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RESEARCH ARTICLE

Effect of edible mushroom antioxidants on the oxidative stability and quality of meat products: advances and research trends through a systematic and bibliometric review

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Abstract

Lipid and protein oxidation remain key challenges that limit the technological, sensory, and nutritional quality of meat products. This systematic review compiles evidence published from 2011 to 2025 on the antioxidant properties of edible mushrooms and their ability to reduce oxidative breakdown in meat matrices. Searches were performed in Scopus and Web of Science, yielding 821 records, of which 60 met the inclusion criteria in accordance with PRISMA guidelines. Across studies, *Pleurotus ostreatus*, *Agaricus bisporus*, *Flammulina velutipes*, and *Hericium erinaceus* consistently showed significant reductions in lipid peroxidation (20% – 40% decreases in TBARS) and moderate reductions in protein carbonylation. These antioxidant effects were mechanistically linked to synergistic interactions among phenolic acids, ergothioneine, flavonoids, and β-glucans. Additional benefits included improvements in color stability, water-holding capacity, and fiber and amino acid profiles. However, substantial variability was present across different species, extraction methods, and inclusion levels. Evidence supporting the inhibition of protein oxidation remains limited, bioaccessibility data are scarce, and standardization of mushroom-based meat products is lacking. Overall, edible mushrooms show strong potential as multifunctional, clean-label antioxidant systems; nonetheless, more mechanistic, quantitative, and digestion-focused studies are needed for industrial-scale application. These findings indicate promising applications in clean-label meat reformulation, although industrial validation and standardized reporting of oxidative markers remain required.

Keywords: Edible mushrooms; antioxidant properties; reformulation of meat products; oxidation of lipids and proteins.

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1. Introduction

The oxidation of lipids and proteins is one of the main deterioration processes of meat matrices that are stored or processed by heat, since the peroxidation of fatty acids and the carbonylation of proteins decrease oxidative stability, alter the structural functionality of biomolecules, and accelerate the technological deterioration of the product (Kim et al., 2024; Torres et al., 2025). These oxidative reactions not only impair technological attributes but also reduce yield due to loss of water-holding capacity and favor irreversible changes in color and texture, thereby impairing the industrial and commercial acceptability of meat products (Bobko et al., 2024).

Beyond technological deterioration, oxidation also affects the nutritional value of meat products. At a nutritional level, this translates into the degradation of essential amino acids, the modification of poly-unsaturated fatty acids, and the formation of low-bioavailability protein adducts, thereby affecting food safety and the nutritional value perceived by

consumers (Borsa et al., 2025; Radzki et al., 2023). At the sensory level, oxidative processes also induce the formation of secondary volatile compounds, responsible for rancid attributes, metallic flavors, and loss of sensory freshness and, consequently, lead to rejection by the end consumer and the reduction of the product's commercial cycle (Bedrnicek et al., 2020; Nguyen et al., 2023).
Despite extensive experimental evidence, no systematic review has integrated the mechanistic, sensory, and nutritional outcomes of mushroom incorporation into meat products, leaving a critical gap in understanding cross-dimensional effects and their implications for clean-label formulation.
In this way, industrial interest has identified parameters for the progressive replacement of synthetic antioxidants with natural antioxidants that can donate protons, chelate metals, and detoxify free radicals. Edible mushrooms are attracting significant interest due to their high levels of bioactive compounds in their fungal structures (Abdou et al., 2023; Lopes et al., 2021). Fungi contains a variety of antioxidant molecules, including phenols, polysaccharides, ergothioneine, glutathione, and organic acids, whose redox synergy has shown efficacy similar to, or even superior to, that of conventional additives in complex food matrices (Jurcaga et al., 2022).
All this combination of chemical, nutritional and technological evidence has led to the evaluation of the use of extracts and/or fractions of edible mushrooms as an antioxidant strategy for the prolongation of the oxidative stability of meat derivatives, as well as to slow down the sensory deterioration associated with rancidity and in the preservation of the functional and nutritional quality of the final product when it is subjected to a period of storage and distributed in good industrial conditions (Fogarasi et al., 2018; Radzki et al., 2024).
An integrative graphical synthesis of this conceptual framework is presented in Figure 1, which connects fungal sources and their bioactive compounds with the main oxidation hotspots in the meat matrix and the resulting technological and sensory outcomes documented across the included primary studies. The figure is intended as a reading map for the present review and integrates evidence from the four most representative primary studies in the corpus, namely Patinho et al. (2021), who described social representations of beef burgers reformulated with *Agaricus bisporus* and identified consumer drivers such as healthiness, novelty and curiosity; Coaguila Gonza et al. (2026), who demonstrated that pressurized-liquid extracts from *Pleurotus ostreatus* cap and stipe differentially stabilize color, lipid oxidation and free amino acid profile in beef burgers during frozen storage; Saldaña & Rios-Mera (2025), who articulated the research needs on sensory perception of mushroom-enriched meat products; and Parí et al. (2025), who reviewed the emerging extraction technologies that govern the recovery and bioactivity of mushroom polyphenols.

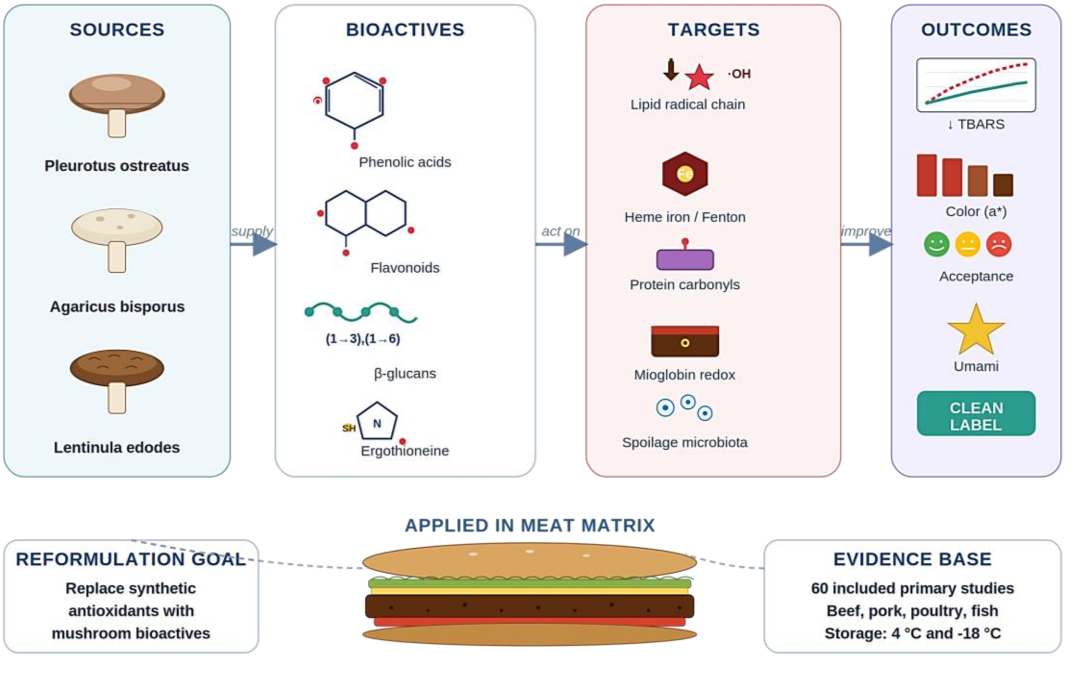


Figure 1. Integrative graphical synthesis of mushroom-derived antioxidants in meat reformulation.

The diagram is organized horizontally in four connected panels. The left panel displays the main fungal sources reviewed in the corpus, namely *Pleurotus ostreatus*, *Agaricus bisporus*, and *Lentinula edodes*. From these sources, the second panel summarizes the principal classes of bioactive compounds extracted and incorporated into meat matrices, including phenolic acids, flavonoids, β-glucans, and ergothioneine, all of which exhibit free-radical scavenging, metal-chelating, and electron-donating capacities. The third panel identifies the oxidation hotspots that these bioactives target inside the meat matrix during processing and storage: the lipid radical chain, heme iron and Fenton chemistry, carbonyl protein formation, myoglobin redox state, and spoilage microbiota. The right panel synthesizes the technological and sensory outcomes most frequently measured across the 60 included primary studies, namely lower TBARS values, color retention, sustained sensory acceptance, umami enhancement, microbial control and clean-label positioning. The cross-section of a beef burger placed at the bottom centre of the diagram illustrates the meat matrix where these interactions take place and connect the reformulation goal on the left with the evidence base of 60 included primary studies summarized on the right. Read together, the four panels make explicit the antioxidant flow that organizes the systematic and bibliometric evidence consolidated in the following sections.

Therefore, the objective of this systematic review is to evaluate the impact of edible mushroom-derived antioxidants on the oxidative stability (lipid and protein) and sensory quality, as well as the nutritional value, of meat products. By synthesizing current empirical findings, this study aims to clarify the mechanistic role of fungal bioactive in meat systems and provide a critical perspective on their potential as functional ingredients for clean-label food formulation.

