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Development of Functional Meat Products Enriched with Plant-Based Bioactive Compounds

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Abstract: Increased consumer interest in healthier, clean label food products has increased research efforts on the production of functional meat products with increased bioactive compounds found in plants. Despite being good sources of high-quality protein and important micronutrients, traditional meat products are commonly criticized to containing high saturated fats, cholesterol and synthetic additives, in addition to the absence of dietary fiber and natural antioxidants. This review provides a critical analysis of the more recent developments in the addition of different plant-derived bioactives, such as polyphenols, carotenoids, dietary fibers, essential oils and plant protein hydrolysates, to meat-based matrices. These compounds have both techno-functional properties: as natural preservatives, they inhibit lipid oxidation, protein oxidation and microbial spoilage, thereby prolonging product shelf life, as well as having health-promoting properties, including antioxidant, anti-hypertensive, anti-inflammatory, and hypocholesterolemia properties. Nevertheless, significant difficulties remain, such as the formation of off-flavors, unwanted color changes (e.g. browning or fading), textural deterioration and decreased overall consumer acceptability in cases of bioactive compound addition beyond optimal levels, which are mostly 0.5-5% w/w. The new encapsulation technologies like microencapsulation, nanoemulsions and edible coatings are identified as the effective methods to conceal the undesirable sensory properties, to control the release of bioactives and retain their functionality even during thermal treatment and storage. The future research needs to focus on human intervention studies to support health assertions, standardization of extraction and incorporation procedure to provide batch-to-batch consistency and use of green technology to produce at sustainable levels. Moreover, the lack of definite regulatory frameworks regarding the labelling of the product of functional meat is also a major obstacle to commercial translation. To sum up, strategic fortification of meat products with plant-based bioactive compounds is a feasible and promising formulation approach to radicalize conventional meat into functional foods that can satisfy the demands of modern consumers regarding their sensual pleasure and health promotion, as long as challenges linked to formulations can be overcome with new processing technologies.

Keywords: Functional meat; Plant bioactive compounds; Polyphenols; Natural antioxidants; Clean-label meat; Lipid oxidation; Reformulation strategies; Meat product development; Encapsulation technology; Phytochemicals.

I. Introduction

Meat has been known to be a nutritionally rich food; it is a source of high-quality protein, bioavailable heme iron, zinc, selenium, and B vitamins (Pereira & Vicente, 2013). Nevertheless, recent 20 years have seen an accumulation of epidemiological data about the risks of colorectal cancer, cardiovascular disease, and type 2 diabetes associated with excess intake of processed meat (Bouvard *et al.*, 2015; Micha *et al.,* 2010). In 2015, the International Agency on Research on Cancer characterized processed meat as being carcinogenic to humans (Group 1), which has triggered a rush to reformulate conventional meat products.

At the same time, the demand of consumers in the so-called clean label products, i.e., the products without synthetic preservatives, artificial colorants, and other chemicals-sounding ingredients has increased significantly (Asioli *et al.,* 2017). Foods prepared the traditional way use synthetic preservatives like sodium nitrite, butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) to preserve, maintain their color, and to ensure safety. Substitution of these multifunctional additives with natural ones is a big technological challenge.

Bioactive compounds obtained through plants have become the most promising candidates to overcome this challenge (Shah *et al.*, 2019). Millennia-old plants have developed complex secondary metabolites of phenolic compounds, terpenes and glucosinolates as defense systems against oxidative stress and pathogens. The same compounds are highly antioxidant, antimicrobial, and anti-inflammatory in their use in food matrices (Fraga *et al.*, 2019). The objective of this review is to synthesize the existing information on the production of functional meat products supplemented with plant-derived bioactive compounds, where the emphasis will be on:

(1) the key classes and sources of plant bioactive
(2) the mechanisms of action in meat products
(3) enrichment technologies
(4) the effects on product quality and safety
(5) the sustainability aspects such as by-product

2. Major Classes of Plant Bioactive Compounds

2.1 Polyphenols

The most chemically diverse and largest group of plant secondary metabolites is the polyphenols, which have aromatic rings with one or more hydroxyl groups (Table 1). They have simple phenolic acids to highly polymerized tannins as the range of their molecular structures, and a correspondingly varied range of functional properties in meat systems.

