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REVIEW

Bioactive Compounds in Plant-Based Meat Analogs: Sources, Functional Roles and Effects on Chemical, Technological and Sensory Quality

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Abstract

Purpose of Review This review aims to evaluate recent studies on plant-based meat analogs enriched with bioactive compounds from agro-industrial by-products, highlighting their sources, functional properties, potential effects on chemical, technological and sensory characteristics.

Recent Findings Components such as polyphenols, curcuminoids, and carotenoids contribute to health benefits due to their antioxidants' capacity. These compounds can also interact with proteins, influencing texture and the structural properties of the food matrix. Such interactions may affect the release of bioactive compounds during gastrointestinal digestion and consequently their bioavailability in the human body.

Summary Incorporating plant-based sources rich in bioactive compounds into meat analogs markedly enhances their antioxidant capacity and functional properties. Nevertheless, certain technological challenges persist, particularly concerning the thermal stability of these compounds, which can degrade during processing.

Keywords Bioactive Compounds · Polyphenols · Plant proteins · Functional foods · Phenolic compounds

Introduction

Waste from the agri-food industry, including by-products and processing residues, is a strategic source for the recovery of bioactive compounds. Among these, dietary fibers have attracted considerable interest due to their potential application as natural additives and functional ingredients in the food industry [1]. The increasing demand for functional foods has driven the expansion of the market for bioactive compounds [2]. Furthermore, the use of natural compounds derived from plants and food processing waste supports the sustainable valorization of agri-food-products by converting residues into value-added resources [3].

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Food production is one of the major global challenges, as demand for food is expected to increase significantly in the coming decades [4]. Initiatives aimed at developing sustainable foods based on plant-based ingredients are aligned with the United Nations Sustainable Development Goals (SDGs), particularly those related to responsible consumption and production, food security, and the reduction of environmental impacts [5]. Consequently, the growing consumer demand for plant-based meat alternatives has stimulated further research into novel ingredients and formulation strategies for these products [6].

Plant proteins are key components in the formulation of plant-based meat analogs, as they play a crucial role in determining product characteristics such as texture, nutritional value, and sensory acceptance. Although most plant proteins can be used as a base for producing meat substitutes, their technological and functional performance may be influenced by several factors, including solubility, water and oil-holding capacity, rheological behavior, amino acid profile, and interactions with other formulation components [7]. Furthermore, enhancing the nutritional and functional quality of these products represents an important strategy, since ingredients such as dietary fiber and bioactive compounds, naturally absent or present in low amounts in conventional meat, can be incorporated into meat analogs during the formulation process [8].

Consumer awareness regarding nutrition has increased alongside rising standards for food products, including meat analogs. Desirable sensory properties, clean label formulations, and the use of natural composition are key attributes expected by consumers. In addition, the incorporation of health-promoting ingredients, such as bioactive compounds, has gained increasing attention [7].

Therefore, the development of new food products can be influenced by the incorporation of innovative ingredients that may provide health benefits. Furthermore, such developments are closely associated with advances in food processing technologies and the expansion of knowledge of bioactive ingredients commonly present in food systems [9]. The incorporation of these compounds into plant-based meat analogs represents an opportunity to add functional, technological, and environmental value, while simultaneously contributing to waste reduction and improving the nutritional profile of these products.

In this context, the review aims to evaluate recent studies on plant-based meat analogs enriched with bioactive compounds from agro-industrial by-products, highlighting their sources, functional properties, potential effects on chemical, technological and sensory characteristics.

Methodology

The study conducted an integrative review to synthesize the available scientific evidence on bioactive compounds present in plant-based meat analogs. In addition to examining their structural and sensory characteristics, as well as the potential use of agro-industrial by-products as sources of these compounds.

Scientific sources were selected through searches in major scientific databases. Search terms were applied English, Spanish, and Portuguese, either individually or in combination, in order to maximize the coverage and precision of the retrieved studies.

