Journal of Health, Population and Nutrition

REVIEW

Open Access

Edible mushrooms as an alternative to animal proteins for having a more sustainable diet: a review

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Abstract

Background High protein sources especially animal protein is being used widely in people's diet. Ensuring a healthy and sustainable diet should be a global priority. Compared to diets rich in animal products, plant-based diets are more sustainable because they have less environmental impact. Aim of this article is to review mushroom's sustainability.

Main body Using meat analogues like mushrooms seems to be a good option because their taste and texture are alike meat and they are sustainable healthy foods as they are good environmental choice due to their less water and land footprint but they are not a cost-benefit food.

Conclusion Mushroom is a good nutritional and environmental meat substitute as it has less water and land footprint but not as a cost-benefit meat alternative. Therefore, the governments should make policies to use mushroom as an economical meat alternative and a source of protein for all consumers.

Keywords Sustainable food, Mushrooms, Plant-based diet, Environmental footprint

Introduction

Food systems are at the epicenter of a growing crisis, driven by rapid climate change, escalating hunger and malnutrition, and deepening social inequality [1]. These systems exert unacceptable environmental impacts and deplete non-renewable resources at an alarming rate [2]. In 2023, the total primary energy consumption globally was approximately 620 EJ (exajoules), with fossil fuels accounting for about 81.5% of this total. This indicates a substantial reliance on non-renewable energy sources, primarily fossil fuels, for global energy needs [3–6]. The food system with every stage of the supply chain, significantly contributes to greenhouse gas emissions (GHGs) [7]. The consequences—global warming, ozone layer depletion, soil and water acidification, desertification, deforestation, land degradation, and species extinction—underscore that human demands surpass the planet's capacity to sustain them, highlighting the urgent need for more sustainable living [8]. Agriculture is the largest contributor to greenhouse gas emissions, with meat and dairy production accounting for the majority. Livestock production, particularly for meat and dairy, is responsible for approximately 74% of global livestock-related emissions, significantly contributing to environmental degradation [9, 10]. Food production consumes vast resources, accounting for 20% of global energy use, 20% of electricity, and 70% of freshwater [11]. Food production has the potential to function as a carbon sink, capturing carbon dioxide from the atmosphere and mitigating greenhouse gas emissions. Nonetheless, food

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remains the primary commodity, and its production is non-negotiable due to the essential need for sustenance [12]. Furthermore, there are substantial inequalities and geographical disparities in both food production and consumption patterns [13]. These elements underscore the intricate challenge of addressing environmental concerns while simultaneously ensuring global food security [14]. Ensuring a healthy and sustainable diet must, therefore, become a global priority [15].

Government intervention in agriculture has historically encompassed a range of policies aimed at reducing food prices, increasing production, improving public health, and expanding both national and global markets [16, 17]. However, the methods for achieving these goals remain contentious, and the political factors that enable or hinder the implementation of meat reduction policies have not been thoroughly explored [18]. Population growth and rising incomes drive food demand and lead to shifts in dietary preferences [19]. These changes, coupled with broader trends, threaten the future sustainability of food and agricultural systems [19]. According to the Food and Agriculture Organization (FAO) of the United Nations, sustainable diets are defined as 'diets with low environmental impacts that contribute to food and nutrition security and a healthy life for present and future generations. Such diets are conservative and considerate of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe, and healthy, while optimizing natural and human resources [20].

In order to maintain a sustainable environment, achieving a better balance between meat consumption and the environmental impact of livestock production is essential [21]. The growing trend toward producing delicious and healthy meatless foods to cater to vegetarians and health-conscious individuals has led to the increased use of affordable plant-based proteins, such as textured soy proteins, mushrooms, wheat gluten, and legumes, as substitutes for animal protein. These meat-like products, which closely mimic the texture, taste, color, and nutritional value of meat, can effectively replace it across various sectors [20]. Compared to diets rich in animal products, plant-based diets are more sustainable, as they require significantly fewer natural resources and exert a lesser impact on the environment [22].

Since humans were gatherers and hunters, mushrooms have been an essential part of their diet [23]. Mushroom-based products are often preferred over other plant-based options for their superior taste [20]. Mushrooms are not only an environmentally and economically viable food choice, but they are also a good source of protein with high-quality nutrients, making them a potential candidate for sustainable food [24–26]. As a nutrient-dense food, mushrooms are the reproductive structures produced by certain fungi, and they are large enough to be seen with the naked eye [27, 28]. Approximately 54% of the global mushroom industry is dedicated to edible mushrooms, 38% to medicinal mushrooms, and 8% to wild mushrooms [29]. The global production of edible mushrooms by genus is distributed as follows: *Lentinula edodes* 22%, *Pleurotus spp.* 19%, *Auricularia spp.* 18%, *Agaricus bisporu*s 15%, *Flammulina spp.* 11%, *Volvariella spp.* 5%, and others 10% [29]. According to the latest estimates, there are at least 12,000 species of mushrooms worldwide, with about 2,000 species considered safe to eat [30]. *Agaricus bisporu*s is the most widely cultivated mushroom globally, followed by *Lentinula edodes* and *Pleurotus spp.* [31].

