Review Article

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Use of bioactive compounds to enhance meat safety and quality

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ABSTRACT

Ensuring the safety and quality of meat remains a major challenge in the food industry due to susceptibility to microbial contamination, lipid oxidation, and protein degradation, which compromise sensory properties and nutritional value. Bioactive compounds have emerged as natural agents capable of enhancing meat safety and quality through antimicrobial, antioxidant, and sensory-modulating activities. These compounds, derived from plants, microbes, animals, or synthesized sources, can inhibit the growth of pathogenic bacteria, prevent oxidative spoilage, maintain color, texture, and flavor, and extend product shelf-life. This review was conducted through a systematic search of scientific literature in databases including Scopus, Web of Science, PubMed, and Google Scholar, covering both foundational and recent studies without restrictions on publication year. Inclusion criteria focused on research reporting the application of bioactive compounds in fresh or processed meat with documented effects on microbial safety, oxidative stability, sensory attributes, or shelf-life. Data were extracted on compound type, source, application method, and observed outcomes, and synthesized narratively to highlight mechanisms, efficacy, and practical implementation. Findings indicate that direct addition, marination, edible coatings, active packaging, and combination with non-thermal processing effectively integrate bioactive compounds into meat products. Synergistic use of multiple compounds often enhances antimicrobial and antioxidant effects while preserving sensory quality. These strategies offer promising alternatives to synthetic preservatives, aligning with consumer demand for natural, safe, and functional foods. Future research should focus on optimizing compound combinations, industrial scalability, and integration with emerging processing technologies to maximize efficacy and product stability. Overall, bioactive compounds represent a sustainable approach for producing high-quality, safe, and shelf-stable meat products.

Introduction

Meat safety and quality remain major challenges in the modern food industry, as meat products are highly susceptible to microbiological contamination, lipid oxidation, and textural deterioration during storage and distribution (Rebezov *et al*., 2024). Pathogens such as *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli* are major causes of foodborne illnesses (Malabadi *et al*., 2024). At the same time, lipid oxidation and protein degradation contribute to undesirable changes in color, aroma, flavor, and nutritional value (Geng *et al*., 2023). These alterations not only reduce consumer acceptability but also lead to significant economic losses for producers due to shortened product shelf life (de Rezende *et al*., 2022). Therefore, innovative strategies to maintain meat safety and quality are critically needed, particularly approaches that reduce reliance on synthetic chemical additives (Samad *et al*., 2025).

In this context, bioactive compounds have emerged as a promising solution (Kurek *et al*., 2022). Bioactive compounds are molecules possessing specific biological activities, including antimicrobial, antioxidant, and sensory-modulating properties, which can enhance meat quality through multiple mechanisms (Pai *et al*., 2022). These compounds encompass diverse chemical classes such as polyphenols, flavonoids, terpenes, alkaloids, organic acids, as well as bioactive peptides and proteins derived from plants, microorganisms, and animal sources (Elshafie *et al*., 2023). Polyphenols and flavonoids, for instance, exhibit strong free radical–scavenging capacity, inhibit lipid oxidation, and suppress microbial growth (Tumilaar *et al*., 2024). In contrast, microbial peptides and animal-derived proteins contribute to pathogen inactivation and improvement of muscle fiber tenderness (Di and Jia, 2024). The diversity of sources and mechanisms of action provides considerable flexibility for the application of bioactive compounds in both fresh and processed meat products (Pogorzelska-Nowicka *et al*., 2018).

The significance of bioactive compound utilization in meat processing extends beyond microbiological safety and chemical stability (Karnwal and Malik, 2024). Bioactive substances also contribute to maintaining sensory quality, including color, aroma, taste, and texture, which are critical determinants of consumer acceptance (Fabela-Morón, 2024). Consequently, bioactive-based approaches enable the development of functional meat products that are safe, shelf-stable, and value-added, while simultaneously reducing dependence on synthetic preservatives that may raise consumer health concerns (Pinto *et al*., 2026).

Recent studies further highlight the synergistic potential among different bioactive compounds and their integration with modern processing technologies, such as non-thermal processing and active packaging systems, to enhance antimicrobial and antioxidant effects (Tian *et al*., 2025). These strategies allow more effective control of meat quality, minimize sensory degradation, and extend shelf life without compromising nutritional value. Such a multifaceted approach is highly relevant in addressing the demands of modern consumers who prioritize safety, natural ingredients, and consistent sensory quality (Kurniawan *et al*., 2026a).

Therefore, this review aimed to present recent findings on the application of bioactive compounds in meat processing, elucidate their antimicrobial, antioxidant, and sensory modulation mechanisms, and explore their potential industrial applications. This review sought to provide comprehensive insights for researchers and industry practitioners regarding

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bioactive-based strategies to improve meat safety, quality, and added value, while also identifying opportunities and challenges associated with large-scale industrial implementation.

Method

This review was conducted using a structured literature search to summarize current knowledge on the use of bioactive compounds for improving meat safety and quality. Relevant studies were identified through electronic databases, including Scopus, Web of Science, PubMed, and Google Scholar, using keywords such as "bioactive compounds," "meat safety," "meat quality," "antimicrobial," "antioxidant," and "non-thermal processing."

Inclusion criteria encompassed studies that evaluated bioactive compounds in fresh or processed meat, with documented effects on microbial safety, oxidative stability, sensory quality, or shelf-life. Excluded were studies focused on non-meat products, lacking experimental or review data, or not available in full text.