2. Methodology

2.1. Research question and review framework

The systematic review was guided by an explicit research question structured according to the PICo framework adapted for non-clinical food research. The Population (P) corresponded to meat products and meat matrices (raw, cooked, fermented, emulsified, or stored); the Intervention (I) corresponded to the incorporation of edible mushrooms or their derivatives (whole tissue, powders, extracts, mycelium, fermented preparations, or spent substrate fractions) as antioxidant ingredients; and the Context/Comparator (Co) included synthetic antioxidants, control formulations without mushroom incorporation, or comparisons among mushroom species and ingredient formats. The primary research question was therefore: "How do edible mushroom-derived antioxidants influence the oxidative stability (lipid and protein oxidation) and overall quality (sensory and nutritional) of meat products?" This main question was operationalized into three sub-questions that guided data extraction and structured the synthesis. (i) Which edible mushroom species and ingredient formats most effectively reduce lipid and protein oxidation in meat matrices? (ii) Which biochemical mechanisms underpin these antioxidant effects? (iii) How do mushroom-based incorporations modify the sensory and nutritional quality of the final product? The components of the research question were directly translated into the search equation (Section 2.2) and into the eligibility criteria (Section 2.3), and they also informed the structure of the data extraction sheet and of the synthesis tables. The full review protocol, including the PICo formulation, search equations, screening flow, data extraction template, and risk-of-bias considerations, is provided as Supplementary Material 1 (Table SM1).

2.2. Search strategy

Scopus and Web of Science were used as data sources, which were accessed on September 20, 2025, with an updated verification search performed on April 30, 2026, which retrieved no new records meeting the eligibility criteria that would have changed the synthesis or the figures presented in this review. The search strategy was designed to identify studies on the antioxidant properties of edible mushrooms and their effects on biomolecule oxidation. General terms related to edible mushrooms (mushroom, fungi, edible mushroom) were used, along with specific species of interest: *Lentinus edodes, Pleurotus ostreatus*, *Agaricus bisporus*, *Boletus edulis*, *Cantharellus cibarius*, *Flammulina velutipes*, *Ganoderma lucidum (reishi)*, *Hericium erinaceus*, *and Tremella fuciformis*. For implementing the search strategies, the equations considered factors such as the search terms, the filters applied, and the date the search was performed, as shown in Table 1.

The search equation included general terms related to edible mushrooms and, more specifically, the scientific names *Lentinus edodes*, *Pleurotus ostreatus*, *Agaricus bisporus*, *Boletus edulis*, *Cantharellus cibarius*, *Flammulina velutipes*, *Ganoderma lucidum*, *Hericium erinaceus*, and *Tremella fuciformis*, *as detailed in* Table 1. The selection of these species was based on a previous exploratory scoping in Scopus and Web of Science (June 2025), which confirmed that they account for more than 70% of the published evidence on edible mushroom antioxidants applied to meat matrices, and on prior reviews documenting their consolidated antioxidant profile and frequent use in food technology research (Heleno et al., 2015; Kozarski et al., 2012; Reis et al., 2014; Smolskaite et al., 2015). These species exhibit the highest reported densities of phenolic acids, flavonoids, ergothioneine, and β-glucans among fungal taxa, providing a sound biochemical rationale for their inclusion in the search equation. Their inclusion, therefore, ensured a comprehensive and representative coverage of the taxa for which both compositional and meat-application evidence is available.

2.3. Eligibility criteria

This research was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement. Several criteria were initially considered, including publication type, content of interest, time frame covered, and accessibility of the selected articles, as summarized in Table 2.

2.4. Study selection

To increase methodological transparency, the review protocol was drafted a priori and aligned with PRISMA 2020 standards. Although the protocol was not registered in PROSPERO, it followed the same mandatory elements, including predefined research questions, eligibility criteria, search strategies, and a structured plan for data extraction and synthesis.

Descriptors related to antioxidant properties included antioxidant, phenolic content, bioactive compound, phenolic compound, polyphenol, and flavonoid. To identify studies addressing biomolecule oxidation, the expressions lipid peroxidation, lipid oxidation, protein oxidation, and protein carbonylation were used. Filters applied to retrieve only original research articles published in open-access scientific journals, ensuring methodological transparency and full traceability of the bibliographic sources consulted.

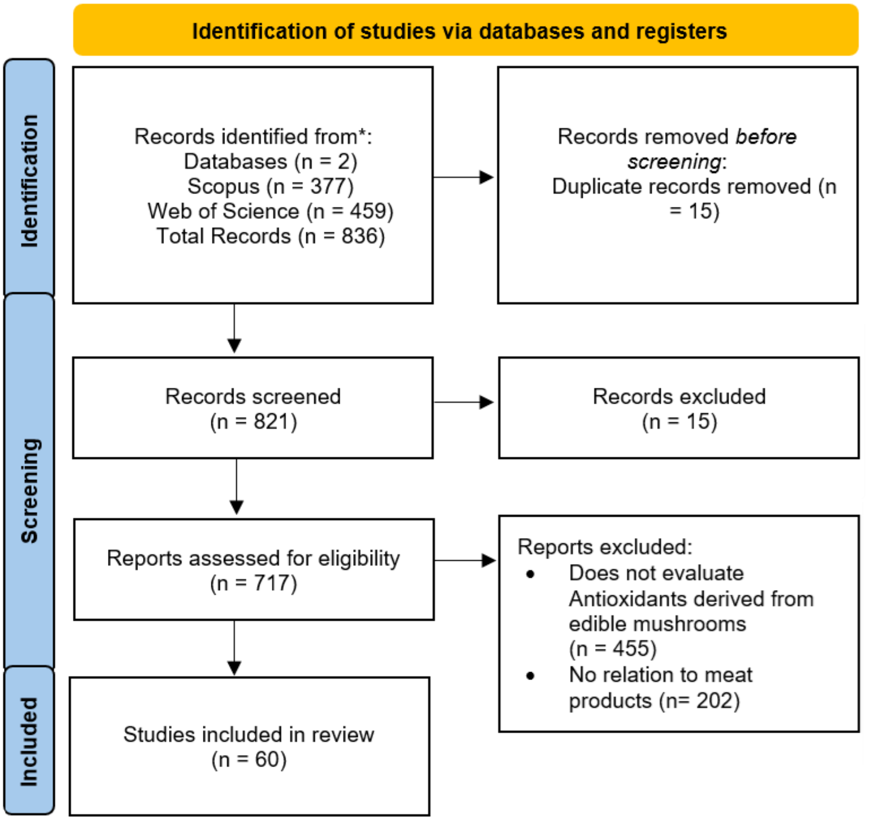
A standardized data extraction sheet was used to collect information on fungal species, extraction methods, meat matrix, storage design, oxidative markers, sensory methodology, and nutritional assessment criteria. Two authors (H.G. and Y.P.) screened titles, abstracts and full texts independently and in duplicate, applying the predefined inclusion and exclusion criteria. Disagreements were resolved by consensus, and a third author (E.S.) acted as adjudicator when consensus could not be reached. The complete review protocol, the calibration set used for inter-reviewer agreement, and the records excluded at the full-text stage with their reasons for exclusion, are in accordance with PRISMA recommendations (Supplementary Material 1). The selection process consisted of two phases: an initial selection of titles and abstracts, followed by the evaluation of the full text, both guided by predefined inclusion and exclusion criteria. During the selection process, 377 records were initially identified in Scopus and 459 in Web of Science, excluding 15 duplicate records, for a total of 836 publications, as illustrated in Figure 2.

Table 1
Search equations used in Scopus and Web of Science

Search equations
Scopus: TITLE-ABS-KEY(mushroom* OR fungi OR "edible mushroom*" OR *"Lentinus edodes"* OR *"Pleurotus ostreatus"* OR *"Agaricus bisporus"* OR *"Boletus edulis"* OR *"Cantharellus cibarius"* OR *"Flammulina velutipes"* OR *"Ganoderma lucidum" OR "Hericium erinaceus" OR "Tremella fuciformis"*) AND TITLE-ABS-KEY (antioxidant* OR "phenolic content" OR "bioactive compound*" OR "phenolic compound*" OR polyphenol* OR flavonoid*) AND TITLE-ABS-KEY ("lipid peroxidation" OR "lipid oxidation" OR "protein oxidation" OR "protein carbonylation") AND PUBYEAR > 2010 AND PUBYEAR < 2026 AND (LIMIT-TO (SRCTYPE,"j")) AND (LIMIT-TO (OA,"all")) AND (LIMIT-TO (DOCTYPE,"ar"))
WoS: mushroom* OR fungi OR "edible mushroom*" OR "*Lentinus edodes*" OR "*Pleurotus ostreatus*" OR "*Agaricus bisporus*" OR "*Boletus edulis*" OR "*Cantharellus cibarius*" OR "*Flammulina velutipes*" OR "Ganoderma lucidum" OR *"Hericium erinaceus"* OR "*Tremella fuciformis*") AND TS=(antioxidant* OR "phenolic content" OR "bioactive compound*" OR "phenolic compound*" OR polyphenol* OR flavonoid*) AND TS=("lipid peroxidation" OR "lipid oxidation" OR "protein oxidation" OR "protein carbonylation"

Table 2
Eligibility criteria for the selection of studies included in the systematic review

Inclusion criteria	Exclusion criteria
Research articles reporting original empirical data, published in peer-reviewed scientific journals (excluding conference proceedings and book chapters even when they report primary data). Articles focused on analyzing the antioxidant properties of edible mushrooms and their effects on lipid and protein oxidation.	Reviews, book chapters, conferences. Articles that consider the effects of the antioxidant properties of edible fungi on protein sources from plants or insects, carbohydrates, and nucleic acids.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).

