

PERSPECTIVES ON EDIBLE MUSHROOMS AND FUNGAL BIOTECHNOLOGY IN MODERN FOOD PRODUCTION SYSTEMS



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Bentham Books

Perspectives on Edible Mushrooms and Fungal Biotechnology in Modern Food Production Systems

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ISBN (Online): 979-8-89881-405-2

ISBN (Print): 979-8-89881-406-9

ISBN (Paperback): 979-8-89881-407-6

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First published in 2026.

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FOREWORD

It is with great pleasure and anticipation that I present this volume, “Perspectives on Edible Mushrooms and Fungal Biotechnology in Modern Food Production Systems.” This book arrives at a critical moment, when the world faces the dual challenge of securing sustainable food systems and addressing nutritional needs through innovative and ecologically responsible approaches. In this context, fungi have emerged not only as ancient allies in food fermentation and preservation but also as modern agents of transformation in food engineering, biotechnology, and sustainable nutrition.

The interdisciplinary structure of this book reflects the complexity and richness of contemporary mycological food research. From the cultivation of edible mushrooms and development of mycoproteins to the integration of fungi into functional foods and meat alternatives, each chapter delivers cutting-edge insights into the scientific, technological, and societal dimensions of fungal applications. The inclusion of themes such as fungal biotechnology, life cycle assessments, circular economy practices, and artificial intelligence in fungal food systems illustrates the forward-thinking nature of this work.

As a food scientist and academic committed to sustainable innovation, I believe this book will serve as a vital reference for researchers, industry professionals, policy makers, and students alike. It highlights the potential of fungal systems to contribute meaningfully to global food security, while also navigating the regulatory, ethical, and technical challenges that accompany novel food development.

I congratulate the editors and contributors for their dedication to advancing knowledge in this promising field. May this work inspire future research, collaboration, and innovation at the fascinating intersection of mycology and food engineering.

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PREFACE

In today's world, the growing global population, concerns about environmental sustainability, and issues related to food security have significantly increased interest in alternative and innovative food sources. In this context, the potential of mushrooms and microscopic fungal organisms in the field of food engineering is being intensively explored by both academic and industrial communities. This book, titled "**Perspectives on Edible Mushrooms and Fungal Biotechnology in Modern Food Production Systems**," offers a comprehensive scientific perspective on the multifaceted contributions of fungi to food science and engineering and presents current advancements in the field in a systematic way.

The book begins by exploring the historical uses of fungi and extends to their integration into modern food processing technologies. Topics such as enzymatic applications, fermentation techniques, and mycological preservation methods are examined as examples where traditional knowledge meets modern science.

Subsequent chapters delve into edible mushroom cultivation, optimization of growth conditions, genetic improvement, and the development of fungal-based protein alternatives. Discussions on functional compounds, health benefits, and regulatory challenges in nutraceutical development provide a well-rounded view of fungi's role in promoting human health. Additionally, the use of fungal metabolites as natural flavor enhancers, colorants, and texturizers highlights their growing importance in food additive innovation.

Chapters focusing on sustainability emphasize resource efficiency, waste reduction, and the integration of circular economy principles in fungal food systems. The book also examines the role of fungi in addressing food scarcity and explores socioeconomic and policy-related barriers and opportunities. As such, it not only provides technical knowledge but also serves as a guide for policymakers and industry professionals.

The final sections explore how advanced technologies such as artificial intelligence, automation, and precision engineering are being integrated into fungal food production. They also highlight safety concerns, regulatory frameworks, and ethical considerations, offering predictions and research needs for the future of mycology in food systems.

The goal of this book is to serve as a comprehensive scientific resource for researchers, academics, food engineers, biotechnologists, and all stakeholders interested in understanding the role of fungal organisms in food systems. We hope that this book will inspire progress toward more sustainable, healthy, and innovative food solutions through the lens of mycology.

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CHAPTER 1**Introduction to Fungal Contributions in Food Engineering****Sebahat Öztekin^{1,*}**¹ Department of Food Engineering, Faculty of Agriculture, Atatürk University, Erzurum, Türkiye

Abstract: Fungi play a crucial role in food science, contributing to traditional and modern food applications. Yeasts, such as *Saccharomyces cerevisiae*, are essential for fermentation processes in bread, beer, and wine, while other species enhance flavor, texture, and nutritional value in traditional foods. Filamentous fungi, including *Aspergillus*, *Penicillium*, *Rhizopus*, and *Fusarium*, serve diverse functions, from producing enzymes and organic acids to forming mycoproteins as sustainable protein alternatives. Advances in biotechnology have expanded their applications, particularly in single-cell protein production, probiotic formulations, and 3D-printed food innovations. Edible mushrooms, including *Agaricus bisporus*, *Lentinula edodes*, and *Pleurotus ostreatus*, are valued for their high protein content, bioactive compounds, and health benefits. However, wild mushrooms require careful monitoring due to potential contamination from heavy metals and environmental pollutants. Truffles (*Tuber* spp.) are highly prized in gourmet cuisine for their distinctive aroma and umami properties. Fungal identification techniques, including molecular, biochemical, and microscopic methods, are essential for ensuring food safety, particularly in detecting mycotoxin-producing fungi. Integrating fungi in circular bioeconomy strategies further enhances sustainability by converting agricultural waste into high-nutrient food sources. By analyzing recent publications, this chapter examines the diverse applications of fungi in food science, including their roles in fermentation, enzyme production, alternative proteins, and functional foods. Current research underscores the potential of mycology in tackling global food security and sustainability challenges, with a focus on developing nutritious and environmentally friendly food solutions.

Keywords: Edible mushroom, Fungal metabolites, Fungi, Mycology, Sustainable food production, Yeast.

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INTRODUCTION

Mycology in Food Science

Mycology plays a crucial role in food science, encompassing microfungi (yeast and filamentous fungi) and macrofungi (mushrooms) that contribute to diverse food applications. Fungi play a dual role in the food system, acting as beneficial and harmful agents. Beneficial fungi, such as *Saccharomyces cerevisiae* in fermentation and *Penicillium roqueforti* in cheese production, contribute to flavor, texture, and preservation. Filamentous fungi like *Fusarium venenatum* can produce mycoprotein, a sustainable, high-quality protein with a balanced amino acid profile, excellent digestibility, and low environmental impact, making it a promising alternative to animal-based proteins [1]. Apart from their role in antibiotic and organic acid production, certain filamentous fungi, such as *Aspergillus flavus* and *Fusarium* spp., can produce mycotoxins, which present significant food safety hazards, necessitating strict monitoring and control measures in food systems [2 - 4]. Regarding edible mushrooms, varieties such as button, shiitake, and oyster are valued for their rich protein content, bioactive compounds, and natural umami-enhancing properties. Furthermore, mushrooms can contribute to sustainable food production by converting agricultural waste into high-nutrient food sources [5].

Fungi have been integral to human diets for thousands of years due to their rich nutritional profile, containing essential and nonessential amino acids. Their use in food and fermented beverages dates back to ancient times. Archaeological findings suggest that wild mushrooms were consumed in Chile around 13,000 years ago. At the same time, reliable records indicate that wild fungi were first systematically utilized in China, a few centuries before the birth of Christ. The earliest evidence of fermentation and fermented food production comes from Babylon and Sumeria. Despite this long history, the full potential of fungi in food applications remained largely unexplored until the second half of the twentieth century, when advancements in industrial microbiology led to their widespread utilization. Since then, various fungi, including yeasts, filamentous fungi, and mushrooms, have been extensively used in food production for both human and animal consumption [6].

Fungal identification in food relies on molecular, biochemical, and microscopic techniques to ensure food safety and quality. Polymerase Chain Reaction (PCR)-based methods, such as DNA barcoding and quantitative PCR, allow precise species identification, while next-generation sequencing provides broader insights into fungal communities. Biochemical approaches, including enzymatic assays and metabolic profiling, help differentiate species based on unique biochemical

markers. Microscopic examination remains valuable for morphological identification, particularly in mycotoxin-producing species. Combining these techniques enhances the accuracy and efficiency of fungal identification in food matrices [7].

The traditional and innovative applications of fungi in food range from mycoprotein-based meat alternatives and Single-cell Protein (SCP) to novel fermentation techniques and advanced food technologies such as 3D printing. These products highlight the versatility of fungi in improving texture, nutrition, and sustainability in future food production [8]. Building on this multifunctionality, the next section examines how yeasts translate these potentials into practical biotechnological applications.

Biotechnological and Functional Applications of Yeasts in Food Science

Yeasts play a fundamental role in food production, contributing to fermentation, flavor development, nutritional enhancement, pigment, and lipid production. Among them, *S. cerevisiae* is one of the earliest domesticated microorganisms, widely used in bread-making, wine making, and brewing. Its ability to ferment sugars into alcohol and carbon dioxide makes it indispensable for producing alcoholic beverages and leavened bakery products [9]. Furthermore, *S. cerevisiae* has gained attention as a promising biological platform for vitamin D production, offering an innovative approach to addressing global vitamin D deficiency. These microorganisms naturally produce ergosterol, a precursor to vitamin D₂, which can be converted into its active form through UV irradiation. This makes yeast-derived vitamin D an attractive option for fortifying foods, dietary supplements, and even pharmaceutical applications. Additionally, advancements in metabolic engineering have enabled the development of yeast strains capable of producing vitamin D₃, the more bioavailable form preferred for human consumption. Given the growing demand for sustainable and vegan-friendly vitamin D sources, yeast-based production presents an eco-friendly alternative to traditional animal-derived supplements, paving the way for broader applications in food and health industries [10]. Although yeasts naturally produce erythro-ascorbic acid, a compound similar to vitamin C, recent advancements in metabolic engineering have enabled them to synthesize L-ascorbic acid (vitamin C) from D-glucose. This innovation not only strengthens yeast's ability to withstand oxidative stress, low pH, and organic acids but also opens new possibilities for its use in food, pharmaceutical, and industrial fermentation applications. These findings highlight yeast as a promising and sustainable platform for vitamin C production, offering an alternative to traditional sources while contributing to bio-industrial advancements [11]. Other yeast species, such as *Candida* spp., *Debaryomyces* spp., and *Hansenula anomala*, also contribute to traditional fermentations

CHAPTER 2**Fungal Biotechnology in Food Processing****Ecem Akan¹ and Evrim Elçin^{2,*}**¹ *Department of Dairy Technology, Faculty of Agriculture, Aydın Adnan Menderes University, Cakmar, Aydın, Türkiye*² *Department of Agricultural Biotechnology, Faculty of Agriculture, Aydın Adnan Menderes University, Cakmar, Aydın, Türkiye*

