

NANOFORMULATIONS OF MUSHROOM EXTRACTS: POTENTIAL FOR CLEAN-LABEL FOOD ADDITIVES

Monika Stojanova¹, Marina S.T. Stojanova², Dragutin A. Djukic³, Leka Mandic³,
Blazo Lalevic⁴

¹Association for Scientific-research, Educational and Cultural Activities “Open Science”,
Ohrid, North Macedonia (ORCID: 0000-0002-6525-7099)

²University of Ss. Cyril and Methodius, Faculty of Agricultural Sciences and Food, Skopje,
North Macedonia (ORCID: 0000-0002-6941-3386)

³University of Kragujevac, Faculty of Agronomy, Cacak, Serbia (ORCID: 0000-0002-
8454-4384; 0000-0002-6364-7122)

⁴Univeraity of Belgrade, Faculty of Agriculture, Serbia (ORCID: 0000-0003-0285-1645)

* Correspondence: stojanova.monika@yahoo.com

ABSTRACT

The increasing consumer demand for clean-label food products has intensified the search for natural alternatives to synthetic food additives. Conventional additives, although effective, are often associated with negative consumer perception and potential health concerns, driving the food industry toward natural, sustainable, and multifunctional ingredients. Edible and medicinal mushrooms represent a promising source of bioactive compounds, including β -glucans, phenolic compounds, polysaccharides, and terpenoids, which exhibit antioxidant, antimicrobial, and immunomodulatory properties relevant to food applications. However, the practical use of mushroom extracts as food additives is limited by their low stability, poor solubility, and reduced bioavailability when applied in complex food matrices.

Nanotechnology-based delivery systems have emerged as an innovative approach to overcome these limitations. Nanoformulations such as nanoemulsions, nanoliposomes, and polymer-based nanoparticles enable the encapsulation and protection of sensitive bioactive compounds, enhancing their stability, controlled release, and functional efficacy. Moreover, the use of food-grade and naturally derived encapsulating materials aligns well with clean-label requirements.

This review provides a comprehensive overview of bioactive compounds derived from edible and medicinal mushrooms, current extraction strategies, and recent advances in nanotechnology-based formulations. Particular emphasis is placed on the potential application of mushroom nanoextracts as clean-label food additives with antioxidant and antimicrobial functions, as well as their role in extending shelf life and improving functional properties of food products. Safety considerations and regulatory challenges associated with the use of nanomaterials in foods are also discussed. Overall, mushroom-based nanoformulations represent a promising and sustainable strategy for the development of next-generation clean-label food additives, although further research is required to support their industrial application and regulatory approval.

Keywords: nanoformulations, mushroom extracts, clean-label, food additives, bioactive compounds.

INTRODUCTION

Food additives play a crucial role in the modern food industry by enhancing product quality, safety, stability, and sensory attributes. They are widely used to prevent microbial spoilage, delay oxidative degradation, and improve texture, color, and flavor. However, the extensive use of synthetic additives has raised growing concerns among consumers due to their artificial origin, potential adverse health effects, and negative impact on product transparency (Awulachew, 2021; Wu et al., 2022). As a result, there is an increasing demand for clean-label food products formulated with natural, minimally processed, and recognizable ingredients (Stojanova et al., 2025).

In response to this trend, natural bioactive compounds derived from plants, algae, and fungi have gained significant attention as alternatives to synthetic food additives. Among these sources, edible and medicinal mushrooms stand out due to their rich chemical composition and long history of safe consumption (Kour et al., 2022). Mushrooms are known to contain a wide range of biologically active compounds, including β -glucans, polysaccharides, phenolic compounds, terpenoids, and proteins, which exhibit antioxidant, antimicrobial, anti-inflammatory, and immunomodulatory activities (Stojanova, 2021). These functional properties make mushroom-derived compounds particularly attractive for food preservation and functional food applications.

Despite their potential, the application of conventional mushroom extracts in food systems remains limited. Many bioactive compounds are sensitive to environmental conditions such as heat, light, oxygen, and pH, leading to reduced stability during food processing and storage. Furthermore, poor water solubility and low bioavailability can significantly diminish their effectiveness in complex food matrices (Bains et al., 2021; Michalska et al., 2025).

