**Optimizing Cultivation Media for Enhanced Cordycepin and Bioactive Compound Production in *Cordyceps militaris*: Recent Trends and Future Prospects**

**Abstract**

A valuable entomopathogenic medicinal fungus called *Cordyceps militaris* has become a promising bioresource for the synthesis of pharmacologically active substances like cordycepin, polysaccharides, and nucleosides. Developing optimized cultivation systems to increase the yield and quality of these bioactive metabolites is becoming more and more popular as the demand for functional foods, nutraceuticals, and bio-pharmaceuticals rises globally. In order to maximize the production of cordycepin and other therapeutic compounds in C. militaris, this review critically analyses recent developments and technological advancements in substrate and media optimization. It highlights cutting-edge farming techniques and investigates potential future paths for environmentally friendly, economically feasible production models. The review assesses the impact of current research findings on mineral supplementation, plant extract enrichments, agro-industrial by-products, and grain-based substrates on metabolite synthesis. The strategic use of elicitors, developments in liquid static and submerged fermentation systems, the possible use of biotechnological interventions, and AI-based growth monitoring systems are also covered. According to recent data, cordycepin content and other bioactive metabolites can be considerably increased in both solid-state and liquid cultivation systems through careful substrate formulation and media enrichment. There is great potential for scalable, economical production through the combination of fermentation optimization and media engineering techniques. Additionally, precision cultivation models and AI-driven environmental monitoring are showing promise as instruments to enhance metabolite profiles and yield consistency. To position *Cordyceps militaris* as a high-value functional food, medicinal mushroom, and sustainable agri-biotech enterprise opportunity, the review highlights the importance of media optimization and astute cultivation techniques in enhancing the plant's therapeutic, economic, and commercial value.

**Keywords:** *Cordyceps militaris*, cordycepin, functional foods, medicinal mushroom, precision cultivation

**Introduction**

Medicinal mushrooms have long been integral to traditional medicine systems, offering a plethora of bioactive compounds with therapeutic potential. Among these, *Cordyceps militaris*, an entomopathogenic fungus, has attracted much interest because to its capacity to generate cordycepin (3'-deoxyadenosine), a nucleoside analogue with several pharmacological effects including anticancer, antiviral, and immunomodulatory (Das *et al*., 2023). Driven by rising consumer desire for natural health products and nutraceuticals, the worldwide market for medicinal mushrooms is expanding fast. With *C. militaris* contributing a major amount because to its broad pharmacological spectrum, the medicinal mushroom market alone is expected to exceed USD 24.2 billion by 2032 (Chen *et al*., 2024).

Though its acknowledged therapeutic value, commercial-scale growing of *C. militaris* has significant constraints in terms of yield consistency, metabolite content variation, and high manufacturing costs. Varying substrate qualities and environmental conditions cause traditional solid-state and submerged fermentation methods to generate inconsistent metabolite profiles. Industrial uses are still significantly hampered by the low natural yield of cordycepin and the high sensitivity of fungal metabolism to growing conditions (Lee *et al*., 2023).
Current fermentation systems are also labor-intensive, unautomated, and have scaling problems. High-yield, affordable, and standardized production systems that satisfy pharmaceutical sector criteria are hard to attain without precise growth monitoring and optimized growing media.

A well-known entomopathogenic ascomycete mushroom, *C. militaris*, naturally parasitizes lepidopteran larvae in temperate forests. Among the many bioactive chemicals found in its mycelium and fruiting body are cordycepin, adenosine, polysaccharides, ergosterol, mannitol, and peptides (Zhang *et al*., 2023).

The main pharmacologically active ingredient, cordycepin, shows pronounced anticancer, immunomodulatory, anti-inflammatory, and antiviral effects. Recent research has validated its efficacy against several cancer cell lines as well as its possible application in controlling metabolic and neurodegenerative diseases (Das *et al*., 2023).

Many elements, including carbon and nitrogen sources, mineral content, pH, temperature, and oxygen levels, affect the biosynthesis of cordycepin. Therefore, improving metabolite production has been seen as a main goal by means of optimising growing media (Chen *et al*., 2024).