Data extraction focused on the type and source of bioactive compounds, application method (e.g., direct addition, marination, coating, or packaging), and observed effects on microbial inhibition, oxidative stability, sensory properties, and shelf-life. Findings were synthesized narratively to highlight mechanisms of action, comparative efficacy, and practical applications in meat processing. This approach enabled a concise yet comprehensive overview of bioactive compound utilization in meat products, ensuring scientific rigor while emphasizing current trends, challenges, and opportunities for future research.

Classification and sources of bioactive compounds

Bioactive compounds are naturally occurring or synthesized molecules that can improve meat safety, quality, and shelf-life, and they are commonly classified based on their origin into plant-, microbial-, animal-derived, and synthetic or semi-synthetic sources (Singh and Negi, 2025). Table 1 summarizes the classification of bioactive compounds used to improve the safety, quality, and shelf life of meat products. Figure 1 illustrates the major sources of bioactive compounds—including plant-derived phytochemicals, microbial metabolites, and animal-based bioactive and their functional roles in improving meat safety and quality.

Plant-derived compounds

Bioactive compounds extracted from plants, including herbs, spices, vegetables, and fruits, have significant potential to improve the safety and quality of meat products (Awad *et al*., 2022). Compounds such as polyphenols, flavonoids, terpenes, and organic acids act as natural antimicrobial and antioxidant agents that can inhibit the growth of pathogens and delay lipid oxidation (Deshmukh and Gaikwad, 2024). Their antimicrobial activity occurs through multiple mechanisms, including disruption of microbial cell membranes, inactivation of essential enzymes, and interference with bacterial metabolism, thereby reducing the risk of food contamination (Angane *et al*., 2022).

In addition to their antimicrobial function, plant-derived compounds also help preserve the sensory quality of meat (Olvera-Aguirre *et al*., 2023). Lipid oxidation and protein degradation are major factors contributing to the deterioration of color, texture, and aroma in meat products (Kurniawan *et al*., 2026b). Plant bioactive compounds can stabilize free radicals and prevent the formation of secondary oxidative compounds, thereby maintaining sensory characteristics during storage. This makes them an effective natural alternative to synthetic chemical additives (El-Gamal *et al*., 2023).

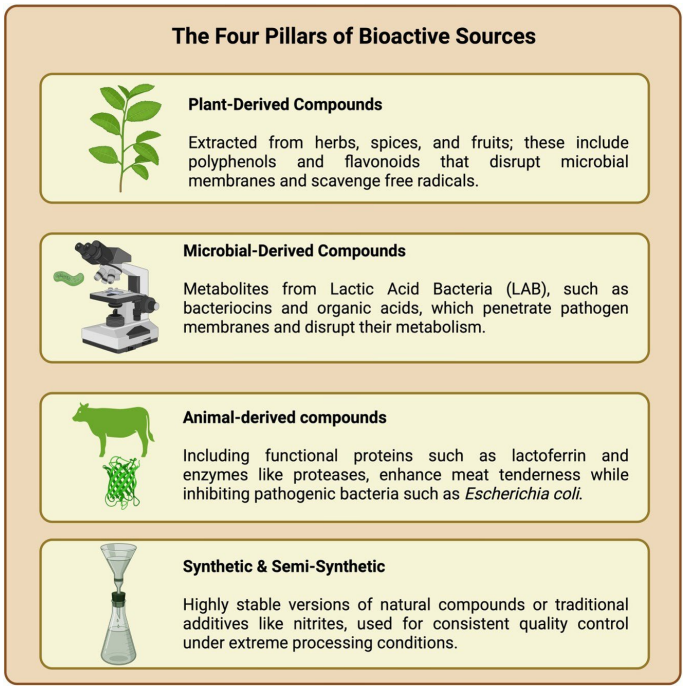

Figure 1. Major sources of bioactive compounds and their functional roles in improving meat safety and quality

The application methods of plant-derived compounds vary widely, ranging from direct addition as spices or extracts, incorporation into marinades, to their use in edible coatings or active packaging systems that

Table 1. Classification and sources of bioactive compounds in meat processing.

Classification	Source / Examples	Mechanism of Action	Applications in Meat	Source
Plant-derived	Herbs, spices, vegetables, fruits; compounds: polyphenols, flavonoids, terpenes, organic acids	Antimicrobial: disrupts microbial membranes, enzyme inactivation; Antioxidant: scavenges free radicals, prevents lipid oxidation; sensory modulation	Direct addition as extract or spice, marination, edible coating, active packaging; often in combination for synergistic effect	(Sun *et al*., 2024)
Microbial-derived	Lactic acid bacteria (LAB); metabolites: organic acids, bacteriocins, antimicrobial peptides	Antimicrobial: membrane penetration, pore formation, metabolic disruption; reduces oxidative degradation	Starter cultures in fermented meat, bio-preservatives in marinades, combined with active packaging; synergistic use with plant bioactives	(Yadav *et al*., 2025)
Animal-derived	Enzymes and functional proteins: lactoferrin, collagen, antimicrobial peptides; proteases, lipases	Antimicrobial: membrane binding and permeability disruption; Antioxidant and sensory: proteolysis improves tenderness, lipases generate volatile aroma compounds	Direct addition, functional ingredients in marinades, integration into active packaging; combinable with plant or microbial bioactives for synergy	(López-Pedrouso *et al*., 2023)
Synthetic / Semi-synthetic	Nitrites, nitrates, synthetic polyphenols, peptide derivatives	Antimicrobial: selective membrane binding, enzyme inhibition; Antioxidant: inhibits lipid and protein oxidation; highly stable	Direct incorporation in fresh or processed meat, active packaging, combination with non-thermal processing; hybrid approach with natural bioactives	(Singh and Negi, 2025)

release compounds in a controlled manner (Latoch *et al*., 2023). These strategies not only enhance microbiological safety but also preserve the functional and sensory quality of meat (Barcenilla *et al*., 2022). Such innovative approaches offer opportunities to produce safer, longer-lasting meat products with added value for consumers who prefer natural ingredients (Lisboa *et al*., 2024).

