



Technological Advancements and Future Prospects in Modern Mushroom Production: A Review

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ABSTRACT

Mushroom cultivation has emerged as a highly sustainable agricultural enterprise, capable of converting agro-industrial waste into nutritious food while simultaneously generating rural employment and income. Recent advancements have transformed traditional, low-input cultivation methods into technology-driven, precision systems. This evolution is characterised by substrate optimisation, controlled-environment cultivation, mechanisation, artificial intelligence (AI), Internet of Things (IoT)-based monitoring, high-efficiency spawn production, and modern post-harvest technologies. These innovations have significantly enhanced productivity, quality, and year-round production capabilities while mitigating contamination risks and labour dependencies. India ranks among the world's leading mushroom-producing countries, with production steadily increasing as consumer awareness of mushrooms' nutritional and medicinal values grows. Looking forward, modern technologies such as climate-controlled growing rooms, vertical farming systems, liquid spawn technology, automated environmental controls, and biofortification are poised to revolutionise the global mushroom industry.

Keywords: Artificial Intelligence, Controlled-Environment Cultivation, Mushroom Cultivation, Spawn Technology, Substrate Optimisation, Technological Advancements

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1. INTRODUCTION

Mushrooms are highly nutritious, macro-fungi rich in proteins, vital vitamins, minerals, dietary fibre, antioxidants, and unique bioactive compounds. Consequently, they play an essential role in global food security, human nutrition, environmental sustainability, and agricultural waste management (Thakur *et al.*, 2025). Unlike conventional agronomic crops, mushrooms do not require fertile soil and can be cultivated directly on lignocellulosic agricultural residues, such as paddy straw, wheat straw, sugarcane bagasse, sawdust, and various industrial

by-products, thereby upcycling wastes into high-value food products (Thakur *et al.*, 2025).

The contemporary mushroom industry is rapidly evolving from traditional, seasonal, low-input systems into advanced, technology-based commercial operations. Modern mushroom farms increasingly employ automated climate-control systems, real-time sensor-based monitoring, multi-tier vertical farming structures, optimised substrates, and AI-assisted production management to maximise biological efficiency, yield, and overall profitability (Fareed *et al.*, 2026).

2. IMPORTANCE OF MODERNISATION IN MUSHROOM PRODUCTION

The modernisation of mushroom cultivation infrastructure offers several clear advantages over traditional production systems. Improved substrate preparation, controlled-environment cultivation, and better crop-management practices enhance biological efficiency by increasing mushroom yield per unit of dry substrate (Fareed *et al.*, 2026). Modern systems also improve the physical appearance, nutritional quality, uniformity, and post-harvest shelf life of mushrooms, which strengthens their market value and consumer acceptability (Fareed *et al.*, 2026). In addition, the use of hygienic production units, automated monitoring, and regulated environmental conditions helps reduce pathogen contamination and associated crop losses. Climate-controlled facilities further enable consistent year-round production by reducing dependence on seasonal weather conditions. Mechanisation and automation also lower labour requirements and improve operational precision, particularly in substrate handling, environmental regulation, harvesting, and packaging. Moreover, modern infrastructure promotes more efficient use of water, energy, and substrate resources, thereby contributing to the long-term sustainability and profitability of mushroom cultivation (Fareed *et al.*, 2026).

3. MAJOR TECHNOLOGICAL ADVANCES IN MUSHROOM PRODUCTION

3.1. Advanced Substrate Optimisation Technologies

Because the substrate serves as the primary nutrient and moisture source for mycelial growth, recent research has focused intensely on improving substrate quality. This is achieved via precise nutrient supplementation and the strategic utilisation of novel agricultural and industrial by-products (Fareed *et al.*, 2026).

Table 1. Modern Substrates and Supplementation Strategies

Substrate	Supplement
Rice straw	Wheat bran
Sugarcane bagasse	Soybean meal
Sawdust	Wheat bran
Corn cobs	Rice bran
Compost + casing soil	Gypsum + bran

Source: Fareed *et al.* (2026)

Key innovations in substrate preparation have improved the efficiency, consistency, and sustainability of modern mushroom cultivation.