While numerous studies have addressed the pharmacological potential of *C. militaris*, few have comprehensively reviewed the latest strategies for optimizing cultivation media and substrate systems specifically aimed at enhancing cordycepin and other therapeutic compound yields. This review bridges that gap by consolidating cutting-edge research, examining:

* Recent advances in substrate selection, including grain-based media and agro-industrial by-products.
* Plant extract and mineral supplementation strategies for media enrichment.
* Innovations in liquid static and submerged fermentation systems.
* Application of elicitors and biotechnological tools for metabolite enhancement.
* Integration of artificial intelligence (AI) and environmental sensors for precision cultivation.

Critically assessing these trends helps this review not only draw attention to the present condition of cultivation media optimization for *C. militaris* but also offer a future-oriented road map combining AI-driven smart cultivation systems for sustainable, high-value production.
Emphasizing the untapped promise of artificial intelligence-based environmental monitoring for consistent, large-scale, and economically feasible cordycepin production, the novelty is in its thorough synthesis of recent substrate engineering methods and technological interventions.

**2. Bioactive Metabolites of *Cordyceps militaris***

Renowned for its varied range of bioactive chemicals, *Cordyceps militaris* shows therapeutic promise. Among these, cordycepin (3'-deoxyadenosine) stands out as the main active component. Structurally similar to adenosine but without a hydroxyl group at the 3' position, cordycepin shows a variety of pharmacological effects including anticancer, antiviral, and immunomodulatory ones. By increasing cytokine production and activating immune cells, cordycepin alters immune responses, causes apoptosis in several cancer cell lines, and suppresses viral RNA synthesis (Zhou *et al*., 2008). A gene cluster made up of Cns1, Cns2, Cns3, and Cns4 coordinates the transformation of adenosine to cordycepin and guards it from degradation, therefore controlling cordycepin biosynthesis (Huang *et al*., 2021).

Apart from cordycepin, *C. militaris* generates several nucleotides and nucleosides including adenosine, uridine, and guanosine. These substances help the fungus's pharmacological profile by showing vasodilatory, anti-inflammatory, neuroprotective, and antidepressant-like qualities (Das *et al*., 2023). Tightly controlled during fungal growth and development, the purine and pyrimidine metabolic pathways create these nucleosides (Huang *et al*., 2021).

*C. militaris* polysaccharides mostly consist of glucose, mannose, and galactose. Among their notable biological effects, these macromolecules increase the activity of natural killer cells and macrophages, hunt free radicals to shield cells from oxidative stress, and suppress tumour growth by causing apoptosis and blocking angiogenesis (Shweta *et al*., 2023). Complex enzymatic pathways including glycosyltransferases and polysaccharide synthases define the biosynthesis of these polysaccharides (Huang *et al*., 2021).
Apart from these, *C. militaris* creates several other bioactive chemicals. A sterol component of fungal cell membranes, ergosterol shows anti-inflammatory and anticancer qualities. A sugar alcohol, D-mannitol has antioxidant and diuretic effects. A peptide called cordymin might have immunomodulatory and antibacterial properties (Das *et al*., 2023). These chemicals are the focus of continuous pharmacological studies and help to increase the therapeutic potential of *C. militaris*.

**3. Cultivation Systems and Media Optimization Strategies**

The cultivation of *Cordyceps militaris* has garnered significant attention due to its therapeutic potential and commercial value. Optimizing cultivation systems and media is crucial for enhancing the yield of bioactive compounds such as cordycepin and polysaccharides (Deshmukh and Bhaskaran, 2024; Trung *et al*., 2024).

Various culture media have been evaluated to determine their efficacy in supporting the growth and development of *C. militaris* mycelia. Studies have shown that media such as chitosan combined with agar and optimized nutrient broth, Kenknight and Munnaiers medium, oat meal agar, and rice extract agar significantly promote mycelial growth compared to standard agar media. Notably, Kenknight and Munnaiers medium demonstrated a 25% higher mycelial growth after 21 days of culture, indicating its superior efficacy in supporting fungal development. (Vardhan *et al*., 2024)

In submerged culture systems, the optimization of culture conditions is vital for maximizing the production of cordycepin. (Jiapeng *et al*., 2014) Research has identified that specific working volumes, particularly 700 mL in a 1000 mL flask, yield the highest cordycepin concentration, reaching up to 2008.48 mg/L. This optimization involves precise control of factors such as dissolved oxygen levels, carbon and nitrogen sources, and incubation parameters (Kang *et al*., 2014).

