



Enhancing the Safety of Meat Products through Chemical and Microbiological Control: A Review

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ABSTRACT

In today's market, consumers are increasingly demanding meat that is not only safe and of the highest quality but also minimally processed and free from unnecessary additives. To meet these evolving expectations, innovative antimicrobial systems and advanced technologies are being developed, aligning with modern trends and lifestyles. From the moment of slaughter to the point of sale, meat is vulnerable to contamination from various sources, both internal and external. These protective approaches help consumer health by lowering the frequency of foodborne pathogens, which include Salmonella, Listeria monocytogenes, and E. coli, among others, that trigger illness. Implementing rigorous hygienic practices is crucial to minimising microbial risks during processing. Chemical and microbiological control measures, such as the use of organic acids, nitrates, nitrites, bacteriocins, and stringent temperature regulation, are employed to safeguard meat quality. The preservation technology enables microbial deactivation alongside meat quality maintenance and

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provides manufacturers with a labelling-friendly antimicrobial method that replaces conventional preservatives. Integrating these methods with Good Hygiene Practices (GHP), HACCP (Hazard Analysis and Critical Control Points), and hurdle technology provides a robust defence against hazards, ensuring the production of safe, high-quality meat products that meet contemporary consumer demands. Combined measures guarantee microorganism safety alongside consumer confidence through an improved delivery of healthy meat products that match clean-label principles.

Keywords: Food safety; meat products; microorganism safety; consumer confidence.

1. INTRODUCTION

Food safety is a fundamental human right, ensuring that the food we consume poses no harm when prepared and eaten as intended (Fung et al., 2018; Gadekar et al., 2021). However, the meat industry faces significant challenges due to potential risks from chemical, biological, and physical contaminants throughout the food value chain. To protect public health and enhance consumer trust, it is essential to continuously advance meat safety practices. This involves leveraging cutting-edge processing technologies, implementing rapid sanitation methods, and adhering to rigorous Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), and Standard Operating Procedures (SOP) (Gadekar et al., 2021). By doing so, we not only prevent foodborne illnesses and minimise economic losses from recalls and legal actions but also build consumer confidence in the safety and quality of meat products.

When consuming meat, there are various foodborne illness risks associated with bacterial contamination. The most important meat-borne pathogens are *Escherichia coli*, *Salmonella spp.*, *Campylobacter spp.*, *Yersinia enterocolitica*, and *Listeria spp.* (Gadekar et al., 2021). Apart from these pathogens, diseases such as BSE (Bovine Spongiform Encephalopathy), Trichinosis and Scrapie pose a health risk to consumers when meat is not handled properly (Gurunathan & Babji).

Chemical and microbiological control strategies are of significant importance ensuring meat safety (Das et al., 2019). These strategies include: prevention of disease transmission by using chemical agents such as disinfectants and antiseptics, extending the shelf life of products by inhibiting the growth of spoilage-causing microbes, promoting environmental protection by managing microbial populations in the environmental settings and preventing food borne illnesses.

Meat spoilage poses a significant economic and public health burden due to the potential risks associated with consuming spoiled meat (Saucier, 2016). From a public health perspective, when meat spoils, it becomes a breeding ground for harmful bacteria, such as *Salmonella*, *Campylobacter*, and *Listeria*, which can cause foodborne illnesses which could cause potentially life-threatening conditions. From an economic perspective, meat spoilage leads to substantial financial losses for both producers, who incur costs associated with wasted resources, and consumers, who face direct and indirect financial losses when they purchase spoiled meat that must be discarded (Ramanathan et al., 2022).

Preventing meat spoilage requires adherence to strict food safety practices throughout the entire supply chain, from production and processing to storage and distribution. Traditional methods of meat preservation include; drying, smoking, brining and canning (Rahman et al, 2023). Current meat preservation methods include, controlling temperature by chilling, freezing and super chilling, controlling water activity with sodium chloride and sugars, and use of different chemicals such as chlorides, nitrites, sulphides, organic acids, phenolic antioxidant and phosphates to control growth of microorganisms to prevent oxidative spoilage and to control autolytic enzymatic spoilage (Addis, 2015).

The purpose of this review is to evaluate and identify effective strategies for reducing the risk of foodborne illnesses associated with meat consumption. This involves examining various chemical interventions, such as antimicrobial agents, preservatives, and irradiation, to inhibit bacterial growth and extend shelf life. Additionally, it entails assessing microbiological control methods, including sanitation practices, hazard analysis and critical control points (HACCP) systems, and pathogen detection techniques. The goal is to ensure the production of safe and wholesome meat products while minimising the use of excessive chemicals or

processes that may negatively impact consumer health or the environment.