Table 1: Major Classes of Plant Bioactive Compounds for Meat Applications

Class	Subclass	Key Compounds	Major Plant Sources	Primary Mechanism
Polyphenols	Phenolic acids	Gallic, caffeic, ferulic, p-coumaric	Coffee, blueberries, apples, cereals	Radical scavenging, metal chelation
	Flavonoids	Quercetin, kaempferol, catechin, EGCG	Onions, tea, apples, berries	HAT and SET mechanisms
	Hydroxytyrosol derivatives	Hydroxytyrosol, tyrosol, oleuropein	Olives, olive mill wastewater	Membrane partitioning, radical

				stabilization
	Tannins	Proanthocyanidins, ellagitannins	Grape seeds, pomegranate, berries	Protein binding, metal chelation
Dietary fibers	Soluble fibers	Pectins, β-glucans, gums	Citrus peels, oats, legumes	Water holding, gelation
	Insoluble fibers	Cellulose, hemicellulose, lignin	Wheat bran, vegetable pomace	Physical entrapment, texture modification
Plant proteins	Legume proteins	Soy protein (7S, 11S), pea protein	Soybeans, peas, lupin	Emulsification, gelation
Glucosinolates	Aliphatic	Sinigrin, glucoraphanin	Broccoli, cabbage, mustard	Antimicrobial (isothiocyanates)

2.1.1 Phenolic Acids

The simplest subclass of polyphenols is the phenolic acids which are derivatives of benzoic and cinnamic acid. The hydroxybenzoic acids (gallic, protocatechuic and vanillic) have a C6-C1 structure whereas the hydroxycinnamic acids (caffeic, p-coumaric and ferulic) have a C6-C3 structure (Robbins, 2003). Caffeic acid, which is abundant in coffee and blueberries, exhibits a strong antioxidant effect by hydrogen atom transfer (HAT) and single electron transfer (SET) processes. The most common phenolic acid in cereal grains is ferulic acid which possesses other UV absorption characteristics and can be used to prevent the degradation of meat pigments caused by photodegradation (Kumar and Pruthi, 2014).

2.1.2 Flavonoids Flavonoids

have a similar C6- C3-C6 skeleton. Notable subclasses are flavonols (quercetin, kaempferol), flavones (luteolin), flavan-3-ols (catechin), and anthocyanidins (cyanidin). The example of structure-activity relationship in antioxidant activity is Quercetin: the 3,4-dihydroxy B ring allows effective delocalization of electrons and the 2,3-double bond conjugated with the 4-oxo group promotes resonance stabilization (Rice-Evans *et al.,* 1996). Epigallocatechin-3-gallate (EGCG) of green tea includes a gallate ester, which significantly increases antioxidant and protein-binding functions (Nagle *et al.,* 2006). Hydroxytyrosol and Olive-Derived Compounds. **2.1.3 Hydroxytyrosol and Olive-Derived Compounds.**

Hydroxytyrosol (3,4-dihydroxyphenylethanol) is one of the most powerful natural antioxidants that have been found. It is nearly exclusively present in olives and olive products with a potency that is attributed to the synergistic effect of a catechol structure to stabilize radicals and a short aliphatic chain that gives it the correct lipophilicity to partition into the membrane (Visioli *et al.,* 2002). By-product valorization is particularly appealing to olive mill wastewater, which currently presents a challenge to the environment as a disposal issue due to its high levels of hydroxytyrosol (up to 5 g/L) (Obied *et al.,* 2005).

