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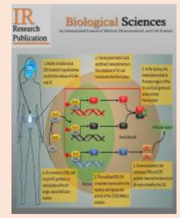

Advances in Mushroom Chitosan Biorefinery and Its Applications in Food Engineering: A Sustainable Approach to Food Preservation and Quality Enhancement

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ABSTRACT

Mushroom-derived chitosan has gained recognition in food engineering due to its numerous advantages over conventional crustacean-derived chitosan, including enhanced biocompatibility, sustainability, and allergen-free properties. Various extraction methods, such as enzymatic, chemical, and green techniques, have been explored, each with distinct advantages and limitations regarding yield, quality, and environmental impact. This study highlights the antimicrobial, antioxidant, and film-forming properties of mushroom chitosan, positioning it as a valuable material for food preservation, packaging, and functional food applications. Despite challenges in optimizing extraction methods and scaling production, the ecological and economic benefits of mushroom chitosan make it a promising alternative to synthetic and animal-derived materials. The findings underscore its potential to contribute to more sustainable food systems by replacing synthetic plastics and chemical preservatives, reducing food waste, and promoting eco-friendly packaging solutions. Future research should focus on optimizing extraction methods for higher yields and quality, enhancing functionalization techniques for specific food applications, and exploring new applications in nutraceuticals and functional foods. Moreover, further research is needed to address scalability challenges and assess the environmental and economic impacts of mushroom chitosan in large-scale industrial applications.

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Introduction

Chitosan is a versatile biopolymer produced by the deacetylation of chitin, one of the most abundant natural polymers, which is primarily found in the exoskeletons of crustaceans, insects, and fungi, including certain mushrooms [1]. This biopolymer has attracted significant interest due to its unique physicochemical properties, such as biocompatibility, biodegradability, and non-toxic nature, which make it suitable for a variety of applications in industries like agriculture, biomedicine, and especially food engineering [2]. The most common commercial source of chitosan has been crustaceans, but the reliance on crustaceans raises issues related to allergenicity and environmental sustainability, as crustacean harvesting and processing generate significant waste and have a large ecological footprint [3]. As a result, researchers are turning toward alternative sources like mushrooms, which provide a more sustainable, plant-based method of chitosan production. Mushroom-derived chitosan not only eliminates allergenic risks associated with crustaceans but also aligns well with eco-friendly production goals due to mushrooms' lower resource requirements and lower environmental impact [4].

In food engineering, chitosan from mushrooms has emerged as a particularly valuable resource due to its excellent antimicrobial, antioxidant, and film-forming properties. These properties make it ideal for applications such as food preservation, where natural antimicrobial agents are in demand, and food packaging, where biodegradable alternatives are preferred over plastics [5]. Mushroom-derived chitosan can effectively inhibit the growth of pathogens like Escherichia coli and Salmonella, thus extending the shelf life of perishable goods [6]. Its antioxidant properties further contribute to preventing oxidation in foods, helping maintain nutritional quality and sensory attributes over time. Moreso, mushroom chitosan is an ideal candidate for bio-based packaging materials due to its film-forming capacity, allowing it to create a protective barrier that is biodegradable and safe for consumers [7].

This study provides a comprehensive overview of recent advancements in the biorefinery and application of mushroom-derived chitosan for food engineering purposes. It aims to explore and evaluate biorefinery processes for extracting high-quality chitosan from mushrooms, including enzymatic and chemical extraction methods, assess the functional properties of mushroom-derived chitosan, such as its antimicrobial, antioxidant, and film-forming capabilities, and highlight its diverse applications within food engineering, including its role in food preservation, packaging, and quality enhancement. Given the rising consumer demand for natural, clean-label products, the use of mushroom-derived chitosan presents an opportunity to support sustainable food systems and reduce reliance on synthetic preservatives and non-degradable packaging [8]. However, the broader adoption of mushroom-derived chitosan in food engineering is hindered by critical research gaps, including the need for optimized, eco-friendly extraction methods, challenges in scaling up production, and limitations in its functional versatility across various food matrices [9]. This study seeks to address these gaps, ultimately contributing to the advancement of mushroom-derived chitosan as a viable and sustainable alternative in the food industry. By addressing these gaps, this study offers guidance for future research efforts, supporting the integration of mushroom chitosan as a sustainable, effective biopolymer in food technology and biotechnology.

