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Advancement Techniques and Procedures in Meat Preservation: A Comprehensive Review

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Abstract: The process of evolution and development of meat preservation methods with regard to efficiency in prolonging shelf life, preserving quality, and ensuring safety is considered in this review. The traditional methods like drying, salting, and smoking are related in view of their historical importance and current relevance. Modern developments, including refrigeration, vacuum packaging, and modified atmosphere packaging, are discussed in relation to enhanced efficiency and practice in the meat industry. The review also covers the role of biopreservation, which makes use of natural antimicrobial agents to enhance the safety of meat products. Further, the review includes new and emerging technologies that include high-pressure processing, irradiation, and nanotechnology applications for their potential to change the face of preservation of meat. These novel methods may offer exciting opportunities to deal with modern food safety and quality issues. As such, this review provides an overview of the preservation techniques while attempting to trace current practices and existing challenges, with a view to suggesting future directions for research and development in meat preservation for food technology advancement and public health.

Keywords: Meat preservation, biopreservation, high-pressure processing, irradiation, and nanotechnology

INTRODUCTION

Meat preservation has always been of real importance to food science and technology, one that is entrenched in the need to extend the shelf life of meat products while ensuring their nutritional quality and safety. Demand for preserved meat dates way back into ancient civilizations where techniques such as drying, salting, and smoking were developed to prevent spoilage and protect against pathogenic contamination. Although such methods were quite effective, technological advances have significantly changed these traditional methods of preservation to modern techniques that are equally effective, if not more so, and safe. The history of preservation is expansive and diverse, with techniques based on resources and climatic conditions. One of the oldest methods of preservation was drying, which depends on the principle of moisture removal to prevent the action of microbes. This technique in arid regions was pivotal, as the sun and wind were used for the drying of meat into such products as jerky and biltong [1]. Salting and curing, employing salt and, more recently, nitrates/nitrates, became common because of the effectiveness at drawing out moisture and creating an environment hostile to bacteria. Whereas smoking had been a combination of drying and the actual antimicrobial effect of smoke compounds, adding flavor and extending the shelf life of meat made it a staple preservation method in many cultures [2]. With the advent of industrialization, and the initiation of refrigeration technology in the 19th century, new approaches to preserving meat were created. Refrigeration and freezing are the most common practices within the meat industry due to the effect of such low temperatures in reducing microbial growth and consequently inhibiting enzymatic activities responsible for spoilage. Refrigeration keeps the meat from 0°C to 4°C, increasing the shelf life by some few days, while

freezing keeps the meat preserved for months at temperatures below -18°C [3]. All of these methods involve steady power supply and some infrastructure, hence applicable in some regions only. The introduction of vacuum packaging in the middle of the twentieth century brought very different principles concerning meat preservation. The air was removed from the package before sealing. Less oxygen is now available for the activities of aerobic bacteria, and oxidation processes are significantly reduced by this technique, which means a substantial prolongation in shelf-life of the meat products [4]. This is further enhanced by modified atmosphere packaging, whereby the atmosphere in packaging is replaced by a mix of specific gases that prevent the growth of microbes and oxidations. Commonly used gases in MAP include carbon dioxide, nitrogen, oxygen, applied for different preservation purposes depending on meat type [5]. Another contemporary method is biopreservation, which makes use of natural or controlled microbiota and their antimicrobial products for attaining an extended shelf life. This makes use of lactic acid bacteria and bacteriocins, acting against spoilage and pathogenic microorganisms. At present, with the increasing interest of consumers towards natural preservation methods devoid of additives, biopreservation has been developed as a powerful tool in a sustainable manner [6]. In the continuous search for more effective and safe ways to preserve meat, some new technologies have proved to be promising. High-pressure processing is an inactivating process that uses high pressure without the need for heat to inactivate microorganisms, thereby preserving the sensory and nutritional qualities of the meat. HPP has been shown to be very effective against a huge number of pathogenic and spoilage flora and is gaining popularity in treating ready-to-eat meat products [7]. Another developing method is irradiation, which exposes the meat to ionizing radiation. This will cause damage to the DNA of microorganisms and make them inactive, reducing the potential for foodborne illness greatly. Despite that, there is consumer resistance against it due to misconceptions related to radiation; comprehensive research proved that this method is safe and effective in preserving meat [8]. Nanotechnology has evolved only recently and is thus promising for meat preservation. Many domains of application include antimicrobial coatings, environmental change-sensitive packaging, and nanosensors for spoilage detection. Nanoparticles that have shown antimicrobial activity against Nanoparticles like silver, zinc oxide, and titanium dioxide have demonstrated antimicrobial properties that can be harnessed for the preservation of meat. While nanosensors are developed to provide real-time information on the freshness of meat and render more effective and responsive preservation techniques [9].