Abstract: Fungal biotechnology plays a vital role in modern food processing, harnessing fungi's unique metabolic capabilities to enhance food quality, safety, and sustainability. Traditionally, fungi were used in fermentation for products such as bread, cheese, and alcoholic beverages; today, they play a central role in industrial enzyme production and biotechnological processes; and in the future, they are expected to drive innovations in genetic engineering, sustainable food production, and pharmaceutical development. Key enzymes, such as amylases, proteases, lipases, and laccases, improve food texture, flavor, and nutritional value across industries such as baking, brewing, dairy, and meat. Innovations like thermostable and immobilized enzymes provide cost-effective, eco-friendly solutions. Fungi also contribute to food preservation, fermentation of foods, confectionery production, and brewing functional beverages, enhancing both sensory qualities and health benefits through bioactive compounds, probiotics, and dietary fiber. Genetic techniques like CRISPR-Cas9 and directed evolution have led to fungal strains with improved enzyme yields and specific functionalities. However, fungi also present challenges, as certain species can cause spoilage and produce harmful mycotoxins. Despite these risks, fungi's positive roles in food safety, biopreservation, and mycotoxin detoxification are significant. Fungal-based solutions, such as mycelium-based packaging and probiotics, align with sustainability and health goals. When managed properly, fungi offer eco-friendly alternatives to synthetic methods, addressing modern challenges in food systems. Overall, fungi contribute to sustainable food preservation, ensuring food safety and quality in a rapidly changing global food landscape. Combining traditional wisdom with cutting-edge biotechnology, fungal applications are redefining food processing, meeting evolving consumer demands for nutritious, safe, and environmentally conscious food products.

Keywords: Bakery, Dairy, Fermentation, Fungal enzymes, Fungi, Genetic engineering, Meat products, Mold, Probiotic, Yeast.

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INTRODUCTION

Fungal biotechnology has emerged as a pivotal field in food processing, leveraging the unique metabolic capabilities of fungi to enhance food production, quality, safety, and sustainability. The application of fungi in food production dates back centuries, with traditional fermentation processes yielding a variety of products, including bread, cheese, and alcoholic beverages. However, the modern landscape of fungal biotechnology is characterized by innovative approaches that harness genetic engineering, enzyme immobilization, and tailored enzyme development to optimize fermentation processes and improve product outcomes.

Fungi, encompassing yeasts and molds, have been utilized for centuries in various food applications, including the fermentation of bread, cheese, beer, and wine. Their ability to secrete a wide range of enzymes, ferment substrates, and produce bioactive compounds has made them indispensable in food processing technologies [1, 2]. Historically, fungi have been central to traditional fermentation processes such as bread making, brewing, and cheese making. In contemporary settings, advances in fungal biotechnology have expanded their use to enzyme production, to the fermentation processes that enhance flavor, nutritional value, and preservation of various food products, bio preservation, and the development of functional foods [3].

Traditional fermentation practices harness specific fungal strains to develop distinctive flavors and textures in foods such as tempeh, soy sauce, and blue cheese. For example, *Rhizopus oligosporus* is essential for tempeh production, while *Aspergillus oryzae* is widely used in soy sauce fermentation. Through their metabolic activities, these fungi generate unique flavor compounds and textures that characterize these foods [4, 5]. Furthermore, fungi are instrumental in producing enzymes that improve food quality; enzymes like amylases and proteases derived from fungal sources enhance processes in baking and brewing by breaking down starches and proteins.

This chapter explores the diverse and evolving applications of fungal biotechnology in food processing, with a particular focus on the functional roles of fungal species and their metabolites in enhancing food quality, safety, shelf life, and nutritional value. It aims to elucidate the enzymatic capabilities of fungi and their industrial relevance in sectors including baking, dairy, brewing, meat, confectionery, and functional foods. A key objective is to examine the integration of modern biotechnological tools, such as enzyme engineering, strain improvement, and precision fermentation, which have advanced the efficiency and specificity of fungal applications. The chapter also addresses the dualistic nature of fungi, recognizing both their beneficial and spoilage-related impacts in

food systems. Ultimately, it positions fungi as essential agents in the development of sustainable, health-oriented, and technologically advanced food production practices.

Enzymatic Breakthroughs and Applications

Fungi have long been recognized for their significant contributions to food biotechnology, particularly through the production of enzymes that facilitate various biochemical processes. Fungal enzymes have emerged as pivotal players in food processing, contributing to a wide array of applications that enhance the quality, safety, and efficiency of food production. The enzymatic capabilities of fungi have revolutionized food processing, offering targeted and efficient biochemical reactions that enhance product quality, reduce processing time, and minimize waste. These enzymes play crucial roles in food processing, enhancing the quality, safety, and nutritional value of food products. Fungal enzymes operate through the catalytic mechanisms that lower the activation energy required for biochemical reactions. They are secreted extracellularly, allowing for easy extraction and purification. This characteristic makes fungal enzymes particularly advantageous over plant or animal-derived enzymes, which often require more complex extraction processes [6, 7]. Fungal enzymes are utilized to enhance food quality and safety. Enzymes such as lipases, proteases, and glycosidases from basidiomycetes have been shown to improve the texture, flavor, and nutritional profile of various food products. For example, lipases can enhance the flavor of dairy products, while glycosidases can be used to modify the sweetness of beverages and baked goods [8]. The ability of fungi to produce a diverse array of enzymes makes them invaluable in food processing, where they can help in the development of healthier and more palatable products.

Fungal enzymes are categorized into several classes, including amylases, proteases, lipases, and laccases, each serving distinct functions in food processing. Amylases, for instance, are crucial in the hydrolysis of starch into simpler sugars, a process essential in the baking and brewing industries. Fungal amylases, particularly those derived from species like *A. oryzae*, exhibit optimal activity under conditions that mimic those found in food processing environments, thus making them suitable for industrial applications [9, 10]. The stability and pH tolerance of these enzymes further enhance their utility, allowing them to function effectively during food production processes. Proteases, another significant class of fungal enzymes, play a vital role in protein hydrolysis, which is essential to produce various food products such as cheese, meat, and fermented foods. Fungal proteases, particularly those from *Aspergillus* and *Penicillium* species, are widely utilized in the dairy industry for milk coagulation and cheese production [11]. The ability of these enzymes to operate under diverse conditions, including varying

CHAPTER 3**Edible Fungi Cultivation and Optimization****Ecem Kara^{*}1, Hatira Taşkın² and Gökhan Baktemur¹**¹ Faculty of Agricultural Sciences and Technologies, Sivas University of Science and Technology, Sivas, Türkiye² Department of Horticulture, Faculty of Agriculture, Cukurova University, Adana, Türkiye

Abstract: Mushrooms are a valuable food due to their nutritional value and medicinal properties. They are ideal for a healthy diet because of their high protein, vitamin, and mineral content and their low fat content. In addition, some compounds having medical importance found in different mushroom species make them valuable as functional foods. The use of agricultural waste in the cultivation of mushrooms is an important step for recycling waste and sustainable agricultural practices. The evaluation of the compost and substrates after cultivation as animal feed or fertilizer shows that mushroom cultivation is an environmentally friendly and sustainable form of agriculture. Mushroom cultivation is an advantageous sector as it is not seasonally dependent, requires less space, and offers frequent production, such as four cycles per year. Increased research on the nutritional value and medical importance of mushrooms has resulted in increased consumption. Developments and diversity in mushroom production technology increase farmers' incomes and contribute to the increase in mushroom production on a global scale. Biotechnological studies carried out to increase the quality and shelf life of mushrooms are becoming an important trend in the sector. In conclusion, sharing comprehensive information on cultivation and optimization of edible mushrooms, developments in mushroom cultivation techniques, and the optimization of growth conditions for increased yields, as well as genetic improvement of edible mushrooms, demonstrates the importance and potential of mushroom cultivation. Studies in this field contribute to sustainable agriculture and food security goals, encouraging the discovery of additional benefits of mushrooms and their use.

Keywords: Climate control, Cultivation, Mushroom, New technology.

INTRODUCTION

Mushroom cultivation has become a major economic player in both local and global markets due to changing consumer preferences and increasing awareness of its health benefits and sustainable farming practices. The increasing demand for

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fresh and natural products in local markets has created opportunities for the growth of small-scale mushroom producers. The direct-to-consumer sales model, often adopted by local farmers, attracts consumers who prioritize freshness and traceability. In addition, the popularity of mushrooms in gourmet restaurants and traditional cuisines has driven growth in the local market [1].

Mushroom cultivation on a global scale has witnessed a significant increase due to its compatibility with many trends. The increasing preference for plant-based diets has given mushrooms extra importance as a valuable source of nutrition and meat alternatives. This change has created a strong demand for mushroom-derived products such as meat substitutes, snacks, and supplements. At the same time, the healthy life and functional foods movement has strengthened the status of medicinal mushrooms, increasing demand for species known to have immune-boosting and cognitive-enhancing properties [1]. Mushrooms have been accepted as a valuable ingredient in dietary/healthy supplements due to their health-enhancing properties, together with their high quality and digestible protein structure [2].

The nutritional importance of mushrooms is not limited to their protein quality and content. They also contain vitamins (especially vitamin B types), mineral elements (such as potassium and selenium), and bioactive components. Polysaccharides are one of the important bioactive components. For example, β -glucans have antioxidant properties and support the immune system. This means support in fighting oxidative stress. Mushrooms are a rich source of phytonutrients with potential therapeutic properties, including anti-inflammatory, anti-cancer, and antimicrobial effects [2]. Cultivating edible mushrooms provides high-quality, digestible protein that is available at a cost-effective price and with a lower environmental impact [3]. Research findings demonstrate that the medicinal properties of mushrooms, including their antioxidant activity, cholesterol-lowering ability, potential to reduce the risk of cancer, hypertension, and hypercholesterolemia, significantly increase their therapeutic potential [4, 5].

Mushrooms have high nutritional content and have various uses. Mushroom cultivation has had an important place in agriculture for centuries, as it shows a high potential in terms of obtaining value-added products, market demand, consumer perception, and health benefits [6 - 8]. The role of mushrooms in the diet and the scope of their cultivation can be advantageous for improving livelihoods, given the declining land, the availability of readily accessible, low-cost agricultural waste, higher production rates, and labor opportunities. Mushroom cultivation is emerging as a profitable agricultural sector that addresses critical issues such as resource efficiency, circular economy, sustainability, and food security, while also offering a more resilient production

model against the adverse effects of climate change [9]. The potential to start at low cost and generate high income in a short time makes mushroom cultivation an attractive source of income for unemployed youth, farmers, and women in rural and urban areas. The fact that it can be practiced even in small areas makes mushroom cultivation more accessible [10].