Initially, individual descriptors were defined and selected from the Health Sciences Descriptors (DeCS) and Medical Subject Headings (MeSH). The search included terms such as *plant-based meat*, *plant protein*, *meat-like*, *meat analogues*, *biologically active compounds*, *components interactions*, *food structure* and *agro-industrial by-products.*

Subsequently, the terms were combined using the Boolean operators "AND" and "OR" to improve the sensitivity and specificity of the search strategy. The final combinations of descriptors and operators were adjusted according to the indexing structure of each database, as detailed in Fig. 1.

Original studies and review articles published within the last ten years (2016 to 2026) that directly addressed bioactive compounds used in meat analogs and their effects on structural, functional, sensory and agro-industrial by-products use were included. Articles not directly related to the scope of this review or focused exclusively on products of animal origin were excluded.

In the first phase, two researchers (Z.C.M. and N.M.S) independently identified the studies potentially eligible for inclusion, based on their relevance to the topic. After screening the titles and abstracts of all retrieved papers, the reviewers selected those that met the established criteria. Only experimental studies addressing bioactive compounds present in meat analogs were included, as well as studies discussing their associated health benefits and agro-industrial by-products using.

The exclusion criteria included: (1) patents, citations, letters, conference abstracts, and case reports; and (2) studies that did not meet the established inclusion criteria.

In phase 2, the reviewers applied the eligibility criteria to the full texts of the selected articles, and the references lists of the included studies were also examined. In both phases, disagreement between reviewers discussed until a consensus was reached. If consensus could not be achieved, the final decision was made by the third reviewer (V.R.O; P.C.B.C and A.R.O).

