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Exploring the role of different varieties of mushrooms in enhancing athletic endurance and recovery

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Abstract
This review evaluates the role of mushroom supplementation in enhancing athletic endurance and recovery. A systematic search of PubMed and Google Scholar, following PRISMA guidelines, identified studies examining the effects of mushrooms on VO_2 max, time to exhaustion, lactate threshold, and recovery markers. Bioactive compounds such as polysaccharides, triterpenoids, and ergothioneine were associated with improved oxygen utilization, reduced oxidative stress, and enhanced post-exercise recovery. *Cordyceps militaris* and *Ganoderma lucidum* showed the greatest potential in boosting endurance performance and reducing fatigue and inflammation. These findings suggest that mushrooms may serve as effective, natural ergogenic aids for athletes. Further high-quality trials are needed to standardize dosages and validate efficacy across diverse athletic populations.

Keywords: Ergogenic aids, antioxidant capacity, functional foods

Introduction
Endurance exercise places a high physiological demand on the muscular, cardiovascular, hormonal, and immune systems, often leading to fatigue, oxidative stress, and inflammation. Nutritional interventions aimed at enhancing endurance and accelerating recovery have gained increasing attention in sports science. In this context, mushrooms—recognized as functional foods have emerged as promising natural ergogenic aids due to their rich composition of bioactive compounds such as polysaccharides, peptides, triterpenoids, nucleosides, and phenolic compounds [1].

Medicinal and edible mushrooms have been traditionally used for centuries for their diverse therapeutic properties. Compounds like lentinan, eritadenine, and ergothioneine contribute to antioxidant, immune-modulatory, and anti-inflammatory effects [2-3]. Notably, ergothioneine's stable redox potential (−0.06V) allows it to scavenge hydroxyl radicals and peroxynitrite effectively, limiting hydrogen peroxide accumulation and reducing exercise-induced oxidative damage [3].

Studies suggest that mushroom supplementation may improve endurance performance by enhancing oxygen uptake, protecting skeletal muscle from oxidative stress, and supporting post-exercise recovery [1]. Triterpenoids and β-glucans found in mushrooms may influence mitochondrial efficiency, modulate inflammatory pathways, and support cardiovascular and respiratory function—key mechanisms underlying endurance adaptation [4].

Although mushrooms were not traditionally emphasized in sports nutrition, recent research underscores their potential as nutraceuticals in active populations, particularly in enhancing aerobic performance [5]. Their role in modulating physiological stress responses and promoting recovery through antioxidant activity and hormonal balance aligns with the demands of endurance athletes [6]. However, a systematic synthesis of controlled evidence on outcomes such as VO_2 max, time to exhaustion, lactate threshold, and recovery markers remains limited.

The present review aims to critically examine the existing human and animal studies exploring the effects of mushroom supplementation on endurance and recovery. It synthesizes data on physiological and biochemical outcomes, identifies key mushroom species investigated, and discusses potential mechanisms relevant to endurance enhancement.

Mushrooms have been widely studied for their diverse therapeutic properties, including immune-modulatory, antioxidant, anti-inflammatory, and neuro-protective effects [7-8]. These properties largely derive from biologically active compounds such as β-glucans, polysaccharides, terpenoids, and phenolic acids, which have been shown to enhance innate immunity, scavenge free radicals, suppress inflammatory mediators, and support neuronal health [9-10]. Collectively, these effects contribute significantly to their potential role in enhancing athletic performance and recovery. The therapeutic properties of various mushrooms are illustrated in Figure 1.

Method

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, utilizing the PSALSAR Framework methodologies. Zotero was employed to collect, manage, and organize references, including the removal of duplicates. This review was structured using the PSALSAR framework to ensure methodological rigor and transparency. The steps of the PSALSAR process applied in this study are summarized in Table 1.

Eligibility Criteria for the Study

Inclusion criteria: Studies that examine the effects of mushroom supplementation on endurance-related outcomes, such as VO2 max, time to exhaustion, lactate threshold, recovery metrics, or biochemical markers (e.g., oxidative stress, inflammation). Eligible studies must involve either human participants (endurance athletes) or animal models, utilizing standardized outcome measurement techniques and interventions that focus on mushrooms.

Exclusion criteria: Studies focusing on populations not engaged in physical activities. Research involving mushrooms for purposes unrelated to endurance (e.g., immunity or cognitive benefits), studies with insufficient data, unclear methodology, or lack of relevant outcomes, and *in vitro* research will be excluded. Studies of low methodological quality or without defined interventions or measurable outcomes will also be excluded.

Type of Intervention

The intervention of interest is mushroom supplementation aimed at improving endurance and recovery. All types of mushrooms studied for their potential endurance-enhancing properties (e.g., *cordyceps, reishi, lion's mane*) were included in certain cases single or mixed mushroom supplementation was reported.

Type of Outcomes

Primary outcomes: VO2 max (a measure of aerobic capacity), Time to exhaustion (a measure of stamina and endurance), Lactate threshold (indicator of performance capacity), Recovery metrics (e.g., time taken for post-exercise recovery).

Secondary outcomes: Biochemical markers such as oxidative stress (e.g., reactive oxygen species), inflammation (e.g., cytokines), and other endurance-related metabolic parameters.

Type of Study

Randomized clinical trials (RCTs) and observational studies (both animal and human) were included.

Search Strategy

Searches were conducted in English with filters for endurance-related outcomes and study types such as RCTs and observational studies. Databases such as PubMed and Google Scholar were explored.

Keywords include

"Mushroom supplementation," "*Cordyceps*," "*Reishi*," "Lion's mane," "Shiitake," "Chaga," "Maitake," "Functional mushrooms," "Edible mushrooms," "Medicinal mushrooms," "Endurance enhancement," "VO2 max," "Time to exhaustion," "Lactate threshold," "Recovery metrics," "Post-exercise recovery," "Aerobic capacity," "Anaerobic capacity," "Oxidative stress," "Reactive oxygen species," "Inflammation markers," "Cytokines," "Antioxidant capacity," "Sports nutrition," "Athletic performance," "Endurance athletes," "Marathon runners," "Cyclists," "Triathletes," "Rowers," "Recreational athletes," "Dietary supplementation," "Nutraceuticals," "Food-based supplements," "Natural ergogenic aids," "Exercise supplementation," "Functional food for athletes."

Boolean operators (AND/OR) and synonyms were used to expand the search.

Data Extraction

The articles were screened for relevance based on their titles and abstracts. Full-text publications were subsequently retrieved to determine final inclusion, with reasons for exclusion documented. The data to be extracted from the eligible studies will include:

Study characteristics: Subject demographics, sample size, study design, intervention type, control type, and study duration.