Mushroom consumption has surged nearly fivefold over the past two decades, driven by growing recognition of their health benefits, improved diet quality, and their classification as a functional food [32]. Global production of cultivated, edible mushrooms has expanded more than 40 times since 1978, increasing from about 1 billion kg in 1978 to over 43 million tons by 2020 [33]. As a result, per capita mushroom consumption has grown rapidly [29]. In Asia, China dominates production, accounting for over 70% of the global supply, producing more than 30 billion kg of mushrooms annually [34]. The rest of Asia contributes approximately 1.3 billion kg, while the European Union, the Americas, and other regions collectively produce about 3.1 billion kg [29]. This significant growth aligns with the global trends toward more sustainable, health-conscious diets. Mushrooms are increasingly recognized as a nutritious, low-calorie, and environmentally friendly food option [33]. Their high protein content, abundance of vitamins, and potential to serve as a meat alternative in plant-based diets have fuelled demand in Southeast Asia, Europe, and North America where mushroom consumption has exceeded 3 pounds per capita annually in recent years [35, 36].

Studies indicate that with the rapidly growing global population and limited natural resources, there is a shortage of high-quality protein sources like meat, which is known for its high biological value. In this context, using meat analogs such as mushrooms appears to be a promising alternative. Mushrooms not only offer a taste and texture similar to meat but also provide significant health benefits and sustainability, making them a viable option for addressing protein needs [26].

The protein composition of mushrooms is notable for its completeness and similarity to animal-based proteins. Mushrooms contain all nine essential amino acids (EAAs), which are amino acids that the human body cannot synthesize and must obtain from food. This is in contrast to many other plant-based protein sources, which often lack one or more essential amino acids [37, 38]. Additionally, mushrooms have a high content of branched-chain amino acids (BCAAs), which are typically found in higher quantities in animal-based proteins. BCAAs include leucine, isoleucine, and valine, and they are important for muscle growth and repair [39]. The amino acid profile of mushrooms is generally well-balanced, making them a valuable source of protein for vegetarians and vegans. They also contain a variety of non-essential amino acids, with glutamic acid being one of the most predominant [37]. In summary, mushrooms offer a complete protein profile with all essential amino acids and a high content of branched-chain amino acids, making them a nutritionally valuable protein source.

This paper aims to explore whether using mushrooms as a substitute for meat products can be a viable economic and environmental choice for making diets more sustainable. It is a review of literature that examines the nutritional, economic, and environmental aspects of mushroom consumption.

Nutritional value of mushroom

Mushrooms are a popular nutritional food due to their low calorie, carbohydrate, fat, and sodium content, and they contain no cholesterol. Additionally, they provide essential nutrients such as selenium, potassium, riboflavin, niacin, vitamin D, and fiber [40]. Their increasing importance in our diets is attributed to their nutritional value, high protein content, and low fat/energy content. Mushroom protein contains all nine essential amino acids needed by humans [41]. However, it is important to note that factors such as growth characteristics, developmental stage, and postharvest conditions can affect the chemical composition and nutritional value of edible mushrooms. Significant variations can also occur both between and within species [42, 43]. This review examines the nutritional value of mushrooms.

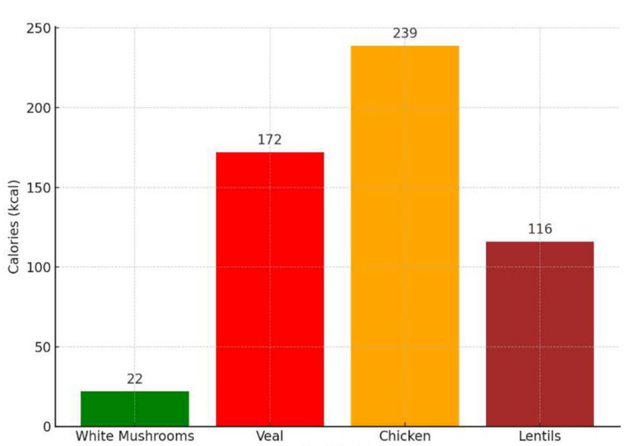

Fig. 1 Caloric content per 100 g for white mushrooms, veal, chicken, and lentils

Energy

Per 100 g, white raw fresh mushroom contain 22 calories, whereas veal contains 172 calories, chicken contains 239 calories, and lentils contain 116 calories [44] (see Fig 1).

Carbohydrates

Polysaccharides are among the most well-known and potent substances derived from mushrooms, recognized for their anti-tumor and immunomodulatory properties [40, 45–48]. Edible mushrooms contain high proportions of carbohydrates, including chitin, substances. While cultivated edible mushrooms are rich in glucose, they contain low amounts of fructose and sucrose [42, 45, 49]. The total carbohydrate content in 100 g of mushrooms is 3.3 g, compared to zero grams in veal and chicken, and 20 g in lentils [44].

Proteins

Bioactive proteins are a key component of mushrooms' functional properties and hold significant pharmaceutical potential. Mushrooms produce a variety of proteins and peptides with notable biological activities, including lectins, fungal immunomodulatory proteins, ribosome-inactivating proteins, antibacterial proteins, ribonucleases, and laccases [50]. Edible mushrooms are also a good source of protein, with concentrations ranging from 200 to 250 g/kg of dry matter; leucine, valine, glutamine, glutamic acid, and aspartic acid are among the most prevalent amino-acids [42, 45, 49]. The total protein content in 100 g of mushrooms is 2.25 g, compared to 24 g in veal, 27 g in chicken, and 9 g in lentils [44].

