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ECONOMIC AND TECHNOLOGICAL ASPECTS OF HYDROPONIC SYSTEMS IN MUSHROOM CULTIVATION TOWARDS PRECISION AGRICULTURE

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ABSTRACT

In this review, we provide an exhaustive economic and environmental analysis of hydroponic and arenumponic systems within the domain of mushroom cultivation, contrasting these modern methodologies with the traditional substrate-based approaches. Our focus is centered on widely cultivated mushrooms such as Oyster, Button, Shiitake, and Morels. We delve into the inherent challenges posed by conventional cultivation methods, such as variable substrate quality, heightened risks of contamination, and the complexities of environmental control. The study presents hydroponics and arenumponics as innovative, substrate-less cultivation strategies that resolve these issues by employing controlled water solutions and sand as a growth medium, respectively. This review examines a spectrum of hydroponic configurations, including deep flow, nutrient film, and aeroponic systems, demonstrating their effectiveness and potential in mushroom farming. We emphasize the economic feasibility and environmental sustainability of these techniques, considering their cost-effectiveness, resource utilization efficiency, and market prospects. Key objectives encompass a thorough review of hydroponic technologies, an evaluation of growth performance vis-à-vis traditional methods, and an assessment of their economic impact. Our research bridges current knowledge gaps by suggesting the integration of recommended economic models, such as Stochastic Frontier Analysis for measuring efficiency, and Cost-Benefit Analysis for assessing financial viability. The inclusion of case studies enriches our insights into the economic and environmental facets of hydroponic/arenumponic mushroom cultivation. We conclude with policy recommendations and directions for future research, advocating for the adoption of hydroponics/arenumponics as sustainable, efficient, and commercially viable alternatives to conventional practices in mushroom agriculture, thereby aligning with the objectives of modern agricultural sustainability.

Keywords: Hydroponic Mushroom Farming, Arenumponic Cultivation Technique, Soilless Mushroom Production, Economic Viability, Precision Agriculture.

INTRODUCTION

Mushrooms, known for their low-fat content, high protein, metabolites, antioxidants, and fiber, offer a range of health benefits, including boosting immunity, enhancing cognitive health, and regulating blood lipids and glucose levels. As a critical sector in the global agro-industry, mushroom cultivation generates over US $34 billion annually. Common varieties like Oyster (*Pleurotus spp*.), Button (*Agaricus spp*.), Shiitake (*Lentinula edodes*), and Morels (*Morchella spp*.) have traditionally been grown on substrates like straw, composts, and wood logs. However, traditional methods face challenges such as low yields, nutrient deficiencies, and contamination risks, exacerbated by land fragmentation and urbanization.

This paper explores hydroponics and suggests a novel approach called arenumponics as a potential solution to these challenges. Hydroponics, a soilless, substrate-less cultivation technique using nutrient-rich water solutions, offers precise nutrient and moisture control, potentially increasing efficiency, and yield. However, traditional hydroponics still requires some form of organic substrate for mushroom mycelium, which acts as a binding and support medium. To address this, we propose arenumponics, where sand replaces organic substrates, providing both support and an inert medium for nutrient delivery for future research and studies.

Our study aims to fill several gaps in current research. Firstly, we will detail specific challenges and limitations of hydroponics in mushroom cultivation, providing a clearer understanding of why these methods are necessary. We will also place our research within the historical context of mushroom cultivation, tracing its evolution and highlighting how hydroponics emerged as innovative alternatives. Additionally, we will compare this method with other emerging cultivation techniques, offering a comprehensive view of the field's advancements.

The article analyzes hydroponic methods in mushroom farming, comparing them to traditional techniques and also focuses on their environmental and economic benefits, particularly regarding sustainability, resource efficiency, and cost-effectiveness. The scope includes a thorough review of hydroponic designs, growth performance comparison, and economic viability suggesting the use of models like Stochastic Frontier Analysis and Cost-Benefit Analysis for further research. The study sets out hypotheses aiming to prove that these soilless or inert substrate methods can enhance productivity and offer a viable commercial alternative to conventional cultivation, to contribute to sustainable agricultural practices.

Objectives

Overview of Hydroponic Techniques: Provide a detailed overview of various hydroponic methods, such as deep flow, nutrient film technique, and aeroponics, emphasizing their operational aspects and suitability for cultivating mushrooms like Oyster, Button, Shiitake, and Morels.
Comparative Growth Analysis: Analyze and compare the growth performance between hydroponic (including arenumponics) and traditional substrate-based cultivation methods. This will include assessments of mycelial colonization rate and yield, demonstrating enhanced performance in hydroponic systems.
Advantages of Hydroponics: Discuss the potential benefits of hydroponic systems over conventional cultivation. The article will emphasize improvements in mushroom quality and productivity due to precise control over nutrients and environmental conditions.
Environmental and Economic Impact Assessment: Evaluate the environmental sustainability and economic viability of hydroponic methods based on existing literature.
Empirical Methodology: Suggest implementation of econometric models for financial viability, providing insights into the economic aspects of hydroponic mushroom cultivation.

These objectives will be addressed comprehensively, contributing to a better understanding of the potential of hydroponic methods in enhancing the efficiency and sustainability of mushroom production.