Outcome measures: VO2 max, time to exhaustion, lactate threshold, recovery metrics, biochemical markers, and any other relevant endurance parameters. A meta-analysis was conducted for studies with comparable quantitative data on outcomes such as VO2 max, recovery metrics, or biochemical markers. Qualitative synthesis was applied for studies with non-uniform metrics.

Study Selection and Study Characterization

As shown in the PRISMA flow diagram. A total 16700 records were identified through search in databases. Duplicate records were identified and removed (n= 14400). After examining the titles and abstract, 300 records were further screened, resulting in 14100 excluded records. Reason for exclusion were Review and Meta-analysis (n= 53), Intervention did not met inclusion (n= 72), *in vitro* studies (n = 38), studies on children and adolescents (n=18), conference proceedings (n=24), non RCT (18), other language (n=26), only Abstract (n=36). (Figure 1) hence they were exclude.

Fifteen records were included, study population comprised of either human participants (endurance athletes) or animal models, utilizing standardized outcome measurement techniques and interventions that focus on mushrooms. Studies included were both randomized clinical trial and observational studies. Articles were classified into three categories: Effects of Mushrooms on Biophysical Parameters, Biochemical Parameters and both among athletes.

The study selection process is summarized in the PRISMA flow diagram (Figure 2).

Overview of Mushroom Species and Performance Parameters

Shiitake Mushroom (*Lentinus edodes*)

Shiitake (*Lentinus edodes*), the second most widely consumed edible mushroom globally, has experienced significant growth in production and usage in recent years [11]. Beyond their nutritional value, shiitake mushrooms offer multifaceted benefits, including disease prevention and overall health promotion [12]. Notably, *Lentinus edodes* was the first medicinal macro-fungus to enter the realm of modern biotechnology. Its rising popularity in the global market is attributed not only to its nutritional properties but also to its diverse therapeutic applications [13].

Shiitake mushrooms are a rich source of biologically active components, including proteins, carbohydrates, and bioactive polysaccharide complexes such as β-D-glucan, heteroglucan, xylomannan, lentinan, and eritadenine. They also contain free sugars, including arabinose, arabitol, mannose, mannitol, trehalose, and glycerol [14]. In addition, shiitake mushrooms are abundant in vitamins B2, B12, and D2, as well as essential micro- and macroelements such as potassium, phosphorus, magnesium, calcium, zinc, copper, manganese, selenium, and iron [15].

Nutritionally, shiitake mushrooms are low in cholesterol and total fat but contain a high proportion of unsaturated fatty acids, contributing to their health benefits. They also produce bioactive compounds with antioxidant, antimicrobial, anti lipidemic, anticancer, anti-cariogenic, and immune regulatory properties, including lentinan, eritadenine, and ergothioneine, as well as essential vitamins such as pro vitamin D2 (ergo sterol and calciferol), B-complex vitamins (thiamine, riboflavin, and niacin), and pantothenic acid. Moreover, they contain minerals in significant concentrations, including magnesium, nickel, copper, phosphorus, strontium, and zinc [2]. Additionally, shiitake extract, as a primary source of ergo thioneine, has the potential to modulate hydrogen peroxide (H_2O_2), nitric oxide (NO), and cytokine levels, potentially enhancing skeletal muscle regeneration following intense exercise [3]. Given their broad range of bioactive compounds, shiitake mushrooms hold immense nutraceutical potential. Their potent antioxidant capacity protects cells from oxidative stress linked to conditions such as cancer and cardiovascular diseases [16-17]. Regular consumption of shiitake mushrooms, as part of an antioxidant-rich diet, may contribute to improved health and disease prevention.

Scarlet Caterpillar Fungus (*Cordyceps militaris*)

Cordyceps militaris, a medicinal fungus in the family Clavicipitaceae, has been extensively studied for its wide-ranging therapeutic effects. Recent animal studies highlight its anti-fatigue action acidic polysaccharides from *C. militaris* decreased fatigue markers and improved learning and memory via the PI3K/Nrf2/HO-1 pathway in exercise-stressed mice [18]. Its principal bioactive compound, cordycepin, demonstrated robust anti-fatigue efficacy in mice through activation of the TIGAR/SIRT1/PGC-1α signaling axis [19]. Additionally, *C. militaris* exerts immunomodulatory, antioxidant, anti-inflammatory**,** and anti-cancer effects through polysaccharides that regulate gut microbiota, oxidative stress, and inflammation pathways [20-21]. Notably, interest in *Cordyceps* for athletic performance was first sparked decades ago, but recent trials have begun to clarify its physiological mechanisms. A 2024 randomized, double-blind study in young athletes reported that daily intake of 1 g *Cordyceps militaris* infusion for three weeks significantly increased oxygen saturation (SpO_2) during high-intensity effort and reduced fatigue time, likely through enhanced red blood cell volume and hemoglobin content [22]. In animal and cellular models, cordycepin and *C. militaris* polysaccharides were shown to boost lactate clearance, stimulate ATP production, promote vasodilation, and reduce oxidative stress via PI3K/Nrf2/HO-1 and mitochondrial regulators like SIRT1/PGC-1α [18-19]. Human studies observing accelerated stem cell recruitment ($CD34^+$/$Pax7^+$) in muscle post-exercise also suggest improved muscle recovery capacity, contributing to sustained high-intensity performance [23].

The *Cordyceps* genus, comprising entomopathogenic fungi known for parasitizing insect larvae, has been used in traditional Asian medicine for centuries. Among these, *Cordyceps militaris* has gained prominence due to its high cordycepin content, immunomodulatory activity, and scalability in artificial cultivation. Modern research confirms that *C. militaris* contains a range of bioactive compounds including cordycepin, adenosine, and polysaccharides, which exhibit anti-inflammatory, anti-tumor, anti-oxidative, and metabolic regulatory properties [24]. Compared to *C. sinensis*, *C. militaris* offers comparable or higher levels of therapeutic compounds, especially when cultivated in optimized media. Its ease of large-scale cultivation and consistent quality make *C. militaris* a superior alternative for pharmaceutical and nutraceutical applications [24].

Caterpillar Fungus (*Ophiocordyceps sinensis* also known as *Cordyceps sinensis*)

Ophiocordyceps sinensis, formerly known as *Cordyceps sinensis*, is a high-altitude, insect-parasitic fungus traditionally revered in Chinese and Tibetan medicine. It is primarily found in the Himalayan region, where it parasitizes ghost moth larvae (*Hepialus armoricanus*) to form its characteristic fruiting structure [25]. Its bioactive components, cordycepin, adenosine, and polysaccharides, have been shown to exert immunomodulatory, antioxidant, anti-fatigue, and metabolic regulatory effects [26]. These properties have led to growing interest in its potential as a natural performance enhancer. Recent human studies indicate that supplementation with *O. sinensis* (1-4 g/day) can improve oxygen uptake, endurance capacity, and blood lactate clearance, especially during high-altitude or prolonged aerobic exercise [27, 26]. Its mechanisms are attributed to enhanced mitochondrial efficiency, red blood cell production, and vasodilatory effects. With standardized cultivation and encapsulation techniques, *O. sinensis* is now widely used in functional sports nutrition products globally [26].