Although the methods of meat preservation have advanced, there are still a lot of challenges. Providing safety and quality of preserved meat is perhaps the most important, since inappropriate preservation methods lead to foodborne illness. Maintaining a proper balance between shelf life and nutritional and sensory qualities of meat is another very important aspect that needs continuous research and development. In addition, consumer preferences for natural and minimally processed foods place the need for finding preservation methods that move in tandem with these trends. The other prime concern in the domain of preservation of meat is related to sustainability. Most of the traditional methods are associated with an energy-consuming process and also rely on non-renewable resources. Therefore, there is a growing emphasis on developing preservation techniques that are environmentally friendly and sustainable. For instance, biopreservation and nanotechnology are the two most emerging ways through which adverse environmental impact from meat preservation can be reduced. Future research in optimizing the available preservation procedures, as well as in the development of new technologies, is needed. In fact, developments in biotechnology and material science can potentially unveil newer antimicrobial agents and packaging materials to be applied in such a way that the better preservation of meat without affecting the safety and quality profile may be achieved. Moreover, an interdisciplinary approach towards food scientists, microbiologists, and engineers is quite necessary to drive innovation in meat preservation. The meat preservation industry has been growing, from the ancient methods to the current and new emerging technologies. Each process, traditional or novel, has its underlying principles, advantages, and limitations. Fusion of such advanced technologies like High-Pressure Processing (HPP), irradiation, and nanotechnology with the former traditional ones is promising for the future in meat preservation. Further research in these methods and their improvement will guarantee that the safety and quality of meat products are kept at a high level while their sustainability meets the evolving requirements of both consumers and the industry.

Meat Preservation Techniques and Procedures

TRADITIONAL PRESERVATION METHODS

Drying

Drying is one of the oldest and most effective processes for the preservation of meat, as it includes the removal of moisture to forestall microbial development. Some examples of techniques include air drying, sun drying, and using dehydrators. In this process, by lowering the activity of water in meat, its tendency for spoilage is reduced. This method continues to be used in many cultures today in products such as jerky and biltong [1].

Drying can be done in natural or artificial conditions. Natural drying methods, like sun drying, are easy and inexpensive but have the disadvantage of being highly weather dependent and often taking several days to weeks. In humid or rainy areas, natural drying cannot be

used without the risk of contamination. Artificial drying, using a dehydrator or an oven, gives good control of the drying conditions and allows for the production of a more uniform product. The process involves spreading strips in a single layer for uniform drying that does not allow the growth of microbial aspects [2].

Freeze-drying belongs to the new generation of drying techniques, whereby the moisture in the meat is removed through sublimation. In this process, the texture and nutritional value of the meat are better conserved in comparison with the methods mentioned above. Freeze-dried meat has good reconstitution and a long shelf life without refrigeration, so it becomes a favorite selection for emergency food supplies and space expeditions [3].

Major problems associated with drying include the high requirements of maintaining constant drying conditions to prevent the growth of spoiler organisms and the possibility of oxidative rancidity in fatty meats. Pre-treatment techniques, such as marinating or dipping the meat in antioxidant solutions, may prevent this from happening [4].

Salting and Curing

Salting involves the rubbing of the meat with salt, which draws out the moisture from it and makes conditions uninhabitable for any bacteria. It is an ancient method fundamental for preserving meat without refrigeration. The salt works by pulling osmosis and hence pulling out the water from microbial cells, dehydrating them, and thus making their growth impossible. This method not only keeps the meat but also enhances the flavor and texture of it [5].