Statement of the Problem

The demand for natural, clean-label products has driven interest in sustainable food packaging and preservation solutions. While chitosan from crustaceans is widely used for its antimicrobial and film-forming properties, its allergenicity and environmental concerns limit its application. Mushroom-derived chitosan offers a sustainable, allergen-free alternative, but its adoption faces challenges such as inefficient extraction methods, scalability issues, and limited functional versatility in food systems. This study addresses these gaps by evaluating extraction techniques, functional properties, and industrial feasibility to support the broader use of mushroom chitosan in sustainable food engineering.

Research Question

The increasing consumer demand for natural, clean-label products has led to a growing interest in the sustainable use of biopolymers like chitosan, particularly derived from mushrooms. However, the broader adoption of mushroom-derived chitosan in food engineering faces several challenges that hinder its widespread implementation. These challenges include the optimization of eco-friendly extraction processes, scalability issues, and limitations in its functional versatility across various food applications.

In this context, this study addresses the following research questions:

- What are the eco-friendly and efficient biorefinery processes for extracting high-quality chitosan from mushrooms?
- What are the diverse functional properties of mushroom-derived chitosan in food engineering, particularly in relation to its antimicrobial, antioxidant, and film-forming capabilities?

- How can the scalability of mushroom-derived chitosan production be improved for industrial applications?
- What are the potential challenges and opportunities in incorporating mushroom-derived chitosan in sustainable food packaging and preservation technologies?

Research Objectives

This research aims to address the identified gaps and contribute to the broader adoption of mushroom-derived chitosan in food engineering. Specifically, the objectives of this study are:

- To optimize eco-friendly extraction processes for producing high-quality mushroom-derived chitosan, focusing on improving yield and purity through sustainable biorefinery methods.
- To evaluate the diverse functional properties of mushroom-derived chitosan, particularly its antimicrobial, antioxidant, and film-forming capabilities, and assess how these properties can be leveraged for food engineering applications.
- To explore the challenges and solutions for scaling up the production of mushroom-derived chitosan, with an emphasis on improving efficiency, reducing production costs, and ensuring sustainability in large-scale applications.
- To investigate the potential applications of mushroom-derived chitosan in sustainable food packaging and preservation, including its role in extending shelf life and reducing food waste.

Materials and Methods

This study employs a systematic review methodology combined with a gap analysis approach to identify and assess the challenges and opportunities in the use of mushroom-derived chitosan in food engineering. The research follows a structured, multi-step approach to ensure rigor and comprehensiveness in achieving the objectives.

Data collection

- A thorough literature search was conducted using reputable databases such as Google Scholar, PubMed, Scopus, and Web of Science. Keywords related to mushroom-derived chitosan, biodegradable chitosan, food applications of chitosan, eco-friendly extraction methods, and functional properties were used.
- The review focused on studies published between 2000 and 2024 to include the most up-to-date research.
- Inclusion criteria: Only peer-reviewed articles, reviews, and studies that presented primary data on extraction methods, functional properties, and applications of mushroom-derived chitosan in food engineering were included.
- Exclusion criteria: Articles that focused on chitosan derived from crustaceans or non-mushroom sources, as well as studies not related to food applications, were excluded.

Data analysis

- The selected studies were analyzed qualitatively to identify common themes, emerging trends, and knowledge gaps in the field of mushroom-derived chitosan. This included a focus on the extraction methods, functional properties, and challenges in industrial-scale production.
- A comparative analysis of the different extraction methods [enzymatic, chemical, and green extraction] was performed to evaluate their eco-friendliness, efficiency, and suitability for large-scale applications.
- Functional properties of mushroom-derived chitosan, such as its antimicrobial, antioxidant, and film-forming capabilities, were examined in relation to their potential use in food preservation and packaging.