Figure 2. PRISMA protocol used to select the articles used in the review.

2.5. Bibliometric analysis

Although many tools are available for bibliometric and text-mining analyses, each has limitations that prevent their universal use. Therefore, following the recommendations of Moral-Muñoz et al. (2020), VOSviewer (version 1.6.20) and Bibliometrix via its Biblioshiny interface in RStudio (version 2025.05.1+513) were used. Both tools are free, user-friendly, and allow flexible customization of visualizations and analysis settings. Microsoft Excel LTSC Standard 2024 was also used for data processing and visualization.

Articles retrieved from Scopus and Web of Science were exported in CSV and TXT formats, respectively, and imported into VOSviewer to analyze keyword co-occurrence and generate networks highlighting thematic clusters and emerging trends. In these networks, each node represents a keyword, with its size proportional to its frequency of occurrence; the distance between nodes reflects the degree of semantic association. Clusters were distinguished using different colors (green, red, blue, and yellow). Bibliometrix was used to evaluate scientific output over time, identifying trends through publication timelines and geographic distribution. Additionally, keyword clouds were created, with the size of each term indicating its frequency of occurrence, allowing quick identification of the most common topics within the field.

Finally, a three-field (Sankey) diagram was created to analyze the relationships among authors, keywords, and countries within the thematic and geographic structure of scientific output. It also highlights the main contributors, dominant topics, and regions with the greatest impact in the field.

3. Results and discussion

3.1. Analysis of studies

The temporal evolution of scientific production related to the application of edible mushroom antioxidants in meat products is presented in Figure 3A. The number of publications remained relatively low and fluctuated between 2011 and 2019, followed by a marked increase from 2020 onwards, reaching its highest level in 2024. This growth reflects the increasing scientific interest in natural antioxidant sources as sustainable alternatives to synthetic additives for improving oxidative stability and maintaining the quality of meat products. Recent studies have demonstrated the effectiveness of edible mushroom-derived ingredients in enhancing antioxidant capacity, extending shelf life, and improving sensory and physicochemical properties in meat systems (Banerjee et al., 2020; Hu et al., 2021; Torres et al., 2022; Fu et al., 2023; Vargas et al., 2023; Aziz et al., 2024).

The geographical distribution of scientific production is shown in Figure 3B. Research activity was predominantly concentrated in China, followed by India and the United States, while countries such as Brazil, Australia, Japan, South Korea, the United Kingdom, Spain, Italy, Germany, and France also contributed substantially to the development of this field. The broad geographic distribution of publications highlights the global relevance of edible mushroom-derived antioxidants and their potential applications in meat systems.

3.2. Network of co-occurrence of keywords

Figure 4 shows the keyword co-occurrence network associated with research on antioxidants derived from edible mushrooms and their application in meat products. The network reveals several interconnected thematic domains that reflect the multidisciplinary nature of this research field.

A prominent group of keywords is centered on the term *antioxidant*, which is strongly associated with *antioxidant activity*, *oxidative stress*, *radical scavenging activity*, *polyphenol*, *phenolic compound*, *flavonoid*, *carotenoid*, *ascorbic acid*, *zinc*, and *iron*. The close relationships among these terms indicate that a substantial portion of the scientific literature has focused on the identification of antioxidant compounds and the evaluation of their ability to neutralize free radicals and mitigate oxidative stress. Another important thematic area is organized around *edible mushroom*, which is linked to terms such as *polysaccharide*, *β-glucan*, *dietary fiber*, *protein*, *terpenoid*, *extract*, and *bioactive compound*. These associations highlight the interest in characterizing the nutritional composition and bioactive constituents of edible mushrooms, particularly those compounds responsible for their antioxidant potential.

The network also includes a methodological domain characterized by keywords related to extraction and analytical procedures, including *extraction*, *analysis*, *total phenolic content*, *methodology*, *experimental study*, and *in vitro study*. The presence of these terms reflects the importance of extraction techniques and laboratory evaluations for the identification and quantification of antioxidant compounds from mushroom matrices.

A further research area is associated with meat applications, where *meat quality* and *oxidative stability* occupy central positions and are closely connected with *lipid oxidation*, *shelf life*, *color*, *texture*, *sensory quality*, *quality*, and *meat product*. This pattern suggests that increasing attention has been directed toward the incorporation of mushroom-derived antioxidants into meat systems as natural alternatives to synthetic additives, aiming to delay oxidative deterioration and preserve product quality during storage.

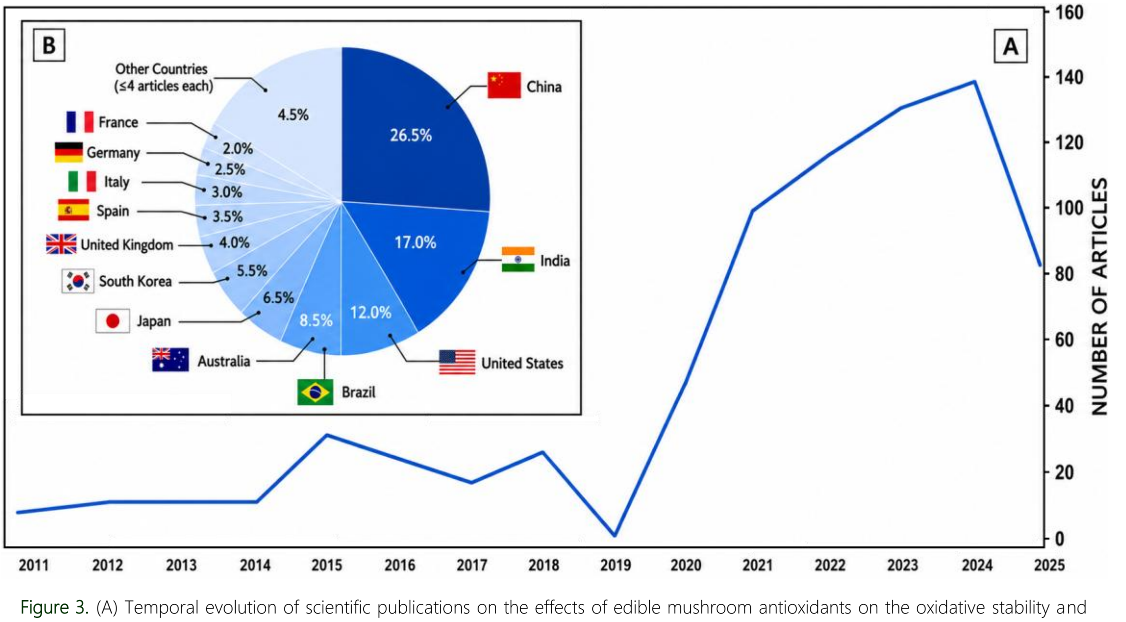


Figure 3. (A) Temporal evolution of scientific publications on the effects of edible mushroom antioxidants on the oxidative stability and quality of meat products between 2011 and 2025. (B) Geographic distribution of scientific publications according to the institutional affiliations of authors by country.