2.2 Dietary Fibers

Carbohydrate polymers of degree of polymerization 3 or above that are not hydrolyzed by endogenous human digestive enzymes are called dietary fibers (Table 1). Fibers are used in meat matrices in various technological applications, such as water-holding capacity (5-20 times dry weight), texture-modifying, emulsion-stabilizing, and physical entrapment of lipid droplets (Mehta *et al.,* 2015). The by-products of fruits and vegetables such as apple pomace, citrus peels, grape pomace supply fiber concentrates with 40-70% dietary fiber and related polyphenols (Ajila *et al.,* 2012).

2.3 Plant Proteins Soy protein

is the most common plant protein that is used in meat-related products, with the option of soy flour (50% protein), soy protein concentrate (70%), and soy protein isolate (90%). The properties of the functional properties are based on 7S and glycinin fraction (11S) with larger 11S/7S ratios giving stiffer gels which are desirable in emulsified meat product (Nishinari *et al.,* 2014). Pea protein has also become a solution to the issue of soy allergens, but it has a lower solubility and emulsifying property (Lam *et al.,* 2018).

2.4 Glucosinolates and Isothiocyanates Myrosinase

helps to break down the tissues of plants of the Brassicaceae, producing isothiocyanates, which are sulphur-containing compounds. Broccoli Sulforaphane has a strong antimicrobial effect against the bacteria *Listeria monocytogenes and Escherichia* coli O157:H7 by reacting with thiol groups on key microbial enzymes (Dinkova-Kostova and Kostov, 2012). The use is sensitive to the management of myrosinase activity, which is usually neutralized by thermal treatment.

3. Mechanisms of Action in Meat Matrices

3.1 Antioxidant Mechanisms

The major degradative process that reduces the shelf life of meat products is lipid oxidation. Plant bioactives act in a number of complementary ways (Table 2).

Table 2: Mechanisms of Action of Plant Bioactive in Meat Matrices

Mechanism	Target Process	Key Compounds	Effectiveness Factors
Radical scavenging	Peroxyl radicals (LOO•)	Catechol-containing phenolics (quercetin, caffeic acid)	BDE of O-H group (315-380 kJ/mol); lipophilicity
Metal chelation	Fe^{2+}, Fe^{3+}, Cu^{2+}	Ortho-dihydroxy flavonoids, tannins	Chelate ring stability; metal accessibility
Singlet oxygen quenching	$^1O_2$-mediated oxidation	Carotenoids, some flavonoids	Conjugated double bond system
Membrane	Bacterial cell	Thymol, carvacrol,	Lipid bilayer

disruption	membranes	isothiocyanates	partitioning; Gram-positive > Gram-negative
Enzyme inhibition	Microbial metabolic enzymes	Isothiocyanates, some flavonoids	Covalent thiol modification; electrophilicity
Quorum sensing interference	Bacterial virulence, biofilm	Quercetin, naringenin, apigenin	Autoinducer receptor binding

Abbreviation: BDE, bond dissociation enthalpy

3.1.1 Radical Scavenging

The phenolic compounds stop radical chain reactions by donating hydrogen atoms to peroxyl radicals (LOO) to produce relatively stable phenoxyl radicals that are not effective oxidation propagators. The standard bond dissociation energy (BDE) of the O-H group of phenols at room temperature is 315-380 kJ/mol, which is significantly lower than the 380-420 kJ/mol needed to abstract methylene hydrogen of polyunsaturated fatty acids (Wright *et al.,* 2001). Additional resonance stabilization is the presence of ortho-dihydroxy (catechol) structures which are intramolecularly hydrogen bonded.

3.1.2 Metal Chelation Lipid oxidation

is catalyzed by transition metal ions (iron, copper) with the transformation of lipid hydroperoxides to reactive alkoxyl (LO•) and peroxyl radicals. Phenolic compounds chelate metal ions with both hydroxyl and carbonyl groups; catechol structure produces five-membered chelate rings especially when the metal ions are chelated (Khokhar and Apenten, 2003). Nevertheless, the heme iron, which is the most common form in meat, is still mostly insoluble in aqueous-phase chelators, but some flavonoids (quercetin, myricetin) also react directly with heme iron, impairing its peroxidase activity.