Lipids

Polyunsaturated fatty acids, which are primarily found in edible mushrooms, may help lower serum cholesterol levels. However, metabolites of unsaturated fatty acids have not been detected in mushrooms [49, 51]. Mushrooms contain low amounts of fat, ranging from 20 to 30 g/kg of dry matter, with linoleic (C18:2), oleic (C18:1), and palmitic (C16:0) being the main fatty acids [42, 45, 49]. The primary sterol in edible mushrooms is ergosterol, known for its antioxidant properties [49]. A diet rich in sterols has been linked to a lower risk of cardiovascular diseases [42]. The total fat content in 100 g of mushrooms is 0.3 g, compared to 8 g in veal, 14 g in chicken, and 0.4 g in lentils [44].

Vitamins and minerals

Edible mushrooms contain significant amounts of ash, ranging from 80 to 120 g/kg of dry matter, with key minerals including potassium, phosphorus, magnesium, calcium, copper, iron, and zinc. They are also a good source of vitamins, featuring high levels of riboflavin (vitamin B2), niacin, and folates, along with trace amounts of vitamins C, B1, B12, D, and E. Notably, mushrooms are the only non-animal food source of vitamin D, making them a unique natural source of this vitamin for vegetarians [52]. Wild mushrooms are generally rich in vitamin D2, whereas cultivated mushrooms, which typically grow in the dark, require UV-B light to produce vitamin D2 [42, 45, 49]. The *P.ostreatus* species is particularly notable for its high levels of folacin, vitamin B1, and vitamin B3 [53]. Mushrooms contain 5–10 times more vitamin B3 compared to vegetables [54]. Additionally, mushrooms can accumulate selenium when grown in soil with high selenium content [55].

Mushrooms are rich in various mineral elements essential for human health. The primary mineral components found in mushrooms include potassium (K), phosphorus (P), sodium (Na), calcium (Ca), magnesium (Mg), and trace elements such as copper (Cu), zinc (Zn), iron (Fe), molybdenum (Mo), and cadmium (Cd) [56, 57]. Additionally, mushrooms can accumulate heavy metals, including cadmium (Cd), lead (Pb), arsenic (Ar), copper (Cu), nickel (Ni), silver (Ag), chromium (Cr), and mercury (Hg) from their growing environment, particularly if the soil or water is contaminated [58]. This accumulation can pose health risks if consumed in large quantities. Therefore, it is crucial to consider the source and cultivation conditions of mushrooms to ensure they are safe for consumption [59]. The mineral content in mushrooms can vary based on factors such as species, age, and the fruiting body size, as well as the type of growing medium used. Wild edible mushrooms generally have higher mineral content compared to cultivated mushrooms [60].

Health benefits of mushroom

The use of mushrooms has expanded significantly, both as a food source and in the fields of pharmaceuticals, nutraceuticals, and cosmeceuticals [29]. Both wild and cultivated mushrooms are valued for their nutritional and medicinal benefits [61]. Mushrooms represent a promising source of new pharmaceuticals and have been used in healthcare to treat various conditions, from common ailments like skin diseases to more complex diseases such as AIDS. These sustainable foods have demonstrated anti-allergic, cholesterol-lowering, anti-tumor, and anticancer properties [62]. This review highlights the health benefits of mushrooms.

Anti-cancer effect

Active components of mushrooms with anti-cancer potential include lentinan, krestin, hispolon, lectin, calcaelin, illudin S, psilocybin, Hericium polysaccharides A and B (HPA and HPB), ganoderic acid, schizophyllan, and laccase, among others. Polysaccharides are particularly notable for their anti-tumor and immunomodulatory properties, with β-glucan being the most versatile due to its broad-spectrum biological activity. Hispolon, a polyphenol compound, is recognized for its strong anticancer properties and its ability to enhance the cytotoxicity of chemotherapeutic agents [63].

Mushrooms contain several biologically active substances with anticancer effects, including polysaccharides, polysaccharide-protein complexes, dietary fiber, certain proteins, terpenoids, steroids, and phenols [64]. Mushroom lectins, a group of proteins, may offer both immunomodulatory and direct cytotoxic effects against cancer cells. The glucoconjugate specificity of lectins can be utilized to study membrane glucoconjugate alterations, classify mutant and tumor cells, and aid in diagnosis and precursor generation. Additionally, some less commonly discussed antitumor mushroom proteins, such as hemolysin, laccase, ribosome-inactivating proteins, and ubiquitin-conjugated proteins, exhibit direct cytotoxic activity in vitro. These proteins hold the potential for medical treatment through genetic engineering and large-scale production.

Antitumor activity has been demonstrated in extracts of fruiting bodies and mycelia from mushrooms across various ecological groups and systems, including those obtained with ethanol, methanol, ethyl acetate, and hot water. Mushroom substances can interfere with tumors through various mechanisms, such as enhancing the host's antioxidant capacity or absorbing carcinogens. Additionally, other mushroom components may inhibit cancer promotion or progression by directly targeting tumor cells, interfering with tumor angiogenesis, or regulating immune responses. When combined with traditional cancer treatments, mushroom products have been shown to reduce side effects [64]. Some studies suggest that high consumption of red meat may be associated with an increased risk of certain cancers, such as colorectal and breast cancer. In contrast, mushrooms offer anti-tumor and anti-cancer properties, making them a healthier alternative (Table 1) [65, 66].

Anti atherosclerotic

Several edible mushrooms have demonstrated anti-atherosclerotic effects in apolipoprotein E–deficient mice by reducing serum total cholesterol levels. These mushrooms serve as good alternative sources for cholesterol-lowering activity due to their ability to inhibit the enzyme HMG-CoA reductase [67].