Nanotechnology-based delivery systems offer a promising strategy to overcome these limitations. Nanoformulations can protect bioactive compounds from degradation, improve their dispersibility and controlled release, and enhance functional performance while enabling the use of food-grade and naturally derived encapsulation materials compatible with clean-label principles (Nisar and Wan, 2025; Stojanova et al., 2025a; Hao et al., 2026). The aim of this review is to critically summarize the bioactive compounds present in edible and medicinal mushrooms, discuss current extraction and nanoformulation strategies, and evaluate their potential application as clean-label food additives, while highlighting safety, regulatory challenges, and future research directions.

BIOACTIVE COMPOUNDS IN EDIBLE AND MEDICINAL MUSHROOMS

Edible and medicinal mushrooms are widely recognized as rich sources of structurally diverse bioactive compounds that contribute to their nutritional, therapeutic, and functional properties. These compounds are responsible for many biological activities relevant to food preservation and functional food development, positioning mushrooms as promising candidates for natural food additives (Stojanova et al., 2024).

β -Glucans

β -Glucans are among the most studied bioactive components in mushrooms. They are polysaccharides composed mainly of β -(1 $\rightarrow$ 3) and β -(1 $\rightarrow$ 6) glycosidic linkages and are abundant in the cell walls of many edible and medicinal species such as *Lentinula edodes*, *Pleurotus ostreatus*, and *Ganoderma lucidum*. β -Glucans exhibit strong immunomodulatory

activity and have also been reported to possess antioxidant and antimicrobial properties, which are highly relevant for improving food stability and safety (Flores et al., 2024).

Phenolic Compounds

Phenolic compounds, including phenolic acids and flavonoid-like structures, are important contributors to the antioxidant capacity of mushroom extracts. These compounds act as free radical scavengers and metal chelators, thereby inhibiting lipid oxidation in food systems. The phenolic content and composition vary significantly depending on mushroom species, cultivation conditions, and extraction methods (Fogarasi et al., 2024).

Polysaccharides and Proteins

In addition to β -glucans, mushrooms contain other polysaccharides and glycoproteins with demonstrated bioactivities. Mushroom-derived polysaccharides have been associated with antioxidant, antimicrobial, and prebiotic effects, while certain bioactive proteins and peptides contribute to antimicrobial and enzyme-inhibitory activities (Ionescu et al., 2025).

Terpenoids and Other Secondary Metabolites

Medicinal mushrooms are particularly rich in terpenoids, sterols, and other secondary metabolites. These compounds have shown antimicrobial, anti-inflammatory, and antioxidant effects, enhancing the functional value of mushroom extracts in food applications (Mwangi et al., 2022).

Functional Properties Relevant to Food Applications

Collectively, mushroom-derived bioactive compounds exhibit antioxidant, antimicrobial, and immunomodulatory activities, making them suitable candidates for natural food preservation, shelf-life extension, and the development of clean-label functional foods. However, their effective utilization in food systems requires strategies to enhance their stability and functionality, which can be achieved through advanced extraction and nanoformulation approaches (Stojanova et al., 2024a; Michalska et al., 2025).

EXTRACTION OF BIOACTIVE COMPOUNDS FROM MUSHROOMS

The extraction of bioactive compounds from edible and medicinal mushrooms is a critical step that directly influences the yield, composition, and functionality of the resulting extracts. Conventional extraction methods, such as hot water extraction, organic solvent extraction, and Soxhlet extraction, are commonly employed due to their simplicity and widespread availability (Stojanova et al., 2024a). Hot water extraction is particularly effective for isolating polysaccharides and β -glucans, while organic solvents are often used to recover phenolic compounds and terpenoids (Parí et al., 2025).

In recent years, growing environmental concerns and clean-label requirements have driven the development of green extraction technologies. Techniques such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and supercritical fluid extraction have gained attention due to their reduced solvent consumption, shorter extraction times, and improved efficiency. These approaches can enhance the recovery of sensitive bioactive compounds while minimizing thermal degradation and environmental impact (Nair et al., 2026).