Chaga Mushroom (*Inonotus obliquus*)

Inonotus obliquus, commonly known as Chaga mushroom, has been used as a folk remedy in Russia, Siberia, and other occidental countries since the 16th century [28]. It primarily colonizes living birch trees across the circumboreal regions of the Northern Hemisphere [29]. Its characteristic irregular, blackened sterile conk resembling burnt charcoal has made it distinct and widely recognized in traditional and modern medicinal contexts [30].

Growing under extremely low environmental temperatures in high latitudes, Chaga develops slowly, which has led to increased interest in its bioactive compounds and pharmacological potential over the past two decades. It contains a variety of chemical constituents, including polysaccharides, triterpenoids, polyphenols, and melanin, which have demonstrated anticancer, anti-inflammatory, antiviral, antioxidant, hypoglycemic, and hypolipidemic activities in long-term clinical and animal studies, with no significant side effects [31]. Among its bioactive components, polysaccharides exhibit the broadest range of biological effects, including anticancer, hypoglycemic, anti-inflammatory, and antioxidant properties [32]. Chaga belongs to the Hymenochaetaceae family within Basidiomycetes and is classified as a white rot fungus. This fungus forms a hyperplastic mycelial mass (sterile conk) on birch trees (*Betula* spp.) after infection, predominantly in temperate and boreal forests across Europe, Asia, and North America [29-30]. Chaga extracts have been traditionally utilized in countries such as China, Korea, Russia, and the Baltic states for their purported antibacterial, hepatoprotective, anti-inflammatory, antitumor, and antioxidant properties [33-34]. Medicinally, Chaga has been used to treat gastrointestinal cancers, cardiovascular diseases, and diabetes with minimal toxicity [28]. Its secondary metabolites include polysaccharides, polyphenols, lanostane-type triterpenoids, and inotodiol [35], which contribute to its health-promoting effects and high medicinal value. Additionally, Recent studies indicate that *Inonotus obliquus* (Chaga) extracts are generally well tolerated with low toxicity in both *in vitro* and animal models, supporting their potential for safe therapeutic use; however, comprehensive human clinical safety data remain limited and warrant further investigation [33,36].

Lion's Mane Mushroom (*Hericium erinaceus*)

Hericium erinaceus, commonly known as lion's mane, is an edible mushroom classified within the family Hericiaceae, order Russulales, class Agaricomycetes, and phylum Basidiomycota, as confirmed by recent fungal taxonomic databases [37-38]. It is widely distributed in East Asian countries such as Japan and China [39]. The mature mushroom is characterized by its distinctive appearance, consisting of numerous long, white, dangling fleshy spines [40]. Traditionally, *H. erinaceus* has been used as an herbal medicine in East Asia, with well-documented health benefits [41- 42].

The medicinal properties of *Hericium erinaceus* include antioxidant, antimicrobial, and anticancer effects [43-44]. Recent studies emphasize its neuroprotective and neuroregenerative potential, largely attributed to bioactive compounds in the mycelia and fruiting bodies, such as polysaccharides, phenolic acids, and terpenoids including hericenones and erinacines [45-46]. These terpenoids have demonstrated the ability to cross the blood-brain barrier and stimulate nerve growth factor (NGF) synthesis and secretion, promoting neuronal growth and repair [47-48]. Studies in animal models have shown that *H. erinaceus* exerts anti-neuroinflammatory and neuroprotective effects [49-51], while also demonstrating promising cognition-enhancing properties [52]. Hericene A, a compound isolated from *H. erinaceus*, has been shown to increase circulating levels of pro-brain-derived neurotrophic factor (BDNF) in mice [53]. In human studies, supplementation with *H. erinaceus* extract has been associated with improved memory and mood, along with increased BDNF levels, particularly in overweight individuals [54]. These findings suggest that *H. erinaceus* and its derivatives may exert BDNF-like neurotrophic effects. Clinical trials have demonstrated cognitive benefits in older adults. In a study involving individuals aged 50-80 years with mild cognitive impairment, daily supplementation with 3 g of *H. erinaceus* over 16 weeks led to improvements in cognitive function, with significant changes observed at weeks 8, 12, and 16 [55]. Similar reductions in cognitive decline were noted in patients with mild Alzheimer's disease following a 49-week regimen of erinacine A-enriched *H. erinaceus* supplementation (three 350 mg capsules daily, each containing 5 mg/g erinacine A [56].

Reishi Mushroom (*Ganoderma lucidum*)

Ganoderma lucidum, commonly known as Reishi or Lingzhi, is a medicinal mushroom renowned for its extensive pharmacological properties. Recent studies have elucidated its diverse bioactive compounds, including polysaccharides, triterpenoids, and proteins, which contribute to its therapeutic effects. These compounds have been shown to possess antioxidant, anti-inflammatory, anticancer, antidiabetic, and hepatoprotective activities [57-58]. Notably, *Ganoderma lucidum* polysaccharides have demonstrated significant anticancer potential through mechanisms such as immunomodulation, anti-proliferation, pro-apoptosis, anti-metastasis, and anti-angiogenesis [59]. Additionally, the mushroom's triterpenoids exhibit anti-inflammatory effects by inhibiting pro-inflammatory cytokines and enzymes [60]. Furthermore, recent advancements in cultivation techniques have enhanced the yield of bioactive compounds, thereby improving the consistency and efficacy of *Ganoderma lucidum* based supplements [61].

Cauliflower Mushroom (*Sparassis crispa*)

Sparassis crispa, commonly known as the cauliflower mushroom or Hanabiratake in Japanese, is a kind of rare, medicinal, edible mushroom with a fruiting body that has rich nutritional value containing many active substances. The main component of *S. crispa* is β-glucan, and its content is between 40 and 43%, which is the highest among mushrooms [62]. This level surpasses that found in many other mushrooms, making it particularly notable for its immuno potentiative properties. *S. crispa* belongs to the kingdom Fungi, phylum Basidiomycota, class Agaricomycetes, order Polyporales, family Sparassidaceae, and genus Sparassis. It is a brown-rot fungus that primarily grows on coniferous tree stumps and is widely distributed in the North Temperate Zone. Scientific studies have demonstrated that both the consumption of *S. crispa* and the β-glucan extracted from it enhance immune function. These effects include increased inflammatory cytokine production in splenocytes, improved peripheral natural killer (NK) cell activity, and anti-tumor properties [63]. It contains glucosyl ceramide (approximately 0.2%), a glycoside of ceramide with potential bioactive properties. One of the most studied components of *S. crispa* is β-1,3-glucan, a type of polysaccharide with β-1,3-glycosidic bonds. This compound has been linked to potential cardiovascular disease and cancer prevention due to its immunomodulatory and immunostimulatory effects [5].