3.2 Antimicrobial Mechanisms

3.2.1 Membrane Disruption

Phenolic substances and essential oil constituents are absorbed into bacterial membranes and alter fluidity and integrity in them. The single membrane is enclosed by a relatively porous peptidoglycan and therefore Gram-positive bacteria are more prone as compared to Gram-negative bacteria whose outer membrane lipopolysaccharide limits the diffusion of hydrophobic compounds (Burt, 2004). Thymol and carvacrol intercalate into the acyl chain region of the membrane, interfering with the gel to liquid crystalline change over. Enzyme Inhibition and Quorum Sensing is the third category of stimulants. Isothiocyanates have a covalent reaction with thiol groups, which inhibits a wide variety of microbial enzymes such as enzymes of energy metabolism and stress response (Fahey *et al.*, 2001). Flavonoids prevent DNA gyrase and dihydrofolate reductase. Quercetin and naringenin, at sub-inhibitory concentrations, disrupt quorum sensing through competitive binding to autoinducer receptors and do not exert a selective pressure to change virulence (Vikram *et al.,* 2010).

3.3 Color Stabilization

Meat color is stabilized by plant bioactives by: (1) inhibiting oxidation of myoglobin by retarding the accumulation of oxidizing species, (2) inhibiting oxidation of myoglobin directly by reducing metmyoglobin to ferrous myoglobin by electron transfer and (3) chelating copper which mediates coupled lipid-myoglobin oxidation Nevertheless, at high concentrations, protein digestibility can be decreased by the protein-binding characteristics of tannins (Bravo, 1998) and some phenolics can be pro-oxidant at high concentrations or in the presence of transition metals (Cao *et al.,* 1997).

4. Enrichment Strategies

The fourth method is known as Endogenous Enrichment (Animal Feeding). Endogenous enrichment is used to deposit bioactives in muscle tissue by changing the diet of animals. It is a method whereby the compounds are dispersed throughout the matrix at the cellular level and could minimize the thermal degradation during processing. Transfer efficiency, however, is usually low with polyphenols, which are highly metabolized and conjugated in the gastrointestinal tract and liver (Manach *et al.,* 2004). Enrichment with vitamin E (200-500 mg/kg feed): dietary supplementation of vitamin E (200-500 mg/kg feed) has been shown to increase muscle 200-500 mg/kg feed) has been shown to increase muscle 200-500 mg/kg feed) has been shown to increase muscle 200-500 mg The supplementation of selenium using selenized yeast raises muscle selenium levels and selenoprotein functions. The enrichment with polyphenols has had varied effects; whereas in some cases, grape pomace and olive leaf supplementation have increased the content of polyphenols in muscles, the effect size is typically small in comparison with direct addition (Luciano *et al.,* 2009).

The enrichment process can also be exogenous (Direct Incorporation). With direct incorporation, there is increased control over end concentrations, as well as access to a broader spectrum of compounds (Table 3). Powder addition of dried plant materials (spices, fruit powders) does not need any special equipment but is challenging to sensory. Extract incorporation enables the delivery of standardized bioactives with less sensory effects; extracts made using water, ethanol, or ethanol-water have varying compositional profiles (Shahidi and Ambigaipalan, 2015).

Table 3: Comparison of Enrichment Strategies

Parameter	Endogenous (Animal Feeding)	Exogenous (Direct Incorporation)
Control over final concentration	Limited, variable	Precise, consistent

Distribution in matrix	Uniform, cellular level	Variable by mixing method
Compound options	Limited by bioavailability	Wide range available
Sensory impact	Generally minimal	Can be substantial
Implementation cost	High (feeding duration)	Moderate to low
Regulatory status	Generally accepted	Requires approval for novel ingredients
Scalability	Limited by animal production cycles	Highly scalable

Encapsulation technologies address limitations of direct incorporation. Spray drying in maltodextrin or gum arabic is commercially mature but exposes bioactives to thermal stress. Liposomal encapsulation protects heat-sensitive compounds but costs remain high for premium applications only (Fang & Bhandari, 2010).