Despite these advances, several limitations remain. Mushroom extracts often suffer from poor stability when exposed to oxygen, light, heat, and varying pH conditions encountered

during food processing and storage (Wen et al., 2025). Additionally, low water solubility and limited dispersibility of certain bioactive compounds can restrict their effectiveness in food matrices. These challenges highlight the need for innovative strategies to protect and deliver mushroom-derived bioactives in food systems (Chellamboli et al., 2025).

Consequently, the integration of extraction techniques with nanotechnology-based delivery systems has emerged as a promising approach to improve the stability, solubility, and functional performance of mushroom extracts, facilitating their application as clean-label food additives (Nisar et al., 2025).

Nanoformulations of Mushroom Extracts

The incorporation of nanotechnology into food systems has opened new opportunities for improving the delivery and functionality of natural bioactive compounds. Mushroom extracts, although rich in health-promoting molecules, often exhibit limited technological applicability due to their instability, low solubility, and reduced efficacy under food processing and storage conditions. Nanoformulation strategies provide an advanced approach to address these challenges by enabling the protection, controlled release, and enhanced interaction of mushroom-derived bioactives within food matrices (Tarahi et al., 2026)

Rationale for Nanoformulation of Mushroom Extracts

Mushroom bioactive compounds are highly susceptible to degradation caused by environmental factors such as oxygen, light, temperature, and pH fluctuations. Phenolic compounds and terpenoids are particularly prone to oxidative degradation, while polysaccharides may undergo structural modifications during thermal processing (Stojanova et al., 2021a). Additionally, the heterogeneous composition of food matrices can limit the dispersion and bioactivity of conventional extracts. Nanoformulation allows for the physical entrapment or molecular association of these compounds within protective carrier systems, thereby preserving their functional integrity and enhancing their effectiveness at lower concentrations (Pateiro et al., 2021).

Nanoemulsions

Nanoemulsions are colloidal systems characterized by droplet sizes typically below 200 nm, resulting in high surface area and improved kinetic stability. In food applications, nanoemulsions are particularly attractive due to their optical transparency, enhanced dispersibility, and compatibility with aqueous systems. When applied to mushroom extracts, nanoemulsions facilitate the incorporation of lipophilic bioactives, such as terpenoids and sterols, into water-based food products (Dhasmana et al., 2025).

From a functional perspective, the reduced droplet size increases the interaction between encapsulated bioactives and reactive species, leading to enhanced antioxidant and antimicrobial activities. Furthermore, nanoemulsions can improve the uniform distribution of mushroom extracts within food matrices, reducing localized concentration gradients and minimizing negative sensory impacts (Nikita and Agnihotri, 2025).

Nanoliposomes

Nanoliposomes are vesicular systems composed of phospholipid bilayers capable of encapsulating both hydrophilic and lipophilic compounds. Their structural similarity to biological membranes makes them highly effective carriers for mushroom-derived phenolics, polysaccharides, and protein fractions. Nanoliposomes provide a physical barrier

against environmental stressors, significantly improving the stability of sensitive compounds during processing and storage. In addition to protection, nanoliposomes enable controlled and sustained release of bioactives, which is particularly relevant for long-term preservation and shelf-life extension of food products. However, their stability can be influenced by factors such as lipid oxidation and aggregation, highlighting the need for optimization using food-grade stabilizers (Mankan et al., 2025).

Polymeric and Biopolymer-Based Nanoparticles

Polymeric nanoparticles, especially those derived from natural biopolymers, have attracted growing interest in clean-label food applications. Polysaccharides such as chitosan, alginate, and starch, as well as protein-based carriers, offer biodegradability, biocompatibility, and regulatory acceptance (Yudishter et al., 2024). These systems allow for tailored release profiles and improved adhesion to food components, enhancing the functional performance of mushroom extracts.

Notably, biopolymer-based nanoparticles can exhibit synergistic effects, as the encapsulating material itself may contribute antioxidant or antimicrobial activity. This multifunctionality is highly desirable for clean-label formulations, where ingredient simplicity is essential (Jafari et al., 2025).