The choice of carbon and nitrogen sources significantly influences the production of bioactive compounds. Sucrose and lactose have been identified as more effective carbon sources for cordycepin production compared to glucose, with sucrose yielding up to 843.63 mg/L of cordycepin (Kang *et al*., 2014). Additionally, peptone and yeast extract serve as optimal nitrogen sources, enhancing both mycelial biomass and metabolite synthesis (Deshmukh and Bhaskaran, 2024).

Environmental factors such as temperature, pH, and inoculum size play a pivotal role in the cultivation process. Optimal mycelial biomass production has been achieved at a temperature of 20°C, initial pH of 5.5, and an inoculum volume of 8% (v/v). These conditions facilitate favorable morphological characteristics and efficient nutrient utilization, leading to enhanced growth (Deshmukh and Bhaskaran, 2024).

The development of synthetic media through rational design has further improved cultivation outcomes. By employing genome-scale metabolic models, researchers have optimized media compositions, particularly the proportions of glucose and ammonia, resulting in increased growth rates and cordycepin production. This approach underscores the potential of metabolic engineering in refining cultivation practices (Raethong *et al*., 2020).

Moreover, the optimization of fermentation conditions, including the control of pH and nutrient concentrations, has led to significant improvements in cordycepin yield. For instance, maintaining a pH of 6.0 and utilizing specific concentrations of glucose and peptone have been shown to enhance exopolysaccharide production, which is closely linked to cordycepin synthesis (Cui *et al*., 2010).

In conclusion, the strategic optimization of cultivation systems and media, encompassing the selection of effective culture media, precise control of environmental parameters, and the application of metabolic engineering techniques, is essential for maximizing the production of bioactive compounds in *Cordyceps militaris*. These advancements not only improve yield and quality but also contribute to the sustainable and cost-effective production of this valuable medicinal fungus (Deshmukh and Bhaskaran, 2024).

Its therapeutic value and commercial potential have made *Cordyceps militaris* a subject of great interest. Increasing the production of bioactive chemicals like cordycepin and polysaccharides depends on maximizing growing systems and media (Deshmukh and Bhaskaran, 2024; Trung *et al*., 2024).

Different culture media have been assessed to gauge their effectiveness in fostering the growth and development of *C. militaris* mycelia. Research has revealed that, when compared to standard agar media, chitosan combined with agar and optimized nutrient broth, Kenknight and Munnaiers medium, oat meal agar, and rice extract agar greatly promote mycelial growth. Especially, Kenknight and Munnaiers medium showed a 25% greater mycelial growth after 21 days of culture, suggesting its better effectiveness in promoting fungal development (Vardhan *et al*., 2024).

Maximizing the production of cordycepin in submerged culture systems depends on the optimization of culture conditions (Jiapeng *et al*., 2014). Studies have shown that certain working volumes, especially 700 mL in a 1000 mL flask, produce the greatest cordycepin concentration, even to 2008.48 mg/L. Dissolved oxygen levels, carbon and nitrogen sources, and incubation settings all undergo exact control in this optimization (Kang *et al*., 2014).
The generation of bioactive chemicals is greatly influenced by the selection of carbon and nitrogen sources. With sucrose producing as much as 843.63 mg/L of cordycepin, sucrose and lactose have been found to be more efficient carbon sources for cordycepin synthesis than glucose (Kang *et al*., 2014). Peptone and yeast extract also provide best nitrogen sources, therefore improving metabolite production and mycelial biomass (Deshmukh and Bhaskaran, 2024).

The growing process is mostly influenced by environmental elements including temperature, pH, and inoculum size. At a temperature of 20°C, initial pH of 5.5, and an inoculum volume of 8% (v/v), optimal mycelial biomass production has been attained. These conditions promote good morphological traits and effective nutrient use, therefore improving growth (Deshmukh and Bhaskaran, 2024).
Rational design has helped to create synthetic media, which has even more improved growing results. Researchers have maximized media compositions—especially the ratios of glucose and ammonia—by using genome-scale metabolic models, therefore boosting growth rates and cordycepin generation. This method emphasizes the possibility of metabolic engineering in improving agricultural practices (Raethong *et al*., 2020).

Furthermore, the optimization of fermentation conditions—including pH and nutrient concentration control—has produced notable increases in cordycepin output. Maintaining a pH of 6.0 and using particular amounts of glucose and peptone, for example, have been demonstrated to improve exopolysaccharide generation, which is closely related to cordycepin production (Cui *et al*., 2010).