5. Impact on Meat Product Quality and Safety

5.1 Physicochemical Properties

The incorporation of plant bioactives affects pH by organic acids in extracts (decreasing pH) or buffering of plant proteins. Dietary fibers are effective in significantly increasing water-holding capacity: insoluble fibers retain water in capillary pores, whereas soluble fibers create hydrated gels. The two mechanisms enhance cooking yield and minimize purge loss (Petersson *et al.*, 2014). Phenolic compounds bind each other to the myofibrillar proteins, and that may enhance gel strength and hardness. But over crosslinking gives unwanted firmness. Incorporation of fiber tends to enhance hardness of the product and decrease its cohesiveness, as well as depending on the size of particles in the fiber (Talukder, 2015).

5.2 Oxidative Stability

In many studies, there is a lower level of thiobarbituric acid reactive substances (TBARS), lower peroxide values, and lower levels of hexanal in the plant enriched products (Table 4). Protection is influenced by lipophilicity (more effective in high-fat foods), processing (cooked vs. raw) and bioactive concentration.

Table 4: Efficacy of Selected Plant Extracts in Meat Products

Plant Source	Product	Concentration	Key Outcome	Reference

Olive mill wastewater extract	Plant-based meat analog	30 g/kg	Reduced TBARS by 60% at 14 days	Tocai Moţoc *et al.* (2025)
Green tea extract	Pork patties	200-300 mg/kg	Extended shelf life by 4-6 days	McCarthy *et al.* (2016)
Grape seed extract	Cooked beef patties	0.5-1.0%	TBARS reduction comparable to BHT	Ahn et al. (2007)
Rosemary extract	Chicken nuggets	0.05-0.20%	Reduced hexanal by 75% at 9 days	Smith *et al.* (2015)
Pomegranate peel extract	Beef burgers	0.5-1.5%	Extended oxidative stability by 8 days	Turgut *et al.* (2016)
Oregano essential oil	Pork sausages	0.05-0.10%	Reduced microbial counts by 2 log CFU/g	Economou *et al.* (2017)

Abbreviations: TBARS, thiobarbituric acid reactive substances; BHT, butylated hydroxytoluene

Comparative studies show some plant extracts achieve protection equivalent to BHA/BHT at comparable concentrations (rosemary, oregano, olive), while others require higher concentrations. The higher cost of plant extracts remains a barrier for price-sensitive market segments.

5.3 Microbial Quality

The antimicrobial effect in meat matrices is usually less impressive than the antioxidant effect because of the effects of phenolic compounds binding to proteins and lipids, which limits the access of microbes to them (Weiss *et al.*, 2010). Oregano and thyme extract lower total viable counts 1- 2 log CFU/g and shelf life up to 2-5 days. Isothiocyanate extracts are active against L. monocytogenes but efficacy is often similar to that of nitrite and concentrations of the extract are usually required to cause unwanted sensory properties (Tajkarimi *et al.,* 2010).

5.4 Sensory Properties

Extracts high in polyphenols add bitterness and astringency, the latter being a response to salivary proteins (Drewnowski and Gomez-Carneros, 2000). Spice and herb extract also add typical flavors, such as rosemary, oregano, and thyme add Mediterranean flavours that can be used with most meat products and fruit extracts can add sweet or sour flavours that are less appropriate in savoury dishes. Functional benefit Consumer studies show moderate levels of enrichment (0.1-0.5% extract) can be functional without generating any sensory difference. The increased concentrations offer more technical advantages, but tend to generate noticeable variations that diminish consumer acceptance (Hwang and Lee, 2017).

6. By-Product Valorization and Sustainability.

Agricultural wastes can be used as bioactive sources because they use agri-food by-products, which meets both economic and environmental goals (Table 5). Hydroxytyrosol is found in olive mill wastewater and pomace in concentrations that are economical to extract and reduces an environmental disposal issue (Roig *et al.,* 2006).