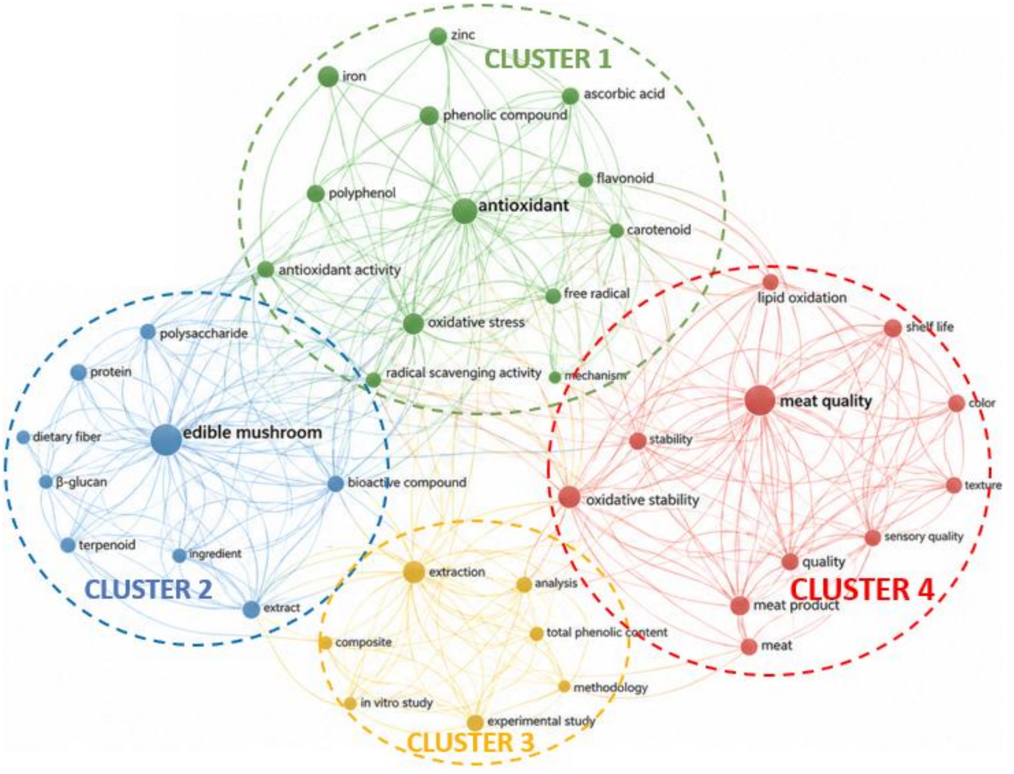


Figure 4. Co-occurrence network of keywords related to edible mushroom-derived antioxidants and their application in meat products (2011–2025).

Overall, the network demonstrates that research on edible mushroom-derived antioxidants integrates studies on the characterization of bioactive compounds, the evaluation of antioxidant mechanisms, methodological developments for compound extraction and analysis, and technological applications focused on improving the oxidative stability and quality attributes of meat products.

3.4. Keyword cloud

Figure 5 illustrates the temporal evolution of the main research topics related to edible mushroom-derived antioxidants and their application in meat products from 2011 to 2025. The progression of keywords reveals a gradual shift from characterizing antioxidant properties to the technological application of mushroom-derived compounds in food preservation.

During the period 2011 – 2015, research was primarily focused on the antioxidant potential of edible mushrooms. The predominance of terms such as antioxidant activity, lipid peroxidation, antioxidants, oxidative stress, phenolic compounds, polysaccharides, and free radical scavenging indicates that studies were primarily focused on identifying bioactive compounds and evaluating their capacity to inhibit oxidative processes. Several investigations reported high antioxidant potential in edible mushrooms and highlighted the contribution of phenolic compounds and polysaccharides to their biological activity (Da Silva and Jorge, 2011; Reis et al., 2011; Kozarski et al., 2012; Leal et al., 2013; Heleno et al., 2015; Smolskaite et al., 2015). These studies established the scientific basis for the subsequent development of mushroom-derived natural antioxidants.

Between 2016 and 2020, the research focus expanded to investigate the biological mechanisms underlying antioxidant activity. Keywords such as oxidative stress, metabolism, enzyme activity, bioactive compounds, functional properties, and mechanisms gained prominence, reflecting increasing interest in understanding how mushroom-derived compounds interact with biological systems and contribute to antioxidant protection. Research during this period emphasized the characterization of polysaccharides, extraction techniques, antioxidant mechanisms, and the functional properties of mushroom-derived compounds (Jablonska et al., 2016; Mitra et al., 2016; Radzki et al., 2016; Zhu et al., 2018; Hu et al., 2019; Deveci et al., 2019; Banerjee et al., 2020). Consequently, edible mushrooms began to be recognized not only as sources of antioxidants but also as functional ingredients with potential applications in food and health-related sectors.

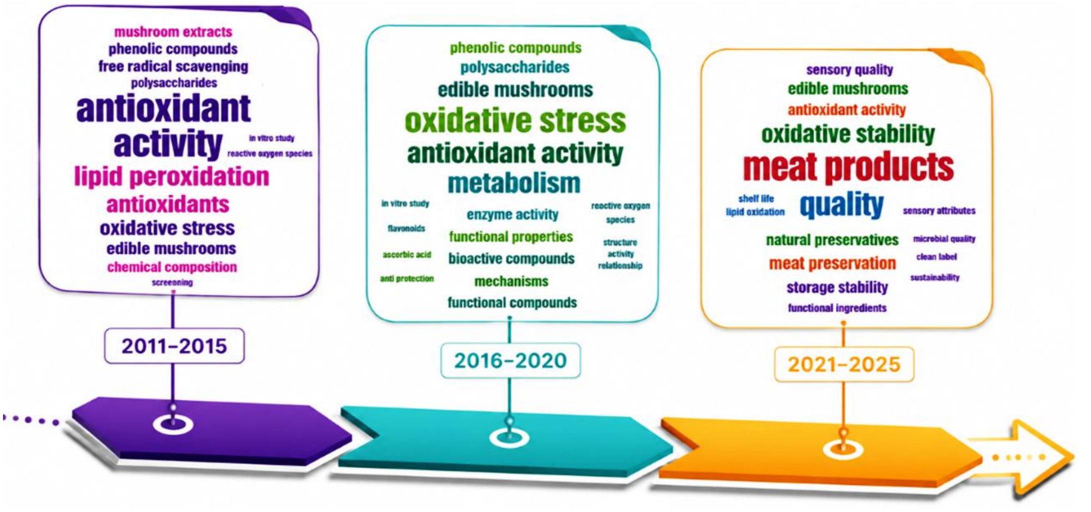


Figure 5. Temporal evolution of research themes related to edible mushroom-derived antioxidants and their application in meat products (2011 – 2025).

In the most recent period (2021 – 2025), the emphasis shifted toward practical applications in food systems, particularly meat products. The dominance of terms such as meat products, oxidative stability, quality, meat preservation, natural preservatives, storage stability, and sensory quality demonstrates growing interest in incorporating mushroom-derived antioxidants as clean-label ingredients to improve product quality and extend shelf life. Recent studies have demonstrated that mushroom-derived ingredients can enhance oxidative stability, sensory properties, nutritional quality, and storage performance in a variety of meat products and meat analogues (Hu et al., 2021; Torres et al., 2022; Fu et al., 2023; Tokarczyk et al., 2023; Vargas et al., 2023; Aziz et al., 2024; Wang et al., 2024; Nan et al., 2025; Torres et al., 2025).

Overall, the temporal evolution of keywords suggests a clear transition from fundamental studies focused on antioxidant characterization to more application-oriented research aimed at enhancing the oxidative stability, quality, and sustainability of meat products. This progression highlights the field's maturation and the growing relevance of edible mushrooms as a source of natural antioxidants in the meat industry.

3.5. Thematic and geographic relationships

Figure 6 presents an integrative visualization of the relationships among the most influential authors, the main research topics, and the countries contributing to the scientific production of antioxidants derived from edible mushrooms and their application in meat products. The Sankey diagram enables the identification of the conceptual structure of this research field by linking the most productive researchers with the predominant themes and the countries that concentrate scientific activity.

In the central panel, terms associated with three major thematic areas stand out. The first is related to antioxidant mechanisms and includes keywords such as antioxidant, antioxidant activity, and oxidative stress, reflecting the interest in understanding the ability of bioactive compounds to neutralize free radicals and reduce oxidative damage. The second thematic area is associated with edible mushrooms and their functional compounds, represented by terms such as mushroom, polysaccharide, *Ganoderma lucidum*, and *Pleurotus ostreatus*, species widely studied due to their antioxidant and technological potential. The third thematic area focuses on applications in meat products and includes terms such as lipid oxidation, shelf life, meat products, and antimicrobial activity, highlighting the interest in using natural antioxidants to improve oxidative stability, extend shelf life, and preserve meat quality.

From a geographical perspective, China emerges as the leading contributing country, followed by Egypt, Thailand, Italy, Spain, Brazil, and other nations with significant participation. The high density of connections among authors, topics, and countries underscores the international and collaborative nature of this research field, as well as the convergence of scientific efforts aimed at developing natural strategies to enhance the quality and stability of meat products.