Recent studies have also highlighted the potential synergistic effects among different plant-derived compounds. The combination of certain herbal and spice extracts can enhance antimicrobial and antioxidant activities compared with single compounds, while also contributing to greater complexity of aroma and flavor (Grigore-Gurgu *et al*., 2025). This approach opens new avenues for the development of more effective and consumer-friendly bioactive-based meat processing strategies.

Microbial-derived compounds

Bioactive compounds produced by microorganisms, particularly lactic acid bacteria (LAB), play an important role in improving the safety and quality of meat products (Hakim *et al*., 2023). LAB can produce various functional metabolites, including organic acids, bacteriocins, and antimicrobial peptides, which effectively inhibit the growth of pathogens such as *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli* (Kim *et al*., 2026). The antimicrobial mechanisms involve penetration of microbial cell membranes, pore formation, and disruption of internal metabolic processes, leading to the loss of viability and proliferation capacity of pathogenic microorganisms (Kurniawan *et al*., 2026b).

In addition to their antimicrobial effects, microbial peptides and metabolites contribute to the chemical stability of meat by reducing lipid and protein oxidation (Wang *et al*., 2022). This activity helps maintain the integrity of color, texture, and aroma in meat products during storage. Unlike synthetic chemical additives, microbial-derived compounds are natural and can be produced through fermentation processes, making them safer for human consumption (Vermelho *et al*., 2025).

The application of microbial bioactive compounds in meat processing is diverse. LAB can be directly added as starter cultures in fermented products, used as biopreservatives in marination processes, or combined with active packaging technologies for the controlled release of antimicrobial compounds (Kaveh *et al*., 2023). These approaches not only extend shelf life but also enhance microbiological safety without compromising sensory quality (Teshome *et al*., 2022).

Recent studies have also highlighted the potential synergistic effects between microbial compounds and other bioactive substances, such as polyphenols or herbal extracts (Vaou *et al*., 2022). Such combinations may provide broader antimicrobial activity and improve resistance to oxidative deterioration while maintaining desirable organoleptic properties (Bensid *et al*., 2022). This integrative strategy offers promising opportunities for the development of safer, higher-quality meat products that align with the preferences of modern consumers (Alam *et al*., 2025).

Animal-derived compounds

Bioactive compounds derived from animal sources, including enzymes and functional proteins, offer a unique approach to enhancing the safety and quality of meat products (Vlaicu *et al*., 2023). Bioactive proteins such as lactoferrin, collagen, and antimicrobial peptides are capable of inhibiting the growth of pathogens, including *Listeria monocytogenes* and *Escherichia coli*, through mechanisms involving binding to microbial cell membranes, disruption of membrane permeability, and inhibition of intracellular metabolic processes (Corrêa *et al*., 2023). These activities help reduce microbiological contamination while extending the shelf life of meat products (Fadiji *et al*., 2023).

Animal-derived enzymes, such as specific proteases and lipases, can also selectively modify the textural and flavor characteristics of meat (Aminlari, 2022). Proteases contribute to the tenderization of muscle fibers through the hydrolysis of structural proteins, whereas lipases generate volatile aroma compounds that enhance sensory complexity (Azmi *et al*., 2023). Both enzymes function in a controlled manner to preserve organoleptic quality without causing excessive degradation that could negatively affect product quality (Dai *et al*., 2024).

The application of animal-derived bioactive compounds can be achieved through direct incorporation into meat products, formulation as functional ingredients in marinades, or integration into active packaging systems that enable controlled release (Vargas-Ramella *et al*., 2025). This approach helps ensure that microbiological safety and sensory quality are maintained throughout storage and distribution (Ogwu and Ogunsola, 2024). Recent studies have highlighted the potential of combining animal-derived bioactive proteins with bioactive compounds from plant or microbial sources to enhance synergistic effects (Machado *et al*., 2025). Such combinations not only broaden the antimicrobial spectrum but also maintain antioxidant stability, resulting in meat products that are safer, more nutritious, and possess enhanced sensory appeal for consumers (Tocai *et al*., 2025).

Synthetic or semi-synthetic bioactive compounds

In addition to natural compounds, synthetic and semi-synthetic bioactive compounds provide a controlled alternative for improving the safety and quality of meat products (Tauchen *et al*., 2025). These compounds are designed to mimic or enhance the antimicrobial and antioxidant activities of natural sources while offering greater stability during processing and storage (Deshmukh and Gaikwad, 2024). Examples include synthetic nitrites and nitrates used as preservatives in processed meat, as well as polyphenol derivatives or synthetic peptides that exhibit specific antimicrobial and antioxidant activities (Bensid *et al*., 2022).