Comparative Advantages and Technological Challenges

Compared to conventional extracts, nanoformulated mushroom bioactives demonstrate superior stability, enhanced solubility, and improved functional efficacy at reduced dosages. This not only enhances food quality and safety but also minimizes sensory alterations. Nevertheless, challenges remain related to large-scale production, cost-effectiveness, and long-term stability. Addressing these issues is essential for successful industrial implementation (Törös et al., 2025).

POTENTIAL OF MUSHROOM NANOEXTRACTS AS CLEAN-LABEL FOOD ADDITIVES

The application of nanoformulated mushroom extracts in food systems represents a promising strategy to meet the growing consumer demand for clean-label products. By combining the natural bioactivity of mushrooms with nanotechnology, these extracts can perform multiple functional roles, including antioxidant, antimicrobial, and shelf-life enhancing effects, while maintaining sensory quality and complying with natural ingredient requirements (Törös et al., 2025; Stojanova et al., 2025).

Antioxidant Function

Oxidative degradation significantly affects the quality, shelf-life, and nutritional value of food products, especially those rich in lipids, such as meat, dairy, and bakery items. Phenolic compounds, β -glucans, and terpenoids derived from mushrooms exhibit strong antioxidant activity, which can be further enhanced when incorporated into nanoformulations. These nanoformulated compounds show improved radical scavenging capacity and greater stability under processing conditions. For example, when mushroom extracts are nanoemulsified, they can be uniformly dispersed in lipid-based systems, enhancing their interaction with free radicals and effectively delaying lipid oxidation. Studies have demonstrated that such formulations can reduce lipid peroxidation and help maintain color stability in meat products during refrigerated storage, illustrating their potential as natural antioxidant additives (Ba et al., 2016).

Antimicrobial Function

Microbial spoilage poses a significant challenge for perishable foods. Bioactive compounds from mushrooms, such as polysaccharides, phenolics, and protein fractions, have demonstrated antimicrobial activity against both Gram-positive and Gram-negative bacteria. The efficacy of these compounds can be further enhanced through nanoformulation, which improves bioavailability, enables controlled release, and promotes more effective interaction with microbial cells. For instance, nanoliposome-encapsulated *Ganoderma lucidum* extracts have been shown to inhibit the growth of *Listeria monocytogenes* and *Escherichia coli* in dairy products, highlighting their potential as natural preservatives (Kumar et al., 2021).

Shelf-Life Extension and Functional Enhancement

By combining antioxidant and antimicrobial properties, mushroom-derived nanoextracts can substantially extend the shelf-life of a wide range of food products. Encapsulation further enhances their functionality by enabling controlled release of bioactives, maintaining activity throughout storage (Kumar et al., 2021). Beyond preservation, these nanoformulations can improve functional food attributes, including immunomodulatory and prebiotic effects, without affecting taste, texture, or appearance. In bakery applications, for example, nanoemulsions of *Pleurotus ostreatus* polysaccharides incorporated into bread formulations have been found to enhance dough stability, slow staling, and provide minor antioxidant benefits, illustrating their dual functionality in supporting both quality and health-promoting properties (Liufang et al., 2024).

Advantages for Clean-Label Formulation

Mushroom nanoextracts align with the principles of clean-label products for several reasons (Chauhan and Rao, 2024).

1. **Natural origin:** Derived entirely from edible or medicinal mushrooms.
2. **Reduction of synthetic additives:** Can partially or fully replace conventional preservatives or antioxidants.
3. **Multi-functionality:** Single ingredient provides multiple technological and health-related benefits.
4. **Compatibility with food matrices:** Nanoformulations enable uniform distribution and minimal sensory impact.

Limitations and Considerations

Despite their potential, practical application of mushroom nanoextracts faces challenges. Scale-up production, long-term stability under diverse processing conditions, and regulatory approval for nanomaterials in foods remain critical issues. Additionally, the interaction of nanoformulated extracts with complex food matrices can affect bioactivity, requiring systematic optimization for each food system.

SAFETY AND REGULATORY ASPECTS

The incorporation of nanoformulated mushroom extracts into food systems raises important safety and regulatory considerations that must be addressed prior to industrial implementation. While mushrooms are generally recognized as safe (GRAS) and have a long history of dietary consumption, nanotechnology introduces novel physicochemical properties that may alter bioavailability, gastrointestinal absorption, and potential toxicity (Stojanova et al., 2024a).