Biological pretreatment with selected microbial inoculants accelerates lignin degradation and improves substrate digestibility for mycelial colonisation. Fermentation-based conditioning, particularly through improved Phase II and Phase III composting, enhances the selective availability of nutrients while suppressing undesirable microorganisms. Nutrient enrichment through the precise addition of organic and inorganic supplements further supports vigorous mycelial growth and improves subsequent flush performance. In addition, the use of agro-industrial residues, including spent coffee grounds, crop by-products, and urban organic wastes, has expanded the range of usable substrates and strengthened the role of mushroom cultivation in waste recycling and circular bioeconomy systems (Fareed *et al.*, 2026).

3.2. Improved Spawn Production Technologies

Spawn quality is a primary determinant of mushroom productivity and crop uniformity. Significant advancements have been made in commercial spawn production, moving away from rudimentary grain techniques toward liquid culture systems, advanced filter technology, automated sterilisation, and high-throughput commercial laboratories (Thakur *et al.*, 2025).

Table 2: Recent Advances in Spawn Production

Technology	Primary Benefits
Grain spawn	Highly reliable, standardised, and widely adopted by smallholders.
Liquid spawn	Accelerates mycelial colonisation and reduces incubation time.
Polypropylene filter bags	Improves gas exchange while significantly reducing contamination risks.
Automated laboratories	Enables large-scale, high-throughput, and uniform production.
Quality-controlled cultures	Ensures genetic stability and consistent, high-yielding performance.

Source: Thakur *et al.* (2025)

3.3. Controlled-Environment Cultivation

The development of controlled-environment agriculture (CEA) represents one of the most significant technological breakthroughs in the mushroom industry. Crucial environmental parameters can now be precisely regulated around the clock using automated control loops (Fareed *et al.*, 2026). Modern commercial mushroom cultivation facilities increasingly rely on advanced infrastructure to maintain precise, stable growing conditions. Smart climate-controlled cropping rooms enable continuous

regulation of temperature, relative humidity, carbon dioxide concentration, light, and ventilation based on crop stage. High-precision modular growth chambers provide greater control over microclimatic conditions and are particularly useful for research, spawn testing, and small-scale intensive production. Automated commercial greenhouses combine protected cultivation with sensor-based environmental control, making them suitable for semi-intensive and commercial production systems. Fully indoor multi-tier vertical farms further improve space-use efficiency by arranging production units in stacked layers, enabling high productivity per unit area and supporting year-round cultivation under controlled conditions.

Table 3. Critical Environmental Parameters in Mushroom Production

Parameter	Physiological Importance
Temperature	Dictates vegetative mycelial growth and triggers primordial (pinhead) initiation.
Humidity	Prevents substrate desiccation and supports optimal fruit-body development.
CO ₂ Level	Directly influences mushroom morphology (e.g., cap diameter vs. stalk length).
Light	Essential for certain species to stimulate primordial formation and pigmentation.
Airflow Ventilation	Regulates fresh air exchange, flushes out excess CO ₂ , and minimises mould growth.

Source: Fareed *et al.* (2026)

3.4. Internet of Things (IoT) and Smart Farming

The integration of the Internet of Things (IoT) has significantly improved the precision and responsiveness of modern mushroom cultivation systems. IoT-enabled sensor networks enable real-time, remote monitoring of critical microclimatic parameters, including ambient temperature, relative humidity, carbon dioxide concentration, and substrate moisture. These sensors continuously transmit data to automated microcontrollers or cloud-based platforms, which can regulate heating, ventilation, air conditioning, misting, and fogging systems according to crop requirements. Such sensor-based automation helps maintain uniform growing conditions, improves crop consistency, reduces manual supervision, and minimises the risk of environmental stress during different stages of mushroom development. IoT applications also support continuous monitoring through mobile or cloud dashboards, automated

climate adjustment, data-driven decision-making, and early detection of abnormal conditions that may indicate contamination, equipment failure, or disease outbreaks. Therefore, IoT-based smart farming has become an important tool for improving productivity, resource-use efficiency, and operational reliability in commercial mushroom production (Fareed *et al.*, 2026).