Another intriguing study highlights the cholesterol-lowering properties and prebiotic effects of Mexican *Ganoderma lucidum* in C57BL/6 mice. The study reports a significant reduction in the expression of lipogenic genes and those responsible for reverse cholesterol transport, along with an increase in the expression of the *Ldlr* gene in the liver. This research identifies *Ganoderma lucidum* as a new source of cholesterol-lowering

Table 1 Summarize information on the anti-cancer effect of mushrooms

	Active Components	Type/Category	Anti-Cancer Potential	Additional Notes
Anti-cancer effect	lentinan	Polysaccharide	Anti-tumor, immunomodulatory properties	
	Krestin	Polysaccharide-protein	Immunomodulatory	
	Hispolon	Polyphenol	Strong anti-cancer, enhances cytotoxicity of chemotherapeutic agents	
	lectin	Protein	Immunomodulatory and direct cytotoxic effects	Used to study membrane glucoconjugate alterations and classify tumor cells
	Calcaelin	Compound	Anti-cancer potential	
	Illudin S	Compound	Anti-cancer potential	
	Psilocybin	Compound	Anti-cancer potential	
	Hericium polysaccharides A and B (HPA, HPB)	Polysaccharides	Anti-tumor, immunomodulatory properties	
	Ganoderic acid	Triterpenoid	Anti-cancer potential	
	Schizophyllan	Polysaccharide	Anti-tumor, immunomodulatory properties	
	Laccase	Protein	Direct cytotoxic activity	Also shows anti-cancer properties in vitro.
	β-Glucan	Polysaccharide	Versatile anti-tumor, broad-spectrum biological activity	Immunomodulatory properties
	Hemolysin	Protein	Direct cytotoxic activity	Potential for medical treatment
	Ribosome-inactivating proteins	Protein	Direct cytotoxic activity	Potential for medical treatment
	Ubiquitin-conjugated proteins	Protein	Direct cytotoxic activity	Potential for medical treatment
	Polysaccharides & polysaccharide-protein complexes	Various categories	Anti-cancer, immunomodulatory, dietary fiber, direct cytotoxic effects	Found in mushrooms with diverse properties
	Ethanol, methanol, ethyl acetate, hot water extracts	Mushroom extracts	Interfere with tumors through mechanisms like enhancing antioxidant capacity, absorbing carcinogens	Mushroom extracts can reduce side effects when combined with traditional cancer treatments

bioactive compounds with prebiotic effects [62]. Additionally, essential fatty acids and statins found in mushrooms are key compounds with anti-atherosclerotic and heart disease benefits [68].

The fruiting bodies of edible mushrooms are also a valuable source of lovastatin, a compound belonging to the statin group, commonly used as a cholesterol-lowering drug. Due to the presence of lovastatin, edible mushrooms may help prevent hypercholesterolemia [69]. On the other hand, red meat, especially when consumed in high amounts, can lead to increased cholesterol levels due to its high saturated fat content. This contrasts with the cholesterol-lowering effects of mushroom proteins [70].

Anti allergic

This effect is attributed to the reduction in specific IgE levels and decreased mast cell sensitization, as indirectly demonstrated by the basophil activation test. Antiallergic effects have also been observed in mice following oral administration of GF polysaccharides or extracts, which inhibited mast cell degranulation associated with atopic dermatitis-like skin lesions. Additionally, these substances alleviated the anaphylactic cutaneous response. Hetland et al. at 2020 found that this effect was due to reduced IgE levels, decreased mast cell infiltration, and altered cytokine expression, which improved the Th1/Th2 imbalance and suppressed type I allergic responses by inhibiting mast cell degranulation. Therefore, GF polysaccharides could serve as a novel therapeutic agent, offering an alternative to corticosteroids or as an adjuvant treatment [71]. In contrast, red meat does not possess inherent anti-allergic properties and can sometimes exacerbate allergic reactions due to its high histamine content [72].

Cardiovascular health

Various synergistic mechanisms may contribute to the protective effects of mushrooms in cardiovascular diseases, including hypolipidemic effects, blood pressure reduction by certain mushroom species, and anti-inflammatory or antioxidant activities, as demonstrated in animal studies. These combined properties may help reduce the risk of atherosclerosis and cardiovascular disease [73]. But, Red meat consumption has been associated with an increased risk of cardiovascular diseases, primarily through mechanisms involving heme iron, atherosclerosis, and dyslipidemia [74].

Prebiotic

Mushrooms are rich in carbohydrates such as chitin, hemicellulose, beta-glucans, alpha-glucans, mannans, xylans, and galactans, making them ideal prebiotics. They stimulate the growth of gut microbiota, providing significant health benefits to the host [62]. Among mushroom polysaccharides, β-(1→3)-D-glucans and their peptide/protein derivatives (polysaccharide-peptide/protein complexes) and proteoglycans are essential prebiotics, playing a crucial role in immunomodulating and antitumor activities.

These prebiotic compounds exhibit effects similar to those of immune effector cells, such as lymphocytes, macrophages, hematopoietic stem cells, T cells, dendritic cells (DCs), and natural killer (NK) cells, which are vital for both innate and adaptive immunity. This leads to the production of biological response modifiers. Several glucans and heteroglycans have shown remarkable immune-enhancing properties, with the potential to stimulate macrophages, splenocytes, and thymocytes [75, 76]. While red meat consumption can negatively impact gut health by increasing intestinal inflammation and disrupting the gut mucosa, prebiotics have the opposite effect, enhancing gut health by promoting the growth of beneficial gut bacteria and reducing inflammation (Table 2) [77].