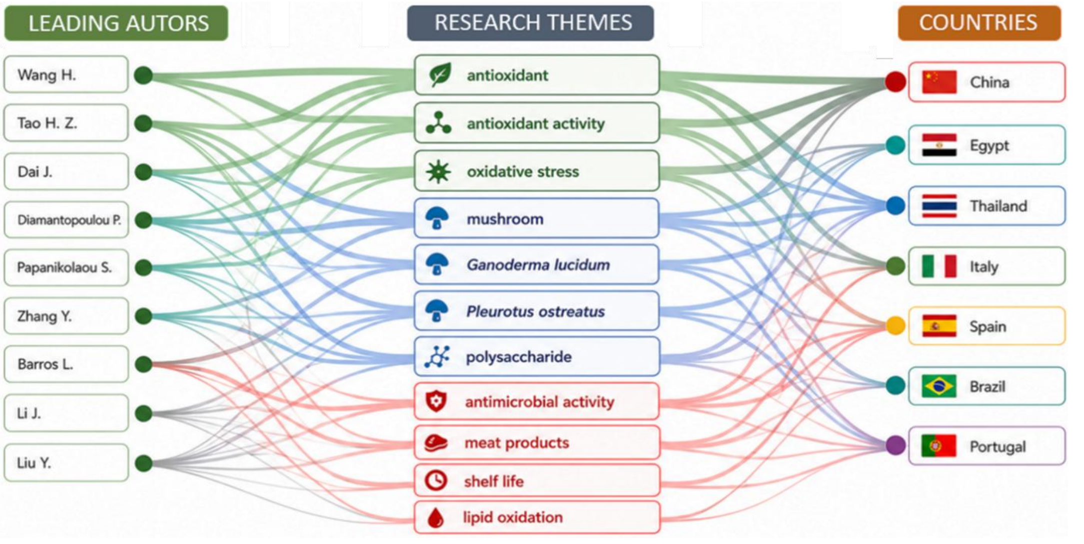


Figure 6. Sankey diagram illustrating the relationships among the most influential authors, the main research topics, and the contributing countries in studies on antioxidants derived from edible mushrooms and their application in meat products (2011 – 2025). The predominant topics are grouped into three major thematic areas: antioxidant mechanisms, edible mushrooms and bioactive compounds, and applications related to oxidative stability and the quality of meat products. AU: authors; DE: authors' keywords; AU_CO: authors' countries of affiliation.

3.6. General insights from the bibliometric analysis

The bibliometric analyses collectively reveal a progressive evolution of research on edible mushroom-derived antioxidants from fundamental investigations focused on the characterization of antioxidant compounds toward applied studies addressing meat preservation and quality enhancement. The increase in publications after 2020 reflects growing interest in natural and sustainable alternatives to synthetic antioxidants, driven by consumer demand for clean-label products and healthier food systems. The co-occurrence and temporal analyses further demonstrate that research has expanded from the study of phenolic compounds, polysaccharides, and antioxidant mechanisms to the development of practical applications aimed at improving oxidative stability, shelf life, sensory attributes, and nutritional quality of meat products (Banerjee et al., 2020; Hu et al., 2021; Torres et al., 2022; Fu et al., 2023; Vargas et al., 2023; Aziz et al., 2024).

Moreover, the thematic relationships identified through the Sankey diagram indicate a strong convergence between research on mushroom bioactive compounds and their technological implementation in meat systems. Species such as *Pleurotus ostreatus*, *Ganoderma lucidum*, *Agaricus bisporus*, and *Lentinula edodes* have emerged as the most extensively investigated mushrooms due to their high content of antioxidant compounds and their potential to enhance product stability and quality. The prominent contributions of countries such as China, India, and the United States also highlight the global relevance of this research area and suggest increased international collaboration in developing natural preservation strategies.

Overall, the bibliometric evidence indicates that edible mushrooms have evolved from being primarily studied as sources of antioxidant compounds to becoming promising functional ingredients for meat preservation. This transition underscores their potential to support the development of sustainable, high-quality, and consumer-oriented meat products.

3.7. Study characteristics and main findings

The scientific literature demonstrates that edible mushrooms exert multifunctional effects on meat products, improving oxidative stability, sensory performance, and nutritional quality. These effects, although interconnected, follow distinct mechanistic pathways that have been increasingly clarified by recent research (Table SM2).

Across the 60 included studies, sample sizes ranged from 3 to 60, with effect sizes most consistently reported for TBARS, carbonyls, DPPH, ABTS, and FRAP assays. Approximately 78% of studies reported lipid oxidation outcomes, while only 32% quantified protein oxidation markers, revealing a methodological imbalance that limits comprehensive oxidative profiling. The following subsections synthesize the evidence using a critical approach, integrating quantitative outcomes, biochemical mechanisms, and cross-study comparisons. The summarized findings supporting each subsection are presented in Tables SM2, SM3, and SM4 (Supplementary Material 2).

3.8. Oxidative stability enhanced by edible mushrooms

Research consistently shows that incorporating edible mushrooms into meat products results in a marked reduction in lipid and protein oxidation, though the magnitude of the effect varies with species, extraction method, and concentration. As summarized in Table SM3, most studies report significant decreases in TBARS values, frequently between 20% and 40%, and meaningful reductions in protein carbonyl content, indicating a comprehensive antioxidant effect across different meat matrices (Fu et al., 2023; Tokarczyk et al., 2023; Torres et al., 2022). These improvements are scientifically relevant because oxidative deterioration contributes to flavor loss, pigment degradation, and textural decline.

However, the magnitude of the effect varied considerably due to heterogeneity in extraction solvents, mushroom processing methods, matrix composition, and storage conditions. Meta-analysis was not feasible due to inconsistent reporting of variance measures and heterogeneous experimental designs. This variability underscores the need for standardized reporting frameworks in functional-ingredient studies. Mechanistically, mushrooms do not operate as simple reservoirs of phenolics but as structured antioxidant systems whose specific compounds interact directly with meat components. *Pleurotus ostreatus* is particularly notable due to its high ergothioneine content, a thiol-based antioxidant that resists thermal degradation and interrupts metal-catalyzed radical propagation (Valério et al., 2024). This biochemical profile explains its superior performance in delaying lipid oxidation and stabilizing haem pigments during refrigerated storage, as repeatedly demonstrated in pork sausages and patties (Torres et al., 2025). In contrast, *Agaricus bisporus* exerts antioxidant effects mainly through flavonoids and organic acids, which enhance reducing power and promote the regeneration of endogenous antioxidants such as thiols and glutathione, thereby improving color stability and reducing TBARS formation (Nan et al., 2025).

In addition to species effects, the application method of mushrooms strongly influences antioxidant potency. Ethanol extracts consistently show the highest activity, often producing 30% – 60% greater radical-scavenging capacity than aqueous extracts or powdered tissues (Jiang et al., 2015). Powders, however, provide the combined advantage of antioxidant action and water-binding capacity, which indirectly reduces oxidative stress by limiting oxygen diffusion and lipid mobility (Banerjee et al., 2020). Fresh mushrooms exhibit lower antioxidant density but contribute structural improvements that complement chemical mechanisms. Across most studies, optimal antioxidant performance is achieved with 2% – 4% powder inclusion, approximately 10% fresh substitution, or phenolic-rich extracts achieving more than 70% DPPH inhibition; above these thresholds, sensory alterations tend to emerge (Gökmen et al., 2024).

Although evidence for lipid oxidation is abundant, research on protein oxidation remains comparatively scarce. Only a minority of studies quantify protein carbonyls or thiol losses, a deficiency that limits full understanding of oxidative processes affecting texture and water distribution (Shen et al., 2022). Furthermore, digestion studies remain limited, although initial evidence suggests that antioxidant activity increases after gastrointestinal simulation, likely due to enhanced bioaccessibility of phenolic compounds and peptides during proteolysis (Torres et al., 2022). These gaps underscore the need for future mechanistic research.

Taken together, the studies integrated in Table SM4 indicate that edible mushrooms, particularly *P. ostreatus*, *A. bisporus*, *F. velutipes*, and *H. erinaceus*, offer robust and reproducible antioxidant benefits supported by biochemical mechanisms, extract-specific activity, and techno-functional interactions with meat matrices.

3.9. Sensory quality improvements mediated by edible mushrooms

In parallel with their oxidative benefits, the literature presents strong evidence that edible mushrooms improve the sensory attributes of meat products, including texture, juiciness, flavor complexity, and color stability. These effects are summarized in Table 3 and arise from both biochemical and structural interactions between mushroom components and meat proteins. Several studies consistently demonstrate increased water-holding capacity and reduced cooking losses, typically 10% - 20%, in formulations incorporating *Pleurotus ostreatus* powders or extracts (Torres et al., 2022). These improvements reflect the ability of mushroom polysaccharides and fibers to reinforce the protein water matrix, creating a more cohesive gel and enhancing juiciness and tenderness (Banerjee et al., 2020).

Color stability is another frequent sensory improvement. Products enriched with *Agaricus bisporus* retain higher redness (a*) and lightness (L*) during storage due to delayed pigment oxidation, an effect directly linked to the antioxidant mechanisms discussed earlier (Fu et al., 2023). This synergy between sensory and chemical stability highlights the multifunctional nature of mushroom-derived bioactives. Species such as *Flammulina velutipes*, which are rich in β-glucans and phenolics, have demonstrated similar color-preserving effects in sausages and emulsified meats (Hu et al., 2021b).