Curing is a type of salting, and it employs the use of nitrites and nitrates to enhance preservation by inactivating Clostridium botulinum and contributing to flavor and color development. Such cured products are consumed worldwide in the form of ham, bacon, and sausages [6]. The nitrites and nitrates used in the curing process react with myoglobin from the meat to form a colored complex—nitrosomyoglobin—responsible for the characteristic pink color of cured meats. Moreover, these compounds give quite a distinct flavor, which is highly esteemed in many culinary traditions.

Curing can be done through either dry curing, which is when the meat is rubbed with salt and other curing agents, or wet cure, which is the immersion of the meat in brine solution. Dry cures are applied to large pieces of meat and often take several weeks. Wet cures are known as brining, a quick method for small pieces or processed meats [7].

The action of nitrites and nitrates does not only preserve the meat but also gives it a pink color and characteristic flavor. However, the health effects from ingesting nitrites and nitrates are still debatable, hence the continued research into alternative products for curing, like celery powder, rich in naturally occurring nitrates [8]. Research has evidenced that, though natural alternatives work, in some cases they do not offer similar protection against pathogens, so their use must be carefully considered [9].

Smoking

Smoking combines drying with the antimicrobial effects of smoke compounds, imparts flavor and color, and prolongs shelf life. Traditional smoking methods, on the other hand, are significantly variable but usually involve the exposure of the meat to smoke from burning wood or other materials. It is the preservative effect of smoke, due mostly to its phenolic compounds with their antimicrobial and antioxidant effects, which is useful in preserving the meat protagonists [10].

There are two main forms of smoking: cold smoking and hot smoking. The former is done below 30°C and imparts flavor without cooking the meat. On the other hand, hot smoking occurs at higher temperatures, making it cook the meat and afford more preservation. Again, the type of wood to be used for smoking will also have a huge impact on the flavor profile in meat, some of the most popular ones being from hickory, mesquite, and applewood [11].

Cold smoking, generally of a longer duration, is applied to products such as smoked salmon that are to be sold raw. It allows the meat to retain a raw texture. Hot smoking is done for goods like smoked chicken or pork where cooking adds value to flavor and safety [12]. Smoke contains a wide variety of compounds that account for its anti-microbial action and characteristic flavor of meats.

Modern developments in smoking include liquid smoke, that might be applied either straight to the products or put into marinades and brines. Liquid smoke is a quite convenient and controlled method of giving smoky flavors, not requiring traditional smoking equipment. Traditionalists say that such liquid smoke doesn't have the same depth of flavor compared to traditional smoking methods [13].

The major problems when smoking is connected with temperature and smoke exposure control in the course of developing the required preservation effect without oversmoking the meat. Improvements in smoking technology, such as smokehouses equipped with precise control over temperature and humidity, have helped to resolve these problems and increase uniformity and quality of products of smoked meats generally [14].

MODERN PRESERVATION METHODS

Refrigeration and Freezing

Most likely, refrigeration and freezing are the two best and most applied techniques in the preservation of meat. This is basically achieved by reducing the temperature

level of meat, which, in effect, slows or entirely inhibits the activities of food-spoiling organisms and pathogens for the elongation of the meat products' shelf life. Refrigeration slows down the growth of microorganisms, while freezing basically stops it by reducing the temperature to levels at which bacteria cannot grow. These practices are followed by many due to their effectiveness and ease. Chilling prolongs the shelf life of fresh meat for a very short period, whereas freezing conserves the meat for an extensive period or even years [4].

Ideal refrigeration involves the storage of meat at temperatures between 0°C and 4°C, and it is recommended for fresh meat storage. At these temperatures, the growth of most spoilage bacteria may be considerably retarded but not completely stopped. That allows storage of fresh meat for a couple of days, dependent on the kind of meat and its initial microbial load. However, Psychrotrophic bacteria may still grow at these temperatures since these microorganisms can grow up to low temperatures. This underlines the importance of surveillance and the maintenance of proper refrigeration conditions with regard to the safety and quality of meat [5].