Table 5: Agri-Food By-Products as Sources of Bioactive

By-Product	Annual Generation (MT)	Key Bioactives	Concentration	Meat Application Potential
Olive mill wastewater	30 million (Mediterranean)	Hydroxytyrosol, tyrosol	0.5-5 g/L	High (antioxidant, clean label)
Grape pomace	15 million (global)	Proanthocyanidins, anthocyanins	3-8% dry weight	High (polyphenol + fiber)
Pomegranate peel	3 million (global)	Punicalagin, ellagic acid	15-25% dry weight	Very high (potent antioxidant)
Apple pomace	4 million (global)	Quercetin, phloridzin, fiber	1-3% polyphenols	Moderate (fiber-rich)
Citrus peels	15 million (global)	Hesperidin, naringin, pectin	2-5% flavonoids	Moderate (pectin + flavonoids)
Potato peels	2 million (global)	Caffeic, chlorogenic acids	0.5-1.5% dry weight	Low to moderate

Green extraction methods have less environmental impact: solvent-free extracts can be formed by using supercritical CO 2 extraction, but high-pressure equipment is required, whereas pressurized liquid extraction and ultrasound-assisted extraction are intermediate methods with less solvent usage (Chemat *et al.,* 2017). Life cycle analysis shows that the overall environmental impact can be decreased by a factor of 30-50 in the case of by-product valorization versus virgin production of bioactive (Galanakis, 2012).

7. Challenges and Future Directions

7.1 Current Challenges

The first challenge is its sensory compatibility. To attain technical functionality at concentration levels that are lower than sensory detection limits it is necessary to think deeply about the bioactive sources, encapsulation technologies and product-specific

optimization (Brewer, 2011).
Retention of bioavailability and bioactivity during processing and storage limits efficacy. Heat treatment (cooking, pasteurization) destroys heat sensitive compounds, and storage losses are further caused by light and oxygen exposure. To some extent, these issues are resolved with the help of encapsulation and regard to careful processing conditions (Davidov-Pardo *et al.*, 2015). Depending on jurisdiction, regulatory approval of novel plant extracts is different. The EU needs new food approval of extracts with no history of significant consumption whereas the US GRAS (Generally Recognized as Safe) decision needs a substantial amount of safety evidence (Nabors, 2005). Cost competitiveness Cost competitiveness with the synthetic preservatives is still a challenge. Although by-product valorization saves on costs, the process of purifying the product to the food-grade level is costly. The gap is still being reduced by economies of scale and better technologies in extraction.

7.2 Future Research

Directions targeted production of bioactives through precision fermentation provides high-purity and uniform bioactives regardless of seasonal or geographical fluctuations. Compounds such as resveratrol, vanillin, and other phenolics have already been successfully produced using yeast and bacterial platforms (Paddon and Keasling, 2014). In parallel, nanoencapsulation technologies—including solid lipid nanoparticles, nanostructured lipid carriers, and cyclodextrin complexes—have demonstrated strong potential to enhance the solubility, stability, and controlled release of bioactives within meat matrices (Ezhilarasi et al., 2013). However, challenges related to large-scale production and regulatory approval still need to be addressed. Furthermore, optimization of the meat–bioactive interface through approaches such as multilayered product structures, emulsion-based delivery systems for lipophilic compounds, and co-crystallization techniques to mask undesirable flavors represents a critical area of advancement (McClements, 2015). In the long term, the development of customized functional meat products tailored to specific health needs—such as cardiovascular protection, glycemic control, and anti-inflammatory effects—will require improved strategies for bioactive stabilization and cost-effective production.

In this context, the collective body of recent research provides strong foundational support for these future directions by demonstrating how functional ingredients and advanced food systems can be effectively designed and applied. For instance, the incorporation of probiotic cultures such as *Lactobacillus rhamnosus* into food systems illustrates the feasibility of microbial-assisted bioactive enrichment (Ahmed et al., 2024), which aligns closely with precision fermentation strategies. Similarly, the development of hybrid protein systems, including soy–whey and whey–corn formulations, highlights the potential for structurally optimized matrices capable of carrying and stabilizing bioactive compounds (Butt et al., 2025a; Butt et al., 2025b). Evidence from nutritional and clinical studies further supports the functional relevance of such bioactives, as phytochemical-rich diets and zinc supplementation have been shown to regulate metabolic pathways, influence IGF-I expression, and modulate epigenetic markers like DNA methylation associated with obesity and insulin resistance (Butt et al., 2026a; Butt et al., 2026b).