Others

Mushrooms have been associated with numerous nutraceutical properties, including the prevention or treatment of conditions such as Parkinson's disease, Alzheimer's disease, hypertension, and an increased risk of stroke. They possess antibacterial properties, strengthen the immune system, and lower cholesterol levels, making them a significant source of bioactive compounds [40]. They are known for their anti-allergic, anticholesterol, antitumor, and anticancer properties, with polysaccharides, particularly β–D-glucans, being the primary active components [23]. Chihara et al. (1969) isolated an antitumor polysaccharide called lentinan from the fruiting body of shiitake mushrooms [23, 78]. Bahl et al. (1983) found that mushrooms have been used to treat epilepsy, wounds, skin diseases, heart disease, rheumatoid arthritis, cholera, intermittent fevers, sweating, diarrhea, dysentery, colds, anesthesia, liver disease, gallbladder disease, and as vermicides (Table 3) [23, 79].

Environmental aspect

Meat production has seen tremendous growth in recent decades and is projected to continue expanding rapidly in the future [80]. However, it is also one of the human activities with the greatest environmental impact [81]. Raising livestock for meat requires substantial amounts of land, water, and feed, making it a highly energy-intensive process [82, 83]. Beyond resource consumption, meat production also releases significant quantities of greenhouse gases (GHGs) into the environment [84, 85]. These emissions contribute to several environmental issues, including climate change, biodiversity loss, and disruptions in the nitrogen cycle [84, 86]. This section examines whether mushrooms can serve as an effective substitute for red meat to mitigate environmental impact.

Comparing the environmental footprint of protein and energy supplied through mushrooms versus red meat yields significant differences (Table 4). Producing 1 kg of mushrooms requires 322 L of water (39 gallons/lb) and results in 1.1 kg (1103 g) of CO2 emissions [87, 88]. In contrast, producing 1 kg of beef demands 15,415 L of water and emits 27 kg of CO2, while 1 kg of mutton requires 8,763 L of water and releases 39.2 kg of CO2 [87, 89]. On a per-serving basis, each unit of protein from red meat comes with a carbon footprint of 993 g, a water

Table 2 Summary of information on the probiotic properties of mushrooms

	Component	Type/Category	Health Benefits/Effects	Additional Notes
Prebiotic	Chitin, Hemicellulose, Beta-glucans, Alpha-glucans, Mannans, Xylans, Galactans	Carbohydrates/Polysaccharide	Serve as prebiotics, stimulate growth of gut microbiota, provide health benefits	Ideal for gut health enhancement, supporting beneficial gut bacteria growth
	β-(1→3)-D-glucans	Polysaccharide	Immunomodulating, antitumor activities	Essential prebiotic, plays a key role in stimulating immune cells such as macrophages and T cells
	Polysaccharide-peptide/protein complexes	Polysaccharide-protein complex	Prebiotic, immunomodulating, antitumor activities	Similar effects to immune effector cells like NK cells, DCs, lymphocytes
	Proteoglycans	Polysaccharide-protein complex	Immunomodulating, prebiotic effects	Important for both innate and adaptive immunity
	Immune Effector Cells (Lymphocytes, Macrophages, Hematopoietic Stem Cells, T Cells, DCs, NK Cells)	Immune cells	Activated by mushroom prebiotics to produce biological response modifiers	Lead to enhanced immunity and anti-cancer responses
	Glucans and Heteroglycans	Polysaccharides	Immune-enhancing, stimulate macrophages, splenocytes, and thymocytes	Boost the immune system, stimulate essential immune cells

Table 3 Summary of information on the mushroom's nutraceutical properties

Nutraceutical Properties	Conditions Treated/Prevented	Key Active Components	Additional Notes
Parkinson's disease	Prevention or treatment	Bioactive compounds	Mushrooms are linked to the prevention of neurological disorders
Alzheimer's disease	Prevention or treatment	Bioactive compounds	Essential prebiotic, plays a key role in stimulating immune cells such as macrophages and T cells
Hypertension	Prevention or treatment	Bioactive compounds	Similar effects to immune effector cells like NK cells, DCs, lymphocytes
Increased risk of stroke	Prevention	Bioactive compounds	Important for both innate and adaptive immunity
Antibacterial properties	Bacterial infections	Bioactive compounds	Mushrooms strengthen the immune system
Strengthening of the immune system	General immune health	Bioactive compounds	
Lower cholesterol	Cholesterol reduction	Bioactive compounds, β–D-glucans	
Anti-allergic properties	Allergies	Polysaccharides, β–D-glucans	
Antitumor and anticancer properties	Tumor and cancer prevention	Polysaccharides, β–D-glucans, lentinan	Lentinan was isolated by Chihara et al. (1969) from shiitake mushrooms
Epilepsy	Treatment	Mushrooms	Historically used in traditional medicine
Wounds	Treatment	Mushrooms	
Skin diseases	Treatment	Mushrooms	
Heart disease	Treatment	Mushrooms	
Rheumatoid arthritis	Treatment	Mushrooms	
Cholera	Treatment	Mushrooms	
Intermittent fevers	Treatment	Mushrooms	
Sweating	Treatment	Mushrooms	
Diarrhea and dysentery	Treatment	Mushrooms	
Colds	Treatment	Mushrooms	
Anesthesia	Treatment	Mushrooms	
Liver and gallbladder disease	Treatment	Mushrooms	
Vermicide (worm infection treatment)	Treatment	Mushrooms	Historically used as vermicides

