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Popular Article

Innovative Approaches for Mushroom Production: Harnessing Technology for Sustainability

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Mushrooms, those delectable and versatile fungi, are not just a culinary treat but also a potential powerhouse for sustainable food production. Unlike resource-intensive crops like meat and vegetables, mushrooms require minimal space, water and nutrients to thrive. This makes them a promising alternative in a world grappling with climate change, land scarcity and food insecurity. Mushroom cultivation has witnessed a paradigm shift in recent years, with a growing emphasis on sustainable practices that not only boost yields but also minimize environmental impact. Conventional mushroom cultivation practices often have their own environmental drawbacks. As the demand for mushrooms continues to rise, it becomes imperative for the industry to adopt eco-friendly production methods. This article explores the advancements in sustainable mushroom cultivation, highlighting next-generation solutions that prioritize environmental stewardship.

Traditional mushroom cultivation often relies on:

1. **Logging:** Massive deforestation to clear land for growing mushrooms on logs.
2. **Pesticides and fungicides:** Heavy use of chemicals to control pests and diseases, contaminating the environment and posing health risks.
3. **Energy-intensive processes:** High energy consumption for heating, cooling and ventilation in large-scale farms.

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4. **Waste generation:** Spent substrate, the material mushrooms grow on, often ends up in landfills, contributing to methane emissions.

Innovative approaches and good cultivation practices for sustainable mushroom cultivation, offering a glimpse into a future of eco-friendly mushroom production:

1. **Recycling agricultural waste:** One of the key challenges in sustainable mushroom cultivation is the efficient management of agricultural waste. Next-gen solutions involve recycling various forms of waste, such as straw, corn cobs and agricultural residues, to create growing substrate materials for mushroom cultivation (Aditya & Jarial, 2023). Replacing wood with recycled agricultural waste like coffee grounds, sugarcane bagasse, pine needles, curry leaves or even cardboard as the substrate (Aditya et al., 2022a). This not only reduces deforestation but also gives new life to waste materials. This approach not only reduces waste disposal issues but also provides a cost-effective and environmentally friendly source of nutrients for mushroom growth (Fig. 1).
2. **Myco-remediation:** Utilizing mushrooms natural ability to break down pollutants to clean up contaminated soil and water. Oyster mushrooms can be used to remediate oil spills, while shiitake mushrooms can help remove heavy metals from soil (Adenipekun & Lawal, 2012).
3. **Vertical farming and Controlled Environment Agriculture (CEA):** Vertical farming is gaining traction as a sustainable solution in the mushroom cultivation sector. Using growing beds in a vertical stack maximises both resource efficiency and space utilisation. Combined with CEA, which involves precise control over factors like temperature, humidity and light, vertical farming ensures year-round production while minimizing energy consumption and waste (Web reference: www.icar.gov.in).
4. **Renewable energy integration:** The mushroom cultivation industry is increasingly incorporating renewable energy sources to power farms. Solar panels, wind turbines and biomass systems are being utilized to generate clean energy, reducing dependence on conventional power sources. This shift not only lowers the carbon footprint but also contributes to long-term cost savings for mushroom farmers (Web reference: www.dmrsolan.icar.gov.in).
5. **Organic farming practices:** Traditional mushroom cultivation often involves the use of synthetic fertilizers and pesticides. However, the latest trend in sustainable mushroom

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farming leans heavily towards organic practices. Organic farming relies on natural inputs, such as organic matter to enrich the compost quality and promote healthy mushroom growth. This not only reduces the environmental footprint but also produces mushrooms free from harmful chemical residues (Web reference: www.icar.gov.in).

6. **Water conservation technologies:** Water scarcity is a global concern and sustainable mushroom cultivation addresses this issue by implementing advanced water conservation technologies. Drip irrigation systems, moisture sensors and rainwater harvesting are being employed to optimize water usage and minimize wastage. By adopting these technologies, mushroom farmers can ensure a more sustainable and eco-friendly approach to water management (Web reference: www.icar.gov.in; www.dmrsolan.icar.gov.in).
7. **Biodegradable packaging:** The sustainability of mushroom production extends beyond the cultivation process to packaging. Next-gen solutions involve the use of biodegradable and compostable packaging materials, reducing reliance on single-use plastics. Mushroom farms are exploring innovative packaging options derived from materials like mushroom mycelium, cornstarch and other plant-based polymers, ensuring a closed-loop system that minimizes environmental impact (Mojumdar et al., 2021).
8. **Mycelium-based products:** Mycelium, the root-like structure of mushrooms, is a versatile and eco-friendly material that goes beyond substrate use. Researchers and entrepreneurs are exploring mycelium-based products as alternatives to traditional materials. From packaging materials to construction components, mycelium's unique properties make it a sustainable and biodegradable resource with a wide range of applications (Mojumdar et al., 2021).
9. **Precision agriculture and Internet of Things (IoT):** The integration of precision agriculture and IoT technologies is transforming mushroom farming. Sensors and monitoring devices provide real-time data on environmental conditions, allowing farmers to optimize resource usage and detect issues before they escalate. This not only improves efficiency but also minimizes resource wastage, contributing to the overall sustainability of mushroom cultivation. Employing sensors and IoT technology to monitor environmental conditions in real-time, allowing for precise adjustments and minimizing resource waste. Using data analytics to optimize growing parameters like temperature, humidity and CO_2 levels for increased yields and reduced environmental impact (Rukhiran et al., 2023).