Ultimately, maximizing the production of bioactive compounds in *Cordyceps militaris* depends on the strategic optimization of cultivation systems and media including the choice of suitable culture media, exact control of environmental factors, and the use of metabolic engineering methods. Apart from increasing yield and quality, these developments help to reasonably and sustainably manufacture this precious medicinal fungus (Deshmukh and Bhaskaran, 2024).

**3. Cultivation Techniques of *Cordyceps militaris***

**3.1 Conventional Methods: Solid-State and Liquid Fermentation**

Predominantly, the growing of *Cordyceps militaris* uses two conventional techniques: submerged fermentation (SmF) and solid-state fermentation (SSF). Growing the fungus on solid substrates like rice, wheat, or other grains gives SSF a surface for mycelial colonization and fruiting body development. Often producing more bioactive chemicals like cordycepin, this approach closely resembles the natural habitat of the fungus. For example, combining rice, wheat, jowar, bajra, and sugarcane bagasse has been shown to improve both fruiting body formation and cordycepin level relative to using rice alone (Borde *et al*., 2023). SSF has also been linked to higher antioxidant activity and better functional qualities in fermented products (Xiao *et al*., 2015).

Conversely, SmF means growing *C. militaris* in liquid nutrient media under controlled conditions, therefore enabling simpler scalability and automation. This approach ensures consistent mycelial biomass generation by allowing exact control over environmental factors. Research has shown that improving medium component, including glucose and yeast extract levels, can greatly increase cordycepin output in SmF systems (Zhang *et al*., 2013). Furthermore, SmF allows for the use of bioreactors, which support large industrial uses.

**3.2 Comparison of Solid-State vs. Submerged Fermentation Systems**

Each approach offers unique benefits and drawbacks when one compares SSF and SmF. Often, SSF is preferred for its capacity to generate fruiting bodies rich in bioactive chemicals, nearly matching the natural growth circumstances of *C. militaris*. Higher levels of cordycepin and other metabolites have been associated with this approach, which makes it appropriate for creating nutraceuticals and functional foods (Trung *et al*., 2024; Borde *et al*., 2023). SSF techniques, on the other hand, are often labor-intensive, time-consuming, and less suited for automation.

In contrast, SmF offers advantages in terms of process control, scalability, and shorter cultivation cycles. The liquid environment allows for uniform nutrient distribution and easier monitoring of growth parameters. SmF is particularly effective for producing mycelial biomass and extracting intracellular metabolites. Nevertheless, it may yield lower concentrations of certain bioactive compounds compared to SSF, and the absence of fruiting body formation can be a limitation for specific applications (Chen *et al*., 2024).

Ultimately, the choice between SSF and SmF depends on the desired end products, production scale, and resource availability. Hybrid approaches and advancements in fermentation technology continue to evolve, aiming to combine the benefits of both methods for optimized *C. militaris* cultivation.

**3.3 Limitations of Traditional Cultivation Methods**

Though SSF and SmF have been shown to be effective in growing *C. militaris*, some drawbacks still exist. SSF presents issues such as the possibility of contamination, the need to preserve consistent environmental conditions, and the labour-intensive character of the process. Solid substrates' dependence can also cause yield and product quality variation. Furthermore, increasing SSF processes for industrial manufacture is still difficult and requires many resources.
Although it provides more control and scalability, SmF presents its own difficulties. Shear stress on mycelial structures caused by the liquid environment could affect metabolite generation. Furthermore, the lack of fruiting bodies in SmF could restrict the range of bioactive chemicals generated since some metabolites are mostly generated during fruiting body development. Moreover, maximizing output by means of nutrient composition and fermentation conditions calls for great study and development (Zhang *et al*., 2013).
Addressing these limitations necessitates ongoing innovation in cultivation techniques, including the development of hybrid systems, genetic improvement of strains, and the application of advanced biotechnological tools to enhance efficiency and product consistency in *C. militaris* cultivation.

**4. Recent Trends in Substrate and Media Optimization for *Cordyceps militaris***​

**4.1 Grain-Based Substrates**

Grain-based substrates have long been foundational in the cultivation of *Cordyceps militaris*, with rice, wheat, millet, and sorghum commonly employed due to their nutrient profiles and accessibility. Recent research has looked at how different grains work together to increase the generation of bioactive chemicals. For example, solid-state fermentation of rice, wheat, jowar, bajra, and sugarcane bagasse produced much more cordycepin than rice by itself, suggesting that mixed substrates may maximise metabolite output (Borde and Singh, 2023). These results imply that maximising the therapeutic chemicals generated by *C. militaris* may depend on careful choice and combination of grain substrates.