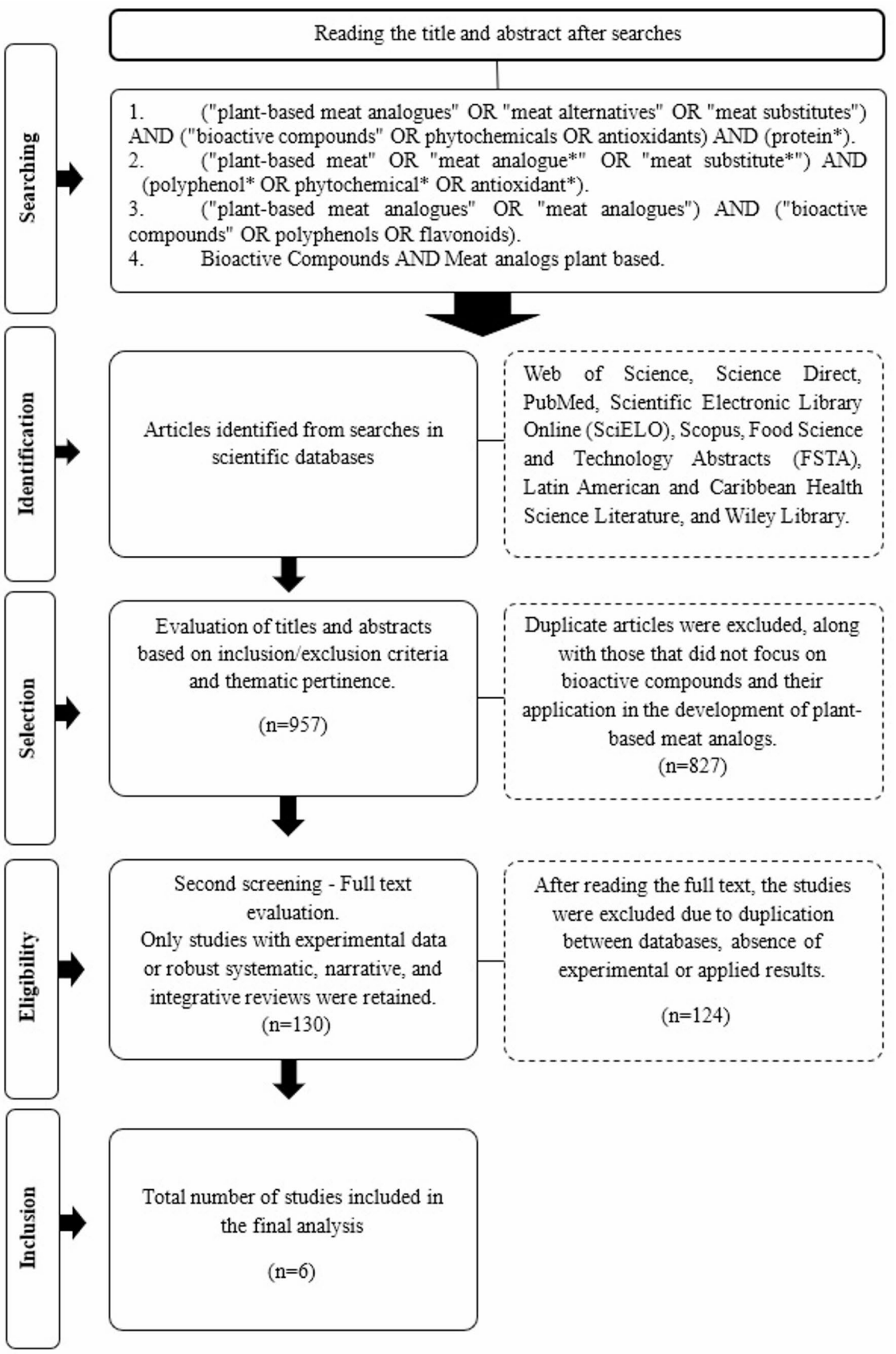

Fig. 1 Flowchart of database searching. Source: Study data

After study selection, the included articles were exported and organized using Mendeley® Cite v1.69.3, for bibliographic management, duplicate removal, and thematic categorization of the selected studies. Data analysis was conducted using a descriptive and interpretative approach, allowing the integration of findings, comparison of results, and identification of gaps in the scientific literature in this field.

New Possibilities in Meat Analogs

Meat analogs are foods designed to mimic the structure and sensory properties of meat, although they differ in their nutritional composition [10]. When evaluating meat analogs, several aspects should be considered, including social, philosophical, cultural and sustainability concerns, in addition to nutritional attributes such as protein quality and content. Furthermore, dietary fiber levels and sensory attributes must also meet consumer expectations [11].

These products have shown remarkable advancements, and plant-based alternatives currently available on the market often contain different ingredients, such as natural oils and extracts (e.g., coconut oil and beet juice), to achieve a nutritional profile similar to or, in some cases superior to, that of conventional meat products [12]. In addition, many plant-based ingredients are derived from legumes, cereals, vegetables, fruits and seeds, as well as agro-industrial by-products. These materials are increasingly being explored as potential sources of bioactive compounds that could be incorporated as natural additives in the meat and meat analog industries [13].

Many different foods are currently being considered for use in meat analogs, including berry pomace from the fruit juice and wine industries. These by-products are rich in dietary fiber, polyphenols, vitamins, minerals, and other bioactive compounds. However, the incorporation of fruit-derived ingredients such as berry pomace presents several challenges, including variability in pomace composition, the presence of unpleasant flavors, and the need for appropriate processing techniques. Zhang and Li [14] highlighted the need for further studies on the pre-processing and incorporation of berry pomace, emphasizing the importance of investigating consumer perceptions and acceptance during the development of new products. Regarding other components, such as polyphenols, factors such as color stability, bitterness, and their potential use as natural additives substitutes should also be considered [11].

Herbs and spices are also rich sources of bioactive compounds and have long been used in meat products and, more recently, in meat analogs. These condiments are incorporated into plant-based products to improve their similarity to traditional meat products while also bioactive compounds. According to Marc et al. [15], commonly used herbs and spices include basil, bay leaf, dill, oregano, coriander, rosemary, marjoram, mint, parsley, sage, thyme and tarragon. These ingredients contribute to improved flavor, enhanced antioxidants' capacity, and antimicrobial properties.