The mechanisms of action of these synthetic compounds generally involve selective binding to microbial membranes, inhibition of key enzymes, and suppression of oxidative reactions in meat lipids and proteins (Fu *et al*., 2022). A major advantage of synthetic compounds is their stability against heat, pH fluctuations, and oxygen exposure, allowing them to maintain bioactive effectiveness under various processing conditions that often reduce the activity of natural compounds (Kurek *et al*., 2022).

The application of synthetic and semi-synthetic compounds in the meat industry is highly flexible (Chi *et al*., 2024). They can be directly incorporated into fresh or processed meat products, used as components in active packaging systems, or combined with non-thermal technologies to enhance shelf life and microbiological safety (Zhang *et al*., 2025). This approach enables more consistent product quality control, although regulatory limits and food safety considerations must always be taken into account (Chhetri, 2024).

Despite their effectiveness, the use of synthetic compounds requires careful evaluation regarding residue levels, potential toxicity, and consumer acceptance (Leskovac and Petrovic, 2023). Current trends indicate the integration of synthetic compounds with natural bioactives as a hybrid strategy, combining the stability and controllability of synthetic compounds with the functional and natural value of organic bioactives, ultimately producing meat products that are safe, durable, and sensorially appealing (Meunier *et al*., 2024).

Mechanisms of action

Bioactive compounds exert their effects on meat quality and safety through multiple mechanisms, including antimicrobial action, antioxidant protection, modulation of sensory attributes, and extension of shelf-life (Petcu *et al*., 2023). Table 2 summarizes the mechanisms of action of bioactive compounds in meat processing, including antimicrobial activity, antioxidant activity, modulation of sensory properties, and extension of shelf life. Figure 2 depicts the mechanisms of action of bioactive compounds in enhancing meat safety, quality, and shelf life.

Table 2. Mechanisms of action of bioactive compounds in meat preservation.

Mechanism	Description	Effects on meat	Application strategies	Source
Antimicrobial activity	Inhibits growth of pathogens via membrane disruption, enzyme inhibition, genetic interference, and biofilm prevention	Reduces contamination risk, controls pathogen proliferation, enhances microbiological safety	Direct incorporation, marinades, edible coatings, active packaging; combination of multiple bioactives for synergistic effect	(Bensid *et al*., 2022)
Antioxidant activity	Neutralizes free radicals, prevents lipid peroxidation, protects protein structure	Maintains color, flavor, texture, nutritional value, and chemical stability	Addition of plant extracts, microbial peptides, or animal proteins; incorporation in marinades or packaging; combination for synergistic effect	(Al Jumayi *et al*., 2022)
Modulation of sensory attributes	Modifies texture, aroma, and flavor through selective proteolysis, interaction with volatile compounds, and inhibition of off-flavor formation	Improves tenderness, preserves natural aroma and taste, stabilizes color	Direct addition, marinades, edible coatings, or active packaging; combined bioactives for enhanced sensory stability	(Jairath *et al*., 2024)
Enhancement of shelf-life	Integrates antimicrobial and antioxidant effects to slow microbial growth and oxidative degradation	Prolongs storage life, maintains safety and quality during distribution	Controlled-release systems like edible coatings or active packaging; synergistic use of bioactives from different sources	(Malav *et al*., 2025)

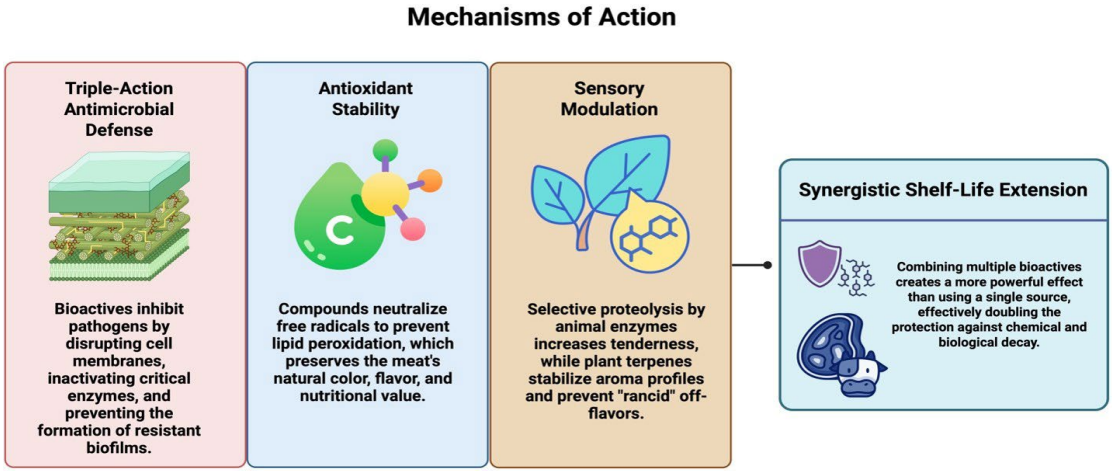

Figure 2. Mechanisms of action of bioactive compounds in enhancing meat safety, quality, and shelf-life.

Antimicrobial activity

One of the primary roles of bioactive compounds in meat processing is their antimicrobial activity, which suppresses pathogen growth and extends product shelf life (Fadiji *et al*., 2023). Bioactive compounds act through multifaceted mechanisms, including disruption of bacterial cell membrane integrity, inhibition of critical metabolic enzymes, and interactions with microbial genetic material that hinder cellular proliferation (Mulat *et al*., 2025). These activities are effective against major meat-borne pathogens such as *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli*, which are commonly associated with foodborne illnesses (Elamary *et al*., 2022).