**4.2 Agro-Industrial By-Products**

Using agro-industrial by-products as substrates provides a reasonable and sustainable way to grow *C. militaris*. Materials including spent brewery grains, corn cobs and soybean hulls have been studied for their effectiveness in promoting fungal growth and metabolite generation. Incorporating spent brewery grains into the growing medium, for instance, has been demonstrated to promote *C. militaris* growth and improve cordycepin synthesis, therefore offering a feasible approach for waste valorization (Andrej, 2014). The use of corncob biochar as a carbon-rich substrate has also shown increases in biomass and cordycepin yields, therefore stressing the possibility of agricultural leftovers in maximizing growing methods (Phoungthong *et al*., 2022).

**4.3 Plant Extract Enrichments**

Incorporating plant extracts into the cultivation media of *C. militaris* has emerged as a strategy to enhance the production of bioactive metabolites. Herbal extracts such as green tea and ginseng are rich in bioactive compounds that can influence fungal metabolism. Studies have indicated that the addition of such extracts can lead to increased antioxidant and immunomodulatory properties in the resulting fungal biomass, suggesting a synergistic effect between the fungus and the plant-derived compounds (Pi *et al*., 2024). These enhancements not only improve the therapeutic potential of *C. militaris* but also open avenues for developing novel functional foods and supplements.​

**4.4 Mineral and Vitamin Supplementation**

Adding certain minerals and vitamins to growing media has been shown to affect the biosynthesis of important metabolites in *Cordyceps militaris*. Enzymatic activities and metabolic pathways are significantly influenced by components including zinc (Zn), magnesium (Mg), selenium (Se), and different vitamins. Selenium-enriched *C. militaris*, for example, has been said to have greater amounts of cordycepin, adenosine, carotenoids, and polysaccharides than non-enriched counterparts (Jing *et al*., 2013). A study also revealed that during in vitro gastrointestinal digestion, selenium-zinc biofortification boosted the release of mineral elements, adenosine, and cordycepin (Zhao *et al*., 2023). Although there are few direct studies on how these supplements affect *C. militaris*, comparable studies in other fungal systems indicate that such additions could promote the synthesis of bioactive chemicals. Mineral supplementation, for example, has been linked to higher yields of preferred metabolites in the growing of other medicinal mushrooms, suggesting possible advantages for *C. militaris* cultivation as well. More study is required to clarify the precise impacts of these supplements on *C. militaris* cordycepin and polysaccharide production.

**5. Technological Advancements in Cultivation Systems**

**5.1 Liquid Static and Submerged Fermentation Advances**

Recent developments in submerged fermentation have greatly improved cordycepin output in *Cordyceps militaris*. Increased yields of this bioactive compound have come from optimizing fermentation conditions including environmental parameters and nutrient makeup (Showkat *et al*., 2024). Adjusting glucose and yeast extract levels as well as phosphate and magnesium levels, for example, has been demonstrated to enhance cordycepin production (Zhang *et al*., 2013).

The addition of vegetable oils as secondary carbon sources in static liquid cultures has been investigated to promote mycelial growth and metabolite generation. This method has shown promise in raising cordycepin yields, thereby providing a reasonably priced option for extensive farming (Tang *et al*., 2018).

**5.2 Use of Elicitors and Stress Inducers**

Research on the use of salicylic acid (SA) and methyl jasmonate (MeJA) as elicitors has focused on encouraging secondary metabolite biosynthesis in *C. militaris*. Acting as signalling molecules, these chemicals set off defensive reactions that result in more generation of bioactive chemicals (Jeyasri *et al*., 2023). Research have indicated that MeJA and SA can increase the production of substances including cordycepin, therefore increasing the therapeutic value of the fungus (Chutimanukul *et al*., 2024).

**5.3 Biotechnological Interventions**

New paths for strain improvement in *C. militaris* have been opened by developments in genetic manipulation methods. Strains with greater metabolite yields have been created using techniques including mutagenesis and genome editing (Hu *et al*., 2024). Targeted changes made possible by the whole genome sequence have allowed scientists to improve certain biosynthetic routes (Thoe *et al*., 2025).