Bulgaru et al. [16] investigated plant-based formulations for meat analogs using chickpea flour, peanut oil extraction residue, pea protein isolate, soy protein concentrate, and soy protein isolate. The authors reported that these ingredients showed strong potential for application in the development of meat analog products. In addition, they highlighted the presence of several polyphenolic compounds in peanut oil residue, including quinic acid, quercetin-3-O-rhamnoside, (+) catechin, catechol, glansreginin A, glansreginin B, hexoside esters of syringic acid, and oligomeric procyanidins (dimers, trimers, and tetramers).

Bioactive Compounds in Food Matrices

Bioactive compounds are naturally occurring substances present in foods or formed during food processing that can modulate metabolic pathways and contribute to beneficial effects on human health [17].

Bioactive compounds can be classified into two main groups: lipophilic compounds, such as essential oils, oleoresins, curcuminoids, and carotenoids, typically extracted with nonpolar solvents, and hydrophilic compounds, such as polyphenols, which are generally extracted using polar solvents [13]. This classification guides extraction strategies and influences the behavior of these compounds in food matrices, including their stability during processing, and their interactions with macromolecules, especially proteins and polysaccharides [13, 17].

Over the last two decades, interest in the extraction of bioactive compounds from plant matrices has increased due to their nutritional value and technological properties [13]. In this context, the valorization of agri-food by-products has emerged as a promising strategy for recovering bioactive molecules and developing functional products. Moreover, this approach aligns with the growing demand for sustainable food systems, as the utilization of by-products for the extraction of high value compounds can promote more efficient use of natural resources, reduce environmental impacts, and generate economic benefits for the food sector [18].

The food industry has shown increasing interest in polyphenols due to their potential to develop products with extended shelf life. This trend is also associated with the reduction of synthetic food additives in formulations. In addition, polyphenols can contribute to the improvement of sensory properties while preserving the nutritional and functional benefits of these compounds [11].

Technological and Sensory Effects of Ingredient Combinations in Plant-Based Meat Alternatives

The development of plant-based meat analogs requires a comprehensive understanding of the techno-functional properties of all ingredients involved in the formulation. This includes not only the protein source, but also dietary fibers and bioactive components present in the formulation [11].

According to Abdullah et al. [10], the nutritional profile of some plant-based meat analogs may be lower than that of conventional protein products, mainly due to the reduced availability of essential amino acids and trace elements. From a technological perspective, plant proteins with good emulsifying capacity, water solubility, and a balanced amino acid profile are particularly desirable. In addition, properties such as gelling ability, viscosity, and water and oil holding capacity are important for the development of stable and structured products. Furthermore, the synergistic interactions between different ingredients used in meat analogs formulations must be considered, as these interactions can either enhance or limit the functional performance of the final product depending on the characteristics of each component [11].

Pinto and Vilela [19] reported that synthetic preservatives, such as nitrates, although effective, are increasingly viewed as undesirable alternatives for food preservation due to potential health risks and growing consumer awareness. In this context, polyphenols have been explored as functional ingredients capable of improving texture and acting as natural preservatives because of their antioxidant and antimicrobial properties. In addition, these compounds may also be used as natural colorants [20].

Bioactive compounds can interact with proteins, and these interactions may be influenced by factors such as stability, bioavailability, and the functional properties of the food system. Protein-bioactive compounds interactions can help protect these molecules from adverse processing and digestion conditions, thereby improving their stability in aqueous matrices and enhancing their intestinal absorption. These characteristics are particularly relevant in low-fat products, such as plant-based meat analogs, where the incorporation of bioactive compounds can increase the nutritional and functional value of the final product [21].