In addition to inhibiting microbial cell growth, several bioactive compounds are also capable of preventing biofilm formation (Mulat *et al*., 2025). Biofilms are microbial communities attached to surfaces and protected by a polymeric matrix, making them more resistant to conventional preservatives (Olaimat *et al*., 2024). Bioactive compounds derived from plant, microbial, or animal sources can reduce microbial adhesion, disrupt cellular communication (*quorum sensing*), and degrade established biofilm structures (Er-Rahmani *et al*., 2024). This significantly enhances microbiological control in meat products, particularly during storage and distribution (Rebezov *et al*., 2024).

The application of bioactive compounds can be implemented through direct incorporation into meat products, use in marination solutions, or integration into active packaging systems that release antimicrobial agents in a controlled manner (Andrade *et al*, 2022). These strategies enable consistent control of microbial populations, reduce the risk of cross-contamination, and maintain the sensory quality of meat without relying heavily on synthetic chemical additives that may pose potential risks to consumers (Samad *et al*., 2025). Recent studies also indicate that combining multiple bioactive compounds from different sources may produce stronger synergistic effects compared with single-compound applications. Such synergy not only broadens the antimicrobial spectrum but also limits microbial adaptation to environmental stress, thereby improving the overall safety of meat products (Vaou *et al*., 2022).

Antioxidant activity

One of the key contributions of bioactive compounds in meat processing is their antioxidant capacity to suppress lipid oxidation and protein degradation, two major processes that reduce product quality during storage (Hadidi *et al*., 2022). Lipid oxidation produces secondary compounds such as aldehydes and ketones, which cause undesirable changes in the aroma, flavor, and color of meat while also reducing its nutritional value (Fu *et al*., 2022). Bioactive compounds, including polyphenols, flavonoids, and bioactive peptides, can neutralize free radicals and inhibit lipid peroxidation reactions, thereby maintaining the chemical and sensory stability of meat products (Jairath *et al*., 2024).

In addition to preventing lipid oxidation, bioactive compounds also protect muscle protein structures from oxidative denaturation (Hadidi *et al*., 2022). This protective effect helps maintain meat texture, muscle fiber tenderness, and water-holding capacity, all of which directly influence sensory quality and consumer acceptance (Lee *et al*., 2023). Antioxidant activity may occur directly through free radical scavenging or indirectly by enhancing the natural defense mechanisms of meat against oxidative stress (Ponnampalam *et al*., 2022).

The application of bioactive antioxidants can be implemented through various approaches, such as the incorporation of plant extracts, microbial peptides, or animal-derived proteins into fresh or processed meat, their use in marination solutions, or their integration into active packaging systems (López-Pedrouso *et al*., 2023). These strategies not only extend shelf life but also minimize undesirable changes in color, aro-

ma, and flavor that commonly occur during cold storage or distribution (Lohita and Srijaya, 2024). Recent studies indicate that combining antioxidant compounds from different sources may produce stronger synergistic effects than single-compound applications (Vaou *et al*., 2022). For example, the combination of plant polyphenols with microbial peptides can enhance free radical scavenging capacity and reduce the formation of secondary oxidation products, thereby significantly improving the chemical and sensory stability of meat (Hadidi *et al*., 2022). This strategy offers promising opportunities to develop safer, longer-lasting, and higher-quality meat products without relying heavily on synthetic chemical additives (Guerra *et al*., 2026).

Modulation of sensory attributes

Bioactive compounds have the ability to modulate the sensory characteristics of meat, including texture, aroma, and flavor, through biological and chemical mechanisms that are specific to their source (Ashaolu *et al*., 2023). Bioactive peptides and animal-derived enzymes, for instance, can perform selective hydrolysis of structural muscle proteins, resulting in softer muscle fibers and improved meat tenderness without reducing water-holding capacity (Anaduaka *et al*., 2023). These changes directly contribute to a more favorable sensory experience for consumers (Li *et al*., 2025).

In addition to texture, plant-derived bioactive compounds such as polyphenols, flavonoids, and terpenes interact with volatile compounds formed during storage or processing, thereby helping to preserve the natural aroma and flavor of meat (Zhang and Piao, 2023). Some compounds can also suppress the formation of undesirable substances produced by lipid oxidation, which typically generate rancid odors and flavors, thus maintaining the organoleptic quality of the product (Al-Shibli *et al*., 2023). Strategies for applying bioactive compounds to modulate sensory properties include direct incorporation into meat products, integration into marination solutions, and the use of active packaging or edible coatings that release the compounds in a controlled manner (Andrade *et al*, 2022). This approach allows gradual control of the sensory profile during storage while simultaneously supporting microbiological safety and chemical stability of the product (Ogwu and Ogunsola, 2024).

Recent studies have demonstrated synergistic effects when bioactive compounds from different sources are combined (Vaou *et al*., 2022). For example, herbal extracts combined with microbial peptides not only preserve the natural aroma and flavor of meat but also enhance tenderness and color stability (Anaduaka *et al*., 2023). This multifaceted approach offers promising opportunities for the development of safe, high-quality meat products that remain sensorially appealing to modern consumers (Rebezov *et al*., 2024).