Flavor enhancement is most pronounced in formulations incorporating species naturally rich in umami-related amino acids and volatile precursors, such as *Coprinus comatus*, *Hericium erinaceus*, and *Pleurotus djamor*. Sensory panel's report improved savoury perception, smoother mouthfeel, and increased aroma complexity associated with fungal-derived volatile compounds and their interactions with Maillard chemistry during cooking (Qu et al., 2023b; Meyer et al., 2023). These attributes are particularly relevant in hybrid meat products, where mushrooms compensate for flavor dilution caused by reduced fat or meat content.

However, sensory benefits are dose-dependent. Concentrations above 30% – 40% fresh substitution or >6% powder can negatively affect texture uniformity and impart earthy or dark notes, particularly in *Agaricus* formulations (Nan et al., 2025). Therefore, precise formulation strategies are required to balance sensory and functional gains.

A notable limitation is that only 14 of the 60 studies incorporated trained sensory panels, and only three included consumer testing. Sample sizes (<30 panelists in most cases) limit the generalizability of sensory outcomes. Future studies should integrate consumer-based sensory methodologies and cross-cultural validation to strengthen external validity.

Overall, the evidence presented in Table MS4 supports the conclusion that edible mushrooms, when incorporated within optimal ranges, reliably enhance sensory quality through mechanisms rooted in matrix structuring, antioxidant protection, and flavor chemistry.

Table 3 summarizes the optimal inclusion levels of edible mushrooms and their derivatives in meat matrices, integrating comparative evidence on functional concentrations, observed benefits, and threshold levels beyond which technological or sensory defects begin to emerge. Across studies, powdered fruiting bodies incorporated at levels of 2% - 4% consistently reduced lipid oxidation and improved water-holding capacity without compromising sensory acceptability (Tokarczyk et al., 2023; Torres et al., 2022, 2025a). Substitution with fresh mushroom tissue up to 10% enhanced juiciness and reduced fat content, although higher replacement rates were associated with color darkening and flavor deviations (Aziz et al., 2024; Fu et al., 2023; Gökmen et al., 2024). Ethanolic extracts exhibited the highest antioxidant potency, frequently achieving DPPH inhibition above 70%, but their application remains constrained by solvent-related and sensory considerations (da Silva et al., 2025; Sezer et al., 2017). Overall, Table 3 establishes evidence-based formulation ranges that balance antioxidant efficacy, techno-functionality, and sensory quality.

3.10. Nutritional quality contributions of edible mushrooms

The nutritional improvements resulting from mushroom incorporation extend beyond simply diluting fat or calories. As shown in Table 4, edible mushrooms provide meaningful improvements in dietary fiber, amino acid composition, lipid quality, and micronutrient density. Studies consistently show increases of 15% to 30% in fiber when mushroom powders or tissues replace part of the meat formulation, yielding products with improved satiety potential and functional gastrointestinal properties (Banerjee et al., 2020b). This fiber increase also contributes to water-holding capacity, indirectly improving texture and moisture retention.

Mushrooms also improve protein quality. In chicken–mushroom formulations, digestibility increases by 10–15%, a result attributed to synergistic interactions between fungal and myofibrillar proteins that promote more efficient enzymatic breakdown (Ali et al., 2022). Species such as *Hericium erinaceus* and *Auricularia cornea* contribute essential amino acids and bioactive peptides with antioxidant and immunomodulatory properties (Khan et al., 2023).

Lipid profile enhancement is another consistent trend. When mushroom oil complexes or mushroom tissues replace part of the fat matrix, the PUFA/SFA ratio increases by 12% – 28%, a nutritionally meaningful shift associated with improved cardiovascular profiles (Nan et al., 2025). Mineral contributions, particularly of zinc, iron, potassium, and selenium, are also significant in wild or specialty species such as Auricularia, Phellinus, and *Termitomyces*, as documented in chemical profiling studies (Sharif et al., 2018). A distinctive nutritional advantage of edible mushrooms is their ergothioneine content, which is low in conventional meats but plays a role in redox homeostasis and cellular protection. Its inclusion through mushroom enrichment contributes an additional layer of nutritional functionality that aligns with contemporary cleanlabel health trends (Valério et al., 2024b).

Despite these strengths, the literature rarely addresses antinutritional factors such as oxalates, chitin, or potential mineral-binding interactions, even though several studies have reported that the chemical composition and cell-wall polysaccharide structure of edible mushrooms may influence mineral bioavailability and protein digestibility. The presence of chitin–glucan complexes and organic acids has been associated with differential mineral retention and binding capacity, which may affect the nutritional interpretation of mushroom-enriched meat products when functional inclusion levels are applied (Heleno et al., 2015a; Reis et al., 2011). The limited attention to these elements represents a methodological gap that should be considered in future nutritional evaluations. Collectively, the evidence synthesized in Table 4 demonstrates that edible mushrooms provide multidimensional nutritional benefits, reinforcing their value as functional ingredients in reformulated meat products.

Table 4 provides a mechanistic mapping of the main bioactive compounds identified in edible mushrooms and links their primary modes of action to functional outcomes observed in meat systems. Ergothioneine, particularly abundant in *Pleurotus ostreatus*, exerts strong antioxidant effects through metal chelation and interruption of radical propagation, resulting in marked reductions in lipid oxidation and enhanced color stability (Tokarczyk et al., 2023; Torres et al., 2022, 2025a) (Torres et al., 2022; Torres et al., 2025; Tokarczyk et al., 2023). β-glucans and other polysaccharides contribute to radical scavenging while simultaneously improving matrix structuring and water retention, leading to improved texture and reduced cooking losses (Aziz et al., 2024; Fu et al., 2023; Gökmen et al., 2024). Phenolic acids, flavonoids, and organic acids further enhance reducing power, modulate redox balance, and stabilize pigments, whereas triterpenoids from *Ganoderma* species display particularly strong antioxidant activity in extract form (da Silva et al., 2025; Sezer et al., 2017; Smolskaite et al., 2015). This table highlights the complementary and synergistic mechanisms underpinning the multifunctional effects of mushroom-derived compounds in meat matrices.

Table 5 outlines the main evidence gaps and methodological limitations identified. A pronounced imbalance is evident in research on lipid and protein oxidation, as only a limited number of studies quantify protein carbonyls or thiol loss, thereby limiting comprehensive oxidative profiling (Tokarczyk et al., 2023; Torres et al., 2022). In addition, compound quantification is frequently disconnected from functional outcomes, precluding dose–response modeling and mechanistic validation (Sezer et al., 2017; Smolskaite et al., 2015). Digestive stability and bioaccessibility of mushroom antioxidants remain poorly explored, despite their relevance for nutritional interpretation (Torres et al., 2022). Antinutritional factors such as oxalates, chitin-related interactions, and potential mineral-binding effects are rarely evaluated, which may lead to unbalanced nutritional claims (Heleno et al., 2015b; Reis, Barros, et al., 2014). These gaps indicate priority areas for future research to strengthen the translational and industrial relevance of mushroom-based formulations.

Table 3
Optimal inclusion levels of mushrooms and extracts in meat matrices

Part of the fungus	Form / Compound	Optimal Concentration	Observed Benefits	Threshold Where Defects Begin	Author
Fruiting body (caps + gills)	Powder	2% – 4%	TBARS ↓ 20% – 30%; WHC ↑ 10% – 15%; acceptable sensory quality	>6% (darkening, texture hardening)	Tokarczyk et al. (2023); Torres et al. (2022); Torres et al. (2025)
Whole fresh fruiting body (pileus + stipe)	Fresh mushroom substitution	Up to 10%	Juiciness ↑, fat ↓, mild antioxidant improvements	>20% – 30% (color, flavor defects)	Fu et al. (2023); Aziz et al. (2024); Gökmen et al. (2024)
Fruiting body tissues (ethanol-soluble phenolic fractions)	Ethanolic extracts	High potency phenolics achieving >70% DPPH	Strongest lipid/protein oxidation protection	Solvent limits; bitterness at high phenolics	Da Silva & Jorge (2011); Sezer et al. (2017); Smolskaite et al. (2015)
Fruiting body fermented (fungal biomass + microbial conversion)	Fermented mushroom preparations	2% – 3% equivalent	Enhanced phenolic release; aroma improvement	Variability in microbial profiles	Jablonska et al. (2016)
Fruiting body blended with oil phase; sometimes with cell-wall fractions	Mushroom–oil complexes	50% – 60% fat replacement	Texture optimized; PUFA/SFA ↑ 25%; TBARS ↓ 30% – 35%	>70% (emulsion instability)	Nan et al. (2025); Wang et al. (2024)
Spent substrate (mycelium-enriched residual biomass)	Spent-substrate extracts	Variable, phenolic-targeted	TBARS ↓ 20% – 28%; color stability ↑	Depends on substrate consistency	Zhu et al. (2018); Mhlongo et al. (2021); Valério et al. (2024)

Table 4
Mechanistic mapping: bioactive compounds based on mechanisms and functional outcomes