Fungal biotechnology offers opportunities to convert wastes into renewable resources to meet the increasing demand for food, animal feed, fertilizer, and energy, while also enhancing recycling efforts [11]. Spent mushroom substrate (SMS) consists of incompletely degraded lignocellulosic compounds [12]. Depending on the fungal species, the degradation efficiency is estimated to be around 40–80% [13]. SMS yields many valuable by-products, including phenolics, sugar polymers, and proteins. They are common, economical, and renewable resources [14]. The composition of SMS varies greatly depending on the geographical location, the mushroom species grown, and the different cultivation techniques used. In the era of a sustainable economy, SMSs have shown potential for use in a wide range of applications. In various studies, SMS has been shown to be effective as a fertilizer and animal feed [15]. SMS has significant potential in the bioenergy sector and can contribute to the production of different types of bioenergy, such as biogas, solid biofuel, *etc* [16].

Many studies have focused on increasing the commercial potential and economic value of mushrooms, as well as their nutritional value [17 - 19]. Catharin Sara *et al.*, [20] have emphasized the importance of environmentally friendly industrial products obtained from mushrooms. Lu *et al.*, [17] reviewed mushroom cultivation, their bioactive properties, and application areas. In their research, they revealed that mushrooms contain prebiotics that positively affect the gut microbiome and general human health. These studies show that mushroom cultivation offers promising benefits in terms of economy and nutrition and that its potential, which has not yet been fully explored, should be examined in more detail. As demand for mushrooms increases globally, the need to investigate innovative methods that will increase the efficiency, sustainability, and productivity of mushroom cultivation is also growing [21, 22].

Market trends indicate that the economic impact of mushroom cultivation is expected to grow steadily. From local markets catering to consumer demands for fresh produce to international markets leveraging health and sustainability trends, the mushroom industry continues to expand its influence. With the development of innovative cultivation techniques and diverse product applications, mushroom farming is poised to not only boost economic growth but also play a key role in redefining food production, public health, and environmental stewardship [23].

CHAPTER 4**Mycoproteins and Meat Alternatives****Mücahit Muslu^{1,*}, Yasemin Çelebi², Salih Sezer³ and Gülşah Çalışkan Koç²**¹ *Department of Nutrition and Dietetics, Faculty of Health Sciences, Kastamonu University, Kastamonu, Türkiye*² *Department of Food Processing, Food Technology Program, Eşme Vocational School, Uşak University, Eşme, Uşak, Türkiye*³ *Laborant and Veterinary Health Program, Eşme Vocational School, Uşak University, Eşme, Uşak, Türkiye*

Abstract: Mycoproteins are examined in this chapter as a novel and sustainable meat substitute. The evolution of fungal-based protein sources is covered first, with an emphasis on edible mushrooms and macrofungi as potential answers to the rising need for alternative proteins. The history and manufacturing processes of mycoproteins are thoroughly examined in this chapter. The nutritional characteristics of mycoproteins are described in detail, emphasizing their low levels of fat and sodium, high protein and dietary fiber content, and their critical micronutrient content. In addition, mycoproteins have positive effects on cholesterol, insulin regulation, muscle growth, and the environment, in addition to other health benefits. Notwithstanding these benefits, issues such as allergic reactions, microbial toxins, and consumer acceptance still exist. The chapter also discusses market trends, pointing out that the mycoprotein industry is expanding significantly due to growing global demand and uses in dairy products, sauces, and meat alternatives.

Keywords: Fungal-based protein source, Health benefit, Macrofungi, Manufacturing, Market potential, Meat alternative, Mushroom, Mycoprotein.

INTRODUCTION

The exploration of alternative protein sources dates back to the late 1950s, when experts began predicting a global shortage of protein-rich food supplies. Alternative meat options encompass various sources, including plant-based proteins (e.g., wheat, pea, and soy), fungal-based proteins (mycoproteins), insect-based proteins, and algae-based proteins. Single-cell proteins produced from microorganisms such as bacteria, fungi, and microalgae represent a promising

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alternative protein source. Compared to traditional animal proteins, the search for sustainable, protein-rich alternatives with a lower environmental impact has led to extensive research into microbial protein production. Notably, the 1960s witnessed a breakthrough in fungal-based proteins with the discovery of *Fusarium venenatum* by British scientists in 1967. Mycoprotein received approval for food use in 1984 and was commercialized under the brand name Quorn in 1985. During this period, agricultural and industrial wastes (e.g., pea processing residues, lignocellulosic materials, pineapple peels, seaweed) were utilized in microbial fermentation to produce mycoprotein biomass. Solid-state fermentation, complemented by surface culture methods, and submerged fermentation are the primary techniques used in mycoprotein production [1 - 5].

Mycoproteins stand out in consumer preferences due to their high nutritional value and positive health effects. They are suggested to have anti-diabetic, anti-hypertensive, anti-atherogenic, anti-carcinogenic, and anti-obesogenic properties, as well as the ability to regulate gut microbiota and improve muscle function. The potential benefits of mycoproteins are given in Fig. (1) [6, 7]. In 1983, the UK Ministry of Agriculture, Fisheries, and Food approved mycoprotein for use as a food ingredient, and in 2002, the US FDA classified it as “Generally Recognized As Safe” (GRAS). The Halal Food Authority has also certified mycoprotein products, with the certifications displayed on packaging. However, primary concerns regarding mycoprotein consumption include the potential production of microbial toxins and allergic reactions [7 - 12].

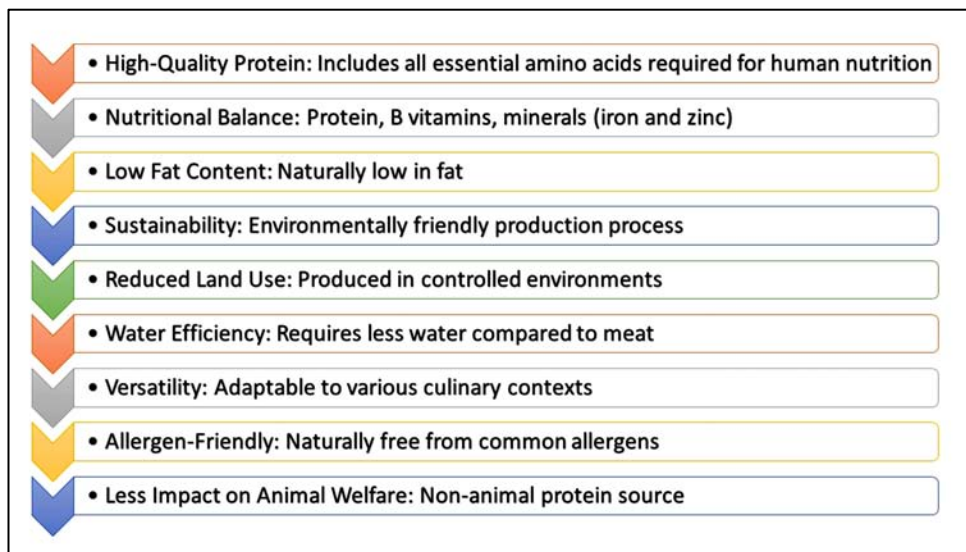


Fig. (1). The potential benefits of mycoproteins [6, 7].

This chapter's goal is to give a thorough introduction to mycoproteins as a substitute protein source by examining their history, production methods, nutritional qualities, health benefits, and market dynamics. It looks at how mycoproteins might help with global food issues like food security, sustainability, and health while figuring out what obstacles stand in their way. This chapter seeks to provide guidance for optimizing mycoprotein consumption in the food business by incorporating insights into production methods, customer acceptance, and market expansion.

Development of Fungal-Based Protein Sources

History of Mycoprotein

The quest for alternative protein sources has a rich scientific history dating back to the late 1950s, when experts anticipated a worldwide scarcity of protein-rich food sources [2]. This prediction spurred extensive research into microbial protein production, evolving through several key phases. Initially, research focused on yeast production, including *Candida utilis*, *Saccharomyces cerevisiae*, and *Torula* species. These food yeasts played a crucial role in human nutrition during the world wars [13]. As research progressed, attention shifted to bacterial strains. A notable example was Imperial Chemical Industries' development of Pruteen, a pig feed derived from *Methylophilus methylotrophus* grown on methanol. The 1960s saw a breakthrough with mycoprotein, a fungal-derived protein source (Fig. 2). British scientists led by Lord Rank discovered *F. venenatum* in 1967, which became the foundation for mycoprotein production [14]. The ATCC PTA-2684 strain was deemed safe because it does not produce harmful microbial byproducts under the controlled growth conditions used in production (28 to 30 °C; pH 6.0) [5]. After nearly two decades of intensive research and development, focusing on optimizing fermentation, reducing RNA content, ensuring safety, and improving texture, mycoprotein received approval for food use in 1984 [3, 14]. In 1984, the United Kingdom's Ministry of Agriculture, Fisheries and Food approved *F. venenatum* A3/5 for use as a food product [5]. Commercialized under the brand name Quorn in 1985, mycoprotein has since expanded globally [3, 4]. Continuous research has enhanced its production efficiency, nutritional benefits, and explored its health impacts, including effects on cholesterol levels, muscle protein synthesis, and appetite control. A significant milestone was reached in 2020 with the opening of Quorn's Fermentation Development Centre 4 [1, 15]. Concurrently, research on filamentous fungi, particularly *Aspergillus oryzae* and *Rhizopus oryzae*, revealed their capability to produce a diverse range of microbial proteins suitable for animal feed [16]. This development marked another significant step in addressing global nutritional needs. Throughout this journey, mycoprotein has evolved from a novel concept to a widely recognized meat alternative. It

Fungi in Functional Foods and Nutraceuticals

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Abstract: Functional foods provide health benefits beyond their basic nutritional qualities. Mushrooms have a significant potential for development and production of functional foods and nutraceuticals in addition to their essential nutritional content. They contain bioactive compounds with beneficial functional properties to enhance food fortification. These important bioactive compounds include ascorbic acid, beta-glucans, carotenoids, ergosterol (provitamin D), fatty acids, triterpenoids, peptides, proteins, and phenolic compounds. Thanks to the compounds they contain, they lead to immune regulation and increase the normalization levels of important neurotransmitters such as serotonin and dopamine, and are considered important in the prevention of obesity, diabetes, cardiovascular diseases, and cancer treatment. Mushrooms also have antiviral, anti-inflammatory, cytoprotective, and antineoplastic therapeutic potential. In addition, their prebiotic activity supports the gut microbiota. Some of the nutritional and medicinal benefits of mushrooms have been described in detail and supported by clinical research. Due to their functional properties, mushrooms are recognized as a new generation of foods, and research continues with hope. However, it is important to note that most scientific studies are conducted on animal models, meaning some evidence regarding mushroom consumption has not yet been confirmed in clinical trials.