The metabolic networks of *C. militaris* have also been better understood by combining bioinformatics and omics techniques including transcriptomics and metabolomics. By means of these technologies, important genes and regulatory mechanisms connected to metabolite generation have been found; they have also helped to direct more optimisation efforts (Thoe *et al*., 2025).

**6. AI-Driven Precision Cultivation Models**

**6.1 Application of AI, IoT, and Machine Learning in Environmental Monitoring**

Recent developments have included Artificial Intelligence (AI), Internet of Things (IoT), and machine learning technologies into the growing of *Cordyceps militaris*, aiming to optimise environmental conditions and improve metabolite generation. IoT-enabled systems, for example, have been created to track vital factors like humidity, temperature, and moisture levels, all of which are absolutely necessary for the best Cordyceps species growth. By means of sensor networks gathering real-time data, these systems enable exact control of the growing environment and guarantee uniform quality and output.
Furthermore, suggested to control substrate environments more efficiently is the combination of fuzzy logic and IoT systems (Irwanto *et al*., 2024). This strategy improves resource efficiency in mushroom cultivation and growth conditions by means of smart decision-making in changing environmental parameters.

**6.2 Predictive Modeling for Yield Consistency and Metabolite Profiling**

Increasingly, machine learning algorithms are being used to forecast and improve metabolite profiles and yield consistency in *C. militaris* growing. These algorithms can find patterns and correlations between environmental conditions and metabolite production by means of analysis of large datasets gathered from IoT devices. Such predictive modelling helps growers to make data-driven decisions, therefore maximizing the generation of useful chemicals like cordycepin by optimizing conditions.
The use of artificial intelligence in metabolomic studies has also helped to better understand the biosynthetic routes in *C. militaris*. Transcriptome-integrated genome-scale metabolic models, for instance, have been used to show metabolic fluxes linked to the biosynthesis of cordycepin and carotenoids under different environmental conditions (Soommat *et al*., 2024; Raethong *et al*., 2020).

**6.3 Recent Developments (2023–2024)**

Recent studies have demonstrated the practical applications of AI-driven systems in mushroom cultivation. For instance, an IoT-based framework was proposed to monitor the lifecycle of *Cordyceps sinensis*, providing insights into optimal cultivation practices and environmental requirements (Memoria *et al*., 2023). Although this study focused on C. sinensis, the methodologies and technologies are transferable to C. militaris cultivation.

Furthermore, the integration of AI and big data analytics has been suggested to address challenges in labor, quality control, and energy consumption in C. militaris cultivation. By optimizing factors such as light, temperature, and humidity, these intelligent systems aim to enhance the efficiency and sustainability of the cultivation process (Chen *et al*., 2019).

In summary, the application of AI, IoT, and machine learning in *C. militaris* cultivation represents a significant advancement in precision agriculture. These technologies offer the potential to optimize growth conditions, enhance metabolite production, and ensure consistent quality, paving the way for more efficient and sustainable cultivation practices.

**7. Economic, Therapeutic, and Commercial Prospects of *Cordyceps militaris***

**7.1 Market Demand Trends for Cordycepin and Medicinal Mushrooms**

The global market for *Cordyceps militaris* is experiencing significant growth, driven by increasing consumer awareness of its health benefits and the rising demand for natural supplements ([Kanhere](https://www.cognitivemarketresearch.com/cordyceps-market-report?utm_source=chatgpt.com#author_details),2025). In 2024, the market was valued at approximately USD 1.07 billion and is projected to reach USD 2.81 billion by 2031, growing at a compound annual growth rate (CAGR) of 12.8% (Verified market research, 2024; Dataintelo, 2024). Regionally, the Indian market is notable, with a valuation of USD 31.07 million in 2024 and an anticipated CAGR of 16.1%, reflecting deep-rooted traditional practices and increasing modern health awareness ([Kanhere](https://www.cognitivemarketresearch.com/cordyceps-market-report?utm_source=chatgpt.com#author_details),  2025)

This growth is attributed to the therapeutic properties of cordycepin, a bioactive compound found in *C. militaris*, which has been associated with various health benefits, including anti-inflammatory and antioxidant effects. The expanding market underscores the commercial viability of *C. militaris* as both a medicinal mushroom and a source of valuable nutraceuticals.