Furthermore, bioactive compounds derived from mushrooms, including *S. crispa*, have been explored as natural sources of estrogenic chemicals, offering potential alternatives to synthetic estrogens without associated adverse effects [65].

Intervention Trials on the Effects of Mushroom Supplementation on Athletic Performance

Effects of Mushrooms on Biophysical Parameters

Mushrooms, long valued for their medicinal properties, are increasingly being investigated for their potential ergogenic benefits in athletic populations [66]. Recent research has focused on their influence on biophysical parameters such as VO_2 max, time to exhaustion, lactate levels, muscle endurance, and energy metabolism [67, 30]. These parameters are crucial indicators of aerobic capacity, muscular efficiency, and overall athletic performance. This section synthesizes current evidence from both human and animal studies evaluating the effects of various mushroom species and blends—including *Cordyceps militaris* [67], *Inonotus obliquus* [30], *Hericium erinaceus* [68], and *Ophiocordyceps sinensis* [66], on key biophysical metrics. By assessing randomized controlled trials and experimental models [48], we aim to elucidate the role of mushroom supplementation in enhancing endurance, reducing fatigue, and modulating metabolic pathways involved in exercise physiology.

A summary of intervention trials examining the effects of various mushroom species on biophysical performance markers is presented in Table 2.

Effects of Mushrooms on Biochemical Parameters in Athletic Performance

Beyond their impact on physical performance metrics, mushrooms have been studied for their influence on biochemical markers related to exercise, recovery, and overall metabolic function. These markers include antioxidant enzymes, inflammatory cytokines, stress-related hormones, and indicators of liver and lipid metabolism [1]. Such biochemical parameters are essential for understanding the physiological mechanisms underlying athletic adaptation and recovery

Various mushroom species, such as *Ganoderma lucidum* (Sharif *et al*., 2023), *Cordyceps sinensis* [69], *Lentinula edodes* [70], and *Inonotus obliquus* [71], have been evaluated for their potential to modulate oxidative stress, improve immune function, and regulate metabolic responses to exercise. The collective findings offer insight into how mushroom supplementation might contribute to enhanced resilience against exercise-induced physiological stress.

Key studies evaluating these biochemical outcomes are presented in Table 3.

Combined Effects on Biophysical and Biochemical Parameters

Some studies have concurrently evaluated both biophysical and biochemical outcomes, providing a holistic view of the impact of mushroom supplementation. These studies are summarized in Table 4. Biophysical parameters, such as oxygen saturation, endurance, and anti-fatigue properties, directly influence an athlete's physical performance, while biochemical markers, including antioxidant activity, hormonal regulation, and hematological changes, offer insights into the body's physiological response to exercise.

A comparison of the combined biophysical and biochemical effects of various mushroom species is presented in Table 4.

Figure 3 provides a visual summary of the combined biophysical and biochemical effects associated with mushroom supplementation.

Results and Discussion

This review synthesizes the current evidence on the effects of mushroom supplementation on athletic performance, integrating both biophysical and biochemical outcomes. Across the included studies, improvements were consistently reported in parameters such as VO_2 max, time to exhaustion, lactate threshold, and markers of oxidative stress and inflammation [66, 72, 1, 9, 10, 36]. Multiple trials involving *Cordyceps militaris* and *Ophiocordyceps sinensis* demonstrated significant enhancements in VO_2 max, aerobic capacity, and endurance in both human and animal models [66, 26, 73, 36, 18]. Time to exhaustion also improved following supplementation with mushrooms such as *Ganoderma lucidum*, *Inonotus obliquus*, and *Lentinula edodes*, indicating improved oxygen utilization and reduced fatigue onset [60, 6, 74, 70, 10].

Additional improvements were observed in physiological markers such as heart rate, blood pressure, and glycogen content, supporting the overall ergogenic potential of these species [75, 28, 74]. In terms of biochemical outcomes, numerous studies reported increased activity of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), along with reduced concentrations of malondialdehyde (MDA), a marker of lipid peroxidation [1, 18, 76, 33].

These findings suggest that mushroom supplementation enhances the body's antioxidant defense system, thereby mitigating exercise-induced oxidative stress. Anti-inflammatory responses were also evident, with reductions observed in interleukin-6 (IL-6), tumor necrosis factor-alpha (TNF-α), and C-reactive protein (CRP) levels [30, 67, 77]. These adaptations may facilitate faster post-exercise recovery and reduce systemic inflammation in athletes.

Hormonal regulation emerged as another potential benefit. Studies involving *Cordyceps sinensis* and *Ganoderma lucidum* reported favorable shifts in the testosterone-to-cortisol ratio, reflecting improved anabolic balance and reduced physiological stress [69, 78, 79]. Improvements in insulin sensitivity and post-exercise glucose regulation were also observed in some trials, suggesting an additional role in metabolic recovery [80, 74].

These performance-enhancing effects are attributed to a diverse range of bioactive compounds found in mushrooms, including β-glucans, triterpenoids, polysaccharides, and ergothioneine [2, 69, 60], compounds are known to modulate immune responses, support mitochondrial function, and enhance cellular antioxidant activity. For example, *Hericium erinaceus* has been shown to activate pathways such as PGC-1α and SIRT1, promoting mitochondrial biogenesis and energy efficiency in muscle tissue [81, 76, 52].

Among the various species, *Cordyceps* exhibited the most consistent improvements across both biophysical and biochemical parameters [18, 36, 72]. However, heterogeneity in study designs, dosages, populations, and intervention durations limits the ability to generalize these findings. Differences in mushroom forms (e.g., extract, powder, capsule), study duration, and sample size further contribute to the variability. Standardized protocols, controlled dosages, and long-term studies are essential to establish the efficacy and safety of mushroom supplementation in athletic populations [82, 10].

Toxicity and Limitations of Medicinal Mushrooms

Despite the growing evidence supporting the ergogenic and therapeutic benefits of medicinal mushrooms, several limitations and safety concerns must be considered. A key issue is the heterogeneity of current research: variations in study designs, dosages, intervention durations, and participant demographics significantly limit the generalizability of findings. Many studies are short-term and lack longitudinal data, making it difficult to ascertain the long-term safety and efficacy of mushroom supplementation. Although mushrooms such as Lion's Mane (*Hericium erinaceus*), Reishi (*Ganoderma lucidum*), and Cauliflower Mushroom (*Sparassis crispa*) are widely recognized for their therapeutic effects, reports of adverse reactions exist, especially when consumed in high doses or by individuals with pre-existing health conditions. For example, Lion's Mane appears safe overall, but long-term safety and allergenic potential in sensitive individuals remain insufficiently studied [43]. Reishi has been associated with mild gastrointestinal disturbances and rare cases of hepatotoxicity, including a fatal instance of fulminant hepatitis potentially linked to its interaction with other substances [83]. It also demonstrated teratogenic effects in zebrafish embryos, suggesting the need for cautious use, particularly during pregnancy. *Sparassis crispa*, although generally safe, may provoke immune overactivation due to its high β-glucan content, possibly aggravating autoimmune conditions [58].