2. CHEMICAL CONTROL MEASURES

Chemical control measures in meat safety are strategies and practices implemented to prevent, reduce, or eliminate chemical hazards in meat products. These measures are crucial for ensuring that meat and meat products are safe for consumption and free from harmful levels of chemical contaminants. They are essential to prevent contamination by pesticides, veterinary drugs, heavy metals, and other harmful chemicals and ensure their safety, quality, and compliance with regulatory standards (Das et al., 2019). These measures involve various techniques and processes aimed at detecting, preventing, and mitigating chemical hazards that may be present in the food chain. Some of the commonly practised chemical control measures are the use of anti-microbiological measures such as organic acids, nitrates and nitrites and natural antimicrobials.

2.1 Organic Acids

Organic acids, ubiquitous natural compounds, exert a profound influence on food preservation, particularly in safeguarding meat products (Ben Braïek & Smaoui, 2021; Bonetti et al., 2020). Common examples in the meat industry include acetic, lactic, citric, and propionic acids. Their antimicrobial efficacy stems from a dualistic mode of action. Firstly, they demonstrably reduce food pH, creating an unfavourable environment for microbial growth (Ben Braïek & Smaoui, 2021; da Costa et al., 2019; Hauser et al., 2016). This effect is most pronounced at acidic pH levels (Ben Braïek & Smaoui, 2021; Theron & Lues, 2007). Secondly, organic acids, particularly in their undissociated lipophilic form, readily penetrate the lipid bilayer membranes of target microorganisms (bacteria, yeasts, and fungi) (Hauser et al., 2016). Once within the cytoplasm, where a higher pH prevails, these molecules dissociate into charged anions and protons. The impermeability of the plasma membrane to these dissociated forms leads to a buildup of intracellular protons, acidifying the cytoplasm beyond physiological tolerance. This drastic pH shift disrupts cellular homeostasis, compromising the functionality of enzymes, structural proteins, and DNA. Furthermore, the generated anions exhibit their own toxicity, inhibiting vital metabolic reactions and ultimately leading to cell death (Anyasi et al., 2017).

2.2 Nitrates and Nitrites

Nitrates, such as potassium nitrate (KNO_3) and sodium nitrate (NaNO_3), and nitrites such as potassium nitrite (KNO_2) and sodium nitrite (NaNO_2) are well known as curing agents in cured meat production (Govari & Pexara, 2015). Nitrites exhibit antioxidant activity, and slow the breakdown of unsaturated fatty acids, as well as the development of secondary oxidation flavour compounds. This effect is primarily due to oxygen depletion by the oxidation of NO to NO_2 in the presence of oxygen (Govari & Pexara, 2015; Honikel, 2008). Thus, the development of rancidity or a warmed off flavour are retarded in cured meat products. Nitrites also exhibit important bacteriostatic and bactericidal activity against several spoilage bacteria as well as foodborne pathogens found in meat products (Bryan & Loscalzo, 2017) especially with *Clostridium botulinum* bacteria. The antimicrobial action of nitrites is likely attributed to reactions associated with the generation of NO or nitrous which cause the inactivation of iron-sulphur proteins of *C. botulinum* vegetative cells leading to the probable mechanism of inhibition of the pathogen in nitrites-cured meat products (Govari & Pexara, 2015). The above information shows that the use of nitrates and nitrites in cured meats is essential for ensuring product safety, extending shelf life, and maintaining quality. However, it is crucial to balance their benefits with health considerations through effective regulation, continued research, and consumer education.

2.3 Natural Antimicrobials

Natural antimicrobials play a crucial role in ensuring meat safety by effectively combating foodborne pathogens and spoilage microbes (Papadochristopoulos et al., 2021). These antimicrobials, derived from plants and microorganisms, offer a safer alternative to chemical preservatives, which are sometimes linked to health issues like obesity and metabolic syndrome. Some of the natural antimicrobials that are used to preserve meat and promote meat safety are essential oils, bacteriocins, edible coatings, and nano-capsule delivery systems (Mishra et al., 2021).

2.4 Essential Oils

Consumers prefer food with no artificial additives. Consequently, there is an increasing demand for naturally preserved foods. Essential oils

extracted from herbs like oregano, thyme, rosemary, cloves, and turmeric contain phenolic compounds such as carvacrol, thymol, and eugenol that exhibit broad-spectrum antimicrobial activity against various pathogens (Klein et al., 2013). These compounds can disrupt bacterial cell membranes, release intracellular contents, or interfere with membrane function by interacting with bacterial proteins. Essential oils are Generally Regarded as Safe (GRAS) by the FDA for human consumption (Chouhan et al., 2017).

2.5 Bacteriocins

Bacteriocins are small peptides produced by certain bacteria, particularly Lactic Acid Bacteria (LAB), to inhibit the growth of closely related bacteria (Alvarez-Sieiro et al., 2016). Many bacteriocins have GRAS status and are easily degraded in the human gastrointestinal tract. Nisin, a well-known bacteriocin approved by the FDA, is used as a food preservative in dairy products and meats to control specific pathogens (Woraprayote et al., 2016).