Gap identification

- The research explicitly identified key gaps in the current literature, particularly in areas related to the optimization of extraction processes, scalability of production methods, and the functional versatility of mushroom-derived chitosan across various food matrices.
- Limitations in current research, such as the lack of studies on large-scale production and the need for improved functionalization techniques, were noted as critical barriers to the broader adoption of mushroom-derived chitosan in the food industry.

Synthesis and recommendations

- Based on the gaps identified, recommendations for future research were synthesized. These include the need for improved extraction methods, scalability solutions, and enhanced functionalization techniques to increase the versatility of

mushroom-derived chitosan in diverse food applications.
- The study also proposed a roadmap for integrating mushroom-derived chitosan into sustainable food systems, focusing on eco-friendly practices and circular economy principles.

Mushroom chitosan biorefinery processes

Overview of biorefinery concepts

Biorefinery is a sustainable approach that uses renewable biological resources to produce valuable compounds, fuels, and other products through integrated processing techniques. In the context of mushroom chitosan, biorefinery involves breaking down mushroom biomass to extract chitosan and other bioactive compounds, enhancing the sustainability of both mushroom cultivation and chitosan production [10]. This biorefinery concept aligns with circular economy principles, aiming to minimize waste and optimize resource use by converting mushroom biomass into high-value products, including chitosan for food and pharmaceutical applications [11].

Table 1. Comparison of extraction methods for mushroom-derived chitosan.

Extraction Method	Advantages	Limitations	Yield	Environmental Impact
Enzymatic Extraction	Mild conditions, eco-friendly	High cost, time-consuming, requires specific enzymes	Moderate to High	Low [biodegradable, minimal chemicals]
Chemical Extraction	High efficiency, fast process	Use of chemicals, potential residuals	High	High [use of chemicals, waste]
Green Extraction [e.g., Ultrasound, Microwave]	Energy-efficient, eco-friendly, faster extraction	Requires optimization, equipment costs	Moderate	Low [minimal chemicals, energy-efficient]

Extraction and purification methods for mushroom chitosan

The extraction and purification of chitosan from mushrooms involve multiple steps that differ from those used with crustaceans, due to the unique structural characteristics of fungal chitosan. Various methods can be employed to achieve high yields of purified chitosan.

Enzymatic extraction

Enzymatic extraction uses specific enzymes, such as chitinase, to break down chitin in the fungal cell wall and convert it to chitosan. This method is advantageous due to its mild reaction conditions, which preserve the molecular integrity and bioactivity of chitosan [12]. Enzymatic methods are also considered more eco-friendly compared to chemical processes, though challenges remain in optimizing enzyme activity for large-scale production [13].

Chemical extraction

Chemical extraction, traditionally the most common method, involves acid and alkaline treatments to deacetylate chitin into chitosan. Although effective in producing high yields, chemical extraction often uses strong acids and bases, posing environmental concerns due to the disposal of hazardous waste [14]. Furthermore, harsh chemical conditions can degrade the molecular structure of chitosan, potentially reducing its functional properties [15].

Emerging green extraction techniques

Recently, green extraction techniques have been developed to reduce environmental impact and improve sustainability. These include ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, which use less toxic solvents and milder conditions. Such methods are gaining popularity due to their efficiency and reduced energy consumption. However, further research is needed to scale these techniques while maintaining consistent chitosan quality [16].