Enhancement of shelf-life

One of the primary objectives of applying bioactive compounds in meat processing is to extend product shelf life by integrating antimicrobial and antioxidant activities (Al Jumayi *et al*., 2022). Bioactive compounds are capable of suppressing the growth of pathogenic and spoilage microorganisms while simultaneously preventing lipid oxidation and protein degradation (Yu *et al*., 2023). The combination of these two mechanisms is particularly important because lipid oxidation can generate compounds that stimulate microbial growth, while microbial contamination can accelerate the chemical and sensory deterioration of meat (Khalid *et al*., 2023).

Bioactive compounds derived from plants, microorganisms, and animal sources can be applied directly or through controlled delivery systems, such as edible coatings or active packaging (Singh *et al*., 2022). These approaches enable the gradual release of bioactive compounds, maintaining effective concentrations during storage while reducing the risk of oxidative damage and microbial proliferation (Kurek *et al*., 2022). As a result, meat remains safe for consumption, and its sensory quality, including color, aroma, and texture, is preserved (Rebezov *et al*., 2024).

Recent studies indicate that the combined use of bioactive compounds from different sources can produce stronger synergistic effects than single-compound applications (Vaou *et al*., 2022). For example, the integration of plant polyphenols with antimicrobial peptides derived from microorganisms or animal proteins not only slows oxidation and inhibits microbial contamination but also helps maintain muscle fiber tenderness and color stability in meat (Tocai *et al*., 2025). This integrative strategy represents an innovative approach in the development of functional meat products that are safe, longer-lasting, and possess enhanced sensory value (Guerra *et al*., 2026).

Applications in meat processing

The application of bioactive compounds in meat processing enhances product safety, quality, and shelf life through various strategies, including direct incorporation, surface treatments, combination with emerging technologies, and integration into packaging systems (Rebezov *et al*., 2024). Table 3 summarizes the different strategies for applying bioactive compounds in meat processing, including their use in fresh meat, processed meat products, non-thermal technologies, and integration into active packaging systems. Figure 3 illustrates the industrial application strategies of bioactive compounds in fresh and processed meat systems.

Fresh meat

Bioactive compounds have significant potential to maintain the safety and quality of fresh meat through various application strategies (Malav *et al*., 2025). One of the primary approaches is marination, in which plant extracts, microbial peptides, or animal-derived bioactive proteins are incorporated into marination solutions to neutralize pathogens and inhibit lipid oxidation (Guerra *et al*., 2026). Marination also facilitates the penetration of bioactive compounds into muscle tissues, thereby helping to maintain meat texture, tenderness, and water-holding capacity during

Table 3. Applications of bioactive compounds in meat processing.

Application area	Strategies	Effects on meat	Examples / Notes	Source
Fresh meat	Marinades, edible coatings, fumigation with volatile bioactives	Reduces pathogen load, inhibits lipid oxidation, maintains texture, color, aroma, and water retention	Plant extracts, microbial peptides, animal proteins; edible coating allows controlled release	(Malav *et al*., 2025)
Processed meat	Direct incorporation into meat matrix, marinades, edible coatings, active packaging	Enhances microbiological safety, prevents oxidation, preserves sensory quality, improves tenderness	Applied in sausages, ham, nuggets, smoked meat; combination of bioactives from different sources can provide synergistic effects	(Olvera-Aguirre *et al*., 2023)
Combined technologies	Integration with non-thermal processing (HPP, PEF)	Synergistic antimicrobial and antioxidant effects, minimal impact on sensory and nutritional quality	HPP or PEF applied after bioactive treatment increases microbial inactivation while preserving color, flavor, and texture	(Guo *et al*., 2024)
Packaging integration	Active packaging with controlled release of bioactives	Maintains microbiological safety, prevents lipid and protein oxidation, extends shelf-life	Plant extracts, microbial peptides, or animal proteins incorporated into polymer films or multilayer coatings; gradual release ensures prolonged efficacy	(Andrade *et al*, 2022)

storage (Rahman *et al*., 2023).

In addition to marination, edible coatings offer a controlled-release method for delivering bioactive compounds (Siddiqui *et al*., 2023). These coatings form a physical barrier on the meat surface while gradually releasing antimicrobial and antioxidant agents (Moura-Alves *et al*., 2023). This strategy not only slows microbial growth and oxidative processes but also preserves the sensory characteristics of meat, including color, aroma, and texture, without relying heavily on synthetic chemical additives (Ashaolu *et al*., 2023). Another method that has been explored is fumigation with volatile bioactive compounds, such as plant essential oils, which can penetrate the meat surface and suppress spoilage microorganisms (Elgadir *et al*., 2025). Fumigation provides additional protection against microbiological contamination, particularly on exposed surfaces, and can be combined with non-thermal technologies to enhance effectiveness without compromising the sensory quality of meat (Khalid *et al*., 2023).