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10. **Community and stakeholder engagement:** Sustainable mushroom cultivation goes beyond technological advancements, it involves fostering a sense of community and collaboration. Next-gen solutions include initiatives that promote local engagement, fair labor practices and ethical sourcing. By involving local communities in the cultivation process and ensuring fair wages and working conditions, the mushroom industry can contribute to social sustainability while minimizing its environmental impact (Web reference: www.icar.gov.in).
11. **Mycological innovations:** Genetic engineering for developing fungus strains with enhanced resistance to pests and diseases, reducing reliance on chemical control methods. Bioprinting uses 3D bioprinting technology to create customized mushroom-growing substrates, potentially leading to even more efficient and sustainable production (Ashmarina et al., 2021).

The adoption of these next-gen solutions offers a multitude of benefits:

1. **Reduced environmental impact:** Less deforestation, water usage and energy consumption contribute to a smaller carbon footprint for the mushroom industry (Aditya et al., 2022b; Aditya et al., 2023).
2. **Improved food security:** Increased mushroom production can provide a nutritious and protein-rich food source, especially in regions facing food shortages (Aditya et al., 2022c).
3. **Circular economy:** Waste-to-wealth approaches and myco-remediation promote a circular economy, minimizing waste and maximizing resource utilization.
4. **Economic opportunities:** Sustainable mushroom cultivation can create new jobs in rural and urban areas, boosting local economies.

Challenges and opportunities:

While the potential of next-gen mushroom cultivation is undeniable, there are still challenges to overcome. Research and development in areas like genetic engineering and bioprinting require further investment. Additionally, consumer awareness and education about sustainable mushroom production practices are crucial to driving market demand for eco-friendly options. Despite these challenges, the future of mushrooms is bright. With continued innovation, collaboration and consumer support, the next generation of mushroom cultivation can play a significant role in building a more sustainable and food-secure future.

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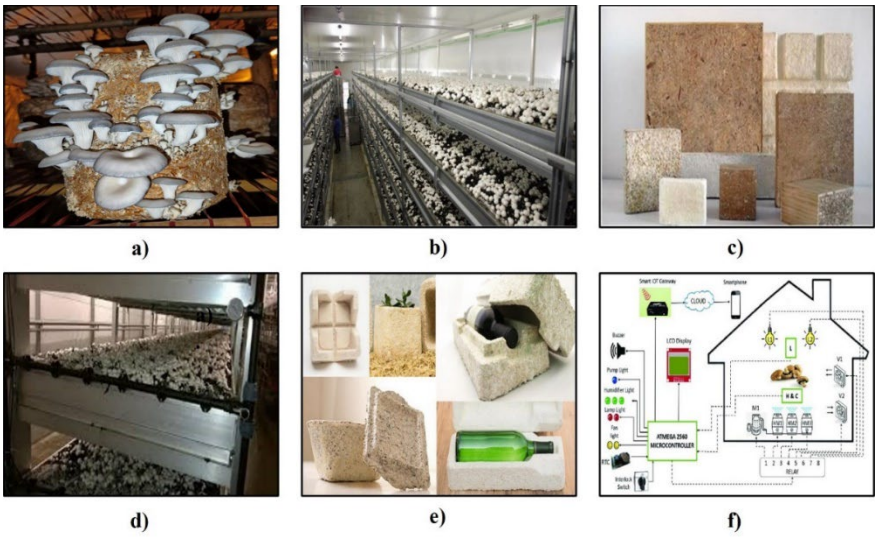

Figure 1. Innovative approaches for sustainable mushroom cultivation; **a).** Elm oyster mushroom (*Hypsizygus ulmarius*) grown on agricultural crop residue (wheat straw) for production of proteinaceous rich superfood by recycling and reuse of waste materials; **b).** Vertical farming of white button mushroom (*Agaricus bisporus*) utilising vertical space for more production and maximising resource efficiency; **c).** Environmentally friendly mycelium-based blocks and bricks prepared from *A. bisporus* and Reishi mushroom (*Ganoderma lucidum*) alternative to traditional building materials; **d).** Use of drip and fogger to maintain optimum moisture and relative humidity for water conservation and quality mushroom production; **e).** Biodegradable packaging materials prepared from mushroom mycelium ensuring and reducing reliance on single-use plastics; **f).** Smart mushroom production technology model by using IoT.

Conclusion

Globally mushrooms are perceived as a versatile resource that holds promise for addressing issues related to human health, food security and environmental pollution. Mushrooms are rich in carbohydrates, protein, fibre, fats, lipids and vitamins, which contribute to enhancing human health, particularly in regions with limited access to nutritious food grains. Conversely, mushrooms have the potential to help address the issue of food security in the face of climate change. The issue pertains to the accessibility of food for populations residing in developed, developing and impoverished nations. In this problem, the mushroom is an optimal solution due to its efficient production in a compact space and at a low cost. The cultivation of edible

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mushrooms can be a valuable process due to their ability to efficiently convert waste from industries and agriculture into nutritive foods. Therefore, mushrooms are highly effective in converting different forms of waste through their enzymatic activity in the mycoremediation process, which is an innovative solution for waste decomposition. As the world grapples with environmental challenges, the mushroom cultivation industry is embracing next-generation solutions for sustainable and eco-friendly production. From organic farming practices to renewable energy integration and mycelium-based innovations, these advancements are reshaping the way mushrooms are cultivated. By adopting these practices, mushroom farmers not only meet the growing demand for their produce but also contribute to a more sustainable and resilient agricultural future. The convergence of technology, innovation, and environmental consciousness marks a promising era for sustainable mushroom cultivation, ensuring a greener and healthier planet for generations to come.

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