Safety Considerations of Nanomaterials

Nanoparticles, due to their small size (<100 nm in many cases) and high surface area, can interact with biological membranes differently from conventional macroscopic particles. Potential safety concerns include (Arshad, et al., 2021):

1. **Enhanced absorption and bioavailability:** While beneficial for functional activity, increased absorption may lead to unexpected systemic exposure.
2. **Toxicological effects:** Depending on the material and particle size, some nanocarriers may induce oxidative stress, inflammatory responses, or cellular uptake beyond intended targets.
3. **Food matrix interactions:** Nanoparticles may interact with other food components, affecting digestibility, bioactivity, or stability.

Current evidence suggests that nanoencapsulation using food-grade materials such as proteins, polysaccharides, and lipids generally presents low toxicity. However, comprehensive in vitro and in vivo studies are required to confirm safety for long-term consumption and across diverse population groups.

Regulatory Landscape

Regulatory frameworks for nanomaterials in food vary globally and are still evolving:

- **European Union (EU):** The European Food Safety Authority (EFSA) requires a thorough risk assessment of engineered nanomaterials in food, including physicochemical characterization, toxicological evaluation, and potential exposure. Novel foods containing nanomaterials must undergo pre-market authorization (European Commission, 2026).
- **United States (FDA):** The FDA evaluates nanomaterials on a case-by-case basis under existing food additive regulations. While there is no specific nano-approval, manufacturers are expected to provide safety data demonstrating equivalence or novel risk assessment.
- **Other regions:** Canada, Japan, and Australia have issued guidance documents emphasizing characterization, toxicology, and labeling considerations.

Labeling and Consumer Transparency

Clean-label principles emphasize ingredient recognition and minimal processing. The use of nanotechnology in food, although enabling natural bioactive delivery, may require careful labeling to ensure transparency and maintain consumer trust. Clear communication regarding the natural origin of the bioactive compound and the safety of the nanoformulation is essential (Mohammad et al., 2022).

Research Gaps

Despite promising results, several knowledge gaps remain:

1. Long-term safety and chronic exposure studies of nanoformulated mushroom extracts.
2. Standardized methods for characterization, stability, and bioavailability assessment of nanoformulations in complex food matrices.
3. Interaction studies with other food components to predict functional efficacy and potential adverse effects.

Addressing these gaps is critical for regulatory approval, consumer acceptance, and safe industrial application of mushroom-based nanoadditives.

CONCLUSION

Nanoformulations of edible and medicinal mushroom extracts represent a highly promising strategy for the development of clean-label food additives. By combining the inherent bioactivity of mushroom-derived compounds with advanced nanotechnology, these systems overcome major limitations of conventional extracts, including low solubility, instability, and reduced bioavailability. Nanoemulsions, nanoliposomes, and polymer-based nanoparticles have demonstrated significant potential to enhance antioxidant, antimicrobial, and functional properties, while maintaining compatibility with diverse food matrices.

The multifunctionality of mushroom nanoextracts offers a distinct advantage for clean-label applications, enabling reduction or replacement of synthetic additives, extending product shelf-life, and contributing health-promoting properties without negatively impacting sensory qualities. Furthermore, the use of naturally derived encapsulating materials ensures compliance with consumer expectations for transparency and minimal processing.

Despite these promising developments, several challenges must be addressed before widespread industrial adoption. These include large-scale production and formulation optimization, comprehensive safety assessment, long-term stability evaluation, and regulatory approval. Additional research is needed to standardize extraction and nanoformulation methods, elucidate mechanisms of bioactive delivery in complex food matrices, and assess consumer perception and acceptance.

In conclusion, mushroom-based nanoformulations constitute a sustainable and versatile platform for the next generation of natural food additives. Their integration into food systems aligns with current trends toward functional, safe, and clean-label products. Continued interdisciplinary research bridging food science, nanotechnology, and regulatory science is essential to unlock their full potential and facilitate industrial implementation.

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