2.6 Nano-Capsule Delivery Systems

Encapsulation of essential oils and bacteriocins in nanoparticles improves their stability and solubility in food products. Nano-capsules ensure a gradual release of antimicrobials over time, enhancing their efficacy in preserving meat (Kaur and Kaur, 2021). Scientists are exploring biopolymer-based nanocarriers like chitosan and alginate for efficient delivery of antimicrobials.

2.7 Edible Coatings and Packaging

Incorporating natural antimicrobials like essential oils or bacteriocins into edible coatings or packaging materials can inhibit microbial growth and prolong the freshness of meat products. Studies have demonstrated the effectiveness of antimicrobial coatings containing oregano or thyme essential oils in reducing pathogen populations in meat patties (Iseppi et al., 2023).

2.8 Impact of Antioxidants on Sensory Qualities

As previously stated, antimicrobials play a crucial role in maintaining the safety and quality of meat products by inhibiting the growth of harmful microorganisms. However, the use of antimicrobials can also impact the sensory quality of meat. Changing the aspects of its taste, aroma, texture, and overall acceptability (Samant

et al., 2015). For instance, a study done in 2023 on the influence of *Moringa oleifera* leaves on the shelf life of ground beef showed the overall acceptability of ground beef deteriorated as the concentration of the *Moringa oleifera* preservatives increased. Higher concentrations of Moringa extract of about 1.5% and 2.0% tend to result in lower sensory ratings across all attributes, suggesting that excessive concentrations may negatively impact the sensory quality of the meat (Mwankunda et al., 2023).

3. MICROBIOLOGICAL CONTROL MEASURES

3.1 Sanitation and Hygiene Practices in Pre-Slaughter Animal Handling and Carcass Decontamination

Sustaining food safety and stemming the tide of illnesses in the animal business necessitates compliance with high standards of sanitation and hygiene regarding animal fetching and carcasses cleaning procedures (Wambui, 2016). Such measures are pivotal in preventing contamination, ensuring proper handling and processing of meat products, and protecting the health of the public. Consequently, taking proper care and treatment of pre-slaughter animals is inevitable so as to reduce stress that may have an adverse impact on the safe and quality meat market. Stress hormones such as adrenaline raise the normal temperature, which may impact the taste and tenderness of the meat. Animal abuse can also lead to injuries that create openings in the meat, which fosters bacterial infection from the hide or excrement (Castellano et al., 2017). Thus, the humane treatment of animals and their transportation has become significant again.

Post-slaughter, there are certain measures taken to disinfect the carcass to minimise the bacterial contamination on the meat surface (Sallam et al., 2020). This process is important in order to prevent the transfer of pathogens that may cause food-borne diseases. To remove carcass contamination, several techniques are employed; these include rigorous washing with water or steam and the use of chemicals through antimicrobial agents (Sohaib et al., 2016). Therefore, proper carcass decontamination has to be done to ensure that there is a reduction in microorganisms while at the same time maintaining the quality and safety of the meat. Slaughterhouse hygiene is crucial in avoiding

contamination between carcasses and ensuring that the processing environment is clean.

3.2 Plant Sanitation Protocols

Plant sanitation measures can be defined as specific measures that have been established to provide specific working guidelines in a manufacturing or processing plant in order to ensure that the environment within the plant is clean (Shahbaz et al., 2020). Such protocols often include having a set hygiene calendar as a fundamental aspect of cleanliness since all the areas in the plant need to be cleaned frequently. This schedule should identify which contents require cleaning and how often these areas should be cleaned, and who will be charged with the responsibility of cleaning these areas. Cleaning protocols should also address various parts of the plant, especially with the materials used in the equipment and the surfaces. It exists in the form of written procedures that outline the cleaning agents to be used, the methods to be employed in cleaning and the safety measures to be observed.

Sanitising procedures include the use of disinfectants or sanitising compounds that have the capability of destroying infectious creatures on the structure, especially in areas that involve food preparation to get rid of hazardous bacteria. The proper training of plant personnel is crucial for people performing cleaning activities to execute them optimally and risk-free (Agüeria et al., 2021). This means that the employees have to be taught the importance of cleanliness, the correct ways of cleaning, and the appropriate PPE to use. Extraordinary observation and check-ups with visual tests to develop into an affirmation that they have been appropriate in the utilisation of cleaners, cleaning hamburgers and that tidiness executions required have been trailed are essential hence (Giné-Garriga et al., 2017). This may include checking for stains or discoloration, observing for microorganisms, or performing any other form of check.