Other mushrooms, such as *Inonotus obliquus* (Chaga), contain high oxalate levels, with documented cases of oxalate nephropathy following prolonged excessive intake, and *in vitro* studies suggest potential hepatotoxicity [75]. *Cordyceps militaris* and *Ganoderma leucocontextum* have shown no significant toxicity in animal models, with no adverse effects reported even at high doses [76, 70]. Similarly, *Cordyceps sinensis* is generally considered safe, but recommendations advise limiting long-term use to a maximum of 4 grams per day due to the lack of comprehensive chronic toxicity studies [77-78]. Toxicological studies on *Shiitake* (*Lentinula edodes*) have revealed low acute toxicity [79]. Although generally safe when cooked, higher oral doses in animal studies have resulted in hematological changes such as leukopenia and reduced hemoglobin levels, suggesting a potential upper intake threshold around 100 mg/kg/day in rats [80]. Specific studies have further clarified safety margins. A subchronic toxicity study using erinacine A-enriched *Hericium erinaceus* mycelia found no adverse effects in rats even at doses up to 2,625 mg/kg/day [81], while another study demonstrated the mushroom's efficacy in wound healing without systemic toxicity [62]. For *Cordyceps militaris*, studies reported no acute or subchronic toxicity up to 4,000 mg/kg/day [82]. Nonetheless, comprehensive long-term human trials remain scarce for most species, emphasizing the need for further research to establish clear upper intake levels and safety guidelines, especially for vulnerable populations and individuals with specific health conditions.

Future Directions

Future research should focus on standardizing dosages and intervention durations across different athlete populations, exploring the synergistic effects of mushroom combinations, conducting large-scale randomized controlled trials, and investigating the impact of long-term supplementation on athletic performance and recovery.

Tables

Table 1: Overview of the PSALSAR Framework Applied to the Review of Mushroom Supplementation Effects on Endurance and Related Outcomes

	Steps	Outcome	Method
PSALSAR Framework	Protocol	Defined study scope	Purpose: To investigate the effects of mushroom supplementation on endurance, VO2 max, recovery, and stamina in athletes.
			Participants: Endurance athletes (no subgroups based on gender, age, or fitness level).
			Treatments: Various mushroom types (e.g., cordyceps, reishi, lion's mane) used in supplementation for endurance outcomes.
			Results: Primary outcomes: VO2 max, time to exhaustion, lactate threshold, recovery metrics.
			Design Parameters: Inclusion of human and animal studies, randomized controlled trials (RCTs), observational studies.
	Search	Comprehensive identification of pertinent research	Databases: PubMed, Google Scholar.
			Keywords: "Mushrooms AND endurance," "Cordyceps AND VO2 max," "Mushroom supplementation AND recovery," etc.
			Tools: Zotero for managing references, eliminating duplicates.
	Appraisal	Critical evaluation of research for quality and bias	Inclusion Criteria: Studies involving mushroom supplementation for endurance outcomes, peer-reviewed, human or animal studies.
			Exclusion Criteria: Studies with incomplete data or low-quality methodology.
			Quality Tools: Use Cochrane Risk of Bias Tool for human studies, ARRIVE Guidelines or SYRCLE's Risk of Bias Tool for animal studies.
	Synthesis	Systematic retrieval and combination of data	Aggregate data on comparable outcomes (e.g., VO2 max, lactate threshold).
			Use RevMan, R (metafor package), or Comprehensive Meta-Analysis (CMA) software for meta-analysis.
	Analysis	Statistical analysis and discussion of findings	Quantitative: Effect sizes (SMD, WMD), heterogeneity analysis, and subgroup analysis for human vs. animal studies.
			Qualitative: Narrative synthesis for outcomes where quantitative synthesis is not feasible, exploring mechanisms (e.g., antioxidants).
	Conclusion	Derivation of conclusions and recommendations	Summarize findings: Identify patterns across human and animal studies, compare effects of different mushroom types.
			Gaps and Future Research: Suggest areas needing further exploration, like clinical trials or specific mushroom varieties.
	Report	Writing and presentation of results	Structure: Abstract, Introduction, Methods, Results, Discussion, Conclusion.
			Reporting: Include heterogeneity, limitations, and implications for future research or practice (e.g., athlete nutrition).

Note: The PSALSAR framework represents the systematic review process steps applied in this study. Abbreviations: RCT = randomized controlled trial; SMD = standardized mean difference; WMD = weighted mean difference; ARRIVE = Animal Research: Reporting of *In Vivo* Experiments; SYRCLE = SYstematic Review Center for Laboratory animal Experimentation.

Table 2: Effects of Mushrooms on Biophysical Parameters in Athletic Performance

Title	Participants	Dosages and blinding	Outcome and finding	References
The Effects of High and Low-Dose Cordyceps Militaris (Parasitic fungus) -Containing Mushroom Blend Supplementation After Seven and Twenty-Eight Days	Trial 1: 40 young adults (19-34 years); Trial 2: 43 young adults (19-34 years), randomized into treatment and control groups.	Trial 1: 1.0-2.0 g/day of PeakO2 mushroom blend; Trial 2: 12 g/day of PeakO2 mushroom blend, both with Gatorade powder.	**Trial 1:** VO2peak □ blood lactate □ **Trial 2:** VO2max□ MT group showed □heart rate □peak power.	Mishra & Upadhyay. (2011)
Chronic supplementation of a mushroom blend on oxygen kinetics, peak power, and time to exhaustion	10 recreationally active adults (mean age = 21.4 ± 2.4 years; mean weight = 75.0 ± 10.6 kg), randomly divided into mushroom (MR, n = 6) and placebo (PL, n = 5) groups.	Dosage: 4 grams/day of mushroom blend (1.3 grams per capsule, 3 times daily) or placebo (maltodextrin) for 3 weeks. Blinding: Double-blind, placebo-controlled	⬆VO2 max ⬆TTE for MR group after 3 weeks. No significant changes in lactate levels between groups. PL group showed no notable changes in any variables.	Hirsch *et al.* (2015)
Effect of Inonotus obliquus Extract Supplementation on Endurance Exercise and Energy-Consuming Processes through Lipid Transport in Mice	Male Institute of Cancer Research mice (n = 8 per group).	IO supplementation at doses of 0 (vehicle), 824 mg/kg (IO-1×), 1648 mg/kg (IO-2×), and 2472 mg/kg (IO-3×) once daily for 6 weeks. Blinding - Not mentioned	□ Muscle volume □ exercise endurance (longer treadmill time) □ higher glycogen storage. □ Serum free fatty acid levels post-exercise. - □ lipid transport and energy metabolism.	Chen *et al.* (2022)
- Increase in muscle endurance in mice by dietary Yamabushitake mushroom (Hericium erinaceus) possibly via activation of PPARδ	Eight-week-old male C57BL/6J mice.	Diet supplemented with 5% (w/w) freeze-dried Yamabushitake mushroom for 24 hours and 8 weeks. Blinding - Not mentioned	□ PPARδ Activation: Up-regulation of target genes (Pdk4 and Ucp3) in mouse skeletal muscle. □ Muscle Endurance: Significant increase in endurance after 8 weeks of supplementation.	Komiya *et al.* (2019)
Anti-stress and muscular endurance effects of natural specimens and laboratory cultured mycelia of Ophiocordyceps sinensis (Berk.) G.H. Sung, J.M. Sung on rats and mice	Rats (for anti-stress activity) and mice (for muscular endurance) used as animal models.	Test groups: 100, 300, and 500 mg/kg body weight of natural and lab-cultured O. sinensis. Positive control: Imipramine (15 mg/kg body weight). Negative control: 0.9% NaCl solution. Blinding - Not mentioned	□ Anti-Stress Activity: Both natural and lab-cultured O. sinensis significantly ($p<0.05$) improved anti-stress markers compared to control. □ Muscular Endurance: Enhanced endurance in mice with significant effects observed at doses of 300 and 500 mg/kg ($p<0.05$). □ Biochemical Markers: Natural and lab-cultured O. sinensis significantly ($p<0.05$) inhibited increases in LDH, cholesterol, and BUN, and prevented decreases in ALP levels in stressed rats.	Harsahay *et al.* (2014)