Freezing, on the other hand, requires temperatures below -18°C for meat to be satisfactorily preserved. At these temperatures, microbial activity is brought almost to a halt, and the physical and chemical reactions responsible for spoilage are significantly slowed. Packaging must be proper to avoid freezer burning. This is what occurs to meat packed in air, consequently dehydrating and later oxidizing the meat. Freezer burn is an undesirable change in the texture, flavor, and appearance of meat. It can be prevented by using vacuum sealed packaging or tightly wrapping products [6].

Temperature consistency is also key because meat refrigeration and freezing rely on that. The temperature fluctuations can introduce formation and growth of ice crystals within meat, which causes cellular damage, leading to the degradation of texture upon thawing. These problems have been somewhat rectified with advancements in refrigeration technologies, including the development of energy-efficient systems that maintain more consistent temperatures [7].

Vacuum Packaging

Vacuum packaging is a process in which the air is sucked out from the packaging before it is sealed, thus creating a vacuum-sealed environment. Thereby, it reduces the amount of oxygen accessible to the growth of aerobic bacteria and slows down the oxidation processes responsible for the spoilage of food materials. In view of this, no wonder vacuum packaging will help assure quality and prolong shelf life for meat products, hence the very common application within the meat processing industry [8].

Vacuum packaging removes oxygen, which plays a significant role in the retention of moisture and flavor in the meat. This process reduces the risk of oxidation, which usually leads to rancidity and color alterations in meat products. Meat vacuum-packaged products are usually stored in either the refrigerator or freezer, and the absence of oxygen will somewhat suppress the growth of aerobic organisms that cause spoilage. However, when oxygen is low, some anaerobic bacteria, such as Clostridium botulinum, will still grow, therefore proper storage temperatures must be maintained to prevent spoilage and ensure safety boost [9].

Most importantly, one of the major benefits of vacuum packaging is that it prevents freezer burn. Without air in the package, the meat that has been vacuum-sealed does not have much of the usual dehydration and oxidation that happens during normal freezer storage. This leads to quality, flavor, and texture retention for a longer period [10].

Vacuum packaging has also been combined with other preservation methods, like sous-vide cooking. Sous-vide involves vacuum-sealing the meat and then cooking it for extended periods at precise, low temperatures. This method not only improves tenderness and flavor, it also provides a preservation additional layer by pathogens killing by heat [11].

Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging is a methos in which air is removed from the package and back-flushed with the appropriate gas mix for meat preservation. The most used gases are CO2, N2, and O2. This extends shelf life through retardation of microbial growth and oxidation. MAP is now widely applied to fresh and processed meat products and confers considerable advantages in terms of long shelf life and quality retention [12].

The exact gas composition of MAP may vary depending on the meat types and the required period of its shelf life. For example, high oxygen MAP with 70-80% O2 and 20-30% CO2 is applied to red meats to preserve their bright red color. The high content of oxygen in it helps to prevail the oxymyoglobin state of the meat pigment and keeps it red. On the other hand, poultry and fish require a low oxygen MAP of 0-2% O2, 20-30% CO2, and 70-80% N2 to avoid oxidative spoilage. Carbon dioxide of the MAP becomes an antimicrobial by preventing spoiling organisms from growing [13].

Special equipment and packaging materials are needed for MAP systems, but they have the advantage of being able to significantly extend shelf life and reduce food waste. Advances in packaging materials, particularly in films, with the development of high-barrier films, have enhanced the performance of the MAP process. This prevents the interchange of gas and provides a stable atmosphere inside the package for uniform preservation conditions [14].

Besides the extension of shelf life, MAP can be used to enhance the safety of meat products. It controls the growth of spoilage and pathogenic microorganisms, hence lowering the risk of foodborne illness. This makes it a very resourceful tool in the line of ensuring the safety and quality of meat products along the supply chain [15].

Biopreservation

Biopreservation involves the use of natural or controlled microbiota and their antimicrobial products to extend shelf life. The concept applies to the natural interactions of antagonist principles of microorganisms on each other, which results in the inhibition of some unwanted spoilage and pathogenic organisms. Examples include lactic acid bacteria and bacteriocins, which inhibit spoilage and pathogenic microorganisms. Growing interest has been depicted by biopreservation methods because of increased awareness among consumers about the need for natural methods of preservation devoid of additives [16].