Keywords: Bioactive compounds, Functional foods, Fungi, Health benefits, Nutraceuticals.

INTRODUCTION

Functional foods are defined as products that provide health benefits over their basic nutritional qualities [1, 2]. Specifically, functional foods are not simply processed products; they are fundamental foods that can be integrated into daily diets to help decrease the risk of illness. These foods possess incomparable

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characteristics that improve overall well-being, in addition to promoting growth [3, 4].

The public exhibits varying attitudes toward functional foods. Consequently, functional foods are not universally known as singular, well-defined entities; instead, a wide variety of foods can be listed under this category. These foods have beneficial effects on human physiology and metabolic functions, thanks to the bioactive components within their structure. In this context, mushrooms have received particular attention, as they have been used for centuries worldwide, particularly in traditional medicine. Their categorization as functional foods is supported by existing research, and research is being conducted on functional bioactive compounds within their structures [5 - 7]. In this study, the aim is to provide information about the content of bioactive components in mushrooms, their functional effects, health benefits, and their effects on human health due to their functional properties. In addition, clinical research and observational studies on some mushroom species are reviewed, and regulation and challenges in nutraceutical development in this field are discussed.

Bioactive Compounds from Fungi

They are known as a valuable source of fiber, vitamins, minerals, and carbohydrates. Moreover, their amino acid profiles resemble those of animal proteins, enabling mushrooms to compete effectively with animal-based products [8]. In addition to their nutritional value, mushrooms contain bioactive compounds with functional effects that enhance food enrichment [9, 10].

The bioactive compounds present in mushrooms are comprised of various naturally derived substances that exert important effects on living organisms. Remarkable bioactive compounds characteristically found in mushrooms include ascorbic acid, beta-glucans, carotenoids, ergosterol (provitamin D), fatty acids, triterpenoids, peptides, proteins, phenolic compounds, and other bioactive substances [11 - 15]. The presence and concentration of these bioactive compounds can vary significantly based on several factors, including species diversity, cultivation conditions, and the maturation stage of the mushrooms. This complex composition varies not only among different mushroom species but also among individual mushrooms, influenced by factors such as developmental stage, fruiting body conditions, age, and storage environment [16, 17]. Consequently, mushrooms possess unique effects and demonstrate distinct functional potentials due to the diverse bioactive components they contain. A detailed list of the bioactive compounds found in mushrooms is provided in Table 1.

Table 1. Bioactive compounds found in mushrooms.

Mushroom	Bioactive Compounds	References
<i>Agaricus subrufescens</i>	β -glucan	[18, 19]
	Carotenoids	[14, 20]
	Ergosterol	[20]
	Fatty acids	[20]
	Lectin	[20]
	Phenolic compounds	[20, 21]
	Polysaccharides	[18 - 21]
	Terpenes	[18, 20]
<i>Armillaria mellea</i>	Alkaloids	[22, 23]
	β -glucan	[24]
	Organic acids	[22, 23]
	Phenolic compounds	[22 - 24]
	Polysaccharides	[25, 26]
	Steroids	[22, 23]
	Terpenoids	[22, 23]
<i>Auricularia spp.</i>	Adenosine	[27]
	β -glucan	[28 - 31]
	Bioactive peptides	[27]
	Exo-biopolymers	[27]
	Melanin	[30, 32]
	Polysaccharide	[13, 27, 33]
	Polyphenolic compounds	[13, 27, 30, 32, 33]
<i>Cordyceps sinensis</i>	Cordycepin	[15, 34 - 37]
	Flavonoids	[15, 34, 35, 37 - 39]
	Nucleotides	[36, 39]
	Phenolic compounds	[15, 34, 35, 37, 38]
	Polysaccharides	[15, 34, 35, 37, 38]
	Sterols	[39]
<i>Fomitopsis betulina</i>	β -glucan	[40]
	Betulinic acid	[12, 41]
	Glucooligosaccharides	[12, 40]
	Polysaccharides	[12, 41]
	Polyphenolic compounds	[12, 41 - 43]
Terpenes	[12, 41 - 43]	

Fungi-Derived Food Additives and Flavors

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Abstract: The growing global population, the decline in edible food sources, technological advancements, and limited time have led to significant changes in society's eating habits. The increasing preference for ready-to-eat and semi-prepared foods has also resulted in higher consumption of food additives. In today's conditions, food additives are used at various stages of the food supply chain, from farm to fork, for different purposes. However, excessive intake of food additives may have negative health effects. For this reason, there has been a growing interest in natural food additives in recent years. Due to their functional properties, edible mushrooms are widely used as versatile ingredients in food product development. This chapter aims to determine the potential of edible mushrooms as food additives. Edible mushrooms can be used as meat substitutes in various food products, reducing fat and animal protein content while increasing dietary fiber and amino acid levels. When used as fat replacers, they lower fat levels in processed foods and enhance sensory properties. When incorporated as flour substitutes in baked goods, they boost dietary fiber, protein content, and antioxidant capacity. Additionally, mushrooms act as natural salt and phosphate substitutes, reducing sodium levels in meat products and replacing synthetic additives while maintaining sensory acceptability and product quality. Mushrooms also have great potential as natural colorants. Their natural origin, low-cost and high-yield production, and wide color spectrum make them suitable for use as food additives. These multifunctional roles of edible mushrooms highlight their potential to enhance nutritional profiles and promote sustainability in food formulations.

Keywords: Edible mushroom, Food additive replacer, Fungal pigments, Sustainability.

INTRODUCTION

The mushroom is the fleshy fruiting body of macro fungi that carries spores. These fungi have gained international interest due to their important food, medicinal, and nutraceutical resources. Mushrooms are renowned around the

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world for their distinct flavor, texture, and taste. Proteins, carbohydrates, fibers, minerals, vitamins, and a low total fat content with a high content of polyunsaturated fatty acids are among its beneficial and significant nutritional components. Furthermore, mushrooms contain abundant levels of vitamins, including thiamine (B₁), riboflavin (B₂), cyanocobalamin (B₁₂), ascorbic acid (C), vitamin D, and vitamin E [1].

Alternative products to animal-based sources have increasingly found a place in diets due to changing living conditions and consumer demands. Factors accelerating the search for alternative protein sources include (1) the expectations of saturated consumer groups for new products, (2) product development efforts aimed at consumers preferring vegan/vegetarian diets, (3) climate change, (4) safety concerns regarding animal-based products, (5) the growing population, and (6) the trend towards healthy eating [2]. Considering all these factors, alternative proteins present themselves as a robust contender against animal-based proteins. Proteins obtained from various sources through different methods are structured into various forms and transformed into highly demanded products, commonly known as meat analogues, which are increasingly becoming a part of consumption habits.

Recently, mushroom-derived proteins have gained attention due to their higher nutritional value compared to plant-based proteins. Mushrooms hold a significant place in many cuisines worldwide because of their flavourful and nutritious properties. Due to their nutritional content and biological potential, they are increasingly being recognized under the terms “next-generation food” and “plant-based meat.” Although most of the research on mushrooms has focused on their polysaccharide composition, mushroom proteins and peptides also represent an important group of bioactive compounds [3, 4]. Mushrooms can be grown more quickly and economically compared to plants and can easily be produced using agricultural or industrial residues. Additionally, mushroom proteins are known for their high thermal and pH stability. Mushrooms contain 5'-nucleotides and free amino acids, which act as water-soluble flavour compounds with “umami” properties. Consequently, mushroom-based products have been reported to be more favoured compared to other plant-based products [5]. Unlike soy proteins, mushroom proteins do not have the aroma issue associated with the “beany” flavour. Mushrooms contain, on average, 19–35% protein by dry weight, which is comparable to soybeans and higher than many other plant-based sources. They also possess a complete amino acid profile, including the eight essential amino acids required by humans and histidine, which is necessary for infants.

The essential amino acid intake values recommended by the World Health Organization (WHO) outline the quantities needed to meet the daily protein

requirements of a healthy individual. The amino acid profile of mushrooms often aligns closely with these recommendations. Some species, such as *Agaricus bisporus*, *Flammulina velutipes*, *Tricholoma matsutake*, and *Pleurotus eryngii*, have even been found to fully meet the daily intake limits. Furthermore, the digestibility range of mushroom proteins is generally between 72–83% (compared to 74% for soy, 82% for rice, 92–94% for meat, and 97–98% for eggs and dairy products) [6]. Mushroom proteins also differ from animal, plant, and microbial proteins due to their antioxidant, antiviral, antibacterial, and antitumor properties [3]. Using edible mushrooms for developing protein-rich food products could serve as a viable alternative to animal-based protein sources [7, 8].

This chapter investigates the potential use of edible mushrooms as natural flavor enhancers, meat, fat, flour, and salt replacers in food products. The nutritional value, functional properties, and ability of mushrooms to improve sensory quality make them a natural and healthy alternative to conventional food additives. Furthermore, their contribution to environmental sustainability, coupled with increasing consumer awareness, encourages their broader application in the food industry. In this context, the chapter provides a comprehensive evaluation of the functional and technological roles of mushrooms in food formulations, aiming to guide future research and industrial applications.

Natural Flavour Enhancers from Fungi

The increasing global population, technological advancements, greater participation of women in the workforce, and limited time have led societies to change their dietary habits. People have started consuming more ready-to-eat and semi-prepared foods, resulting in increased exposure to food additives.

Nutrition involves the intake of macro- and micronutrients to meet physiological needs. However, in recent years, interest has shifted toward consuming foods that not only meet these needs but also meet these needs and positively impact health due to their bioactive components [9]. In line with this trend, processed foods containing high levels of animal products, fats, salts, and artificial additives, which can negatively affect health if consumed excessively, have drawn attention to healthier or functional alternatives to replace synthetic food additives. The increase in greenhouse gas emissions caused by animal protein production and its sustainability issues has prompted behavioral changes among consumers. Consequently, it has raised the demand for plant-based products [10]. Similarly, the demand for natural alternatives to synthetic food additives has also increased [11]. Vegetables, grains, edible seeds, tubers, algae, and even insects are being consumed as sources of protein and dietary fiber [12 - 14].