Comparative analysis of extraction efficiency and yield

A comparative analysis of the efficiency and yield of these extraction methods is essential for identifying the optimal approach for different applications. Chemical methods generally produce higher yields but at the cost of potential environmental damage and structural alteration of chitosan. Enzymatic methods, while eco-friendly, may yield lower

Figure 1. Flowchart of mushroom chitosan extraction process. Figure above illustrates the step-by-step process of extracting chitosan from mushrooms, highlighting the various methods involved. It begins with mushroom selection and preparation, followed by a decision point for choosing the extraction method, including enzymatic, chemical, and green extraction techniques. Figure 1 shows how each method leads to the purification and drying steps, ultimately resulting in the final chitosan product.

amounts, and their effectiveness varies with enzyme specificity and reaction conditions [17]. Emerging green techniques show promise in achieving a balance between yield, efficiency, and environmental sustainability, though further optimization is required for industrial applications [18].

Functional properties of mushroom chitosan

Physicochemical properties

Mushroom-derived chitosan exhibits a range of physicochemical properties that make it highly suitable for various industrial applications, especially in food engineering. These properties include solubility, molecular weight, and degree of deacetylation, all of which influence its functionality in different applications. Chitosan is soluble in acidic solutions, typically those with a pH below 6, due to the presence of amino groups in its structure that can protonate in acidic conditions [19]. The molecular weight of chitosan, which is determined by the degree of polymerization, affects its mechanical strength, film-forming ability, and viscosity [20]. Higher molecular weight chitosan tends to form stronger films with better structural integrity, which is useful in food packaging. Moreso, the degree of deacetylation, or the extent to which the chitin has been modified to chitosan, impacts its solubility and reactivity, directly influencing its applications in various industries [21].

Antimicrobial and antioxidant properties

Mushroom-derived chitosan is known for its significant antimicrobial and antioxidant properties, which are crucial for its application in food preservation and packaging. The antimicrobial activity of chitosan is attributed to its ability to interact with the cell membranes of microorganisms, disrupting their structure and causing leakage of essential cellular components, ultimately leading to cell death [22]. Studies have shown that chitosan effectively inhibits the growth of a wide range of foodborne pathogens, including Escherichia coli, Salmonella spp., and Listeria monocytogenes, making it a potent natural preservative [23]. In addition, chitosan's antioxidant properties help in scavenging free radicals and reducing oxidative stress in food products. The amino and hydroxyl groups in chitosan can donate electrons to neutralize free radicals, preventing the oxidation of lipids and other components in food, thus enhancing shelf-life and maintaining nutritional quality [24]. These combined antimicrobial and antioxidant effects make mushroom-derived chitosan a promising natural alternative to synthetic preservatives and antioxidants.

Biodegradability and biocompatibility

Mushroom chitosan is highly valued for its biodegradability and biocompatibility, which are essential attributes for sustainable food packaging and biomedical applications. As a biodegradable polymer, mushroom chitosan can naturally break down in the environment without leaving toxic residues, making it a more eco-friendly alternative to synthetic plastics [25]. This property is particularly important in the context of food packaging, where reducing environmental impact is a key concern. In addition to its biodegradability, chitosan is biocompatible, meaning it does not elicit an adverse immune response when in contact with living tissues. This characteristic is particularly useful in biomedical applications such as wound healing, drug delivery, and tissue engineering [26]. Its biocompatibility also ensures its safety in food applications, as it does not pose any significant risk to human health when ingested. These properties contribute to the growing interest in mushroom-derived chitosan as an environmentally friendly material with diverse applications in both food and medical industries.

Applications in Food Engineering

Role in food preservation

Mushroom-derived chitosan plays a significant role in food preservation due to its antimicrobial, antioxidant, and film-forming properties. Chitosan can extend the shelf life of perishable food products by inhibiting the growth of spoilage microorganisms and pathogens, such as Escherichia coli and Salmonella [27]. The antimicrobial activity is mainly attributed to the ability of chitosan to interact with microbial cell walls, causing structural disruption. Moreso, chitosan's antioxidant properties help in reducing oxidative stress in foods, preventing lipid peroxidation, and maintaining the quality of both fresh and processed foods. Its use in food preservation is especially appealing for clean-label products, as consumers are increasingly seeking natural alternatives to synthetic preservatives [28]. Moreover, its biocompatibility ensures that it can be used in food products without affecting taste, texture, or nutritional value.