Compound Class	Primary Mechanisms	Functional Outcomes in Meat Systems	Representative Species	Part of the fungus	Author
Ergothioneine	Chelates Fe^{2+}/Cu^{2+}; interrupts radical propagation	Strong lipid oxidation delay; stable through cooking & digestion	*Pleurotus ostreatus*	Fruiting body (gills + caps)	Torres et al. (2022); Torres et al. (2025); Tokarczyk et al. (2023)
β-glucans / polysaccharides	Radical scavenging; matrix structuring; water binding	WHC ↑; cooking loss ↓; texture ↑	*Flammulina*, *Pleurotus*, *Hericium*	Cell wall of fruiting body; mycelium	Fu et al. (2023); Aziz et al. (2024); Gökmen et al. (2024)
Phenolic acids	Hydrogen donation; redox cycling; metal chelation	TBARS ↓20% – 40%; color stability ↑	*Agaricus*, *Lentinula*	Fruiting body; ethanol extracts	Sezer et al. (2017); Smolskaite et al. (2015); Da Silva & Jorge (2011)
Flavonoids	Reducing power; synergy with amino acids	Color protection; protein oxidation ↓	*Agaricus bisporus*	Fruiting body; peel-rich fractions	Aziz et al. (2024); Gökmen et al. (2024)
Organic acids	pH modulation; microbial inhibition	Enhanced shelf-life; lipid stability ↑	*Agaricus*, *Pleurotus*	Fruiting body	Fu et al. (2023); Aziz et al. (2024)
Triterpenoids	Strong redox behavior; antimicrobial	High antioxidant capacity (>85% DPPH)	*Ganoderma* spp.	Carpophore + mycelium	Smolskaite et al. (2015); Sezer et al. (2017)
Umami amino acids (Glu, Asp)	Flavor enhancement; synergy with nucleotides	Sensory acceptance ↑	*Pleurotus*, *Flammulina*	Fruiting body (caps + gills)	Torres et al. (2022); Gökmen et al. (2024)

Table 6 integrates the critical factors that modulate the antioxidant, sensory, and nutritional effects of edible mushrooms in meat products, including species selection, ingredient format, and processing conditions. Comparative evidence indicates that *Pleurotus ostreatus*, *Agaricus bisporus* and *Flammulina velutipes* consistently provide the strongest antioxidant effects due to their high phenolic content, ergothioneine levels and β-glucan density (Aziz et al., 2024; Fu et al., 2023; Gökmen et al., 2024; Tokarczyk et al., 2023; Torres et al., 2022). Extracts maximize antioxidant potency, whereas powders and fresh tissues offer superior techno-functional and sensory performance, highlighting the need to align ingredient format with formulation objectives (da Silva et al., 2025; Jablonska et al., 2016; Nan et al., 2025; Smolskaite et al., 2015). Processing methods such as fermentation, freeze-drying and irradiation further modulate bioactive availability and functional performance, underscoring the importance of processing–ingredient interactions (Sezer et al., 2017; Tokarczyk et al., 2023). Collectively, Table 6 provides an integrative framework that links experimental evidence to practical decision-making for clean-label meat reformulation.

3.11. Advances and emerging trends in mushroom-derived antioxidants for meat reformulation

The combined evidence from the systematic and bibliometric analyses converges on three emerging trends that delineate the trajectory of this research field. First, the literature is moving from descriptive evaluations of antioxidant capacity towards mechanistic studies that link compound classes (ergothioneine, β-glucans, phenolic acids, flavonoids, organic acids, and triterpenoids) to specific oxidative endpoints in meat matrices. Tables 5 and 6 consolidate this shift by showing where the evidence is robust (lipid oxidation in pork patties and emulsified sausages reformulated with *Pleurotus ostreatus* and *Agaricus bisporus*) and where critical gaps remain (protein-oxidation markers, in vitro digestion, and pilot-plant validation). Second, ingredient format is increasingly recognized as a determinant of functional performance. Powders favor technological functionality, ethanol extracts favor antioxidant potency, and fermented or mycelium-based preparations open new avenues for clean label formulations, although standardization of these formats is still incipient. Third, the bibliometric evidence indicates that research is gradually shifting from East Asian and European centers towards a more globally distributed network of authors and institutions, with growing contributions from Latin American groups working on circular-economy applications, such as the use of spent substrates and agro-industrial by-products for mushroom cultivation. Taken together, these advances support a transition from screening fungal antioxidants to rationally designed mushroom-based antioxidant systems for meat reformulation, with explicit consideration of mechanism, format, matrix interactions, and digestive fate.

Table 5
Evidence gaps and limitations in current research

Research Area	Evidence Gap Identified	Implications	Priority for Future Studies
Protein oxidation	Very few studies quantify carbonyls or thiol loss	Incomplete oxidative profile	High priority
Compound quantification	Lack of phenolic/flavonoid quantification linked to outcomes	No dose–response modeling	High
Mechanisms in meat matrices	Interactions with proteins/lipids are largely inferential	Limits the mechanistic conclusiveness	High
Digestive stability	Rare in vitro digestion studies	Poor understanding of bioaccessibility	High
Antinutritional factors	Neglected (oxalates, chitin effects)	Unbalanced nutritional claims	Moderate
Long-term storage	Most studies ≤15–21 days	Limited industrial relevance	Moderate–High
Consumer sensory testing	Few real consumer panels	Weak generalizability	Moderate
Industrial-scale trials	No pilot-plant applications	Unknown scalability	Critical gap

Table 6
Summary of critical factors influencing the antioxidant, sensory, and nutritional effects of edible mushrooms in meat products

Thematic	Authors	Factor evaluated	Comparative findings across studies	Implications for meat systems
Species differences	Torres et al. (2022); Fu et al. (2023); Aziz et al. (2024); Tokarczyk et al. (2023); Gökmen et al. (2024); Sezer et al. (2017)	Species differences	*P. ostreatus*, *A. bisporus*, and *F. velutipes* show the highest phenolics, ergothioneine, β-glucans, and the strongest DPPH/ABTS inhibition.	Superior lipid/protein oxidation control; candidates for functional formulation.
Ingredient format (fresh, powder, extract, mycelium)	Da Silva & Jorge (2011); Smolskaite et al. (2015); Jablonska et al. (2016); Torres et al. (2025); Nan et al. (2025)	Ingredient format (fresh, powder, extract, mycelium)	Extracts = highest antioxidant potency; powders/tissues = best techno-functionality; mycelium = high antioxidant yield but limited standardization.	The optimal choice depends on the target: oxidative stability vs. texture/emulsion performance.
Processing effects (drying, fermentation, irradiation)	Jablonska et al. (2016); Smolskaite et al. (2015); Sezer et al. (2017); Tokarczyk et al. (2023)	Processing effects (drying, fermentation, irradiation)	Freeze-drying preserves 25% – 40% more phenolics; fermentation increases phenolic acids 20% – 35%; irradiation enhances β-glucan synthesis 25% – 35%.	Processing modulates antioxidant availability; fermentation and freeze-drying show the strongest enhancement.
Matrix interactions with meat proteins and lipids	Torres et al. (2022); Torres et al. (2025); Gökmen et al. (2024); Fu et al. (2023); Nan et al. (2025)	Matrix interactions with meat proteins and lipids	Mushroom polysaccharides improve WHC and emulsion stability; phenolics and ergothioneine reduce TBARS 20% – 35% and protein carbonyls 15% – 25%.	Synergistic effects extend shelf life and maintain color/texture stability.
Digestive stability and bioaccessibility	Zhu et al. (2018); Mhlongo et al. (2021); Valério et al. (2024)	Digestive stability and bioaccessibility	Few studies report post-digestion data; in vitro digestion often increases phenolic release by ~30%.	Post-digestive antioxidant effects remain understudied but suggest promising bioactivity.
Nutritional and sensory outcomes	Fu et al. (2023); Aziz et al. (2024); Gökmen et al. (2024); Torres et al. (2022)	Nutritional and sensory outcomes	Mushrooms increase PUFA/SFA ratios, reduce energy density (9% – 16%), and improve sensory acceptance at moderate inclusion levels.	Enable healthier formulations with minimal sensory trade-offs.
Knowledge gaps identified	Across all authors in dataset, especially Smolskaite et al. (2015); Torres et al. (2025); Nan et al. (2025)	Knowledge gaps identified	Limited data on protein oxidation; inconsistent reporting of phenolic quantification; scarce digestion models; lack of species–form comparative trials.	Research must shift from descriptive to mechanistic, standardized analyses.