However, these effects can also influence the technological and sensory properties of the product, promoting changes in texture, color, and flavor. A common sensory effect associated with the presence of flavonoids, terpenes, and phenolic acids is the increase in bitterness and astringency. Therefore, strategies to optimize formulation and processing conditions are essential to improve consumer acceptance of these products [22].

Figure 2 shows the incorporation of bioactive compounds into plant-based analogs, highlighting their interactions with proteins, potential structural effects, and impact on sensory attributes.

Characteristics of Plant-Based Meat Analogs with Added Bioactive Compounds

Several strategies have been explored to incorporate phenolic-rich extracts, whole plant ingredients, and agro-industrial by-products into meat analogs providing not only protein and fiber but also bioactive compounds. This approach has been supported by the findings of Da Silva et al. [11], who highlighted the role of polyphenols-rich plant ingredients in plant-based products. Similarly, Kolodziejczak et al. [7], experimentally reported the antioxidant effects of compounds incorporated into pea-meat analogs.

Table 1 summarizes recent studies on plant-based meat analogs enriched with bioactive compounds, emphasizing the plant sources, the main phenolic compounds incorporated, and their reported effects on antioxidant properties and nutritional quality.

In general, the studies summarized in Table 1 indicate that the incorporation of plant sources rich in bioactive compounds into meat analogs significantly improves the antioxidant capacity and functional properties of these products. However, technological challenges remain, particularly regarding the thermal stability of bioactive compounds, which may degrade during processing.

Anthocyanins are a good example of the technological challenges related to the incorporation of bioactive compounds. These pigments are very sensitive to temperature and light and therefore need to be protected after extraction in order to diminish degradation by external environmental conditions [9]. Phenolic compounds can have a positive effect on the preservation of food by reducing lipid and protein oxidation through scavenging reactive oxygen species and chelating pro-oxidant metal ions. In addition, some flavonoids and phenolic acids are antimicrobials against spoilage microorganisms, hence supporting the partial substitution of synthetic preservatives [13, 23, 9].

The incorporation of bioactive compounds into meat products has also been reported in the literature. Grispoldi et al. [1] demonstrated that the addition of apple pomace to the meat mixture used for salami production improved total phenolic content (8.56 mg GAE/g), among the flavonoids found by the study are: quercetin-**3**-*O*-galactoside (1039.54 mg/kg), quercetin-**3**-*O*-arabinofuranoside (563.69 mg/kg), phloridzin (396.18 mg/kg), quercetin-**3**-*O*-rhamnoside (quercitrin) (319.15 mg/kg), quercetin-**3**-*O*-xyloside (287.72 mg/kg), quercetin-**3**-*O*-glucoside (42.06 mg/kg), chlorogenic