Chitosan-based edible coatings and films

Chitosan-based edible coatings and films have emerged as innovative solutions to enhance food preservation and reduce food waste. These coatings can form protective barriers around food, preventing moisture loss, gas exchange, and microbial contamination. Chitosan's film-forming ability is particularly beneficial for fruits, vegetables, and meats, as it helps to retain their freshness, texture, and nutritional content [29]. Moreover, the biodegradable nature of chitosan offers an environmentally friendly alternative to synthetic plastic films that are commonly used in food packaging. These edible coatings can be easily ingested, eliminating the need for disposal and minimizing environmental pollution. Research has shown that chitosan-based films can also be enriched with natural antioxidants or antimicrobials, enhancing their functionality and contributing to longer shelf lives of food products [30].

Potential as an antimicrobial packaging material

Mushroom chitosan is an ideal candidate for antimicrobial packaging materials due to its natural antimicrobial properties. When incorporated into packaging films or coatings, chitosan can provide an active barrier that not only protects the food from physical damage but also inhibits microbial growth. This is particularly useful for foods that are prone to bacterial contamination, such as dairy products, meats, and fresh produce. The antimicrobial effect of chitosan is typically enhanced when combined with other natural preservatives or antimicrobial agents, such as essential oils or silver nanoparticles [31]. As consumers demand more sustainable and safer packaging materials, chitosan-based antimicrobial packaging presents a viable alternative to conventional plastic packaging, reducing the need for chemical preservatives and minimizing food waste due to spoilage [32].

Other functional food applications (e.g., nutraceuticals, flavor stabilization)

Beyond its applications in food preservation and packaging, mushroom chitosan has potential as an ingredient in functional foods, including nutraceuticals and flavor stabilization. Due to its ability to bind with dietary fats and cholesterol, chitosan is commonly used in weight management supplements and cholesterol-lowering nutraceutical products [33]. It has also been shown to have prebiotic properties, stimulating the growth of beneficial gut bacteria, which contributes to digestive health. In addition, chitosan can help stabilize flavors in food products, especially in beverages, where its film-forming and emulsifying properties can reduce flavor degradation caused by oxidation or microbial activity [34]. Chitosan's role in functional foods is expanding as researchers continue to explore its potential for promoting health and wellness through various bioactive mechanisms.

Advantages of Mushroom-Derived Chitosan over Conventional Sources

Comparative benefits of crustacean-derived chitosan

Mushroom-derived chitosan offers several advantages over traditional crustacean-derived chitosan. The primary difference lies in the source of chitosan: crustaceans, such as shrimp and crabs, are often used to extract chitin, which is then processed into chitosan. However, mushroom-derived chitosan is extracted from fungal sources, which offers unique benefits. Firstly, mushrooms provide a more sustainable and renewable resource compared to crustaceans, which require marine environments and may contribute to overfishing and environmental degradation [35]. Furthermore, chitosan derived from mushrooms generally contains a higher degree of acetylation, which can influence its solubility and functional properties. While crustacean-derived chitosan is more commonly studied, mushroom chitosan is gaining attention for its comparable, if not superior, properties, such as enhanced bioactivity and biodegradability [36]. Moreso, mushroom-derived chitosan has been shown to exhibit more favorable biocompatibility and lower allergenic potential compared to crustacean-derived chitosan, making it a safer alternative for individuals with shellfish allergies [37]. This makes mushroom-derived chitosan a more versatile and widely accepted material, especially in food and biomedical applications.