Figure 7 organizes these emerging directions into four research axes: mechanisms, technology, ingredient formats, and consumer perception. The mechanisms axis captures the shift from descriptive antioxidant screening towards mechanistic studies that link specific compound classes to oxidative endpoints in the meat matrix; an open question that crosses this axis is why caps and stipes of the same species can perform differently as antioxidant sources, as reported by Coaguila Gonza et al. (2026) for Pleurotus ostreatus extracts in beef burgers. The technology axis consolidates evidence reviewed by Parí et al. (2025) on emerging green extraction methods, including pressurized liquid extraction, supercritical CO_2, ultrasound, and microwave-assisted extraction. The formats axis highlights the valorization of underexploited fractions, such as the stipe, which accounts for 25% to 33% fresh mushroom weight. Finally, the consumer axis builds on the research agenda articulated by Saldaña and Rios-Mera (2025), and on the social-representation evidence reported by Patinho et al. (2021).

The diagram is organized as a radial layout with a central core labeled FUTURE RESEARCH and four quadrants connected to it by dashed lines. The upper-left quadrant (MECHANISMS) shows a phenolic structure releasing a free radical and the molecular targets affected, namely protein carbonyls, myoglobin, and other oxidative endpoints, expressing the open mechanistic questions that remain in the field. The upper-right quadrant (TECHNOLOGY) depicts the four families of green extraction methods reviewed in the corpus, namely pressurized liquid extraction, supercritical CO_2 extraction, ultrasound, and microwave-assisted extraction, drawn with their characteristic equipment silhouettes. The lower-left quadrant (FORMATS) shows the four functional ingredient formats, namely extract, powder, mycelium, and flour, plus a transformation arrow that explicitly highlights the valorization of the stipe fraction (25 to 33 percent of the fresh mushroom weight).

The lower-right quadrant (CONSUMER) integrates a brain icon for consumer neuroscience, three hedonic faces for emotional response, and a panel of three people with a clean-label tag, capturing the multidisciplinary dimensions required to bridge laboratory antioxidant performance and consumer perception. Together, the four axes shown in Figure 7 frame a coherent research agenda for the next decade of mushroom-derived antioxidants applied to meat products.

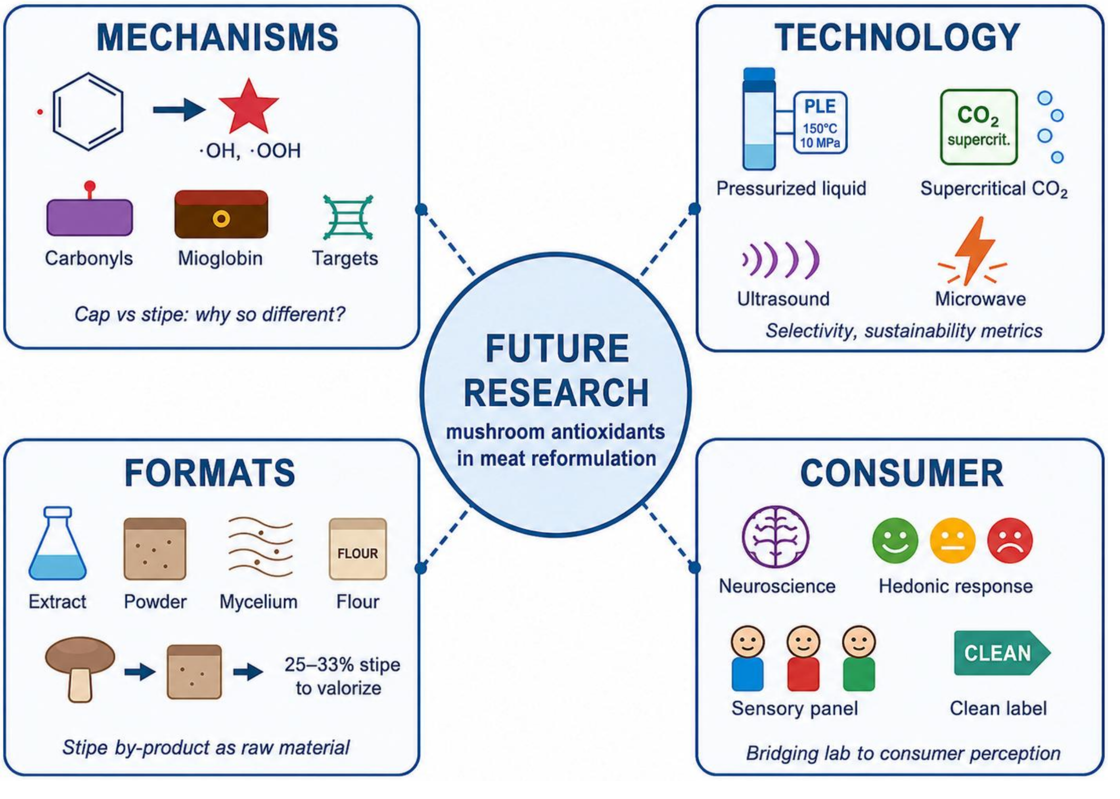


Figure 7. Future research directions in mushroom-derived antioxidants for meat reformulation.

4. Conclusions

The evidence synthesized in this review demonstrates that edible mushrooms constitute a technologically relevant and mechanistically active source of natural antioxidants that can improve the oxidative stability, sensory performance, and nutritional quality of meat products. Species such as *Pleurotus ostreatus*, *Agaricus bisporus*, *Flammulina velutipes*, *Lentinula edodes*, and *Tremella fuciformis* consistently reduce lipid and protein oxidation through complementary biochemical mechanisms involving phenolic acids, flavonoids, ergothioneine, and structurally diverse β-glucans. These compounds interact with meat proteins and lipids through radical scavenging, metal chelation, and stabilization of interfacial protein–water structures, producing measurable protection under chilled, frozen, and thermally processed conditions.

The findings of this review confirm that edible mushrooms provide a mechanistically diverse set of antioxidant compounds that can mitigate oxidative deterioration in meat products. However, the strength of evidence varies substantially across oxidative outcomes, species, and ingredient formats. While lipid oxidation reduction is well supported, protein oxidation remains underexamined, and dose-response modeling is largely absent. These limitations must be considered when interpreting the technological and nutritional benefits of mushroom incorporation.

Beyond confirming their antioxidant efficacy, findings highlight that mushroom-derived effects are strongly dependent on species and ingredient format. Extracts generally exhibit higher phenolic content and greater immediate antioxidant activity, while powders and whole tissues provide additional techno-functional benefits, such as improved emulsion stability, water-holding capacity, and color retention, suggesting synergistic interactions between antioxidant molecules and the meat matrix. Mycelium-based ingredients also show promising bioactivity but require further standardization before industrial application. Despite substantial progress, notable research gaps remain. Protein oxidation endpoints are still less frequently measured than lipid oxidation, limiting the understanding of how mushroom compounds protect structural proteins during processing and storage. Likewise, studies assessing bioaccessibility and post-digestive stability of mushroom antioxidants in meat systems are scarce, preventing clear conclusions about their nutritional contribution beyond processing. Mechanistic work on compound matrix interactions, particularly involving mushroom polysaccharides and myofibrillar proteins, is also urgently needed. Additionally, comparative evaluations across species, extraction methods, and incorporation formats remain insufficient to determine which combinations offer optimal technological performance.

Overall, edible mushrooms show strong potential as clean-label antioxidant systems for meat products, offering a scientifically grounded alternative to synthetic additives. Advancing this field will require integrated studies that couple molecular characterization with meat-model experimentation, standardized oxidation biomarkers, and in vitro digestion approaches. Strengthening the mechanistic and techno-functional evidence base will be critical for enabling rational formulation strategies and supporting the broader adoption of mushroom-based ingredients in the meat industry.

Taken together, these findings underscore that the antioxidant performance of edible mushrooms in meat systems depends not only on their biochemical richness but also on their interactions with the matrix's structural and oxidative environment. The comparative evidence across studies reveals heterogeneous yet convergent patterns: extracts exhibit the highest phenolic density and immediate radical-scavenging activity, powders and whole tissues enhance techno-functional stability, and species such as *Pleurotus ostreatus* and *Agaricus bisporus* consistently outperform others in reducing both lipid and protein oxidation. This integrative mapping highlights the need for a mechanistic framework that links molecular composition, processing form, and matrix interactions, particularly during storage and gastrointestinal digestion. Strengthening the analytical depth of future studies, including standardized protein-oxidation markers, digestion models, and comparisons across species forms, will be essential for translating mushroom bioactives into rationally designed, clean-label antioxidant systems for the meat industry.

Another critical gap identified is the limited mechanistic elucidation of how mushroom polysaccharides, phenolics, and sulfur-containing antioxidants interact with meat proteins during storage and cooking. Few studies apply molecular tools such as FTIR, Raman spectroscopy, or LC-MS to characterize these interactions. Incorporating such analytical approaches would significantly strengthen causal explanations regarding oxidation control.

Future research should prioritize standardized reporting of oxidative markers, cross-species comparative trials, gastrointestinal digestion models, and pilot-plant validation of mushroom-based antioxidant systems. Establishing these methodological pillars will be essential to translate laboratory findings into industrially scalable, clean-label preservation strategies for meat products.

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