3.3 Cleaning Procedures

The cleaning processes within a plant environment are well-structured processes that aim at eradicating all forms of stains, debris, or any other form of fouling on the surface or on the tools used in the plant. It is to be noted that certain processes form part of cleaning procedures and they include preparation whereby all the equipment, tools, and cleaning agents needed to perform the clean-up should be

obtained and made ready. Sometimes it may not be easy to clean equipment without dismantling it due to specific designs that require different cleaners to penetrate the small holes and surfaces that are hard to reach. Another involves the use of proper cleaning agents or soaps, scrubbing or washing using proper cloth or sponge, and then washing off the cleaning solution (Hola, 2014). After washing, there may be a need to disinfect to eliminate any resistant bacteria or undesirable microbes on the surface (Assadian et al., 2023). This step is usually washing or cleaning the surface with disinfectant or sanitizer that is recommended by the manufacturer. This implies that after washing all the surfaces, they should be thoroughly wiped off with a dry cloth since moisture trapped on the surfaces can cause bacterial growth. When cleaning activities involved disassembling the equipment, the same had to be reassembled as well as the manufacturer's recommendations.

3.4 Worker Hygiene Training and Practices

Educating staff on the aspects of food hygiene is mandatory, and this is one of the crucial measures any organisation in the food industry must undertake. It consists of ensuring foods do not get contaminated, the knowledge of food, temperature of foods, and denotes precision and wastage.

The staff training to minimise cross-contact is one of the significant aspects of food hygiene in need of constant enforcement with the goal of ensuring that bacteria is not transferred from one food item to another or from one surface to the other. From this point of view, measures like hand washing, the use of gloves, and keeping environments clean are paramount in this regard (Kirchner et al., 2021). It also focuses on sensory attributes, work areas, proper food storage, staff cleanliness, and how to avoid bacterial growth since knowledge greatly influences the food temperatures and the corresponding bacteria generation risks (Moye et al., 2018). For instance, the raw meat product must not be allowed to have temperatures above 4°C, while the cooked foods must have at least 57°C.

Another area that is addressed in food hygiene training is efficiency increase, as food handlers are being encouraged to store and rotate foods properly to minimise wastage (Kumar et al., 2021). Further, it is essential to follow legal standards on food hygiene among others, with staff awareness being vital in making sure the

food handlers meet the legal demands of state and federal law (Panghal et al., 2018). It qualifies employees in the correct measures to undertake in a bid to meet the considerable standards of cleanliness and tidiness that the food industry needs in its interaction with the dangers of the world. Moreover, practices of frequent visits by health departments speak volumes about the importance of staff training in the construction and maintenance of these standards.

3.5 Refrigeration and Freezing Principles for Inhibiting Microbial Growth

In refrigeration, the control of temperature is vital since microbes grow at a slow pace, the recommended range is between 0°C and 4. 4°C in which the majority of the bacteria, yeast, and moulds cannot double their rate of reproduction. Though the utilisation of refrigeration helps in the prevention of the growth of microbes none of them are completely eradicated in food products. Proper cooling increases the speed at which microorganisms amass metabolic products and decreases the rate of enzymatic reactions, which helps to preserve food quality (Amit et al., 2017).

Preservation through freezing is another important method that slows microbial growth by selecting a food temperature below 0°C, creating ice crystals that destroy the structure of the microbial cells and make them unavailable (Nowak & Jakubczyk, 2020). One of the key factors is a rapid rate of freezing to avoid the formation of large ice crystals that can undermine the texture and quality of the product.

An equally effective way is the use of chilling, along with freezing in order to prolong the shelf time. Measures such as reheating, refrigeration, and freezing are normally employed, whereby perishable foods are first refrigerated to lower microbial growth and then frozen for further storage (Abdel-Aziz et al., 2016). This dual approach of action facilitates a reduction in bacterial growth, thus enhancing the shelf life and safety of the food.

3.6 Influence of Proper Temperature Monitoring on Meat Safety

Temperature control is mandatory during each stage of supply chains, especially for businesses that handle products that require specific storage temperatures such as pharmaceuticals, food, and biologics. Limiting the temperatures at the time of production, packaging, shipping, and storage is key to the stability, safety, and

effectiveness of medicinal products (Mercier et al., 2017). Here are some key reasons why proper temperature monitoring is essential.

Preservation of Product Quality: They also threaten the effective quality of products that we wish to preserve in their quality and take time to produce. Sustaining the right temperature range retains flavours and aromas, nutritive value, and efficacy of drugs, vaccines, and foods with short shelf-forms. Separately controlling temperature levels at each step ensures that products do not spoil, decline in quality, or get contaminated (James & James, 2023).

Compliance with Regulations: Industry regulators such as the Food and Drug Administration have set high standards for transporting and storing sensitive products that are vulnerable to the external environment. This complicates matters as they may suffer legal repercussions, recall their products, or seriously damage their reputation. The use of thermometers guarantees compliance with the set legal requirements, proving working companies' responsibility for product quality and citizens' health (Al-Busaidi et al., 2017).