Ecological and sustainability benefits

The production of mushroom-derived chitosan is considered more ecologically sustainable compared to crustacean chitosan. Mushrooms are fungi that can be cultivated with minimal environmental impact, requiring significantly fewer resources such as water and energy. Moreover, the cultivation of mushrooms can be integrated with agricultural waste, such as sawdust and straw, which supports the idea of a circular economy by reusing biomass that would otherwise be discarded [38]. In contrast, crustaceans are marine animals that require specific aquatic ecosystems for farming, often contributing to overfishing and environmental imbalances, especially when harvested in large quantities. Mushroom cultivation also avoids the use of chemicals and additives commonly associated with industrial shellfish farming, making the production of mushroom chitosan a cleaner and more environmentally friendly process. Moreso, mushroom chitosan itself is biodegradable and non-toxic, which enhances its appeal as a sustainable, eco-friendly material for various applications, particularly in food packaging and waste management [39]. These ecological and sustainability benefits make mushroom-derived chitosan a compelling alternative in light of growing concerns about environmental pollution and sustainability in the biopolymer industry.

Consumer acceptance and regulatory considerations

Consumer acceptance of mushroom-derived chitosan is increasing, particularly because it offers a plant-based, allergen-free alternative to crustacean-derived chitosan. Many consumers are becoming more conscious of allergens and environmental concerns, and products derived from mushrooms are perceived as safe and natural. Mushroom-derived chitosan is also gaining popularity in the clean-label movement, where consumers prefer products with fewer chemical additives and preservatives [40]. Moreso, the vegan and vegetarian market sees mushroom-derived chitosan as a favorable alternative, as it aligns with plant-based product preferences. From a regulatory standpoint, mushroom-derived chitosan has been considered safe for use in food and pharmaceuticals, with fewer concerns about allergic reactions compared to crustacean-based chitosan, which may be problematic for individuals with shellfish allergies [41]. Regulatory bodies, such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), have approved chitosan as a food additive in specific applications, and mushroom chitosan is expected to follow similar regulatory pathways due to its non-toxic and biodegradable nature. Furthermore, the growing demand for plant-based and eco-friendly products has influenced regulatory trends, making mushroom-derived chitosan a more appealing option for food and packaging industries seeking to meet sustainability standards.

Research Gaps and Future Directions

Optimization of extraction techniques for higher yield and quality

One of the significant research gaps in mushroom-derived chitosan is optimizing extraction techniques to improve both yield and quality. Current methods of extraction, such as enzymatic, chemical, and green extraction techniques, can vary in terms of efficiency and effectiveness, often resulting in low yields or compromised quality of the chitosan obtained [42]. While enzymatic methods are generally considered more environmentally friendly, their cost and time efficiency remain a challenge for large-scale applications. Chemical extraction, although highly efficient, can involve the use of harsh chemicals, raising concerns about their environmental impact and the purity of the final product [43]. Emerging green extraction techniques, such as ultrasound-assisted extraction and microwave-assisted extraction, have shown promise in increasing yield and reducing processing time, but further optimization is needed to achieve the ideal balance between cost, efficiency, and environmental impact [44]. Future research should focus on fine-tuning these methods and exploring novel approaches to increase both the quantity and quality of mushroom-derived chitosan, making it more viable for commercial applications.

Improving functionalization methods for enhanced application in foods

Another crucial area for future research lies in improving functionalization methods for mushroom-derived chitosan to enhance its application in food products. Chitosan can be modified by grafting or crosslinking to enhance its mechanical properties, bioactivity, and interactions with other food ingredients. For example, functionalization can improve its solubility, making it more effective in various food matrices [45]. However, the methods used for functionalizing chitosan are still in their infancy, and more research is required to identify efficient, cost-effective techniques for tailoring its properties to specific food applications. Functionalization also has the potential to enhance chitosan's antimicrobial and antioxidant properties, which are vital for food preservation and packaging. Moreso, exploring the incorporation of bioactive compounds, such as polyphenols, essential oils, or probiotics, into chitosan can further enhance its value as a functional food ingredient [46]. Investigating these methods will expand the scope of chitosan-based products in food engineering.