Note: This table summarizes studies investigating the impact of various mushroom species and supplements on biophysical outcomes related to athletic performance, including VO2 max, muscle endurance, exercise duration, and biochemical markers. Dosages and blinding methods vary across studies, with both human and animal models included.

Table 3: Effects of Mushrooms on Biochemical Parameters in Athletic Performance

Title	Participants	Dosages and blinding	Outcome and finding	References
Effect of shiitake (lentinus edodes) extract on antioxidant and inflammatory response to prolonged eccentric exercise	Healthy male subjects (exact number not specified).	Shiitake mushroom extract: 700 mg, administered twice daily for 10 days. Blinding - Not mentioned	□ IL-10 levels.	Zembron-Lacny *et al.* (2013)
Improving Training Condition Assessment in Endurance Cyclists: Effects of Ganoderma lucidum and Ophiocordyceps sinensis Dietary Supplementation	7 healthy male amateur cyclists aged 30-40 years participating in "Gran Fondo" cycling races.	Daily supplementation with 3 capsules of Cordyceps sinensis and 2 capsules of Ganoderma lucidum. Blinding - Not mentioned	□Testosterone/Cortisol Ratio: After 3 months of supplementation, statistically significant improvement in the ratio, suggesting protection against NFO and OTS. □Antioxidant Activity: Enhanced free radical scavenging capacity in athletes' serum post-race, indicating reduced oxidative stress.	Rossi *et al.* (2014)
Sparassis crispa Intake Improves the Reduced Lipopolysaccharide-Induced TNF-α Production That Occurs upon Exhaustive Exercise in Mice	Male C3H/HeN mice divided into three groups: 1. Normal chow + resting sedentary, 2. Normal chow + exhaustive treadmill running, 3. SC chow (5% SC powder for 8 weeks) + exhaustive treadmill running.	Mice consumed chow containing 5% SC powder for 8 weeks prior to the intervention. Blinding - Not mentioned	□ Plasma and tissue TNF-α levels and □ TLR4 and MyD88 expression. - SC intake attenuated the reduction of TNF-α, TLR4, and MyD88 levels in the plasma and small intestine Suggesting a protective effect on immune function.	Uchida *et al.* (2019)
Evaluation of Shiitake Mushroom (Lentinula edodes) Supplementation on the Blood Parameters of Young Thoroughbred Racehorses	20 young Thoroughbred racehorses, divided into two groups: supplemented (n=10) and control (n=10).	Supplemented group received 30 g of Lentinula edodes daily for 4 months. Blinding - Not mentioned	□Monocyte levels in the supplemented group on day 56 ($p = 0.000986$). □Alkaline phosphatase: Significantly lower levels in the supplemented group across all sampling days. □Glucose Reduced on days 28 ($p = 0.009109$) and 56 ($p = 0.025749$). □ Aspartate aminotransferase (AST): Decreased on day 56 ($p = 0.017258$). □ Lactic acid Reduced on day 28 ($p = 0.037636$). □ Cholesterol consistently decreased across all sampling days.	Soroko-Dubrovina *et al.* (2022)

Note: This table presents findings from studies examining the biochemical effects of mushroom supplementation on athletes and animal models. Key outcomes include changes in inflammatory markers, antioxidant activity, hormonal balance, and various blood parameters. The studies vary in participant type, dosage, duration, and blinding methods.

Table 4: Effects of Mushrooms on Biophysical and Biochemical Parameters in Athletic Performance

Title	Participants	Dosages and blinding	Outcome and finding	References
Improved Oxygen Saturation and Performance of Athletes using Cordyceps militaris	48 athletes aged 16-35, divided into four groups of 12 athletes each.	Cordyceps militaris: 1 g/day. Whey protein: 10 g/day. Combined supplementation: 1 g/day Cordyceps militaris + 10 g/day whey protein. Blinding - Double-blinded	↑Higher oxygen saturation (95%). -- Stabilized heart rate (90±5 bpm). ↑running times (5 km: 13.5 min, 200 m: 25 sec). -- Reduced treadmill fatigue (2.5x lower than control). Haematological improvements: ↑ RBC size, Hb, HCT, and oxygen flow. Combined supplementation did not outperform Cordyceps militaris alone.	Pasha *et al.* (2024)
Beneficial Effect of Cordyceps militaris on Exercise Performance via Promoting Cellular Energy Production	Experimental study with administration of CMEE and red ginseng as a control group. Grip strength tests were performed weekly, and blood samples were analyzed for biochemical markers related to exercise performance.	G1: Vehicle-treated normal control group (no dosage specified) G2: Red ginseng 100 mg/kg (orally once daily for 12 weeks) G3-G5: Cordyceps militaris treated groups (50, 150, and 300 mg/kg, orally once daily for 12 weeks) Blinding - Not mentioned	□ Exercise performance through the enhancement of ATP production rather than directly reducing muscle fatigue.	Choi *et al.* (2020)
Polysaccharides from Cordyceps sinensis mycelium ameliorate exhaustive swimming exercise-induced oxidative stress	Experimental study with four groups receiving CSP at varying doses or water (control) for 28 days, followed by exhaustive swimming exercise.	CSP administered orally in doses of 100 mg/kg (LC), 200 mg/kg (IC), and 400 mg/kg (HC). No blinding, randomly divided	□ Exhaustive swimming time in LC, IC, and HC groups. - □SOD, GPx, and CAT activities in CSP-treated groups (IC and HC showed the most increase). - □MDA and 8-OHdG levels in all CSP-treated groups.	Yan *et al.* (2014)
Anti-fatigue activities of polysaccharides extracted from Hericium erinaceus	Experimental study with 28-day treatment using oral doses of HEP followed by a forced swimming test to assess physical endurance and biochemical markers of fatigue.	HEP administered orally at 50 mg/kg, 100 mg/kg, and 200 mg/kg for 28 days. Blinding - Not mentioned	↓ BLA, SUN, and MDA levels. □Increased tissue glycogen content. - □SOD and GPx activities.	Liu *et al.* (2015)
Effect of Lentinula edodes on Morphological and Biochemical Blood Parameters of Horses	Longitudinal experimental study with five blood sample collection sessions over 5 months.	Supplemented group received 60 g of shiitake mushrooms daily for 5 months. Blinding - Not mentioned	□ Lymphocytes (session 3), monocytes (session 4), basophils, hemoglobin, and hematocrit in the supplemented group. □ Alkaline phosphatase significantly in sessions 2, 4, and 5. □ Calcium levels observed in session 4. □ Gamma-glutamyl transferase significantly in session 2. □bilirubin and glucose levels in supplemented group. □albumin/globulin ratio in supplemented group.	Soroko *et al.* (2022)