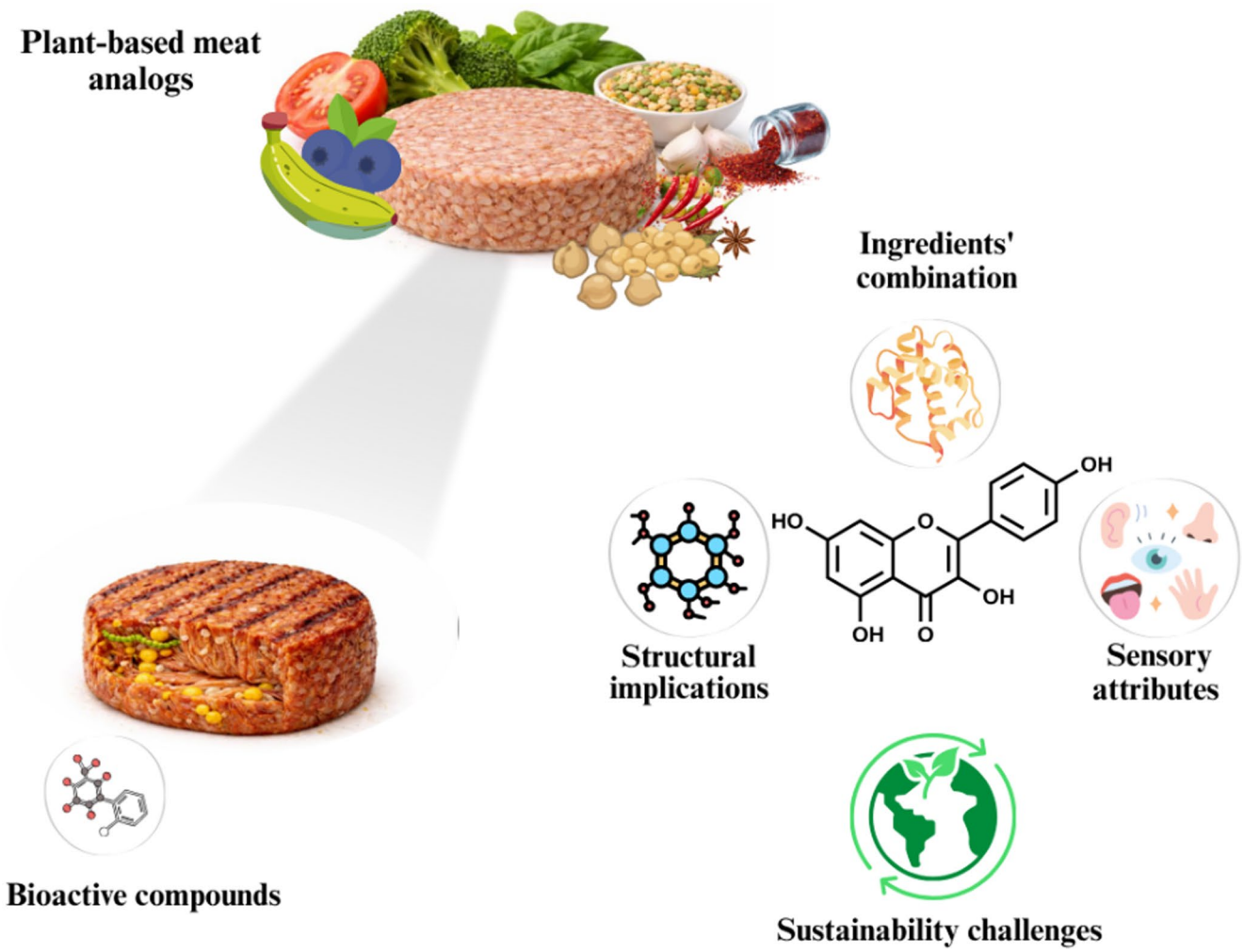

Fig. 2 Plant-based meat analogs and the role of bioactive compounds in chemical, technological and sensory quality. Source: Prepared by the author (2026). Designed using Canva Pty Ltd. (Sydney, Australia). Canva Pro Software Canva (2025).

acid (37.17 mg/kg) and quercetin-**3**-*O*-pentoside (23.13 mg/kg) microbiological quality, nutritional composition, and antioxidant activity through the ABTS obtained (22.13 mg TE/g) and DPPH (11.77 mg TE/g).

A similar approach has been applied to meat analogs. Kołodziejczak et al. [7] developed meat analogs based on textured pea protein combined with açaí, canola, and olive oils, as well as propolis extract, buckwheat honey, and jalapeño/chili pepper extract. Their results indicated that formulations containing honey presented higher polyphenol and flavonoid contents, which were associated with greater antioxidant capacity.

In this context, the use of agro-industrial by-products may offer functional and nutritional benefits for meat analogs. Asha et al. [23] developed burgers using banana peels and reported that formulations containing banana peel, particularly the T2 (70 g banana peel/100 g hamburger patty, per person) treatment, exhibited high fiber content, enhanced antioxidant capacity, and greater water retention capacity compared with conventional chicken burgers.