CHAPTER 7

Sustainable Practices in Mycological Food Production

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Abstract: The growing global population, resource depletion, and environmental concerns demand sustainable methods in food production systems. Mycological food production is a viable pathway for sustainability owing to its low resource demands, compatibility with circular economy concepts, and capacity to utilize agricultural biomass. This chapter analyzes sustainable methodologies in mushroom production, emphasizing improvements in resource efficiency, waste management, and life cycle assessment (LCA) evaluations. Key aspects include the transformation of agricultural waste into valuable substrates, the reduction of greenhouse gas (GHG) emissions, and the integration of spent mushroom substrates into diverse applications such as biofuels, soil amendments, and wastewater treatment. Through innovative techniques and closed-loop solutions, mushroom production not only addresses nutritional and environmental challenges but also contributes significantly to achieving global sustainability goals. This study underscores the critical role of mycological food systems in fostering a resilient and eco-friendly agri-food sector.

Keywords: Circular economy, Environmental impact, Fungal biomass, Mushroom cultivation, Mycological food systems, Spent mushroom substrate resource efficiency, Waste management.

INTRODUCTION

In the 21st century, companies and society are encountering major changes and a multitude of obstacles. The concept of sustainability poses significant issues that are more integral to modern business structures. With a forecast world population of 9.6 billion by 2050, there will be a corresponding increase in food demand, estimated to rise by 70% compared to today [1]. As a consequence, sustainable economic development has emerged as a major topic in local and international

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political and social discourse in recent years. Food systems cannot survive catastrophes such as the COVID-19 pandemic unless they are sustainable, which is why the European Green Deal's Farm to Fork strategy seeks to make them egalitarian, healthy, and ecological [2]. Even before the pandemic, to improve the quality of human life worldwide, the United Nations set a series of Sustainable Development Goals to be managed by 2030 [3].

With increasing knowledge about climate change, resource depletion, and a growing global population, agri-food companies need to reconfigure their supply chains to consider both environmental and economic consequences of their actions. In practice, due to several sources of uncertainty in agri-food supply chains (FSC), all the necessary information is not available beforehand [4]. Sustainability means meeting current demands without compromising the capability of future generations to meet their own requirements [5]. Taking into account social, economic, and environmental aspects, the scientific community has created a number of measures to evaluate the sustainability of FSCs. Nevertheless, there is disagreement about a uniform procedure for using these footprints and dimensions [6]. A food system that is sustainable meets current requirements for nutritious, healthful, as well as culturally appropriate food without hindering the needs of future generations [5]. Acknowledging the role of mushroom production in sustainability and addressing these goals and challenges will facilitate the future viability of mushroom agriculture. Mushrooms need energy, materials, and water inputs to produce, much like any other food product. Information about the effects of food systems on energy and the environment is increasingly sought [7].

Mushrooms offer an excellent alternative for sustainable development due to their economic value in supply chains, superior nutritional properties, and compatibility with circular economy principles [3]. Mushrooms are fungi of considerable nutritional significance, with over 2000 edible species found globally [8]. The most commonly farmed species are oyster mushrooms (*Pleurotus* spp.), shiitake mushrooms (*Lentinula edodes*), and button mushrooms (*Agaricus bisporus*) [9]. The cultivation of edible mushrooms is becoming increasingly popular due to brief harvest cycles, cheap input necessities, limited land demands, and an abundance of agricultural biomass [10]. Food and Agriculture Organization Statistics (FAOSTAT) indicated an upward trend in output from 2000 to 2020, culminating in a production volume of 42,792,893 tonnes and representing a gross value of \$45,200,678 in 2020 [11]. Elements of a sustainable mycological food production process are illustrated in Fig. (1).

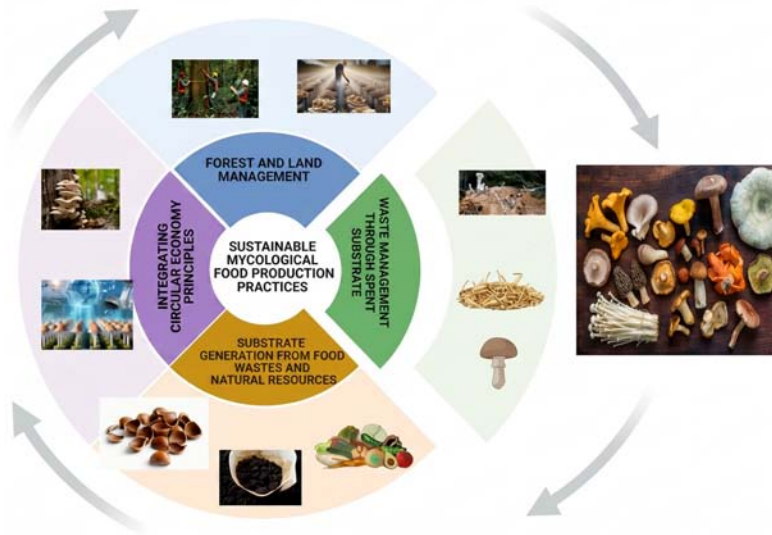


Fig. (1). Elements of a sustainable mycological food production process (Created with BioRender.com).

The cultivation of mushrooms presents the possibility of an appropriate alternative in this regard, due to its low land and resource needs, quick harvest cycles, and ability to use agricultural biomass. With over 2,000 edible species and growing economic importance, mushrooms fit well with circular economy principles and make a significant contribution to the global food supply. The increasing demand for sustainable food production underlines the role of mushrooms in addressing the environmental and nutritional challenges of modern food systems. Therefore, this chapter focuses on clarifying the significance of sustainable practices in mycological food production by scrutinising resource efficiency, waste reduction and management, and Life Cycle Assessment (LCA) studies centred on the principles of a circular economy.

Resource Efficiency and Management in Fungal Cultivation

Resource efficiency in supply chains begins with an understanding of resource utilization and its consequences [1, 12, 13]. Consequently, a significant portion of success in fostering resource consumption awareness relies on the firms' readiness and capacity to share information [1, 14]. The decreasing availability of natural resources is emerging as a pressing issue for our industrial, economic, and political systems. Several recent corporate and government reports have been published expressing increasing concerns about the limited supply of natural resources in the near future and the potential consequences for industries [1]. A more sustainable food supply system can only be achieved by a thorough examination of resource flows, especially in the food production and processing

Mycological Impacts on Food Security

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Abstract: Edible fungi are valued as nutraceuticals and functional foods because of their rich content of unique bioactive compounds and their high nutritional quality. Their elevated protein levels, unique bioactive polysaccharides, and rich mineral content make edible fungi an excellent alternative for consumers, particularly vegetarians and vegans. Wild edible fungi play a crucial role in food safety and address nutritional deficiencies, and serve as vital economic resources for many local communities, rural areas, and minority groups. Increasing the production of cultivated fungi and exploring new food preservation techniques can help create job opportunities, enhance food safety, improve socio-economic conditions, and boost the health and nutritional status of individuals and communities. Additionally, the development of mycotourism presents an innovative strategy for providing rural areas with alternative income sources. Edible fungi offer a versatile range of functionalities that allow them to replace various common food ingredients and additives. While their incorporation can lead to nutritional benefits and potential health advantages, it also positively impacts the technological and sensory properties of the final food product to ensure consumer acceptance. The framework governing mushroom-based foods is complex and requires ongoing attention to ensure consumer safety and improve trade. There is a necessity for further efforts in harmonizing international regulations, specifically regarding wild-harvested fungi. As the regulatory landscape for fungi products evolves, the importance of food safety, accurate labeling, and sustainable methods grows significantly. It is essential to align EU and national regulations, especially for wild-harvested fungi, with international standards to safeguard consumers and encourage edible fungi trade. Biotechnological methods, such as fermentation and enzymatic hydrolysis, are used to modify the composition of edible fungi, ultimately aiming to increase their health-beneficial and nutritional attributes.

Keywords: Edible fungi, Food additive replacer, Food ingredient replacer, Food safety, Food security, Mushroom, Mycotourism, Nutrition, Socio-economy, Waste recycling.

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INTRODUCTION

Edible fungi have a unique chemical composition that makes them an excellent choice for various consumers. Wild edible fungi serve as a primary source of income and food security in many parts of the world, particularly among low- and middle-income populations. The rich nutritional content makes edible fungi an effective and helpful tool to address nutritional deficiencies in these communities. Furthermore, cultivating fungi offers a viable strategy for tackling various socio-economic issues, including unemployment and poverty.

This chapter explores how edible fungi contribute to food security in the face of climate change and population growth, which contribute to food shortages. Cultivating edible fungi offers numerous advantages, particularly for local communities and consumers. It helps reduce food scarcity while tackling challenges such as poverty, unemployment, malnutrition, and inequality impacting women and minorities. This underscores notable socio-economic and health benefits. Additionally, edible fungi can serve as supplements (replacers) in various food products for diverse technological and sensory purposes. Furthermore, utilizing agri-food waste for growing edible fungi promotes recycling and provides sustainable alternatives for both the agricultural and industrial sectors' wastes.

Fungi as a Solution to Nutritional Challenges

Edible fungi can be classified as nutraceuticals because they are rich in beneficial nutrients [1]. Over 130 therapeutic properties have been identified in edible fungi, including antioxidant, antibacterial, antiviral, antifungal, antitumor, anti-inflammatory, hepatoprotective, cardiovascular protective, detoxifying agent, anti-diabetic, and anti-hypercholesterolemic [2]. Moreover, edible fungi serve as a healthy food option for people with hypertension, thanks to their low sodium content and high levels of potassium. Edible fungi are rich in a wide range of bioactive compounds, including proteins, fats, polysaccharides, minerals, vitamins, phenolic substances, flavonoids, carotenoids, tocopherols, terpenoids, alkaloids, folates, volatile oils, and enzymes [2].

Vegetarians and vegans often lack important elements such as calcium, selenium, and vitamin B₁₂, making edible mushrooms an ideal food for this category of consumers [3].

Energy

The energy values of mushrooms vary by species, ranging from 1516 to 1736 kJ/100 grams of dry matter (DM) for five varieties of wild edible mushrooms [4]. Mushrooms are an excellent choice for weight loss and can be beneficial in a nutritional program aimed at managing hypercholesterolemia and cardiovascular diseases [5].

Proteins

Proteins are fundamental components of the body, vital for cell structure and enzyme function. The World Health Organization (WHO) recommends a daily protein intake of 0.75 grams per kilogram of body weight for adults [6]. The nutritional quality of fungal proteins is similar to that of proteins from animal sources [1]. Diets high in animal protein can pose health risks, including an increased likelihood of cardiovascular diseases and certain types of cancer [6].

Edible mushrooms are rich in protein, comprising 12-35% of their DM, with a nutritional quality and digestibility that surpass those of plant proteins. The protein composition in mushrooms is comparable to and in some cases even better than that of soy protein, and is similar to the protein quality found in hen's eggs [7]. Additionally, some edible fungi contain higher levels of protein than wheat and milk [1]. When evaluating protein intake, it is crucial to assess not only the quantity but also the digestibility and amino acid composition.