**7.2 Potential of *C. militaris* as a High-Value Functional Food**

Apart from its therapeutic uses, *C. militaris* is being acknowledged as a functional food because of its high concentration of bioactive components including polysaccharides, cordycepin, and ergosterol. These components help it to control several health issues including hyperlipidaemia and inflammation (Saranya *et al*., 2021; Chou *et al*., 2024).
Including C. militaris into dietary products presents a possible way to provide health advantages via daily use. Its adaptability fits different food types, including drinks, snacks, and supplements, satisfying the rising consumer desire for functional foods that support wellness.

**7.3 Sustainable and Scalable Agri-Biotech Business Models**

Growing C. militaris opens doors for scalable agri-biotech company ideas that are sustainable and environmentally friendly. Using agricultural waste as a foundation for mushroom growth not only lowers production costs but also supports environmental sustainability aims.
Genetic engineering and fermentation technology developments have increased *C. militaris* production scalability even more. Meeting the growing market demand, these developments allow the regular manufacture of high-quality mushrooms with increased amounts of bioactive chemicals (Hu *et al*., 2024).

Furthermore, the move towards automated and intelligent growing systems using artificial intelligence and IoT technologies helps to optimise resources and exact environmental control. This combination helps to create effective, large-scale manufacturing plants able to provide the worldwide market with C. militaris products

All things considered, Cordyceps militaris is quite commercially interesting, therapeutically useful, and economically viable. Its increasing market demand, functional food uses, and fit with sustainable farming methods help it to be a great asset in the agri-biotech and nutraceutical sectors.

**8. Future Perspectives in *Cordyceps militaris* Cultivation and Applications**

**8.1 Unexplored Substrates and Bio-Waste Valorization**

The investigation of other substrates and the valorisation of bio-waste offer interesting possibilities for sustainable Cordyceps militaris cultivation. Recent research has shown that spent mushroom substrate (SMS) is a renewable biomass that provides an environmentally friendly way to manage resources and waste (Devi *et al*., 2024; Antunes *et al*., 2020). The use of agro-industrial waste products like wheat bran and maize cobs has also been studied to improve C. militaris growth and metabolite generation, therefore supporting a circular economy in mushroom production (Pilafidis *et al*., 2022).

**8.2 AI-Integrated Automated Cultivation Units**

C. militaris cultivation systems are being transformed by the combination of artificial intelligence (AI) and Internet of Things (IoT) technologies, therefore changing conventional agriculture methods. Advanced growing facilities now use real-time monitoring and AI-driven environmental controls to maximise growth conditions, therefore improving yield and quality. Moreover, the creation of wireless multisensor systems has improved the accuracy of environmental parameter measurements, therefore enabling quick and sterile solid-state fermentation processes (Lin *et al*., 2020).

**8.3 Synergistic Use of Plant Bioactives and Nanoparticles**

A new approach to increase the therapeutic potential of C. militaris is being formed by combining it with plant-derived bioactives and nanoparticles. The synergistic fermentation of C. militaris with herbal substrates, for example, has been demonstrated to improve antioxidant and immunomodulatory properties, suggesting possible uses in functional food creation (Pi *et al*., 2024). Eco-friendly techniques have also allowed C. militaris extracts to be used in the biosynthesis of gold nanoparticles, which could be useful for biomedicine (Gawas *et al*., 2023).

**8.4 Genomic Tools for Enhanced Metabolite Synthesis**

Deeper insights into the biosynthetic pathways of key metabolites in C. militaris have been provided by advances in genomic and transcriptomic studies. Targeted genetic manipulations to increase metabolite production have been made possible by the discovery of genes linked to cordycepin synthesis (Chai *et al*., 2024). Furthermore, the overexpression of certain glycosyltransferase genes, such as CmUGT1, has been shown to greatly boost the production of cordycepin and polysaccharides, therefore stressing the possibility of genetic engineering in maximising C. militaris growth (He *et al*., 2024).

Ultimately, the future of Cordyceps militaris cultivation is in the combination of sustainable practices, modern technologies, and biotechnological breakthroughs. These strategies taken together seek to improve the efficiency, scalability, and therapeutic value of C. militaris, therefore highlighting its importance in the areas of sustainable agriculture, functional foods, and nutraceuticals.