Note: This table summarizes studies assessing both biophysical and biochemical effects of various mushroom species and their extracts on athletic performance. Outcomes include improvements in oxygen saturation, exercise endurance, oxidative stress markers, biochemical blood parameters, and fatigue-related biomarkers. The studies include human and animal subjects with varying dosages and blinding protocols.

Table 5: Comparison of Different Mushrooms & Their Effects

Mushroom Type	Primary benefit	VO2 max improvement	Anti-Fatigue properties
Shiitake Mushroom (Lentinus edodes)	Improves energy metabolism and immune support	Limited evidence	Supports muscle recovery and reduces tiredness
Scarlet Caterpillar Fungus (Cordyceps militaris)	Enhances aerobic capacity and energy levels	Significant	Reduces fatigue and improves endurance
Caterpillar Fungus (Ophiocordyceps sinensis)	Enhances oxygen utilization and stamina	Moderate to significant	Reduces fatigue and boosts endurance performance
Chaga Mushroom (Inonotus obliquus)	Rich in antioxidants, aids recovery	No direct evidence	Supports recovery by reducing oxidative stress
Lion’s Mane Mushroom (Hericium erinaceus)	Enhances cognitive and mental focus	Not studied directly	Limited anti-fatigue properties observed
Reishi Mushroom (Ganoderma lucidum)	Immune modulation and recovery aid	Limited or inconclusive	Moderate effect in reducing fatigue
Cauliflower Mushroom (Sparassis crispa)	Immune enhancement and anti-inflammatory	Limited evidence	Potential to reduce inflammation-related fatigue

Note: VO2 max improvement indicates the extent of enhancement in maximal oxygen uptake reported in studies. Anti-fatigue properties refer to evidence of reduced physical or mental fatigue associated with mushroom supplementation. Evidence levels range from limited to significant based on available research in athletic populations.

Figures Legends

Figure 1. Therapeutic properties of mushrooms.

Flowchart illustrating the therapeutic roles of various medicinal mushrooms. Each mushroom is represented visually, with linked branches denoting its bioactive properties such as immunomodulation, anti-inflammatory action, antioxidant activity, and endurance enhancement.

Figure 2. PRISMA flow diagram of study selection.

Flowchart representing the screening process for inclusion in the review. It shows records identified (n = 16,700), those excluded, and final studies included (n = 15), along with reasons for exclusion at the eligibility stage.

Figure 3. Biophysical and biochemical effects of mushrooms.

Diagram highlighting the dual effects of mushroom supplementation. Biophysical benefits include improved oxygen transport, muscle recovery, and endurance. Biochemical effects include reduction in oxidative stress, inflammation, and enhancement of energy metabolism.