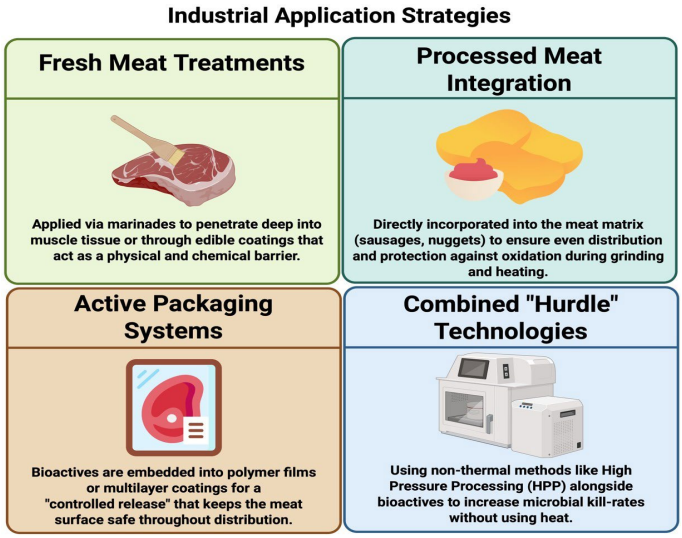

Figure 3. Industrial application strategies of bioactive compounds in fresh and processed meat systems

Processed meat products

Bioactive compounds play a strategic role in the processing of meat products, including sausages, ham, nuggets, and smoked meat, with the aim of improving microbiological safety, maintaining sensory quality, and extending shelf life (Sen *et al*., 2022). In processed meat products, the risk of pathogen growth and lipid oxidation increases due to grinding, mixing, and heating processes that enlarge surface area and increase oxygen exposure (Shimizu and Iwamoto, 2022). Bioactive compounds derived from plants, microorganisms, and animal sources can inhibit the proliferation of spoilage microorganisms and suppress the formation of oxidative compounds, thereby preserving the chemical and sensory stability of the products (Teshome *et al*., 2022).

The use of bioactive compounds in processed meat is commonly achieved through direct incorporation into the formulation, allowing the compounds to be evenly distributed and interact with protein and lipid components (Shahidi and Pan, 2022). Their antimicrobial activity effectively suppresses the growth of pathogenic bacteria such as *Listeria monocytogenes* and *Salmonella* spp., while their antioxidant properties help maintain the natural color, aroma, and flavor of the product (Deshmukh and Gaikwad, 2024). In addition, certain bioactive compounds, such as microbial peptides and animal-derived proteins, can modify texture, enhance tenderness, and improve water retention during processing and storage (Aminlari, 2022).

Another approach involves integrating bioactive compounds into edible coatings or active packaging applied to processed meat products prior to storage (Nunes *et al*., 2023). This method enables controlled release of the compounds and maintains effective concentrations on the product surface, which is the area most susceptible to contamination and oxidation (Dixit and Singh, 2025). Such strategies support microbiological safety and preserve organoleptic quality without the need for synthetic chemical additives that may reduce nutritional value or consumer acceptance (Teshome *et al*., 2022).

Combined technologies

The integration of bioactive compounds with non-thermal technologies offers an innovative approach to enhance meat safety and quality without compromising sensory properties or nutritional value (Khalid *et al*., 2023). Non-thermal technologies, such as High Pressure Processing (HPP) and Pulsed Electric Field (PEF), are capable of inactivating pathogenic and spoilage microorganisms without excessive heating, which typically leads to protein denaturation, color changes, or nutrient degradation (Abelbaevich *et al*., 2024). When combined with bioactive compounds, antimicrobial and antioxidant activities can be synergistically enhanced, resulting in more comprehensive protection against microbiological and oxidative deterioration (Chen *et al*., 2022).

In practical applications, HPP or PEF can be applied to meat products that have been treated with bioactive compounds through marination, edible coatings, or active packaging systems (Nunes *et al*., 2023). The high pressure or electric fields used in these processes increase microbial cell membrane permeability, allowing bioactive compounds to penetrate more effectively and disrupt the metabolic activity of pathogens (Zhao *et al*., 2024). This mechanism not only accelerates microbial inactivation but also reduces the required dosage of bioactive compounds, thereby preserving the optimal sensory quality of the product (Pravallika *et al*., 2025).

Another advantage of this combined approach is the protection against lipid oxidation and protein degradation (Bayram and Decker, 2023). The antioxidant activity of bioactive compounds remains effective because non-thermal processing does not involve high temperatures that could compromise their stability (Cano-Lamadrid and Artes-Hernandes, 2022). As a result, the color, aroma, and texture of meat are maintained while the shelf life of the product is significantly extended (Shaltout, 2024).

Recent studies indicate that the combination of bioactive compounds with non-thermal processing can produce stronger synergistic effects compared with single-method applications (Souza *et al*., 2025). For instance, the use of HPP on meat marinated with plant extracts possessing antioxidant and antimicrobial properties significantly enhances pathogen inactivation while delaying lipid oxidation during cold storage (Olvera-Aguirre *et al*., 2023). This approach provides promising opportunities for the development of modern functional meat products that are safe, long-lasting, and possess high sensory quality without relying on conventional heat treatments or synthetic chemical additives (Samad *et al*., 2025).

Packaging integration

The integration of bioactive compounds into active packaging represents an innovative strategy in meat processing to maintain microbiological safety, chemical stability, and sensory quality (Rebezov *et al*., 2024). Active packaging systems are designed to release antimicrobial and antioxidant compounds in a controlled manner during storage, thereby creating an unfavorable environment on the product surface for the growth of pathogens and spoilage microorganisms (Deshmukh and Gaikwad, 2024). This approach effectively extends the shelf life of meat without requiring additional chemical additives within the product itself (Bodie *et al*., 2024).

Bioactive compounds used in active packaging can originate from various sources, including plant extracts, microbial peptides, and animal-derived proteins (Kussmann *et al*., 2023). Their mechanism of action involves direct contact between the meat surface and the gradually re-

leased bioactive compounds, leading to the inactivation of microorganisms such as *Listeria monocytogenes*, *Salmonella* spp., and *Escherichia coli*, while simultaneously suppressing lipid oxidation and protein degradation (Sun *et al*., 2024). This strategy helps maintain the color, aroma, texture, and nutritional value of meat during cold storage or transportation (Alam *et al*., 2024).