Furthermore, the incorporation of plant by-products may positively affect the sensory properties of meat analogs. Nichita et al. [2] reported that samples enriched with phenolic compounds exhibited greater perceived moisture and firmness, along with fresher aromas associated with vegetables and legumes. Moreover, reduction in garlic odor, gumminess, and elasticity indicates an overall improvement in the sensory quality of the products.

Orădan et al. [3] conducted a systematic review on the use of fruit extracts in meat products as natural antioxidants, preservatives, and colorants. The authors reported that flavonoids exhibit antimicrobial activity and contribute significantly to the preservation of meat products. In addition, they pointed out that fruit processing

Table 1 Characteristics of plant-based meat analogs added with bioactive compounds

Author/ Year	Meat substitute product	Plant source/by-products	Bioactive compounds	Main Findings
Asha et al. [23] Bangladesh	Burger	Banana pulp and banana peel	Total phenolic compounds (TPC)	The formulation containing 70 g banana peel/100 g burger (T2) showed the highest antioxidant activity (AA) and TPC in both raw (44.57% AA; 171.74 mg GAE/100 mL) and cooked burgers (35.66% AA; 158.70 mg GAE/100 mL). T2 also exhibited the highest fiber content (5.14%), water-holding capacity (89.40%) and potassium concentration (768.35 mg/100 g). Although cooking reduced antioxidant activity and TPC in all formulations, T2 maintained superior values and sensory acceptance comparable to the control for overall acceptability and texture.
Szpicer et al. [9] Poland	Burger	Pea protein, chickpea flour, black chokeberry (*Aronia melanocarpa*) encapsulated anthocyanin extract	Anthocyanins	The addition of anthocyanin microcapsules (2.74%) increases the antioxidant capacity (44.58%) of the product, while maintaining good overall acceptance (7.42).
Vargas et al. [24] Brazil	Burgers: commercial plant-based burgers (PB1), homemade plant-based burgers (PB2), and meat-based burgers (MB)	PB1 (Water, textured soy protein, isolated soy protein, pea protein, chickpea flour, coconut fat, canola oil, natural flavor, methylcellulose, salt, beetroot powder) PB2 (Chickpeas, beetroot, carrots, oat flour, sour tapioca starch)	Phenolic acids (chlorogenic and p-coumaric acids) and flavonoids (quercetin, luteolin, apigenin, genistein and daidzein)	HPLC-MS/MS identified a diverse profile of flavonoids and phenolic acids in plant-based burgers, with PB2 showing the highest diversity of phenolic compounds. Commercial plant-based burgers (PB1) exhibited higher protein (39.6%), fat (13.2%) and ash (7.87%) contents than PB2, whereas PB2 showed the highest carbohydrate content (81.3%). The identified phenolic compounds were associated with antioxidant potential, although they contributed less to structural network formation than the metabolites predominant in meat burgers.
Kołodziejczak et al. [7] Poland	Burger	Textured pea protein, canola oil, olive oil, acai oil, propolis, buckwheat honey, jalapeno extract	Polyphenols, Flavonoids	The samples with buckwheat honey had higher polyphenol content, especially the H-AO group (370.54 mg/100 g), while the control group had the lowest values; for flavonoids, the control group had (72.27–77.77 mg/100 g), the groups with propolis and jalapeño pepper had intermediate values, and the groups with honey had the highest levels (90.71–103.03 mg/100 g).
Cai et al. [25] Canada	Extrudates high-moisture meat analogs	Sunflower seeds and pea protein isolate	Chlorogenic acid (phenolic compound), Phytic acid	High-moisture meat analogs showed protein quality similar to chicken and beef, with high protein content, high digestibility, and tryptophan as the limiting amino acid, in addition to a reduction in antinutritional compounds after extrusion.
Nichita et al. [2] Romania	Salami	Lentils, mushrooms, and extra virgin olive oil	Phenolic compound	The phenolic compounds and antioxidant activity at the end of the storage period highlighted the importance of adding to meat substitutes bioactive molecules from extra virgin olive oil that can make the food better.