The free amino acid content in edible mushrooms is less than 1% of their DM [8]. The most common amino acids present include leucine, valine, glutamine, glutamic acid, alanine, and aspartic acid [9]. Mushroom proteins contain all the essential amino acids, giving them a superior nutritional profile compared to most plant-based proteins [8]. They provide all the essential amino acids that are often lacking in vegetables, including lysine, tryptophan, and methionine [5].

The protein fractions of edible mushrooms are abundant in different types of proteins, such as albumins, globulins, glutelins, glutelin-like materials, prolamins, and prolamine-like substances [8]. Additionally, edible fungi produce a range of biologically active proteins and enzymes, including lectins, fungal immunomodulatory proteins, ribosome-inactivating proteins, antimicrobial and antifungal proteins, ribonucleases, and laccases [10].

The ratio of essential amino acids to total amino acids indicates the nutritional value of protein. Edible mushrooms contain high ratios, for *Leccinellum crocipodium* and *Boletus speciosus*, this ratio is 0.31 and 0.43, respectively [7]. Additionally, the nutritional quality of proteins is also indicated by the ratio of

Novel Food Products From Fungi

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Abstract: The rapid growth of the world's population makes it essential to develop novel food products with improved nutritional properties and a reduced environmental footprint. New production approaches are needed to ensure adequate quantities of high-quality food. The unique properties of fungi due to their content of essential and non-essential amino acids, digestible and indigestible carbohydrates, phenolic compounds, sterols, terpenoids, minerals, vitamins, lipids, essential fatty acids, monounsaturated, and polyunsaturated fatty acids make them a great candidate for the production of novel foods. Furthermore, fungi are relatively easy to grow, making large-scale production feasible. They also have low water and carbon footprints. In addition, they are very important for vegetarians and have great potential for use in the development of vegan products, as they can mimic the taste, texture, and nutritional composition of meat products, and commercial fungal-based vegan products are already available on the market. In addition, edible fungi enhance the nutritional and functional properties of cereal-based products, offering high potential for the development of functional and health-oriented products. In the near future, it is likely that fungi will open up new areas of application in the food industry.

Keywords: Edible fungi, Fungal-based vegan products, Innovative food, Meat alternatives.

INTRODUCTION

The World Resources Institute has reported that the world population is expected to be around 10 billion by the year 2050 [1]. In this context, sustainable nutrition becomes a priority. Sustainable healthy diets should be nutritious, safe, sensitive to biodiversity and ecosystems, acceptable, accessible, affordable, environmentally friendly, and have low carbon and water footprints [2]. Nevertheless, husbandry of livestock for animal-based food production causes more pollution, greater water and land use, and loss of biological diversity compared to the cultivation of crops [3]. In addition, when all sources of greenhouse gas emissions in the food chain are considered, it is concluded that

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animal-based foods produce significantly more carbon dioxide equivalents per kilogram than plant-based foods [4]. On the other hand, plant-based products do not contain all the essential amino acids in sufficient amounts and may even have anti-nutritional compounds that reduce the bioavailability of protein [5]. As a result of the aforementioned rapid global growth, animal or plant-based food sources will not be able to feed this population in the near future. It is therefore imperative to develop new food products with improved nutritional properties and reduced environmental footprints. In this context, fungi are emerging as a future sustainable food source [6]. Fungi and fungal by-products have a long history in the food industry, and play an important and versatile role in food production at diverse stages from cultivation to consumption. Fungi have been used as food ingredients in the production of beverages such as beer, cider, sake, and wine, and fermented foods such as bread since 6000 BC, and in the production of cheese since at least 7500 BC. They have also been consumed directly as food in the form of mushrooms since early agriculture [7]. Although archaeological findings indicate that edible mushrooms were associated with Chilean inhabitants as early as 13,000 years ago, the first reliable record of mushroom consumption dates back a few hundred years before the birth of Jesus and was found in China [8]. It is also recorded that the Sumerians and Babylonians were the first to use fungi in the fermentation process and the production of fermented foods [9]. Despite a long history of using fungi, their potential was only fully explored in the second half of the 20th century. Ever since, the fungal kingdom, which includes yeasts, fungi, and filamentous fungi, has been utilised in a wide range of food products [10].

It is possible to produce food of better quality and at a lower cost on a large scale by using fungi as a source. In addition, fungi have a high potential for use in the production of high-value-added novel foods [11]. They have many advantages for use in the food industry, particularly as alternative proteins, including greater resource efficiency, complete amino acid profiles including essential amino acids, nutritional benefits, and reduced ethical issues [12, 13]. Besides their nutritional value, fungi also have therapeutic effects due to the various bioactive metabolites they contain, such as polysaccharides, dietary fiber, steroids, polyphenols, triterpenoids, and β -glucan [14]. This chapter aims to explore the innovative applications of fungi in food, covering the development of fungal-based vegan and cereal-based products, examining successful market case studies, and current consumer trends related to these novel ingredients.

Innovative Fungal Foods and Ingredients

It is becoming increasingly difficult to supply high-quality food for the world's exploding population. In this context, innovative food products are one of the fastest-growing and emerging areas of the food industry [15].

It is a known fact that the livestock sector causes a very high environmental impact. It occupies the largest area of land used for anthropogenic purposes and accounts for around 18% of total greenhouse gas emissions, more than the transport sector. The production of animal-based products is also resource-intensive [5]. Plant-based foods, and especially proteins, are commonly utilised as alternatives to animal-based foods or as ingredients in the production of functional foods, depending on their cost-effectiveness and healthcare benefits. But, there are also disadvantages to plant-based foods, such as the lack of one or more essential amino acids and the large areas of land needed to grow them. In addition, although algae and insects have recently emerged as valuable alternative protein sources, seasonal, geographical, and availability constraints restrict their utilisation [16].

Recently, with growing global awareness of diet and health concerns, there has been a growing interest in food products developed from fungi. Fungi have a high nutritional value, are low in fat, and do not contain any cholesterol. Edible fungi are a great source of protein as they have both essential and non-essential amino acids [10]. As well as amino acids, they also contain digestible and indigestible carbohydrates, phenolic compounds, sterols, terpenoids, minerals, vitamins, lipids, essential fatty acids, monounsaturated, and polyunsaturated fatty acids [17]. Since agricultural crops produce huge amounts of waste, and fungi can grow on agricultural waste or other industrial waste products, their cultivation is both simple and very cost-effective. In addition, they are less susceptible to seasonal or climate variations, require less fertiliser and pesticide, much less land, and less man-power than plant or animal-based food production [18]. They also have a low water footprint and a low carbon footprint, which improves the nitrogen cycle in ecosystems. Reports indicate that using fungal-based protein instead of ruminant meat products can considerably decrease deforestation and greenhouse gas emissions [16]. Humpenoder *et al.*, [19] predict that even replacing 20% of beef with fungal protein could reduce deforestation by 55%, CH₄ emissions by 10% and NO₂ emissions by 5%.

Fungi obtained from cheap waste sources can be turned into high-value-added food products, contributing both economically and environmentally [16]. It can also have a positive impact on the sensory properties of foods such as meat alternatives and their acceptance by consumers [14]. Thus, their high nutritional value enables them to be considered as functional foods. As well as being highly nutritious, their rich aroma and taste make them ideal for developing innovative food products [17].

Fungi can be divided into three main groups according to their life history: Unicellular fungi, multicellular fungi, and macrofilamentous fungi. Yeasts,

Advances in Food Engineering Technologies for Fungi

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Abstract: Food engineering technologies that enable progress in fungal cultivation are critically important for increasing accuracy and optimizing efficiency in agricultural processes. Especially in fungal production, precise automation and Artificial Intelligence (AI) applications that go beyond the limits of classical agricultural techniques aim to make these processes more reliable and sustainable. This study examines the role of automation and precision agriculture applications in fungal cultivation, presenting digital solutions that can replace traditional methods. Data obtained using AI and Machine Learning (ML) play a critical role in early diagnosis of fungal diseases and prediction of nutrient deficiencies. ML and computer vision techniques are effectively used in assessing plant health and ensuring optimal use of agricultural resources. Additionally, innovations in fungal processing and storage technologies are discussed, along with the potential changes that these technologies may create in agricultural processes.

Keywords: Artificial intelligence, Automation, Computer vision, Decision support, Digital crop life cycle, Environmental variability, Fungal cultivation, Image analysis, Imaging techniques, Machine learning, Precision agriculture, Sustainability, Targeted treatment.

INTRODUCTION

Technological developments in the fields of agriculture and food engineering offer significant potential to increase the efficiency and sustainability of fungal cultivation. Fungal cultivation, unlike other agricultural production processes, requires very sensitive environmental conditions, and maintaining these conditions at an optimum level is limited by traditional methods. These

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difficulties of fungal cultivation can be overcome by integrating automation and precision farming techniques in production processes.

In this context, the role of automation in fungal production is of critical importance both in terms of reducing human-induced errors and in the more efficient use of resources [1]. Chapter 10 focuses on automation and precision farming applications in fungal cultivation. Precision cultivation enables the optimization of environmental parameters by instantly monitoring production processes with the integration of sensors, imaging systems, and other digital technologies. These systems provide high accuracy in data collection processes, allowing more effective strategies to be developed in production management. In addition, agricultural production processes become more sustainable, and operational efficiency increases with the labor savings provided by automation.

In this context, Table 1. Summarizes how automation and digital technologies are applied in fungal cultivation Table 1. The opportunities offered by these systems contribute to sustainable agriculture goals by increasing agricultural productivity while reducing environmental impacts. For example, the areas of use of AI and ML techniques in fungal cultivation are also examined. AI and ML contribute to the development of decision support systems in critical agricultural processes such as early diagnosis of fungal diseases, nutrient management, and harvest timing. For example, optimum growing conditions can be determined by creating image analysis of disease symptoms and yield prediction models, thanks to computer vision techniques. These technologies play an important role in making agricultural processes both more efficient and environmentally sustainable.

Table 1. Automation and precision agriculture in fungal cultivation: Methods and objectives.

Category	Purpose	Method
Automation in Fungal Cultivation	Optimize production, reduce labor costs, and minimize human errors	Use of sensors, robotic systems, and Internet of Things (IoT) to monitor environmental parameters (temperature, humidity, CO ₂ levels, etc.). Implementation of automated harvesting and packaging systems to increase efficiency and reduce contamination.
Precision Agriculture	Increase efficiency and sustainability.	Continuous monitoring of soil and environmental conditions using IoT-based sensor networks. Optimize growing conditions and improve resource use (water, energy, etc.) through data analytics.
AI and ML	Early disease detection, optimizing growth conditions, and predictive maintenance	Use of models such as Support Vector Machines (SVMs), Decision Trees (DTs), and Deep Neural Networks (DNNs) for real-time data analysis. Improve disease detection and agricultural processes using image recognition tools.