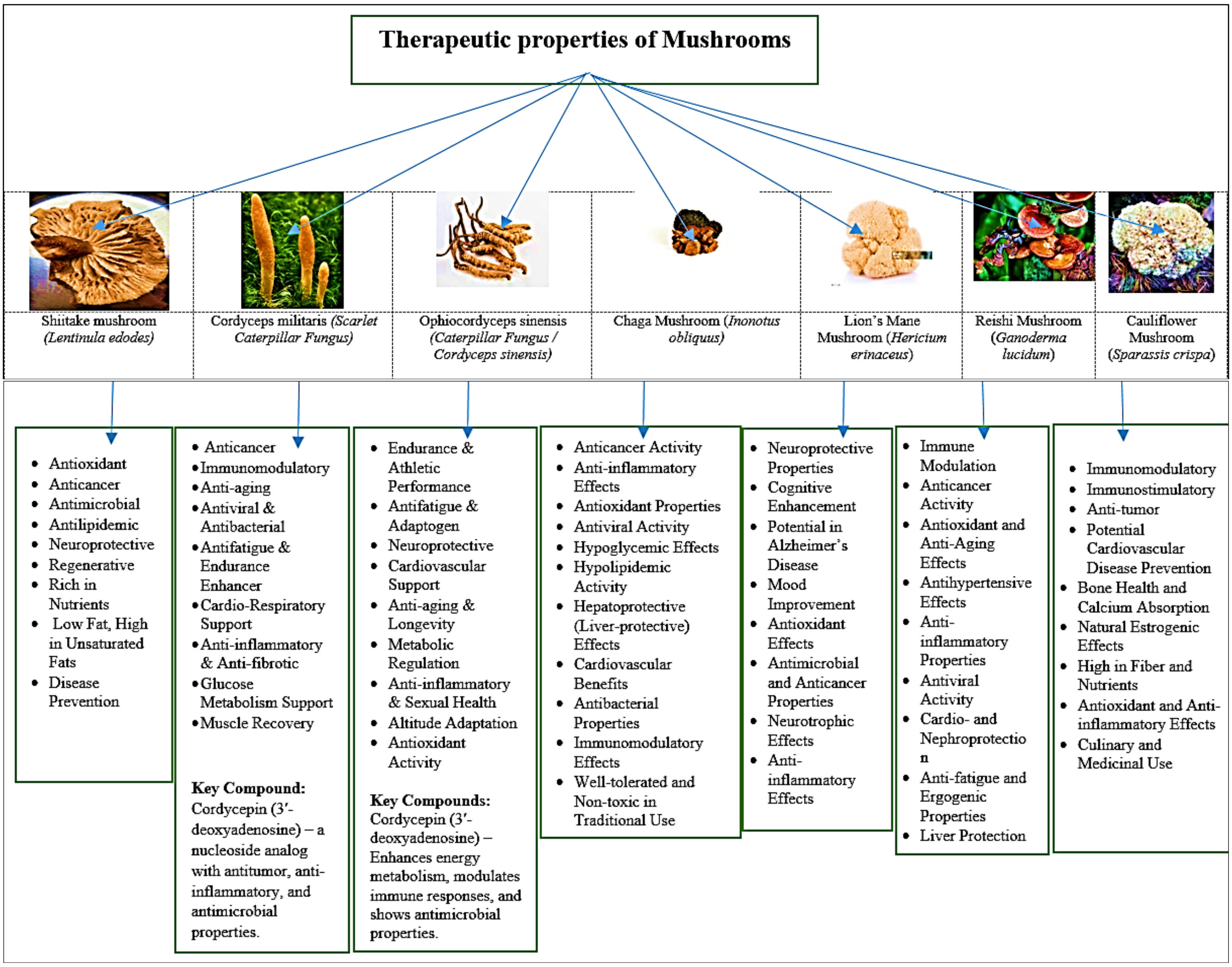

Fig 1: Therapeutic properties of various mushrooms

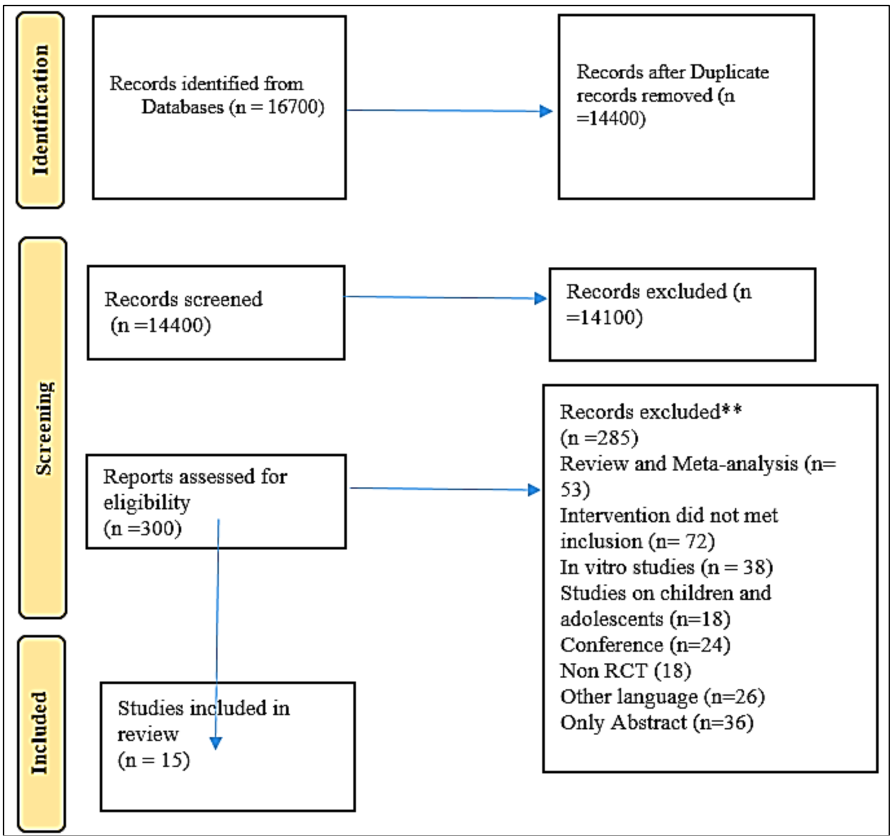

Fig 2: PRISMA Framework

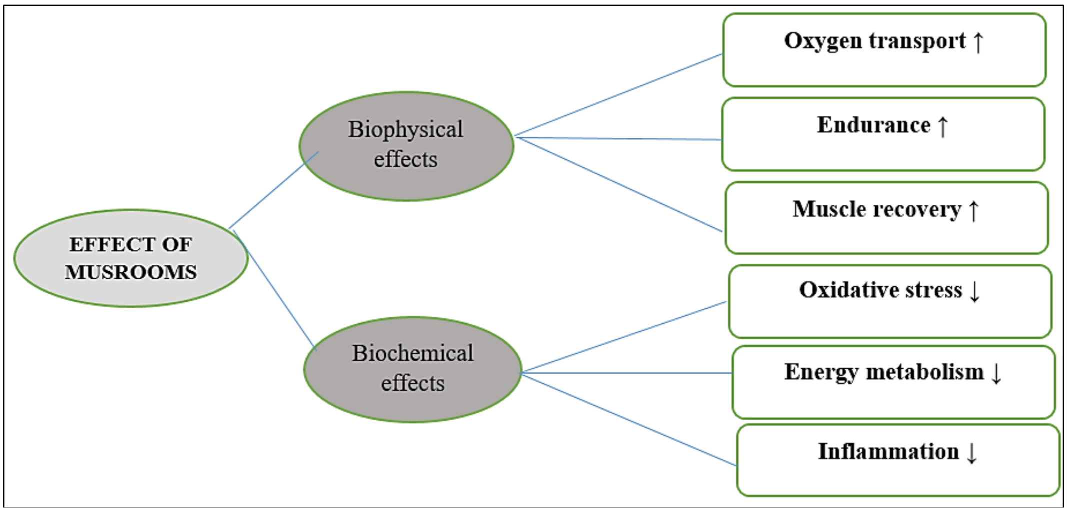

Fig 3: Biophysical & Biochemical Effects of Mushrooms

Conclusion

The present review highlights the growing evidence supporting the role of mushroom supplementation in enhancing both biophysical and biochemical parameters associated with athletic performance. Species such as *Cordyceps*, *Ganoderma*, *Hericium*, and *Inonotus* have demonstrated improvements in VO_2 max, endurance, antioxidant activity, hormonal balance, and recovery processes. These benefits are largely attributed to a unique profile of bioactive compounds, including β-glucans, polysaccharides, triterpenoids, and ergothioneine. While current findings are promising, heterogeneity in study designs, dosing protocols, and participant characteristics limits generalizability. Future research should prioritize well-controlled human trials with standardized supplementation protocols, clearly defined outcome measures, and comprehensive safety assessments to establish mushrooms as credible ergogenic aids in sports nutrition.

Author Contributions

Conceptualization, data curation, and formal analysis were carried out by Dr. Swati Vyas (S.V.), who also provided overall guidance and supervision throughout the review process.

Writing - original draft preparation, review, and editing were done by Priyal Vijay (P.V.). Funding acquisition and investigation were not applicable, as this work is based on a narrative review without external funding support. Both authors have read and approved the final version of the manuscript.

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Conflicts of Interest

The author declares no conflict of interest.

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