3.5. Artificial Intelligence and Automation

Artificial Intelligence (AI) and Machine Learning (ML) are increasingly being integrated into commercial mushroom farms to improve production accuracy, decision-making, and operational efficiency. AI-based systems can support growth prediction by tracking mycelial colonisation, pinhead formation, and successive flush cycles, thereby helping growers plan irrigation, ventilation, harvesting, and marketing operations more effectively. Machine learning models can also assist in yield forecasting by analysing environmental data, crop images, substrate conditions, and previous production records, thereby improving supply planning and reducing market mismatches. In disease management, computer-vision tools can help detect early symptoms of weed moulds, bacterial blotch, and other abnormalities before they spread widely across the crop. AI-driven environmental optimisation further enables automatic adjustment of climate setpoints such as temperature, humidity, carbon dioxide concentration, and airflow to maintain favourable growing conditions while improving energy efficiency. In addition, automated resource-management systems allow continuous tracking of inputs, labour, crop performance, and production losses. Thus, the application of AI and ML in mushroom cultivation can strengthen precision management, reduce production risks, and enhance profitability in commercial production systems.

3.6. Vertical Farming Technology

Vertical farming systems have become an important innovation in modern mushroom production because they maximise biological output within a limited physical area. These systems use multi-tier, vertically stacked growing racks inside controlled indoor facilities, allowing growers to increase production volume without requiring large areas of agricultural land. By maintaining localised control over temperature, humidity, carbon dioxide concentration, airflow, and light, vertical farms provide a stable microclimate for uniform mycelial growth and fruiting. They also improve resource-use efficiency by optimising space, water, energy, and labour inputs. This approach is particularly useful in urban and peri-urban areas, where land availability is

limited but demand for fresh mushrooms is high. Therefore, vertical farming offers strong potential for scalable, year-round mushroom production with higher productivity per unit area and better control over crop quality.

3.7. Mechanisation and Automation

Industrial-scale mechanisation has substantially improved operational efficiency, product uniformity, and process reliability in modern mushroom production facilities. Mechanised systems are now used for bulk raw material mixing, Phase I, Phase II, and Phase III compost preparation, automated substrate bagging, block pressing, and bottle-filling operations. Continuous-flow steam sterilisation tunnels further improve hygiene and reduce contamination risks by ensuring uniform sterilisation of substrates and production materials. In addition, computerised environmental monitoring systems and automated harvesting, sorting, packaging, and weight-handling lines help reduce manual errors, improve labour efficiency, and maintain consistent product quality. These technologies are particularly important in large-scale commercial units where production volume, hygiene standards, and market uniformity must be maintained continuously. As a result, countries with advanced mushroom industries have increasingly adopted mechanised production frameworks to address rising labour costs, improve operational precision, and ensure standardised mushroom quality across production batches (Thakur *et al.*, 2025).

3.8. Post-Harvest and Value-Addition Technologies

Mushrooms are highly perishable because they lack a protective cuticle and have high respiration and moisture loss rates after harvest. Therefore, advanced post-harvest management is essential for preserving freshness, nutritional quality, market appearance, and export suitability. Integrated cold-chain systems, including immediate vacuum precooling and refrigerated transport, help slow physiological deterioration and microbial spoilage. Packaging technologies such as Modified Atmosphere Packaging (MAP), Equilibrium Modified Atmosphere Packaging (EMAP), and high-barrier vacuum packaging reduce respiration rate, moisture loss, and quality deterioration during storage and distribution. Advanced freeze-drying or lyophilisation is also useful for retaining bioactive compounds and producing shelf-stable mushroom products. In addition, value-added processing into high-protein mushroom powder, vitamin D-fortified mushroom slices, ready-to-cook products, and ready-to-eat mushroom-based foods can diversify market

opportunities and reduce post-harvest losses. These interventions collectively improve shelf life, enhance consumer acceptability, and expand the commercial and export potential of mushroom products (Thakur *et al.*, 2025).

4. CURRENT STATUS OF MUSHROOM PRODUCTION IN INDIA

India's mushroom sector is experiencing robust growth, with annual production reaching approximately 0.33 million tonnes, solidifying its position among the world's leading producers (Thakur *et al.*, 2025). The market relies heavily on specific species, though diversification is underway.