(Table 1) cont....

Category	Purpose	Method
Hyperspectral Imaging (HSI)	Detect fungal infections and optimize product quality	Collect spectral data using HSI and combine it with ML for early detection of fungal infections. Increase accuracy in detecting diseases and pathogens in crops.
Data-Driven Decision Making	Enhance decision accuracy and response time.	Data collection and analysis through cloud-based platforms. Automate decision-making processes using AI to adjust environmental factors and enhance efficiency through predictive analysis.

Automation and Precision Agriculture in Fungal Cultivation

Automation and precision farming techniques in fungal cultivation have become indispensable for optimizing production processes and increasing efficiency with the integrated use of modern technologies. Innovative approaches such as environmental control systems, smart sensors, imaging techniques, and robotic systems allow for high-quality products by providing precise management at every stage of production. Precision farming includes systems that continuously monitor fungal growth conditions and automatically adjust environmental factors as necessary. These systems continuously monitor important parameters such as substrate moisture, temperature, carbon dioxide levels, and light, supporting healthy and productive fungal growth [2]. Automation minimizes human intervention, reducing labor costs and eliminating error risks [3]. Such systems also allow more effective management of resources such as water, energy, and fertilizer used in production processes, which increases sustainability in agriculture and reduces environmental impacts [4].

Automated imaging and data analysis systems, integrated with AI and ML algorithms, help determine and maintain optimal conditions for fungal cultivation. Computer vision techniques are particularly effective in early detection of lesions or disease symptoms on fungi, with recent studies demonstrating over 97% accuracy in classifying fungal pathogens such as *Lasioidiplodia* species, providing farmers with fast and precise information [5]. Such data-driven approaches play a major role in decision-making processes and significantly increase efficiency in fungal cultivation. Moysiadis *et al.*, discuss the nutritional benefits of fungi, which are rich in essential nutrients, proteins, minerals, and vitamins, and encourage their inclusion in our diet. Many farmers grow fungi in controlled environments, such as greenhouses, where specific atmospheric conditions are maintained. Recent IoT technologies have started providing innovative solutions in agriculture [6]. The study explores how ML can be applied to monitor the growth of *Pleurotus* fungi. Using the YOLOv5 (You Only Look Once version 5) model, the researchers detected different growth stages of fungi and identified when they were ready to harvest, achieving an F1-score (harmonic mean of

CHAPTER 11**Challenges and Regulations in Fungal Food Engineering****Ömer Utku Çopur^{1,*} and Mehmet Dilmenler¹**¹ *Department of Food Engineering, Faculty of Agriculture, Bursa Uludag University, Bursa, Türkiye*

Abstract: Novel food approaches become more popular over time due to the healthy nutritional trends and also environmental concerns. Fungi-based foods are attracting increasing attention as an important component among all these trends and approaches due to their rich nutritional value, relatively environment-friendly production processes, and their low-fat content profile. However, a strong need for careful attention arises in terms of food safety and consumer health, despite all the nutritional and environmental advantages of edible fungi. Allergens, heavy metal accumulation, mycotoxin contamination, and microbial growth are the aspects that primarily require assessment as potential food safety risks. This chapter examines these intrinsic/extrinsic risks in relation to species biology, cultivation substrates, post-harvest processing, and storage conditions. It also discusses the difficulties in analytical determination of trace contaminants in complex mushroom matrices. Following the risk landscape, multi-layered mitigation strategies such as inspection schemes grounded in Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP), cold chain, modified/active atmosphere packaging, irradiation, fermentation, and enzymatic detoxification are evaluated. The Codex Alimentarius guidelines on a global scale are compared with the new food regulations in the EU, North America, and Asia markets, and the common risk assessment principles, traceability, and labeling requirements are summarized. The chapter also addresses patent trends in the field of mycoproteins, enzymes, and biomaterials; ethical-social debates around genome editing, circular economy, and citizen science. In conclusion, this study, which integrates microbiology, process engineering, analytical chemistry, and policy dimensions, provides a comprehensive roadmap for food engineers, regulators, and entrepreneurs to bring mushroom-based products to market in a safe, sustainable, and consumer-confident manner.

Keywords: Edible mushroom processing, Food safety risk assessment, Fungi-based foods, Safety hazards in fungi.

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INTRODUCTION

Fungi-based foods, which stand out in modern nutrition systems due to their low environmental footprint, high protein and fiber density, and rich composition of functional components, may also pose multi-layered hazards such as heat-tolerant allergens, endogenous toxins, heavy metal accumulation, mycotoxins, and rapid microbial spoilage. This chapter outlines a wide range of risks from species biology to cultivation substrates, from post-harvest processes to global legislation, revealing analytical detection challenges and evaluating mitigation strategies such as GMP- and HACCP-based inspection schemes, cold chain, Modified Atmosphere Packaging (MAP), irradiation, fermentation, and enzymatic detoxification from a technical and practical perspective. In addition, the chapter compares current regulations in the EU, North American, and Asian markets with Codex Alimentarius and explores ethical and social considerations, including patent trends, genome editing, circular economy, and citizen science. Thus, a holistic roadmap is presented for food engineers, regulators, and entrepreneurs to bring safe, sustainable, and consumer-trusted fungi-based products to the market.

Safety Concerns and Allergenicity of Fungal Foods

Fungi-based foods, primarily due to their rich nutritional profiles, have been evaluated as an important nutritional source in various geographies throughout human history [1]. In modern times, edible fungi have again become popular, especially in the health nutrition trends due to their low-fat content, besides having a rich nutritional profile including essential vitamins, minerals, and dietary fiber [1, 2]. However, despite all this nutritional content, edible fungi require a high level of attention in terms of food safety. Among the vast diversity of mushroom species, certain mushroom species may bring significant hazards such as heavy metal accumulation, production of potential toxins, or becoming susceptible to microbial contamination [2, 3]. Moreover, some specific fungal proteins may pose health risks of allergic reactions for individuals with sensitivity to allergens [4]. Consequently, during the handling of all operations in the mushroom supply chain, from cultivation to consumption, allergenicity, toxicity, and other potential environmental impacts require careful consideration to ensure consumer health following the food safety [3, 4]. This chapter aims to address potential food safety risks that may arise from any stage of the edible mushroom production chain with a multidimensional perspective and draw an outline for the assessment of food safety risks. The chapter further intends to offer perspectives for producers, consumers, and policymakers in the development of a sustainable system of edible fungi processes within the scope of food engineering.

Endogenous Toxins and Allergenicity

Mechanisms of Allergenicity in Edible Macrofungi

Edible macrofungi are widely recognized as beneficial dietary components, primarily due to their substantial contents of protein and fiber, as well as their appreciable levels of essential vitamins and minerals [1, 4]. Particularly, the nutritional properties and potential antioxidant effects of species such as *Agaricus bisporus*, *Lentinus edodes*, and *Pleurotus* spp. have been widely investigated [1]. However, current data in the field of food allergy show that 520 million people worldwide may experience allergic reactions to different foods, and that food allergy can be seen in approximately 3-10% of children and up to 10% of adults [5]. Allergic reactions resulting from mushroom consumption often occur as IgE-mediated type I hypersensitivity, and the presence of allergenic proteins can lead to severe symptoms in some individuals [4]. Although skin prick tests and specific IgE measurements are still common in the diagnosis of food allergy, cellular tests such as the basophil activation test are also increasingly important, but the most definitive confirmation is often provided by well-designed food challenge tests [5].

Fungal allergens can stimulate the immune system through both spore inhalation and food consumption, leading to cross-reactivity, which can lead to a variety of conditions ranging from mild oral allergy syndrome to severe anaphylaxis, within the scope of “Fungus Food Allergy Syndrome” [6]. Components such as β -glucan, chitin, and protease in the cell wall of fungi can affect immunity not only through IgE-mediated mechanisms but also by activating Th17 cells or other inflammatory pathways [7].

Clinical cases reported in different geographies show that the allergenic profiles of edible mushroom species (e.g., *A. bisporus*, *L. edodes*, *Grifola frondosa* (maitake), *Lyophyllum decastes*, and *Hypsizygus ulmerius* (Shimeji) can be quite variable [8, 9]. For example, while partially heat-sensitive proteins in the range of 8–15 kDa have been detected in species frequently consumed in East Asian cuisine, such as Maitake and Shimeji, the presence of different heat-resistant protein bands has also been reported in Shiitake [9, 10]. The detection of proteins in *A. bisporus*, some of which can maintain their allergenic properties despite cooking processes, with sizes of 10, 27, or 36 kDa, emphasizes that care should be taken when processing these mushrooms in the food industry or when choosing cooking methods [8, 11].

From a food engineering perspective, this situation shows that the allergenic risk that may arise during the production and processing stages of different mushroom species varies according to the specific protein structure of each species. The

The Future of Mycology in Food Engineering

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Abstract: Fungal food innovations are revolutionizing food engineering through their ability to transform low-value agricultural byproducts into high-protein, functional, and natural ingredients. Solid-media and immersion fermentations, precision fermentation lines, and artificial intelligence-driven process optimization are being used to overcome environmental constraints such as high greenhouse gas emissions and land use of conventional animal protein production, and bioaccessibility of nutrients is being increased through ultrasonic/enzymatic extraction, encapsulation, and advanced drying techniques. Genetic and metabolic engineering approaches suppress toxin synthesis and enhance nutritional value, while omics-based data integration and real-time sensor monitoring make production processes rapidly scalable. Cultivation of new species, automated climate chambers, and microenvironmental IoT sensors are expanding product diversity and yields, while also expanding the currently limited repertoire of cultivable fungi. These technological advances also create multidimensional effects ranging from biofertilizer and biological control applications in agriculture, waste utilization, and heavy metal bioremediation in the environment, to the development of immune-boosting, antioxidant, and neuroprotective compounds in the field of health. Fungal-based production reduces greenhouse gas emissions and contributes to rural development. Current challenges in consumer acceptance, mycotoxin control, and regulatory compliance can be overcome with sensory optimization, ethical assessments, and transparent labeling strategies. Fungal biotechnology is considered a prominent platform in future food systems in terms of sustainability and economic value creation.

Keywords: Circular economy, Functional foods, Fungal food innovations, Mycoprotein.