Risk Mitigation and Enhanced Customer Satisfaction: Temperature excursions may be damaging to the product quality and effectiveness in its purpose. Accurate temperature control systems assist in tracking and locating different temperatures that require variation to the right conditions and then take appropriate action. This hedge against product loss helps contain wastage and protect the business from incurring losses due to spoiled stocks. The delivery of high-quality products over a long period will improve the quality of the customer satisfaction which encourages customer loyalty to the company. Proper temperature control improves and enhances the quality of the products supplied to the end users strengthening the reputation of the company (Aung & Chang, 2014).

Cost Savings: Of key importance, accurate thermometer control curtails spoilage by temperature fluctuations and thereby minimises losses through waste, costly recalls, and inventory control. Thus, time-dependent data on temperature helps in correct cold chain management and affects the correct route determination, energy saving, and other factors influencing organisational performance (Rodriguez & Palallos, 2024).

3.7 Time-Temperature Indicators for Safe Handling

The Temperature Time Indicators (TTIs) play a critical role in ensuring that the transport and storage of products is not detrimental to their quality, especially in sensitive sectors like the food and drug industries. These controllers provide a visible record of the time/temperature history of the food product and thus monitor for exposure to temperatures outside the required limits (Aguilar et al., 2022). With the use of TTIs, a company is in a position to monitor temperature as well as ensure appropriate compliance throughout storage, transport, and handling, which can timely prevent compromise of the product quality, safety as well as integrity in the supply chain. The monitoring types of TTIs can vary and can be divided into partial history indicators, full history indicators, and an essential temperature that is crucial for monitoring (Pandian et al., 2021).

In fact, profit, safety, quality assurance, and control are some of the definite and clear advantages of time-temperature indicators. TTIs play a role in reducing avoidable losses due to deterioration, averting the occurrence of food-borne illnesses, and generating real-time information on temperatures for enhanced quality. It is a common procedure that governmental agencies and regulating institutions such as the World Health Organization (WHO) and the Food and Drug Administration (FDA) monitor the use of TTI applications to ensure compliance with safety standards though there are special guidelines in sectors like seafood production to retain the freshness and safety of food products. Finally, the present paper has elucidated that the TTIs are the appropriate tools that are useful in preventing the contamination of foods by pathogenic bacteria as well as ensuring the quality of the foods that is fit for human consumption (Pandian et al., 2021).

4. ANALYTICAL TECHNIQUES FOR MICROBIOLOGICAL CONTROL

4.1 Traditional Culturing Methods for Pathogen Detection

With the choice of the right analytical control techniques, microbiological control can be made easier, the main and most common techniques that are commonly used in the identification and measurement of microorganisms are as follows: Microbiological control is required in numerous

economic sectors for example food industry, drug manufacturing, healthcare, and the environment, among others due to the need to maintain product safety and quality. Microbial identification technologies are very important in determining the presence of any special organism or pathogens that may cause harm to the body. Culturing depicts a conventional method that has been applied in pathogen presence identification but it has disadvantages as it is opposed to present molecular methods (Rajapaksha et al., 2019).

Other methods of culturing used in the identification of pathogens include culture media, streak plates, biochemical tests, antibiotic susceptibility, serological tests, colony morphology, gram staining, and analytical profile index (API) phenomenon. Although these techniques have been pioneered in microbiology many years back, they have several challenges like extended procedures, intricate contamination issues, and lack of efficiency when it comes to the identification of non-cultural or fastidious microorganisms.

The following are some of the main factors that have led to the integration of various modern molecular techniques like polymerase chain reaction (PCR), next-generation sequencing, and immunological assays along with the traditional methods for improved efficiency of pathogen detection: These advancements contribute to the increase in efficiency and reliability in microbiological control so as to get desirable and quality products from different industries. (Bahrulolum et al., 2021).

4.2 Rapid Detection Methods: PCR Vs Immunoassays

The Polymerase Chain Reaction (PCR) technology is becoming widely used in the detection of foodborne pathogens to the extent that a large number of tests have become available and scientifically proven in food microbiology laboratories. PCR helps to get rapid, instant confirmation of pathogens, with the result it also brings quantitative data. However, it is essential to note the pitfalls of PCR, including intermittently producing false negative and false positive results during routine testing, and the impact of this on the population (Cohen & Kessel, 2020).

The ones known as ELISA (Enzyme-Linked Immunosorbent Assay) and ELFA (Enzyme-Linked Fluorescent Assay) have a great specialty

in functioning as they target bacterial surface antigens using special proteins. These assays offer the advantage of yielding faster results as compared to the time-honoured plating methods which rely on the antigen-antibody reactions. That being said, they can be affected by cross-reactivity and might therefore give false-positive outcomes. However, all these drawbacks do not negate the usefulness of immunoassays given the capacity to identify pathogens within a short span (Cai, 2021).

In its broadest sense, there is PCR which is also a quick and efficient method of determining microorganisms present in food through the DNA constituents, the immunological methods are also fast as they employ antigen-antibody interactions though more prone to false positives. It is therefore dependent on various factors such as the speed, precision, and testing parameters at the Centre.