**Results and Discussion**

This paper brings together modern technologies and techniques meant to improve the manufacture of cordycepin and other bioactive metabolites in Cordyceps militaris. All essential for creating scalable, affordable, and standardized production systems, the main goal was to assess developments in substrate optimization, fermentation technology, elicitor applications, genetic interventions, and AI-driven cultivation monitoring. Under solid-state fermentation, grain-based substrates—especially mixes of rice, wheat, jowar, and sugarcane bagasse—have outperformed single-grain media, producing better fruiting body morphology and higher cordycepin yields (Borde & Singh, 2023). Agro-industrial by-products like spent brewery grains and corncob biochar have also become sustainable, low-cost substrate choices boosting biomass and bioactive chemical production (Phoungthong et al., 2022). Media enrichment with plant extracts including green tea and ginseng not only raised antioxidant capacity but also strengthened cordycepin and polysaccharide biosynthesis (Pi *et al*., 2024).

In submerged fermentation systems, static liquid cultures supplemented with vegetable oils or selenium and zinc biofortification demonstrated up to a 30% improvement in cordycepin synthesis ([Jiapeng](https://www.sciencedirect.com/science/article/abs/pii/S0308814612015324) *[et al](https://www.sciencedirect.com/science/article/abs/pii/S0308814612015324)*[., 2014](https://www.sciencedirect.com/science/article/abs/pii/S0308814612015324), [Zhao *et al*., 2023](https://www.sciencedirect.com/science/article/pii/S0023643822012890)). Elicitors like methyl jasmonate and salicylic acid also effectively triggered secondary metabolism pathways, boosting metabolite production ([Jeyasri *et al*., 2023](https://pubmed.ncbi.nlm.nih.gov/10026785/), Chutimanukul *et al*., 2024). Biotechnological interventions have accelerated strain improvement through targeted mutagenesis, genome editing, and overexpression of glycosyltransferase genes such as *CmUGT1*, significantly enhancing cordycepin and polysaccharide output (He *et al*., 2024, [Chai *et al*., 2024](https://pmc.ncbi.nlm.nih.gov/articles/PMC11120935/)). Furthermore, transcriptomic and metabolomic analyses integrated into genome-scale metabolic models have enabled precise predictions of biosynthetic fluxes and media formulations to optimize metabolite synthesis under various cultivation conditions (Raethong *et al*., 2020, [Soommat *et al*., 2024](https://pmc.ncbi.nlm.nih.gov/articles/PMC10967962/)).

Importantly, real-time environmental monitoring and predictive modelling for yield consistency have been made possible by the arrival of AI, IoT, and fuzzy logic-controlled environments, with case studies showing better resource efficiency and metabolite profiles in both Cordyceps sinensis and C. militaris systems (Memoria *et al*., 2023, Irwanto *et al*., 2024). Combined with AI-driven decision support, these precision agriculture technologies have been shown to effectively preserve ideal humidity, temperature, and substrate conditions for consistent high-quality output (Lin *et al*., 2020).
Economically, the worldwide Cordyceps militaris market is expected to expand at a CAGR of 12.8%, driven by consumer demand for functional foods and nutraceuticals; India's market shows an even greater growth path of 16.1% yearly (Kanhere, 2025). While sustainable business models using agro-waste substrates and automated cultivation systems are positioning C. militaris as a key agri-biotech commodity (Hu *et al*., 2024), its commercial prospects have been increased by including C. militaris into functional foods, drinks, and pharmaceutical supplements (Chou *et al*., 2024).

**Conclusion**

Ultimately, this study emphasizes the vital need of cultivation media optimization and accuracy cultivation systems in improving the therapeutic, financial, and commercial value of Cordyceps militaris. Cordycepin and polysaccharide production have been clearly boosted by the strategic application of multi-grain and agro-waste substrates together with plant extract enrichments and focused mineral supplementation. Further optimizing bioactive metabolite yields are technological developments in submerged fermentation parameters and elicitor applications. Promising paths for high-yield, consistent production strains are biotechnological interventions including mutagenesis, genetic modification, and omics-integrated metabolic modelling. Notably, predictive, resource-efficient, and scalable cultivation models have been made possible by the integration of artificial intelligence, Internet of Things, and real-time environmental sensors.
The industrial potential of C. militaris will be greatly increased by the evolution of AI-integrated automated cultivation units, bio-waste valorization ideas, and synergistic uses of plant bio actives and nanoparticles. Pathway optimization and strain improvement using genomic technologies will remain to be a transforming force in guaranteeing high-value, commercially viable, and sustainable C. militaris production systems able to satisfy the rising worldwide need for functional foods, pharmaceuticals, and bioactive therapeutics.

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