**

Autolytic Enzymatic Spoilage

Post-mortem enzymatic activity contributes to meat spoilage by catalyzing chemical reactions that degrade proteins and lipids. Proteases break down polypeptides, altering texture and flavor **(Toldrá & Flores, 2000).** Enzymes like calpains and cathepsins play crucial roles in post-mortem autolysis **(Gram & Huss, 1996; O'Halloran *et al.*, 1997)**. During post-mortem aging at low temperatures (around 5°C), proteolytic activity leads to the formation of biogenic amines, which encourage microbial proliferation **(Kuwahara & Osako, 2003; Rahman & Velez-Ruiz, 2007).**

Alterations Associated With Spoilage

The deterioration of meat is influenced by the presence of various substrates, such as glucose, lactic acid, nitrogenous compounds, and free amino acids. These substances serve as primary precursors for microbial metabolites that play a significant role in spoilage **(Nychas *et al.*, 2008).** The survival and activity of microorganisms in meat depend on multiple factors, leading to observable spoilage effects like visible growth (e.g., slime formation), changes in texture (e.g., degradation of polymers), and the development of off-odors and off-flavors **(Borch *et al.*, 1996; Gram *et al.*, 2002; Nychas *et al.*, 2008).** As noted by **(Dainty, 1996)**, microbial metabolism generates compounds such as fatty acids, ketones, and alcohols, produce fruity or sweet aromas. Conversely, the formation of hydrogen sulphide, methylsulphide, and dimethylsulphide is responsible for unpleasant, sulphurous odors. Additionally, **Jay *et al.* (2005)** highlighted that diamines like cadaverine and putrescine, produced during meat spoilage are markable indicators of spoilage.

Off Odours and Flavours

The volatile components of microbial catabolites include a variety of compounds such as sulphur compounds, aldehydes, ketones, organic acids, volatile fatty acids, ethyl esters, alcohols, ammonia, and other metabolites. These volatile compounds, along with non-volatile ones, significantly impact the sensory quality of both fresh and cooked meat, depending on their olfactory thresholds and interactions **(Casaburi *et al.*, 2015).** In aerobically stored meat, undesirable odours often described as putrid, cheesy, sulphuric, sweet, or fruity are commonly detected **(Borch *et al.*, 1996).** The production of these unpleasant odours is largely driven by bacteria such as Pseudomonas spp. and *B. thermosphacta*, whose metabolic activities generate these compounds **(Nychas *et al*., 2008).** For instance, the aerobic metabolism of glucose by *B. thermosphacta* produces foul-smelling compounds like acetone and acetic acid **(Koutsoumanis *et al*., 2006).** Sulphur-based compounds, such as hydrogen sulphide from Enterobacteriaceae and dimethyl sulphide from Pseudomonas spp., contribute to sulphuric odours. Cheesy smells, often associated with acetoin, diacetyl, and 3-methylbutanol, are produced by bacteria including Enterobacteriaceae, *B. thermosphacta* and homofermentative *Lactobacillus* spp. **(Casaburi *et al*., 2015).** In low-oxygen environments, anaerobic metabolism generates less intense odours compared to aerobic metabolism, which is why modified atmosphere packaging with reduced oxygen levels is more effective in preserving meat quality **(Pin *et al*., 2002).**

Colour Alteration

Any deviation from the preferred bright cherry -red color often leads to meat being discarded, resulting in significant waste (**Mancini and Hunt, 2005; American Meat Science Association, 2012).**The production of hydrogen sulphide by bacteria such as *L. sakei, H. alvei,* and *S. putrefaciens* causes the conversion of muscle pigments into green sulphomyoglobin, a process driven by glucose consumption. Notably, sulphomyoglobin does not form under anaerobic conditions **(Borch *et al*., 1996).** Additionally, *Leuconostoc* spp. and related bacteria like *Weissella viridescens* can induce green discoloration in meat. This occurs due to the formation of hydrogen peroxide, which oxidizes nitrosomyochromogen when the meat is exposed to oxygen **(Dušková *et al*., 2013).** *Shewanella. putrefaciens* is also known to cause green discoloration in vacuum-packed meat **(Doulgeraki *et al*., 2012).**

Gas Production

Clostridium spp. can generate large amounts of gases such as hydrogen (H2) and carbon dioxide (CO2). This can lead to "blown pack" spoilage **(Yang *et al*., 2014)** in vacuum-packed meat, which is characterized by swelling of the packaging due to gas accumulation. Other signs including putrid odours, exudate formation, extensive proteolysis, and changes in pH and colour. This type of spoilage is commonly seen in chilled, vacuum-packed meat products and is caused by psychrophilic and psychrotrophic bacteria. Lactic acid bacteria (LAB) also play a significant role in generating the volatile organic compounds found in the headspace of spoiled meat **(Hernandez-Macedo *et al*., 2012).**

Filaments and Ropy Slime

Ropy slime formation is a common issue in vacuum-packed, cooked meat products, primarily caused by bacteria such as Lactobacillus spp. and Leuconostoc spp. These microorganisms produce long, unwanted polysaccharide filaments that can form between the meat's surface and its casing or between slices. The slime acts as a protective barrier for the bacteria, helping them retain moisture **(Bjorkroth and Korkeala, 1997).** Additionally, *Weissella viridescens* is associated with both ropy slime formation and green discoloration. When this bacterium forms colonies on moist surfaces, it creates a continuous layer of greenish slime (**Dušková *et al*., 2013).**