4.3 Recent Advancements in Biosensors for On-Site Monitoring

Biosensor development has advanced substantially over the past years, especially for on-site analysis across various domains such as environmental microbiology for instance water quality examination. Biosensors that integrate biological sensing elements with physicochemical converters have numerous advantages which include; high sensitivity, selectivity, portability, fast response, as well as real-time monitoring capabilities (Blais et al., 2015). Some of the most significant developments in the progress of biosensors include size reduction, which makes portable and field applications of biosensors possible. Greater selectivity has been observed through improved biorecognition mechanisms and signal amplification techniques to improve the detection of low analyses concurrently in more complicated matrix systems. Self-sensing and real-time monitoring have significantly changed the approach to environmental monitoring as parameters are tracked over time and remedial action is taken (Arockiasamy et al., 2023).

4.4 High-Pressure processing (HPP)

The non-thermal preservation procedure High-Pressure Processing (HPP) subjects food materials to hydrostatic pressures ranging from 400–600 MPa to remove pathogenic microorganisms with no impact on sensory values or nutritional content. Tests conducted recently proved HPP demonstrates its capability

to eliminate pathogens while retaining food quality in multiple food items such as ready-to-eat meats and dairy products with no necessity of heat treatments or chemical additives (Gilstrap et al., 2023; Kateh et al., 2024). The technology shows special advantages for preserving perishable foods by maintaining their freshness while extending their shelf life.

4.5 Ozone Treatment

The utilization of ozone gas (O₃) as an effective oxidizing agent through ozone treatment destroys a large range of microbial organisms from bacteria and viruses to fungi. Ozone treatment works with gas and water solution states because the breakdown produces only oxygen without dangerous chemical compounds. Research studies prove that microbial contamination management occurs successfully through ozone treatment because this method destroys microorganisms which enhances food safety standards and extension of shelf life in vegetables and grains and meat products (Xue et al., 2023). Food quality preservation demands better control of ozone exposure parameters between concentration and time duration to prevent negative effects on the products.

Other advancements include multiplexing to deal with the ability to detect more than one analyte at once, interfaces for integration with the IoT technology to allow for constant monitoring and control of data, enhanced stability and durability to allow for the long-term use of the devices, interfaces that make operating the devices and interpreting the results easier, and constant work to make such diagnostic tools more affordable. Altogether, these advancements redefine on-site monitoring paradigms through superior sensitivity, true contemporaneous monitoring, transportability, the ability to employ multiplex analysis, Internet of Things compatibility, solidity, ease of use, and cost-effectiveness.

5. INTEGRATED APPROACH TO MEAT SAFETY

An integrated food safety management system (FSMS) is essential for the global food industry to address the challenges posed by multiple and fragmented food safety standards. By consolidating these standards into a comprehensive and unified framework, businesses can achieve cost efficiency, simplified compliance, enhanced food safety, global market access, improved collaboration, and adaptability to emerging challenges

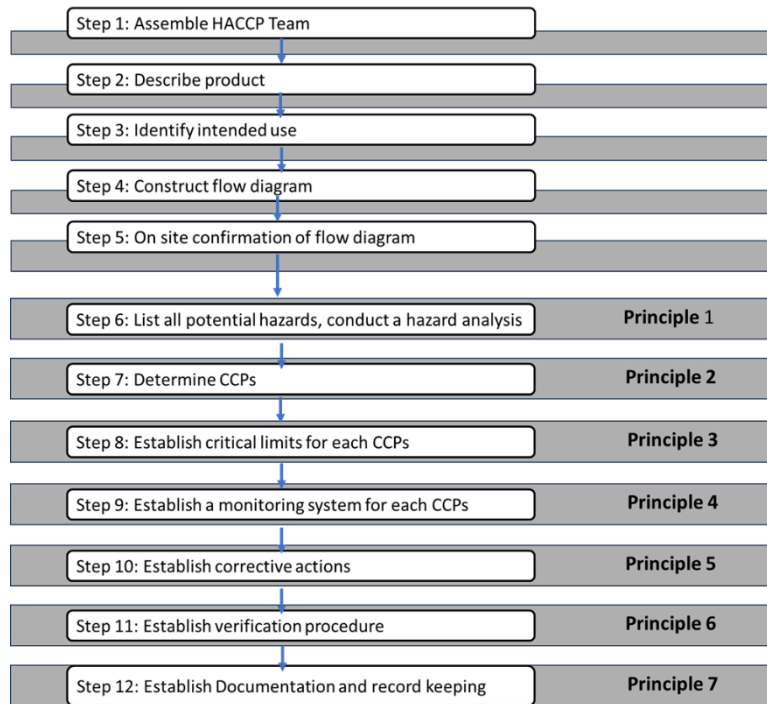


Fig. 1. HACCP principle and steps (Kamboj et al., 2020)

(Ravensdale et al., 2018). An integrated FSMS aims to streamline these standards into a unified system that covers multiple aspects of food safety with a single certification. Its benefits include; cost efficiency, simplified compliance, enhanced food safety, global market access, technical harmonisation and improved collaboration among stakeholders.