Scalability challenges for industrial application

Although mushroom-derived chitosan shows great promise in food applications, scalability remains a significant challenge for industrial production. Current extraction and functionalization methods may work well on a small scale but often face issues when scaled up for large-scale production. Key challenges include high operational costs, inconsistent quality of raw materials [mushrooms], and difficulties in maintaining efficiency across large volumes [47]. Moreso, the logistics of sourcing mushrooms in sufficient quantities for commercial use can be a bottleneck, as large-scale mushroom cultivation requires substantial resources and infrastructure. Future research should focus on developing more efficient and scalable extraction techniques, optimizing the raw material supply chain, and investigating the use of agricultural waste [such as mushroom by-products] to ensure a sustainable and cost-effective supply of chitosan for industrial applications [48]. Overcoming these scalability issues will be crucial for the widespread adoption of mushroom-derived chitosan in the food industry.

Environmental and economic impact assessments

As the demand for sustainable food packaging and ingredients grows, it is important to assess the environmental and economic impacts of using mushroom-derived chitosan. While mushroom chitosan is considered environmentally friendly compared to crustacean-derived chitosan and synthetic polymers, a comprehensive life cycle assessment (LCA) is needed to quantify its environmental footprint across production, processing, and disposal stages [49]. Research should focus on evaluating the carbon footprint, water usage, and overall environmental impact of chitosan production, as well as its biodegradability and end-of-life scenarios. On the economic side, further studies are required to assess the cost-effectiveness of mushroom-derived chitosan compared to conventional food preservatives and packaging materials, considering factors such as raw material costs, extraction methods, and scalability. This research will help stakeholders in the food industry understand the true sustainability of mushroom-derived chitosan and inform decision-making for broader adoption [50].

Exploring new applications in functional foods and nutraceuticals

Mushroom-derived chitosan has significant potential in the growing field of functional foods and nutraceuticals, but its applications remain underexplored. Chitosan's ability to reduce cholesterol levels, aid in weight loss, and act as a prebiotic makes it an attractive ingredient in dietary supplements and functional foods [51]. However, much of the existing research focuses on its use in food preservation, packaging, and basic health benefits. Future research should explore more diverse applications in functional foods, such as their potential for improving gut health, modulating the microbiome, and supporting immune function [52]. Moreover, there is scope for investigating the synergistic effects of mushroom-derived chitosan with other bioactive compounds to enhance its health benefits in nutraceuticals [53]. The development of chitosan-based formulations for targeted health benefits could significantly expand its marketability and utility in the wellness and dietary supplement industries.

Results and Discussion

Extraction methods

The use of eco-friendly extraction methods such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) offers significant advantages over traditional methods. These techniques reduce the environmental footprint by decreasing energy consumption and eliminating harmful solvents. However, enzymatic extraction, although sustainable, struggles with cost-effectiveness and processing time, which limits its practical application at larger scales.

Functional properties

Mushroom-derived chitosan exhibits excellent antimicrobial, antioxidant, and film-forming properties. These properties are crucial for food preservation, as chitosan can effectively inhibit the growth of harmful pathogens like E. coli and Salmonella, offering a safer alternative to synthetic preservatives. Moreover, its biodegradability presents a promising solution to the global issue of plastic pollution, positioning mushroom chitosan as a key material in sustainable food packaging.

Scalability and production challenges

Scalability remains one of the major challenges for the widespread use of mushroom-derived chitosan. While lab-scale extraction methods show promising results, transitioning to industrial-scale production presents challenges related to raw material variability and high production costs. The use of agricultural waste for mushroom cultivation could potentially address raw material sourcing issues, but more research is needed to make this approach viable for large-scale production.

Consumer acceptance and health benefits

Mushroom-derived chitosan offers an advantage over crustacean-derived chitosan, particularly in terms of biocompatibility. As allergies to shellfish are common, the allergen-free nature of mushroom chitosan makes it a safer alternative for many consumers. Moreover, its appeal aligns with the growing demand for clean-label products, which emphasize natural ingredients. Moreover, health benefits such as aiding in weight management and reducing cholesterol further increase its value, opening up avenues for its use in functional foods and nutraceuticals.