Furthermore, active packaging allows regulation of the release rate of bioactive compounds through polymer material design, multifunctional layers, or nano-incorporation (Jaiswal *et al*., 2026). These technologies help preserve compound stability, protect them from degradation caused by light or oxygen, and enable release according to storage conditions, thereby maintaining antimicrobial and antioxidant effectiveness throughout the product's shelf life (Kramar and Kostic, 2025). Another advantage of integrating bioactive compounds into packaging systems is the flexibility of application across various types of meat products, including both fresh and processed meat (Nunes *et al*., 2023). This approach supports the development of functional meat products that are safe, durable, and capable of maintaining high sensory quality, while reducing reliance on synthetic chemical preservatives (Rebezov *et al*., 2024). Active packaging strategies are increasingly relevant in the context of modern consumer trends that emphasize safety, nutritional value, and the use of natural ingredients (Singh *et al*., 2022).

Challenges and limitations

Although bioactive compounds demonstrate significant potential in improving meat safety, quality, and shelf life, their application still faces several challenges that must be addressed (Kurek *et al*., 2022). One of the primary issues is the stability of bioactive compounds during processing and storage. Many natural compounds, such as polyphenols and flavonoids, are susceptible to degradation caused by heat, oxygen, light, or extreme pH conditions (ElGamal *et al*., 2023). This degradation can reduce their antimicrobial and antioxidant activities, thereby decreasing their effectiveness in protecting meat from spoilage (Ben Akacha *et al*., 2023).

Another challenge relates to their influence on sensory properties. Certain bioactive compounds may impart bitter tastes, strong aromas, or undesirable color changes, particularly when applied at high concentrations (Fabela-Morón, 2024). This requires careful dosage optimization or combination with alternative strategies—such as edible coatings or active packaging—to ensure that the organoleptic characteristics of meat remain acceptable to consumers (Nunes *et al*., 2023).

Regulatory considerations and human consumption safety also represent critical factors (Sorbo *et al*., 2022). Each bioactive compound, whether natural or semi-synthetic, must comply with food safety standards and permitted dosage levels established by relevant regulatory authorities (Lopez-Rodriguez *et al*., 2025). Adequate toxicological studies and adherence to residue limits are essential prerequisites for large-scale industrial application (Pognan *et al*., 2023).

In addition, production costs and industrial scalability pose practical challenges (Kaur *et al*., 2025). The extraction and purification of bioactive compounds, their incorporation into meat products, and the implementation of controlled delivery technologies such as edible coatings or active packaging may increase production costs (Nunes *et al*., 2023). For successful industrial implementation, these strategies must be optimized to remain economically feasible while maintaining product effectiveness and quality (Oteri *et al*., 2023).

Future perspectives

The development of bioactive compounds in meat processing still holds broad innovative potential, particularly through integration with modern technologies (Sun *et al*., 2025). Approaches such as edible films, nanoencapsulation, and intelligent active packaging offer controlled-release mechanisms that can enhance the stability of bioactive compounds, strengthen antimicrobial and antioxidant activities, and preserve the sensory quality of meat during distribution and storage (Vlaicu *et al*., 2023). These technologies enable the application of bioactive compounds at lower doses while maintaining higher effectiveness, thereby minimizing potential negative impacts on product aroma, flavor, or color.

In addition, there is considerable opportunity to develop bioactive compounds tailored to specific types of meat, such as poultry, beef, or pork (Jairath *et al*., 2024). The chemical and microbiological characteristics of each meat type differ, meaning that targeted bioactive compounds could provide optimal protection against pathogens and lipid oxidation while preserving the distinctive texture and sensory attributes of each product (Guo *et al*., 2024). This approach supports more precise and efficient strategies for functional meat processing (Sun *et al*., 2025).

Evaluation of bioactive compound efficacy at the industrial scale, as well as consumer acceptance, is also a crucial aspect for sustainable development (Dhar *et al*., 2026). Laboratory-based studies should be followed by field trials under real distribution and storage conditions while considering consumer preferences related to taste, aroma, and labeling claims such as "natural" or "free from synthetic additives" (Gordon *et al*., 2025). Such an approach would provide a more realistic assessment of the benefits of bioactive compounds, enable formulation adjustments, and support broader adoption of these technologies within the modern meat industry (Samad *et al*., 2025).

Conclusion

Bioactive compounds play a pivotal role in enhancing meat safety and quality by combining antimicrobial, antioxidant, and sensory-modulating activities. Plant-, microbial-, animal-, and synthetic-derived compounds have demonstrated effectiveness in inhibiting pathogen growth, preventing lipid oxidation, preserving texture and color, and extending shelf-life. Application strategies, including direct addition, marination, edible coatings, and active packaging, enable practical integration into both fresh and processed meat products.

These findings underscore the potential of bioactive compounds as natural alternatives to synthetic preservatives, offering safe, functional, and consumer-friendly solutions. Future research should focus on optimizing compound combinations, evaluating scalability in industrial settings, and integrating advanced technologies, such as non-thermal processing, to maximize efficacy while maintaining sensory quality. Overall, the strategic use of bioactive compounds presents a promising avenue for producing high-quality, safe, and sustainable meat products.

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Conflict of interest

The authors have declared no conflict of interest.

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