The integration of both chemical and microbiological control measures is essential for ensuring comprehensive meat safety protocols. While chemical control measures can help reduce microbial contamination on the surface of meat products, they may not always penetrate deep enough to eliminate all pathogens present (Ben Braïek & Smaoui, 2021). On the other hand, microbiological control measures focus on overall hygiene practices and temperature management to prevent microbial growth throughout the production process (Rebezov et al., 2021). By combining these two approaches, a more robust system for ensuring meat safety can be established. Chemical interventions can complement microbiological controls by providing an additional layer of protection against pathogens that may survive standard sanitation practices. This integrated approach helps mitigate risks associated with microbial contamination at multiple points along the meat supply chain.

5.1 Hurdle Technology Approach

Hurdle technology is a multifaceted approach employed in the food industry, including meat processing, to fortify food safety. This strategy erects multiple barriers that pathogens must surmount to proliferate (Ishaq et al., 2021; Khan et al., 2017). By meticulously combining diverse preservation techniques, each targeting distinct microbial vulnerabilities, this methodology potently inhibits microbial growth. This synergistic interplay augments pathogen control efficacy while concurrently preserving nutritional and sensory attributes. (Rahman, 2014). Consequently, hurdle technology emerges as a promising paradigm for elevating overall food quality and mitigating rigorous processing demands. This combinatorial strategy not only enhances food safety but also extends product shelf life and reduces the incidence of foodborne illness, thereby safeguarding both consumer health and product integrity.

5.2 Hazard Analysis and Critical Control Points (HACCP) principles

HACCP is a systematic preventive approach to food safety that addresses physical, chemical, and biological hazards as a means of prevention rather than finished product inspection (Kamboj et al., 2020). In the case of meat and meat products, HACCP plans are developed to identify

potential chemical hazards such as contaminants, additives, or residues at critical points in the production process. According to the WHO, there are seven basic principles that should be followed for HACCP implementation while the Codex Alimentarius (Food and Agriculture Organization) has 12 steps that start before these seven principles. These steps are shown in Fig. 1. For the HACCP system to work effectively there needs to be a partnership between the top management, plant manager, quality assurance officers and the plant workers (Pearson & Dutson, 2012).

Establishing a comprehensive food safety management system demands substantial resources. To alleviate the financial and operational burdens on small enterprises, governmental and industry support or incentives may be essential. The contemporary food safety regulatory landscape is characterised by a series of certifications, including GFSI, Organic, Global GAP, HACCP, and ISO. Although each standard contributes uniquely to food safety, their cumulative impact imposes considerable challenges for businesses, especially smaller entities, in terms of compliance costs and operational complexity (Ravensdale et al., 2018).

6. FUTURE TRENDS AND RESEARCH DIRECTIONS

6.1 Development of Novel Antimicrobials and Natural Preservation Techniques

Although it was somewhat of a digression, the development of new antimicrobial compounds is indeed a crucial area of research and development in food preservation methods utilizing natural preservatives. The challenges in developing new antimicrobials and eco-friendly preservation methods are recognized as a promising area in the field of microbiology as well as food technology due to the constantly growing bacterial resistance to conventional antibiotics and the trends in the market that are shifting towards more natural food consumption. Since the pathogenic microorganisms are always on the prowl, it is high time to develop better strategies to contain them and to address the consumer's palate of wanting more safe and minimally processed foods. The recent development of novel antimicrobials expands various strategies such as phage therapy, antimicrobial peptides, and nanotechnology that hold the potential for selective and effective

action against antibiotic-resistant significant pathogens (Murugaiyan et al., 2022).

High Pressure Processing (HPP) also enables gentle preservation that retains the tastes and textures of foods and discourages moisture loss, while extending their shelf-life without requiring additives of any kind. Based on plant-originated essential oils, HPP, and fermentation, antimicrobial bioactive compounds, high-pressure, and advantageous microbes are used to preserve shelf-stable sensory and nutritive values of perishability-prone foods. These enhancements are valuable in addressing the goals of preventing off microbial resistance and achieving consumers' expectations for enhanced food fare safety and sustainability (Abass et al., 2014).

6.2 Antimicrobial Resistance (AMR) and its Impact on Control Strategies

AMR remains a major global health threat due to improper usage of antimicrobial drugs, including the overuse of such drugs. It has thus reduced the effectiveness of commonly used antibiotics negating the all-important fight against infections consequently increasing morbidity, mortality as well as the economic cost of diseases internationally. However, drugs like *E. coli* and *Staphylococcus aureus* that have become resistant to most of the known antibiotics are proving hard to manage as compared to other simple infections. In addition, AMR not only interferes with basic aspects of healthcare delivery, but it also endangers more complicated and necessary medical interventions like surgeries, chemotherapy, and transplants, which increases the probability of treatment failure and adverse health effects (Fymat, 2017).