Table 4 Environmental footprint and cost comparison of mushrooms with red meat (per one kilogram)

	Land footprint (m^2)	Carbon footprint (g Co2)	Water footprint (m^3)	Cost (US $)
Mushroom (1 kg)	0.46	1103	0.3	3.08
Red meat (1 kg)	37.5	33,100	12.1	12.49
Per pro (mushroom)	0.02	50	0.015	0.14
Per pro (red meat)	0.13	118	0.043	0.044
Per cal (mushroom)	0.002	3.9	0.001	0.011
Per cal (red meat)	0.018	15.99	0.006	0.006

*The energy (protein) of one kilogram of red meat and mushroom considered 2069 Kcal (280 g) and 280 Kcal (22 g) respectively

footprint of 0.386 m^3, and a land footprint of 1.127 m^2 [87, 89, 90]. Conversely, using 310 g of mushrooms reduces these figures significantly: the carbon footprint drops to 341 g of CO_2, the water footprint to 0.0998 m^3, and the land footprint to 0.142 m^2 [87, 88, 90]. This represents a reduction in carbon emissions by 65%, water usage by 75%, and land use by 87% (see Fig 2).

Each serving of red meat (one ounce or about 30 g) provides an average of 60 Kcal of energy, which is equivalent to 210 g of mushrooms [91]. The environmental impact of this amount of mushrooms includes a carbon footprint of 231 g [88], a water footprint of 0.067 m^3 [87], and a land footprint of 0.0966 m^2 [90]. These figures reflect reductions of 76% in CO_2 emissions, 82% in water usage, and 91% in land use compared to red meat. Although the quantity and quality of protein from mushrooms and red meat differ, replacing red meat with mushrooms can achieve similar environmental benefits while still meeting nutritional requirements for both energy and protein. Therefore, substituting red meat with mushrooms not only significantly lowers environmental impacts but also promotes a more sustainable diet (see Fig 3).

Economical aspect

People generally consume what they can afford. For a diet to be considered sustainable, it must be economically viable and equitable. Affordability implies that the food provides high nutrient density at a reasonable cost [92]. This section evaluates whether mushrooms can serve as a cost-effective alternative to red meat, given their low