Summary of the Study

- The research highlights the significant environmental and economic benefits of using mushroom-derived chitosan in food systems, particularly in reducing reliance on non-degradable plastics and synthetic preservatives.
- The study also identifies critical gaps in current research, such as the need for optimized extraction methods, consistent raw material sourcing, and cost-effective scaling of production processes.
- The future of mushroom-derived chitosan in food engineering is promising, with further research needed in functionalization, industrial-scale production, and consumer acceptance.

Conclusion

Mushroom-derived chitosan is gaining recognition in food engineering due to its numerous advantages over conventional crustacean-derived chitosan, including better biocompatibility, sustainability, and allergen-free properties. Various extraction methods, such as enzymatic, chemical, and green techniques, have been explored, each with distinct advantages and limitations regarding yield, quality, and environmental impact. Mushroom chitosan's antimicrobial, antioxidant and film-forming properties position it as a valuable material for food preservation, packaging, and functional food applications. Despite challenges in optimizing extraction methods and scaling production, its ecological and economic benefits highlight its potential to replace synthetic and animal-derived alternatives in the food industry. The integration of mushroom-derived chitosan in sustainable food engineering offers significant implications. As a biodegradable, non-toxic material, it can help reduce reliance on synthetic plastics and chemical preservatives, contributing to a more eco-friendly food system. Its roles in food preservation, as an antimicrobial agent, and in food packaging could extend shelf life and reduce food waste, addressing both environmental and food security challenges. Moreover, its low environmental impact during cultivation and extraction processes makes it a renewable resource, supporting the circular economy and meeting consumer demands for natural, clean-label products. Mushroom chitosan provides an opportunity to align with broader sustainability goals, such as reducing waste and promoting health-conscious food choices. The future of mushroom chitosan biorefinery is promising, with considerable potential for both industrial applications and broader integration into food systems. Advances in biotechnological extraction and functionalization methods will improve the efficiency and performance of mushroom chitosan for large-scale use. Research into new applications in functional foods and nutraceuticals could unlock additional health benefits, expanding its utility beyond food preservation and packaging. As scalability challenges are addressed, mushroom chitosan could become a key material in sustainable food engineering. With growing consumer interest in plant-based, eco-friendly products, continued interdisciplinary research will be crucial in realizing the full potential of mushroom chitosan, paving the way for a more sustainable and health-focused food ecosystem.

Contribution of Authors

- Aisha Ameera Abdullah: Conceptualization of the study, drafting of the manuscript, and detailed writing of the Introduction and Advantages of Mushroom-Derived Chitosan Over Conventional Sources sections. Supervised the overall framework and ensured content alignment.
- Shehu-Alimi Elelu: Contributed to the Mushroom Chitosan Biorefinery Processes, including Extraction and Purification Methods for Mushroom Chitosan and Comparative Analysis of Extraction Efficiency and Yield. Provided insights into biorefinery processes and sustainability considerations.
- Musa Ojeba Innocent: Wrote the Functional Properties of Mushroom Chitosan section, specifically focusing on Physicochemical Properties and Biodegradability and Biocompatibility. Reviewed the manuscript for technical accuracy.
- Ganiyat Omotayo Ibrahim: Authored the Applications in the Food Engineering section, including Chitosan-based Edible Coatings and Films, Potential as an Antimicrobial Packaging Material, and Other Functional Food Applications. Conducted a review of recent innovations in food engineering applications.
- Tijani Abiola Tajudeen: Contributed to the Research Gaps and Future Directions section, focusing on Optimization of Extraction Techniques for Higher Yield and Quality, Scalability Challenges for Industrial Application, and Environmental and Economic Impact Assessments. Provided key references and critical analysis.
- Mustapha Abdulsalam: Coordinated the collaboration among co-authors, edited and integrated all sections into a cohesive manuscript, and contributed to Applications in Food Engineering with a focus on Role in Food Preservation. Conducted a comprehensive review of the literature and finalized the document for submission.

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Conflict of Interest

The authors have declared no conflicts of interest.

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