INTRODUCTION

A growing population with limited resources is forcing a new perspective on the entire food chain. Fungal resources stand out for their ability to transform low-value plant waste into high-quality protein and nutraceutical ingredients. With modern gene editing platforms and data-driven strain selection algorithms, fungal

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metabolism can now be precisely tailored for taste, safety, and yield. This chapter examines how all these advances can combine to transform mushrooms from an ingredient into a cornerstone of sustainable nutrition for the future.

Predicting Trends in Fungal Food Innovations

Food engineering is being transformed by factors such as the rapidly growing world economy, the rising significance of sustainability concerns, and the increasing demand for the production of food [1]. Amid all these rising requirements, various innovative applications and approaches come into play, varying from plant protein sources to laboratory-grown meat. In recent years, fungal food studies have become a rising option among all these potential solutions. The prominent position of fungi in the food industry becomes increasingly stronger due to the fact that their research areas have a great diversity. These research areas vary in a wide range from genetic and metabolic improvement studies on existing species, to methods for waste utilization or from obtaining bioactive components, the production of mycoproteins and Single-Cell Proteins (SCP) or studies focusing on their capability to show a therapeutic effect against the damages caused by oxidative stress due to being natural antioxidant sources. Fungi may provide significant advantages, due to their various aspects such as high biomass yield, nutritional value, functional properties, and sustainable production methods based on their diverse genera and strains presence in nature [2 - 8].

Fungus is a member of the group of eukaryotic organisms that also includes yeast, molds, and mushrooms. Market share of mushroom-based meat substitutes expanded thanks to the commercial success of mycoprotein products, even creating a consumption environment where mushrooms' share expands in a competitive way with the traditional food applications [9, 10]. Mushrooms that are rich in bioactive components such as beta-glucan, chitosan, phenolic compounds, vitamins, and enzymes are also increasing their importance in the functional food development practices, with the intention to use them for human health benefits [11 - 13]. Furthermore, by different technological approaches, mushrooms offer a positive environmental impact by their potential to be evaluated in terms of waste utilization using different materials as substrates by techniques such as Solid State Fermentation (SSF) and Submerged Fermentation (SmF), also carry a potential to be enriched in terms of nutritional value by microbial gene editing and proteomics applications so that the protein content or sensory properties may be improved [14 - 16]. Many topics, such as sustainable production methods, circular economy potential, innovations in functional food and nutraceuticals, mushroom-based meat substitutes, new generation protein sources, probiotic and prebiotic applications, genetic and metabolic engineering

approaches, consumer acceptance, and marketing strategies, are discussed. Considering industrial use of mushrooms, adopting it at scale not only creates nutritionally rich and safe products, but also supports resource efficiency and environmentally friendly production models [17, 18]. This chapter delineates the expanding strategic role of mycology within food engineering by critically examining mushroom-derived proteins, functional ingredients, natural pigments, and circular-economy applications through an integrated lens. It clarifies prevailing technical, regulatory, and market challenges while identifying priority research directions such as advanced fermentation, genetic and metabolic engineering, and consumer acceptance studies needed to unlock the full potential of fungal resources. In doing so, the chapter offers academia and industry a forward-looking roadmap for harnessing fungi to advance sustainable, nutritious, and economically viable food systems.

Fungal Proteins and Meat Substitutes

The problem of feeding a growing population requires meeting protein needs in a reliable, nutritious, and sustainable way [5]. The high ecological footprint of animal products leads to the use of fungal proteins becoming more prevalent, along with plant proteins [8].

Mycoprotein is a food component generally obtained from the filamentous fungus called *Fusarium venenatum* and is rich in protein content and amino acid profile [19, 20]. Mycoprotein, which has achieved commercial success in Europe and North America, has an extremely low environmental impact compared to conventional meat production, both in terms of greenhouse gas emissions and land use [9, 21]. SCP, the biomass obtained using yeast or filamentous fungi, has become an increasingly important subject for the alternative protein source development and feed additive studies [22].

Effective use of mushroom-based proteins for industrial operations strongly depends on some factors, such as fermentation conditions optimization, fungal strains selection, nutritional media formulations, reduction of nucleic acids, and studies to improve sensory quality [5]. SSF and SmF methods have different effects and advantages on the efficiency of production and product quality. While SSF has the potential for reducing water consumption and provides an environment for certain types of mycelium to grow efficiently, SmF creates a possibility to provide continuous production systems [23, 24].

Fungal proteins may also be subject to superior hybrid products in terms of amino acid profile and functional properties when combined with plant-derived proteins. As plant-based nutrition trends have started to increase in recent years, mushroom proteins play a more important role in becoming an alternative to meat due to

Fungi, Fungal Products, and Food Security: A Scientific Perspective

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Abstract: The exponential growth of the global population has intensified the need for innovative strategies to ensure food security. Fungi, particularly mushrooms, offer dual benefits as sustainable food sources and agricultural productivity enhancers. Mushrooms are highly nutritious, protein-rich, and represent a partial alternative to meat. They support the dietary needs of a growing population and require extensive research to enhance yields, environmental compatibility, and minimize harmful secondary metabolites. Fungi substantially enhance agricultural productivity by improving soil health and promoting plant growth through mycorrhizal associations. Moreover, they serve as biocontrol agents against pests and pathogens. Products derived from fungi, such as enzymes and fermented foods, also enhance food quality, safety, and preservation. Beyond their direct consumption, fungi contribute to environmental sustainability by driving bioremediation processes, breaking down waste and pollutants, and holding the potential for sustainable biofuel production. Advances in genetic engineering and nanotechnology further expand their applications, enabling precise crop management and the development of innovative bio-based materials. Fungi are reservoirs of bioactive secondary metabolites with anticancer, antidiabetic, and anti-inflammatory properties, offering immense potential for advanced applications in food and genetic engineering. These characteristics make fungi a promising solution for addressing food security efficiently and economically. However, challenges like fungal toxicity, complexities in industrial-scale cultivation, and regulatory barriers remain. Future research should focus on safer fungal strains, optimizing production,

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and reducing harmful by-products. Harnessing fungi's potential could revolutionize global food systems, ensuring sustainability and productivity while addressing food security challenges effectively. Their multifaceted roles underscore the importance of continued exploration and development to maximize their contributions to global food security and environmental management.

Keywords: Food security, Fungi as bioenhancers, Genetic engineering in food production, Mushrooms as meat alternatives, Secondary metabolites.

INTRODUCTION

Fungi exhibit remarkable diversity and inhabit various ecological niches. Due to their distinct morphological characteristics, fungi give rise to various secondary metabolites. These secondary metabolites may exert both beneficial and detrimental effects on humans. For example, a class of secondary metabolites known as mycotoxins is associated with harmful repercussions. Numerous toxic fungi possess attributes that can compromise the quality of food and grains. Furthermore, due to their pathogenic nature, fungi are responsible for severe diseases in crop plants. Nevertheless, they also provide substantial benefits to humanity, serving as a food source in the form of mushrooms and as producers of essential industrial and pharmaceutical products, including antibiotics, food colorants, and enzymes. The diverse applications of fungi in industrial, edible, and pharmaceutical domains present opportunities for exploitation through comprehensive research and development in biotechnology, food science, and the fermentation industry. Significant potential remains for isolating novel fungal metabolites, which can contribute positively to the nutritional and health sectors, thereby ensuring a safer future for humanity [1].

This chapter aims to examine the multifaceted roles of fungi in improving global food security through sustainable practices, biotechnology, and environmental management. The principal aim is to furnish a scientific perspective on how fungi and their derivatives can function as alternative food sources, agricultural enhancers, and agents of biocontrol and bioremediation. Furthermore, it addresses potential challenges and future research directions for optimizing the safe and effective utilization of fungi in food systems.

FUNGI AND THE FOOD SAFETY FRAMEWORK

Food Security

Various international agencies delineate food security through diverse definitions, which can be summarized as follows: "A condition whereby all individuals, at all times, have physical, social, and economic access to sufficient, safe, and

nutritious food that satisfies their dietary needs and preferences for an active and healthy life.” In its contextual meaning, this definition signifies the availability of high-quality and preferable food from the national to the individual level. Consequently, food security is realized when access to quality food is ensured for all age groups, free from mobility, inequity, or financial constraints. Conversely, food insecurity hinges on various indicators, ranging from the national to household and individual levels, which constitute the strategies implemented to confront this challenge. In contemporary discussions, food security, nutrition, and sustainability are interrelated concepts, often examined within the same framework to develop coping mechanisms to combat food insecurity [2].

Role of Fungi in Food Security

Fungi significantly impact various stages of the food cycle, from production to processing and consumption. At the production stage, fungi act as crucial agents in food cultivation, decomposing organic matter, facilitating the availability and recycling of soil nutrients, and influencing plant growth by forming symbiotic relationships with plants. Additionally, fungi are an essential food source, with mushrooms serving as a meat alternative due to their high protein content. Furthermore, at the processing stage, fungi form the backbone of the fermentation industry, contributing to creating a wide range of foods and beverages that offer diverse colors, flavors, and textures, enhancing consumer choice. Several enzymes and bioactive compounds essential for improving food safety and shelf life are by-products of fungi. Fig. (1) provides insight into the beneficial and detrimental effects of fungi [3].

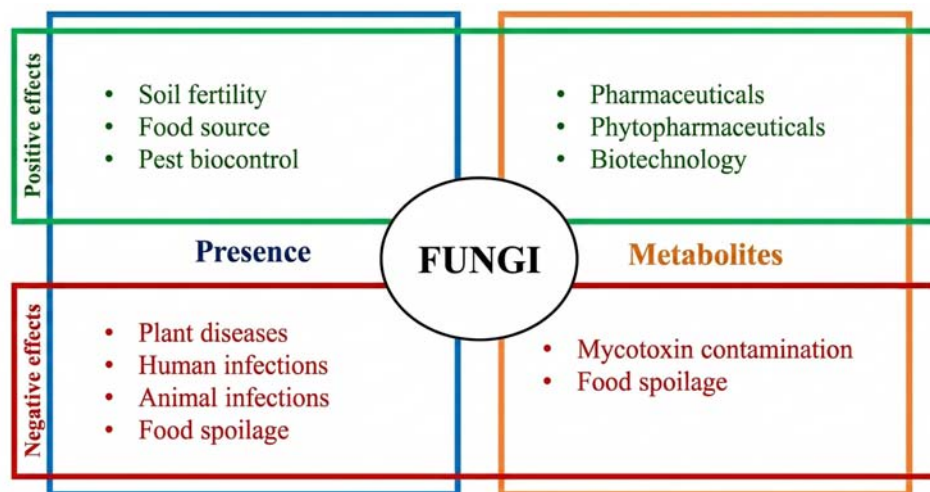


Fig. (1). An illustrative representation of the advantageous and detrimental roles of fungi [4].

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