Moreover, comparative evaluations of conventional and alternative meat products demonstrate that physicochemical, microbial, and sensory properties can be optimized without compromising safety or consumer acceptability (Butt et al., 2024; Butt et al., 2025c), which is essential for successful bioactive integration into meat systems. Supporting this, studies on functional dietary components—such as olive and flaxseed oils in mitigating hepatotoxicity (Khan et al., 2024) and probiotic yogurt in improving metabolic health and weight management (Rashid et al., 2026)—reinforce the therapeutic potential of bioactive-enriched foods. These findings directly complement technological strategies such as emulsion systems and multilayered delivery approaches proposed for meat-bioactive interfaces. Additionally, insights from human physiology and biomechanics research (Mahmood et al., 2026) extend the application of functional foods toward performance and recovery, while research on artificial intelligence and sustainability emphasizes the importance of integrating technological innovation and socio-environmental considerations into future food system development (Kamal & Butt, 2026; Khurshid et al., 2026).

Overall, the integration of these studies with emerging technological advancements underscores a clear transition toward next-generation functional meat products, where precision fermentation, nanoencapsulation, and optimized delivery systems are combined with evidence-based nutritional strategies. This convergence not only addresses current limitations in stability, scalability, and consumer acceptance but also paves the way for personalized, health-oriented, and sustainable food solutions (Ahmed et al., 2024; Khan et al., 2024; Butt et al., 2024; Butt et al., 2025a; Butt et al., 2025b; Butt et al., 2025c; Butt et al., 2026a; Butt et al., 2026b; Rashid et al., 2026; Mahmood et al., 2026; Kamal & Butt, 2026; Khurshid et al., 2026; Paddon and Keasling, 2014; Ezhilarasi et al., 2013; McClements, 2015).

8. Conclusion

Plant-based bioactive compounds provide a feasible approach toward designing functional meat products that meet the concerns of the population about their health and the desire of the consumer to use clean-label ingredients. The key classes, such as polyphenols, dietary fibers, plant proteins, and glycosylates, have multifunctional antioxidant, antimicrobial, and health-promoting properties due to their well-characterized multimodal mechanisms that comprise radical scavenging, metal chelation, membrane disruption, and enzyme inhibition. Animal feeding is a method of endogenous enrichment, which can spread bioactives evenly but with low transfer efficiency of most polyphenols. Direct addition of powders, extracts or encapsulated preparations allows exogenous enrichment with more accurate control of the final concentrations and a broadened range of compounds such as agri-food by-products. Valorization of olive mill wastewater, grape pomace, pomegranate peel and other by-products fits into the concept of the circular economy and minimizes expenditures. The incorporation of plant bio actives usually enhances oxidative stability and in many cases is as protective as the synthetic antioxidants. Smaller in effect, antimicrobial effects are able to increase shelf life by 2-5 days with the proper extracts. Moderate levels of enrichment (0.1-0.5% extract) have functional advantages but are not perceivable in sensory properties in many products. There are still critical issues to overcome higher concentration sensory compatibility, bioactive degradation in processing and storage, regulatory acceptance of novel extracts, and competitive cost with synthetic preservatives. Future research needs are precision fermentation to achieve consistency, high purity; nanoencapsulation to achieve increased stability and finer release; hybrid product approaches to the optimum meat-bioactive interface; and life cycle analysis to quantify environmental benefit. The production of functional meat products that have been fortified with plant bioactives is a noteworthy way in which the meat industry can address the changing consumer needs, societal health advice and sustainability demands. Interdisciplinary cooperation between food scientists, nutritionists, sensory specialists, and process engineers is needed to maximize these complicated matrices to achieve success.

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