Since they produce some by-products that are of an antimicrobial nature, including organic acids, hydrogen peroxide, and bacteriocins, lactic acid bacteria are generally utilized in biopreservation procedures. They may be added as starter or protective cultures in order to prevent the growth of undesired spoilage organisms and pathogens in meat products. The resulted organic acids by lactic acid bacteria decrease the pH of the meat, thus making the environment, as a whole, not conducive to the growth of these harmful bacteria [17].

Nisin is one of the bacteriocins, which are active antimicrobial peptides produced by some bacteria. Bacteriocins inhibit a very wide range of bacteria, from Listeria monocytogenes to Staphylococcus aureus. Bacteriocins may either be added directly to meat products or used in conjunction with lactic acid bacteria for their enhancement of antimicrobial effects. The application of bacteriocins for meat preservation is an active field of research as the investigations are on for new bacteriocins and optimization of their application [18].

Biopreservation can be combined with other techniques, such as MAP or refrigeration, in order to improve their effectiveness. For example, the combination of LAB with refrigeration could result in a synergistic effect that may further extend the shelf life of meat products beyond that obtained with either of these methods alone [19].

In addition to LAB and bacteriocins, other natural antimicrobial agents under research for their potential in biopreservation include essential oils and plant extracts. Many of these natural compounds have been reported to have antimicrobial activities and could be used to improve the safety and quality of meat products. However, the use of such compounds for preserving meat is prone to careful dealing with their sensory effects and legality aftermath [20].

EMERGING METHODS IN MEAT PRESERVATION

High-Pressure Processing (HPP)

High-pressure processing is the new technique that uses high pressure for inactivating microorganisms and spoilage organisms in meat without the application of heat. This is one of the most favored methods in the food industry for maintaining the sensory and nutritional qualities of meat while extending its shelf life.

Mechanism and Process: HPP subjects products meat to pressures between 100 MPa and 600 MPa, equivalent to approximately 14,500 psi to 87,000 psi, for a period of time that ranges from a few minutes to several hours, depending on the needs. Due to this high pressure, the cellular structures of microorganisms like bacteria, yeasts, and molds are disrupted; hence, they become inactivated. All this is achieved without very significantly altering the flavor, color, or texture of the meat, since it is a cold process [21].

Compared to microbial safety, other advantages of HPP also extend to the preservation of the natural juices of the meat, which may improve its final product sensory qualities. In addition, HPP can be applied to a wide variety of products within the categories of red meat, poultry, and seafood, thus giving this technology broader applications in the meat industry [22].

Applications and Limitations: Increasingly, HPP is applied to ready-to-eat meat products due to its high effectiveness in extending shelf life while ensuring the safety of foods. It provides excellent benefits to products like deli meats, sausages, and pre-cooked meals by killing pathogens such as Listeria, Salmonella, and E. coli, maintaining the quality of the product [23].

However, the high operational costs involved in HPP form the main drawbacks to its wide adoption. The infrastructure is rather expensive to install and maintain, hence acting as a major obstacle to small and medium-scale enterprises. Besides, while HPP proves to be very potent against a long list of pathogens, it does not inactivate all types of microorganisms, like some bacterial spores [24]. Optimization of the conditions of HPP in parallel with a cost reduction is a continuous process in order to popularize this technology.

Irradiation

Another developed method of meat preservation is irradiation, which involves exposing meat to ionizing radiation. The process damages the DNA of microorganisms; hence, making them inert and increasing the shelf life of the meat. Though consumers have raised some concerns due to misinformed

information on radiation, this process is regarded as a safe and successful way of preservation [25].

Types of Radiation and Process: There are three major kinds of ionizing radiation used in the irradiation of meat: gamma rays, electron beams, and X-rays. Gamma rays are emanated from radioactive isotopes like Cobalt-60 or Cesium-137. Electron beams and X-rays are created by linear accelerators [26]. All these methods are different in terms of their penetration capabilities and energy level, greatly influencing each one regarding various meat products and several types of packaging.