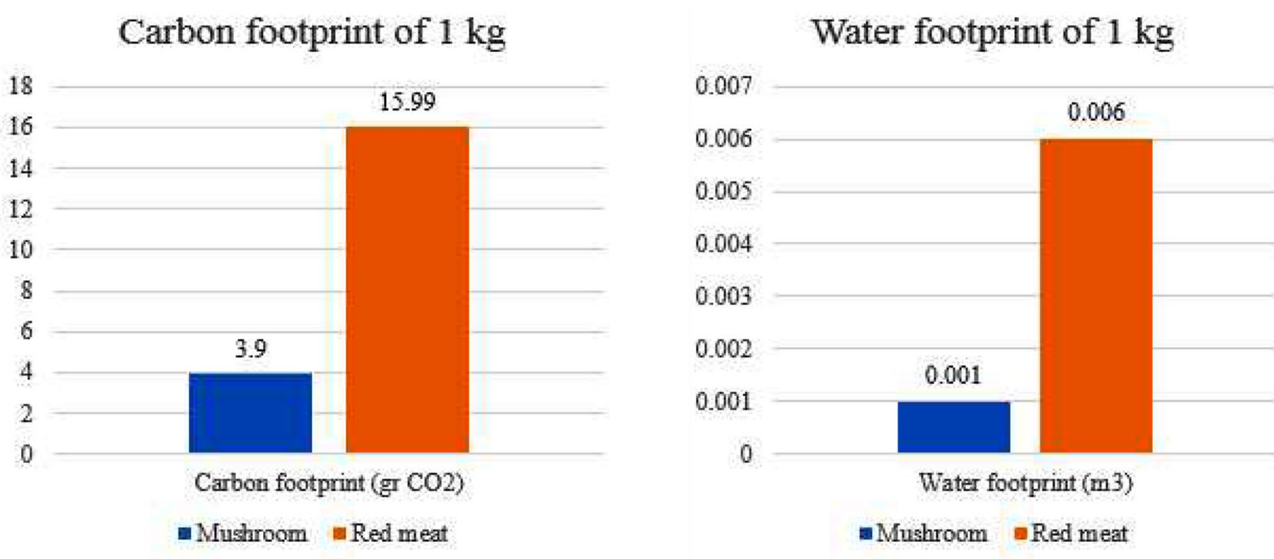

Fig. 2 Carbon and water footprint of 1 Kg of mushroom and red meat

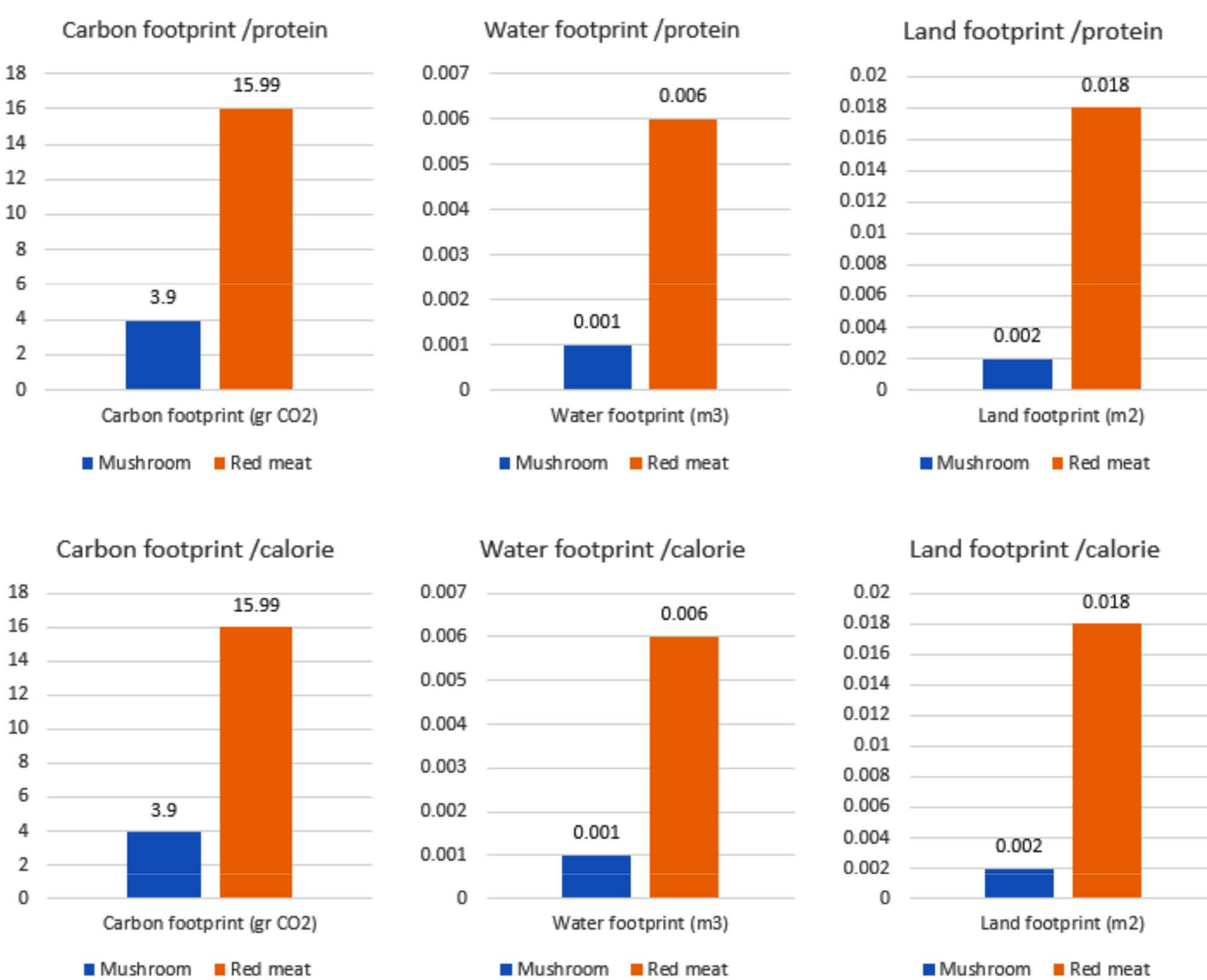

Fig. 3 Carbon footprint, water footprint and land footprint of mushroom and red meat per protein and calorie

calorie, low fat, high protein, and rich mineral and fiber content [93, 94].

As shown in Table 1, the cost per unit of protein and energy for mushrooms and red meat was compared. As of July 9, 2022, the global price for red meat is approximately $12.49 per kilogram [95], whereas mushrooms cost about $3.08 per kilogram [96]. One kilogram of red meat provides 280 g of protein and 2070 kilocalories, while one kilogram of mushrooms offers 22 g of protein and 280 kilocalories. This translates to a cost of $4 per 100 g of protein for red meat and $14 per 100 g of protein for mushrooms. For energy, red meat costs $0.60 per 100 kilocalories, while mushrooms cost $1.10 per 100 kilocalories. Consequently, red meat is 71% cheaper in terms of protein and 45% cheaper in terms of energy supply compared to mushrooms. The authors have no relevant financial or non-financial interests to disclose.

Although mushrooms are cheaper than red meat on a per-weight basis, they are more expensive when considering the amount of protein and energy they provide. While mushrooms may offer significant environmental and nutritional benefits as a meat substitute, they do not appear to be a cost-effective option compared to red meat. Thus, replacing red meat with mushrooms may not be an economically viable decision for achieving a sustainable diet.

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Discussion.

This study reviewed the benefits of mushrooms as a nutritional and environmental meat substitute. However, mushrooms are not currently a cost-effective alternative to meat. To enhance their economic viability, there is a growing need to invest in mushroom farming and production to make mushrooms a more affordable choice.

Meat production has increased by 5–13% over the past decade and is approaching peak production [26]. Red meat is a valuable source of high biological value protein, and essential macro and micronutrients such as protein, iron, and vitamins B12 and B6. However, with the exception of vitamin B12, these nutrients are also available in plant-based foods, albeit in less bioavailable forms [97]. Diets high in red and processed meat (RPM) contribute significantly to environmental degradation, accounting for an estimated 14–30% of all human-made greenhouse gas emissions, making it the largest source of anthropogenic methane emissions [98]. As the demand for RPM rises, so does the pressure to use intensive farming practices, which increases the demand for animal feed, primarily derived from monoculture grain crops like corn and soybeans, leading to deforestation, particularly in regions such as the Amazon [99]. Additionally, producing meat-based protein requires more land, water, fuel, fertilizer, and pesticides than producing plant-based protein [100]. For instance, up to 25 kg of animal feed and 15,000 L of water are needed to produce 1 kg of beef, depending on the farming methods used [101, 102]. This underscores the unsustainability of RPM and highlights the need for viable alternatives [99].