Meat Preservation

Meat preservation became vital for maintaining its quality during long distance transportation, preventing adverse changes in texture, color, and nutritional value, especially with the rapid expansion of supermarkets **(Nychas *et al*., 2008).** The primary objectives of preservation are to stop microbial spoilage and reduce oxidation and enzymatic degradation. Over time, various methods have been utilized to preserve meat for future use. From the start of meat consumption, humans have created different techniques to extend its shelf life. Food preservation is a crucial element of food security and safety, aiming to extend the shelf life of food and its products while maintaining their nutritional quality, safety, and sensory attributes **(García-Díez *et al*., 2021).** Traditional preservation methods, including refrigeration, freezing, canning, and chemical preservatives, have been vital in ensuring food availability **(Rahman & Velez-Ruiz 2007).**

1- Drying

Drying, or dehydration, is one of the oldest techniques for preserving meat. By reducing the meat's moisture content to approximately 10-20%, this process prevents bacterial growth and deactivates enzymes **(Javeed and Ram, 2015).** While sun-drying was traditionally used, modern methods often rely on ovens or dehydrators. For home use, meat is typically sliced into thin strips, boiled at high temperatures to eliminate bacteria, and then dried in an oven. When stored in airtight containers, dried meat can last sound for 1-2 months **(Lonergan *et al.*, 2019).**

2- Canning

Canning is a widely used preservation method in which meat is sealed in jars or cans and exposed to hot water for 8-10 minutes before being cooled to approximately 38°C **(Nafissatou *et al.*, 2020).** This process eliminates oxygen, thereby inhibiting bacterial growth. To further extend shelf life, additives like sodium benzoate, sodium sorbate, and ascorbic acid are commonly incorporated **(Omorodion and Odu, 2014).** The meat is sterilized using high-temperature steam, and for poultry, either a hot or raw pack method is employed, depending on the intended outcome **(Downing, 2013).**

3- Smoking

Smoking is a preservation technique that utilizes smoke from burning wood or plants. The heat generated by the smoke removes moisture from the meat's surface, inhibiting bacterial growth. However, smoking is most effective when paired with salting or other additives. There are three main types of smoking: hot smoking, which cooks the meat; smoke roasting, similar to hot smoking; and cold smoking, which dries the meat without cooking it **(Owen and Sam, 1998).** It is important to avoid using smoke from certain plants, as this can produce carcinogenic compounds **(Phillips, 1999).**

4- Freezing

Freezing is a highly effective preservation method that slows bacterial and enzyme activity in meat. Although freezing reduces bacterial growth, it does not completely stop it. Also, freezing can't stop the enzymatic activity once it starts. Storing meat at temperatures below 0° C significantly slows bacterial activity, but it remains present. Maintaining temperatures around -12°C helps preserve meat quality for longer periods without significant loss of flavor **(Sohaib *et al.*, 2016).** To prevent contamination, airtight freezer bags are essential, and quick freezing is recommended over slow freezing, as the latter can damage the meat's cellular structure as a result of large ice crystals formation which press the cell wall resulted in rupture and release of cell contents **(Rahman and Velez-Ruiz, 2007).** Additionally, storing meat at around -18°C for 20-30 days can eliminate parasites, such as Taenia cysts **(Pankina *et al.*, 2019).**

5- Chilling

Chilling is the process of cooling meat shortly after slaughter to inhibit bacterial growth. This method helps maintain the meat's color, tenderness, and weight while prolonging its shelf life. For instance, lamb carcasses must be chilled rapidly post-slaughter to preserve quality **(Liang *et al.*, 2022).** Chilling is typically done at temperatures between 0°C and 4°C. Effect of chilling of course less when compared with freezing due to presence of cold-tolerant bacteria that grow at refrigeration leading to food spoilage.

6- Salting or curing

Curing is a time-honored preservation technique still widely practiced today. Sodium chloride (salt) is frequently used on meat to extract moisture and suppress bacterial growth. This can be done by either rubbing salt directly onto the meat or immersing it in a saltwater solution. Through osmosis, moisture is drawn out of the meat, creating an environment where microbes struggle to survive. Additionally, curing enhances the meat's flavor and increases its shelf life **(Parthasarathy and Bryan, 2012).** In modern practices, salt solutions are often injected directly into the meat tissues **(Chellaiah *et al.*, 2020).**

7- Fermentation and pickling

Fermentation and pickling are other preservation methods. Fermentation is a controlled process that relies on microbes operating in an oxygen-free environment, whereas pickling uses high salt concentrations to restrict bacterial growth. The duration and strength of the pickling solution are crucial for preserving the meat and enhancing its taste **(Barrett, 2003; Mani, 2018).**

8- Irradiation

Irradiation, also known as cold sterilization, employs various forms of radiation, such as gamma rays and UV light, to reduce bacterial growth and extend the shelf life of meat. Gamma radiation is especially effective for prolonging meat preservation, while UV rays are utilized for surface sterilization to kill bacteria but it can't penetrate through meat tissues and its effect considered superficial (**Ellis *et al.*, 2004).**

Conclusion

Meat spoilage is a major issue, leading to economic losses, food waste, and health risks. Factors like microbial growth, enzymatic activity, and oxidation cause deterioration in quality. Effective preservation methods, such as drying, smoking, canning, and refrigeration, help extend shelf life and ensure food safety. As global meat demand rises, improving preservation techniques is crucial to reducing waste and maintaining safety and quality. Future advancements should focus on sustainable and efficient preservation strategies to enhance meat longevity and safety.

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