Due to this minimal temperature increase in the meat, it is often called "cold pasteurization." Some of the main sources of foodborne illness are Salmonella, E. coli, and Listeria; as such, one of the most significant advantages of irradiation is its ability to decrease these pathogens [27]. Moreover, it retards the ripening process of fruits and vegetables and controls insect pests.

Safety and Consumer Perception: Irradiated meats must be labeled as irradiated, and rigorous testing has proven the process doesn't allow the food to become radioactive nor change the nutritional value of the food significantly. Quality of the food is maintained and food is fit for consumption. Consumer resistance however is still a problem due to false beliefs and ideas about radiation. Consumers require education and labeling to change perceptions and acceptance of irradiated foods [28].

Nanotechnology

Nanotechnology is such a new field with colossal potential for bettering the preservation of meat. It makes use of nanoparticles and nanomaterials to enhance the safety of food and prolong its shelf life through various mechanisms [29].

Nanoparticles in Preservation: Nanotechnology in meat preservation involves the use of antimicrobial nanoparticles such as titanium dioxide, zinc oxide, and silver. These nanoparticles can be added to coatings or packaging materials to prevent the growth of microorganisms. For example, silver nanoparticles are found to have very strong antimicrobial properties that could be used in coating meat surfaces, hence decreasing contamination and spoilage [30].

Smart Packaging and Sensors: Nanotechnology allows the development of smart packaging materials that are responsive to environmental changes. Nanocomposites with antibacterial activity could be used in packaging to prevent spoilage. Furthermore, nanosensors can be integrated into meat packaging material to obtain an identification of its status. These sensors have the ability to detect spoilage indicators, such as gas emissions or changes in pH levels, thus providing real-time information about the freshness of the meat [31].

Future Prospects and Challenges: Although the application of nanotechnology in meat preservation is considered to be in a developing stage with much promise, there are still difficulties encountered. Nanotechnology must ensure that such issues as regulatory approval, potential toxicity, and cost-effectiveness are resolved before it can be applied extensively in the industry [32]. Researching new nanoparticles and technologies has continued to improve the preservation of meat in a safe and environmentally sustainable manner.

CONCLUSION

Necessarily, over time, the techniques of preserving meat went from the ancient variety to current and emerging technologies, showing growth in food science and technology. Traditional practices of drying, salting, and smoking provided a great base for the preservation of meat by extending shelf life and enhancing flavor. These methods remain relevant today and are applicable, especially in areas where technological resources are minimal or in those instances where traditional flavor is desired. In meat preservation, refrigeration and freezing brought control of both spoilage and safety through reduction of microbial proliferation and inactivation of enzyme activity. It is then with the adjunctive techniques of vacuum packaging and MAP that modern meat industry gains prominent, convenient methods for extending shelf-life while maintaining quality. Biopreservation has evolved to become a natural, additive-free process of meat preservation using beneficial microorganisms and their by-product antimicrobials to inhibit spoilers and pathogens. This satisfies, hence, the increasing consumer preference for natural methods of preservation, and on the other hand, presents a sustainable substitute for artificial additives. Up-and-coming technologies like HPP, irradiation, and nanotechnology are currently the future of meat preservation. While HPP does not involve heat, it has been considered a critical feature in their technology for the improvement of the sensory and nutritive properties of the meat during storage. Irradiation, though a highly effective pathogen-killing strategy that greatly extends shelf life, is still rejected by consumers because of its mistaken reputation for radiation. However, nanotechnology holds the promise, with current technology in research and development, of providing improved preservation through antimicrobial coatings and smart packaging solutions. Notwithstanding these successes, there are a host of issues that remain to be resolved. The safety and quality of preserved meat need special attention in view of shelf-life prolongation together with nutritional and sensorial preservation. Among the lines of study that, in this respect, remain open for future research, several relate to the optimization of traditional techniques and the exploration of new technologies, while others are connected with regulations and problems of consumer acceptance. Advanced technologies coupled with

traditional methods point toward a very promising way forward in meat preservation. Further innovation and improvement of these techniques will better position the industry to meet the consumers' demand for safety, quality, and sustainability in meat products. The future development of these and other technologies, together with continuous research and interdisciplinarity, will be important promoters of further progress against the ever-changing challenges in meat preservation.

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