Mushrooms stand out as a high-quality plant-based protein source, containing all nine essential amino acids, which is rare among other plant proteins [39]. For instance, cereals are low in lysine, and legumes lack sulfur amino acids like methionine and cysteine. Mushrooms provide a complete protein profile, making them an excellent dietary choice, especially for vegetarians and vegans [103]. Additionally, mushrooms are more economical and sustainable than animal proteins and other plant sources such as soy, peas, lentils, and nuts requiring fewer resources and a shorter growth cycle [104]. Mushrooms also provide a wide range of vitamins, minerals, and antioxidants, exceeding many traditional plant proteins in nutritional value [105]. Mushrooms' versatility in culinary applications makes them a convenient and accessible protein source for individuals aiming to reduce their consumption of animal products [35]. Therefore, mushrooms should be considered not just as a diversification source of non-animal proteins but also a superior option in many respects because of their complete protein profile, sustainability, and rich nutrient content.

Population growth is driving interest in plant-based meats as a solution to the increasing demand for protein and the sustainability issues associated with animal protein, such as rising animal feed needs and increased greenhouse gas emissions [106]. Research indicates that promoting greener plant-based protein options, such as plant-based meat analogues, can help mitigate the adverse environmental impacts of animal protein production [100, 106]. Adopting a healthy and sustainable diet, which includes reducing meat consumption, could prevent an estimated 10.9 to 11.6 million deaths annually as over consumption of meat in some countries could cause diseases may prevent death rate. Also, it could reduce greenhouse gas emissions, limit anthropogenic global warming to below 2 °C, protect environmental biodiversity, and decrease competition for water and other natural resources [107]. Various types of meat analogues, including cultured meat, mycoprotein, and plant-based meat, offer promising alternatives [106].

This study highlights that mushrooms serve as effective nutritional and environmental alternatives to meat, making them a viable option for sustainable food [24–26]. Plant proteins, including those from mushrooms, are rich in amino acids, fiber, polyunsaturated fatty acids, and carbohydrates [108]. Transitioning from animal to plant proteins can support environmental stability, address ethical concerns, improve food affordability and security, meet consumer demands, and tackle protein-rich malnutrition [109, 110]. Kumar et al. (2017) demonstrated that meat analogues like mushrooms are advantageous due to their umami flavor, meat-like texture, and overall health and sustainability benefits [24, 26].

According to the findings of this study, while mushrooms are promising nutritional and environmental alternatives to meat, they are not currently a cost-effective option. Replacing red meat with mushrooms is not economically advantageous. To achieve a sustainable diet, foods must not only be nutritionally adequate and environmentally friendly but also economically fair and affordable [20].

Food prices and affordability, defined as household food costs relative to income, are crucial in determining food choices [111, 112]. Affordability affects food consumption levels, balanced nutrition, quality of life, and life expectancy [113]. Additionally, the affordability of a diet is a key component of food security [114–117]. Therefore, for mushrooms to be considered a viable sustainable food alternative, they must become more economically feasible. In fact, one kilogram of mushrooms has lower protein content compared to a kilogram of meat. The cultivation of mushrooms cannot be increased without the establishment of large facilities equipped with climate control and the subsequent rise in energy usage which is not sustainable. Consequently, actions and policies are needed to improve the economic viability of mushroom production.

Governments have long played a role in supporting agricultural production to enhance farmers' livelihoods and ensure food security. One effective approach to promoting plant-based diets is through subsidies for plant-based foods, which can reduce the demand for animal products and increase the availability of plant-based alternatives. For instance, 40% of the corn traded globally is produced in the United States due to substantial subsidies for corn producers.

In recent years, there has been a growing recognition of the significant costs associated with non-communicable diseases (NCDs). This has added a public health dimension to government agricultural policies, emphasizing the need to shift production towards healthier food options and away from harmful products like tobacco [17]. Tax incentives and subsidies could be directed towards specific sustainable plant products, such as mushrooms, to lower their prices and improve affordability.

Additionally, the prices of animal products should reflect their environmental externalities, including greenhouse gas emissions and land use. Research indicates that price signals can effectively influence consumer behavior. For example, a study on fruit and vegetable consumption among youths in the United States found that reduced prices led to increased consumption [118].

Conclusion.

Mushrooms, as a plant-based protein, are a nutritious and environmentally friendly substitute for meat, offering significant advantages in terms of lower water and land footprints. However, they are not currently a cost-effective alternative to meat. To make mushrooms a viable and affordable option for all consumers, governments should implement policies to support their production and reduce costs. By doing so, mushrooms can become a more economical source of protein and contribute to more sustainable dietary practices.

Abbreviations

AIDS	Acquired immunodeficiency syndrome
FAO	Food and Drug Administration
GHGs	Greenhouse gases
HMG COA reductase	3-hydroxy-3-methylglutaryl coenzyme A reductase
LDL	Low-density lipoprotein
NCDs	Non-communicable diseases
RPM	Red and processed meat

Acknowledgements
Not applicable.

Author contributions
KHAP and SRS designed the study and wrote the first draft of the manuscript. KI performed statistical analyses and ZN contributed to draft editing and revisions. All authors read and approved the final manuscript.

Funding
No funding was received to assist with the preparation of this manuscript.

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

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 21 August 2024 / Accepted: 19 November 2024
Published online: 30 November 2024

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