Table 4: Market Share of Major Mushroom Species in India

Mushroom Species	Scientific Name	Market Share (%)
Button mushroom	<i>Agaricus bisporus</i>	70
Oyster mushroom	<i>Pleurotus</i> spp.	17
Paddy straw mushroom	<i>Volvariella volvacea</i>	9
Milky mushroom	<i>Calocybe indica</i>	3
Others (Shiitake, Medicinal, etc.)		1

To further accelerate the growth of mushroom production in India, national research institutions such as the ICAR-Directorate of Mushroom Research and government agencies such as the National Horticulture Board are promoting technological upgrading across the production and value-chain system. Important interventions include adopting fully pasteurised, ready-to-spawn Phase III computerised bulk compost, which can improve substrate uniformity, reduce contamination, and support commercial-scale production. Greater emphasis is also being placed on highly automated, contaminant-free spawn production facilities to ensure the availability of high-quality planting material. Breeding programmes and strain improvement efforts are contributing to the development of high-yielding, temperature-tolerant mushroom varieties suitable for diverse agroclimatic regions. In addition, precision climate-controlled cropping rooms are being promoted to enable year-round cultivation, particularly in plains where seasonal temperature variation often limits production. Modern processing hubs and decentralised cold-chain infrastructure are also essential for reducing post-harvest losses, improving market access, and strengthening the competitiveness of the Indian mushroom sector (Thakur *et al.*, 2025).

5. CHALLENGES IN TECHNOLOGY ADOPTION

Despite the considerable advantages of modern technologies in mushroom production, their widespread adoption is still constrained by several socio-economic and technical challenges. Establishing automated, climate-controlled cultivation systems requires a high initial capital investment, which may be difficult for small- and medium-sized growers to afford. In addition, continuous operation of heating, ventilation, air conditioning, and sterilisation units, as well as other controlled-environment systems, can lead to substantial energy costs. Another major limitation is the shortage of technically skilled personnel, including specialised mushroom agronomists, who can manage advanced production systems, diagnose crop problems, and maintain equipment efficiently. Biological risks also remain significant, as contamination by competing moulds, bacteria, viruses, and other pathogens can cause serious crop losses even in modern facilities. In many regions, growers still face inconsistent access to high-quality, genetically pure commercial spawn, which affects crop uniformity and yield stability. Weak rural cold-chain infrastructure further contributes to post-harvest losses and distress selling, especially because fresh mushrooms are highly perishable. Moreover, volatile market prices and poorly organised marketing channels reduce profitability and discourage investment in improved technologies. Therefore, technology adoption in mushroom cultivation requires not only improved infrastructure but also affordable financing, skill development, reliable spawn supply, stronger cold-chain systems, and better market organisation (Fareed *et al.*, 2026).

6. FUTURE PROSPECTS

The future of the global mushroom industry is expected to be shaped by the convergence of biotechnology, digital agriculture, automation, and environmental engineering. Over the next decade, mushroom production systems are likely to move toward AI-driven precision agriculture, where autonomous cropping units use neural networks and real-time sensor data to regulate growth conditions, predict crop performance, and reduce production risks. Advanced automation, including robotic harvesting supported by computer vision, may further improve harvesting accuracy by identifying mushrooms of suitable cap size, maturity, and quality. Next-generation substrates are also expected to play an important role, particularly through engineered and highly selective formulations that shorten incubation periods, improve biological efficiency, and

reduce contamination. Nutritional biofortification offers another promising direction, as mushrooms can be enriched with vitamin D₂, selenium, zinc, and functional medicinal compounds to meet growing consumer demand for health-promoting foods. In addition, circular bioeconomy models may integrate mushroom farms with bioenergy units and agro-industrial waste streams, allowing better recycling of residues and reducing environmental burdens. The development of myco-materials from spent mushroom substrate and mycelial networks also presents new opportunities for producing biodegradable packaging, vegan leather, and eco-friendly construction materials. These future prospects indicate that mushroom cultivation is likely to expand beyond food production into nutrition, biotechnology, waste management, and sustainable material industries (Fareed *et al.*, 2026; Thakur *et al.*, 2025).

7. CONCLUSION

Modernisation and the integration of cutting-edge technologies have successfully elevated mushroom cultivation from a seasonal, backyard hobby into a highly efficient, industrialised, and sustainable agro-enterprise. Innovations spanning substrate optimisation, automated spawn preparation, controlled-environment agriculture, IoT, AI, and sophisticated post-harvest protocols have collectively amplified productivity, product quality, and farm profitability. To sustain this momentum, continued public and private investment in targeted research, rural infrastructure development, and proactive technology-transfer mechanisms will be essential. Harnessing these advancements will be indispensable for securing global food security, mitigating environmental waste, and driving rural employment and economic development worldwide.

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