The consequences of AMR are not restricted to health only but include significant losses in healthcare organisations and macroeconomic Terms. This means that drug-resistant infections exert even higher pressure on healthcare systems in terms of both expenditures; the need for more expensive treatments and longer hospital stays, as well as reduced efficiency due to the loss of work days. In addition to that, AMR poses a significant risk to global health by reducing the efficacy of conventional treatments for infectious diseases and making it easier to spread resistant pathogens across borders. In order to tackle AMR, one needs to implement a comprehensive 'One Health' approach, which

takes into account human health, animal health, and ecological surroundings. Intensive cooperation with the rest of the sectors is important for controlling AMR control further, which involves supporting research and development for new antimicrobial agents, diagnostics, and vaccines, making policy changes for appropriate use of antimicrobials, and enhancing healthcare (Fymat, 2017).

6.3 Consumer Preferences for Minimally Processed and Clean-Label Products

The general trends in the consumption of food and beverages are minimal processing and clean ingredients resulting from health and wellness concerns, transparency in labelling and packaging, ecological considerations, and self-promotion on social media. The clean-label taste as a trend is majorly fueled by a consumer's desire for simple natural-sounding food ingredients that are well labeled. Such a tendency is possibly related to the overall trend seen to path products that are considered to be of better health value, security, and sustainability (Aschemann-Witzel et al., 2019).

Promotional drivers influencing the consumers include general health consciousness, request for clear labels, preservation concern creativity, perceived health aspect concerning clean label products, and the impact of social media in creating awareness. This means that more and more consumers are willing to go further towards more natural and real food, better quality than quantity, genuine and sustainable products, and responsible sourcing. By associating themselves with these values, more and more brands will have the opportunity to target the select market of consumers who are more conscious about what they are buying and the kind of impact that it has on their health, environment, and ethics (Hoek et al., 2017).

To sum up, planetary health concerns, the desire for simple label products, and the urge for more transparent product information reflect the interaction of health awareness, transparency, environmentalism, perceived health benefits, social media, natural flavor, quality ingredients, genuine and ethical reputation, and demand. It is imperative that brands are able to identify such trends and be ready to adapt, especially as consumers may begin to demand products and services that are more relevant to their changing lifestyles (FuiYeng & Yazdanifard, 2015).

6.4 Balancing Safety with Sensory Qualities and Shelf-Life

Some of the measures that can be employed as precautions and prevention measures in food production in order to enhance both the safety and sensory qualities of the products include: Essentially, proper methods must be followed, using factors such as temperature, and humidity, and light in order to inhibit microbial growth or degradation of the food. Methods in minimal processing for bread include washing and freezing to eliminate food-borne risks while retaining natural qualities.

In this focal area, careful attention is paid to the choice of ingredients, and to ensure that they meet specific standards of safety and are appealing to the sense of taste, smell or sight. Original packaging products also preserve the food in order to avoid contamination from the external environment while at the same time preserving the sensory attributes of the food in the long run. Another aspect that can't be ignored is the necessity to maintain the temperature properly during production and storage to avoid bacterial growth and have the accumulated product taste good (Nicola & Fontana, 2014).

Pertaining to quality control and assurance, rigorous testing and sensory analysis by qualified and accredited taste panels help to make quality products that meet set safety standards and recipes regarding sensory appeals. Constant evolution derived from feedback and progressive technological findings makes it possible to fine-tune the whole process and not only the aspects of safety and sensory characteristics. These integrated strategies should enable the production of safe and palatable, attractive sensory qualities such as taste, texture, smell, and appearance of bottles (Singh-Ackbarali & Maharaj, 2014).

7. CONCLUSION

This review highlights the importance of safeguarding meat safety throughout the food chain. Stringent control strategies encompassing both chemical and microbiological interventions are demonstrably indispensable in protecting public health from foodborne illness outbreaks, minimising economic burdens, and ensuring regulatory compliance. Furthermore, these combined measures foster consumer trust by guaranteeing the safety and wholesomeness of meat products. Antimicrobial properties of organic acids, nitrates and nitrites and

bacteriocins help promote meat safety by inhibiting spoilage organisms and enhancing shelf life. While antimicrobials are essential for ensuring food safety and extending shelf life by inhibiting microbial growth in meat products, their use can have implications for sensory quality. It is crucial for food producers to strike a balance between microbial control and preserving the desirable sensory characteristics of meat to meet consumer expectations and preferences. In conclusion, a comprehensive approach that integrates chemical and microbiological controls alongside robust Good Manufacturing Practices (GMP), Good Hygiene Practices (GHP), Standard Operating Procedures (SOP), and HACCP systems is pivotal for ensuring the unwavering safety of meat and meat products throughout the food chain.

DECLARATION OF COMPETING INTEREST

The authors declare no competing conflict of interest.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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