Source: Study data

industries generate millions of tons of by-products, such as peels and seeds, which can pose environmental risks if not properly managed. Therefore, the use of agro-industrial by-products as sources of these compounds constitutes a promising clean-label strategy towards the shelf-life extension and the improvement of the nutritional quality of plant-based meat analogs.

Study Limitations

Despite the advances in the application of bioactive compounds in plant-based foods discussed in this integrative review, several limitations should be considered when interpreting the findings. During the literature search, it was difficult to identify studies that simultaneously evaluated the

incorporation of bioactive compounds, their interactions with plant proteins, and their combined effects on the structural, functional, and sensory properties of the plant-based meat analogs.

Another limitation concerns the methodological heterogeneity across the studies included in this review. Differences in plant sources, types and concentrations of bioactive compounds, and processing conditions, such as extrusion, heat treatments, and fortification strategies, make direct comparisons difficult and limit generalizability of the reported effects, as also highlighted by Szpicer et al. [9] and Nichita et al. [2].

Another aspect that should be considered is the formulation of meat analogs, as some studies focus only on basic formulations without providing detailed product characterization or evaluating processing conditions. Consequently, product properties may change during processing and structuring stages, which can negatively affect product quality.

Considering these limitations, future research should adopt more integrated and comprehensive approaches to better elucidate the effects of bioactive compounds on the structure, functional, and sensory properties of plant-based meat analogs. Furthermore, nanotechnology represents a promising strategy, particularly for the encapsulation and controlled release of bioactive compounds, potentially improving their stability, bioavailability, and the preservation of sensory quality.

Conclusion

This study showed that, among the bioactive compounds investigated, polyphenols are the most widely studied in plant-based meat analog formulations, mainly due to their antioxidant capacity, antimicrobial potential, and contribution to the oxidative stability of products. The incorporation of these compounds, especially those derived from agro-industrial by-products, reinforces the alignment between technological innovation and the sustainable resource use strategies, reflected in the valorization of these residues and the improvement of the functional profile of foods.

Analysis of the reviewed studies indicated that burgers were the most frequently evaluated meat analog in the experimental research, possibly due to their simpler technological structure and high consumer acceptance.

Overall, the incorporation of bioactive compounds into meat analogs resulted in increased antioxidant capacity and, in some cases, improvements in water retention and structural stability. However, these effects depend on the plant source, concentration, proportion, and processing conditions employed.

The content of bioactive compounds or by-products incorporated into the food matrix remains a challenge, as high levels may cause astringent or bitter taste, altering the color and texture of the product. Therefore, it is essential to establish optimal incorporation levels that balance technological functionality and sensory acceptance. Special attention should be given to potential interactions with plant protein, which may affect bioavailability and structural behavior. The findings of this review highlight that the inclusion of bioactive compounds in plant-based meat analogs represents a promising strategy to enhance technological and nutritional value while contributing to agro-industrial by-products using.

Nevertheless, further standardized experimental studies are required to determine suitable incorporation levels of bioactive ingredients without compromising sensory attributes or promoting undesirable interactions with plant proteins. Additionally, future research should evaluate the thermal stability and degradation of bioactive compounds during processing.

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    - This study aimed to evaluate how different types of plant-based fats influence the physicochemical properties of meat analogs The analysis focused on texture, color, fatty acid composition, total antioxidant capacity and anti-inflammatory activity, as well as polyphenol and flavonoid content, in addition to consumer acceptance of the pea protein–based plant burger.
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    - The study evaluates the formulation of innovative meat analogs gluten free and without soy, enriched with microencapsulated anthocyanins and achieved high sensory acceptance.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests Paulo Cezar Bastianello Campagnol is a Section Editor of Current Food Science and Technology Reports. He was not involved in the review process of the manuscript. The authors have no other competing interests to disclose.

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