1. MUSHROOM BIOLOGY

In exploring hydroponic and arenumponic methods for mushroom cultivation, it's crucial to understand the mushroom life cycle, comprising the vegetative mycelial and the reproductive fruiting body phases. Mycelial growth depends on key macronutrients such as Carbon (C), Nitrogen (N), Phosphorus (P), Potassium (K), and Magnesium (Mg), alongside vital micronutrients like Iron (Fe) and Zinc (Zn) (Carrasco et al., 2018). These nutritional needs and environmental factors such as the carbon-to-nitrogen ratio, temperature, pH, and aeration are pivotal in hydroponic systems (Wu et al., 2004; Jayasinghe et al., 2008). This understanding is essential to our research objectives, guiding the optimization of hydroponics and arenumponics for enhanced mushroom growth and yield.

2. CONVENTIONAL CULTIVATION METHODS

Conventional mushroom farming predominantly utilizes organic substrates like rice bran, wheat straw, various cotton wastes, and animal manures, essential for both vegetative and mycelia growth (Fasidi et al., 2016). This traditional method encompasses several steps: substrate preparation, spawn inoculation, and maintaining fruiting room conditions. The entire process, from substrate preparation to harvesting, spans 10 days to 6 months post-spawning (Chang, 2001).

The preparation of substrates involves a meticulous process. Initially, substrates are mixed, hydrated, pasteurized, sterilized, and conditioned. Composting, a critical phase in substrate preparation, typically occurs in two stages. The first phase primarily focuses on reducing the carbon-to-nitrogen (C:N) ratio, while the second phase involves pasteurization, crucial for eliminating competitive microorganisms and maintaining the moisture content of the substrate at approximately 70% (Lim et al., 2013).

Spawn, a vital component in mushroom cultivation, is prepared by inoculating sterilized grains, such as millet or wheat, with mycelium cultures. This spawn provides the necessary nutrition for the mycelium to colonize the substrate. The addition of spawn, typically ranging from 0.5% to 5% of the substrate's weight, is known to enhance yields (Buendia et al., 2016). The inoculated substrate is then placed in growth environments, such as beds, racks, or trays, where controlled conditions are maintained. Ideal temperatures for mycelium colonization range from 22–28°C, with relative humidity kept between 80-90%, ensuring adequate moisture for growth (Flegg, 1979).

Adequate air exchange within the growing environment is essential to remove accumulated CO_2, thus providing sufficient oxygen for optimal mushroom growth. Under these conditions, mushrooms typically reach a harvestable size within 10-15 days (González-Fandos et al., 2008, Cheng et al., 2013).

However, recent literature indicates gaps in traditional cultivation methods, particularly regarding the efficient use of resources and environmental sustainability. Innovations in substrate optimization and the development of less resource-intensive cultivation practices are areas needing further exploration.

3. CHALLENGES IN CONVENTIONAL MUSHROOM FARMING

3.1. Substrate Quality Issues: Traditional cultivation often relies on agricultural residues and waste as substrates, which can vary in quality. Poor-quality substrates may lead to nutrient deficiencies, adversely affecting mushroom yields along with contamination risks (Ferdousi et al.)

3.2. Contamination Risks: The process of sterilization is crucial in conventional methods. Such contamination can lead to outbreaks of fungal, viral, and microbial diseases, affecting mushroom growth and development (Ferdousi et al., 2019; Easin et al., 2017).

3.3. Toxicity: In cultivated mushrooms, significant levels of heavy metals were found, with the highest concentrations being: Pb in *Agaricus bitorquis* and *Hypholoma fasciculare*, Cd in *Hydnum repandum*, Fe in *Bovista plumbea*, Cu in *Tricholoma terreum*, Mn in *Laccaria laccata*, and Zn in *Agaricus bitorquis* (Tüzen et al., 1998;Yamaç et al., 2007). Additionally, hydroponics allows precise control of nutrient ratios ensuring safe mushroom cultivation (Asaduzzaman et al., 2022).

3.4. Insufficient Environmental Control: Conventional cultivation often lacks the infrastructure for precise environmental control. These inadequacies like temperature, light quality and periods, humidity, and O_2/CO_2 ratio, essential for optimal mushroom development affect critical growth parameters (Rahman, 2018; Ferdousi et al., 2019, Ferdousi et al., 2019).

3.5. Resource Inefficiency: Post-harvest, a significant portion of the nutrients in the substrate remain unutilized, leading to waste (Grimm et al., 2018). Small-scale farmers, particularly those with limited capital, often cannot fully utilize available resources, including land and infrastructure. Moreover, the reuse of spent compost can carry the risk of disease transmission between crops (Gurung et al., 2020).

4. HYDROPONIC SYSTEMS FOR MUSHROOM CULTIVATION

4.1 Deep Flow Technique (DFT): DFT supports mushrooms on floating rafts in an aerated nutrient solution. This technique has been shown to enhance mycelial colonization by about 25% and increase yields by up to 123% compared to soil-based cultivation, particularly with oyster mushrooms, marking a significant advancement over conventional methods (Gume et al., 2013).

4.2 Nutrient Film Technique (NFT): In NFT, a thin layer of nutrient solution continuously flows over the roots in a slightly inclined channel. This system has proven effective in boosting the total biomass of mushrooms, producing around 427g total weight, with 309g being edible, thus offering a substantial improvement over traditional cultivation practice (Re et al., 2021).

4.3 Aeroponics: Aeroponics involves spraying a fine mist of nutrient-rich water directly onto the suspended mushroom roots. This method promotes optimal growth and development by speeding up mycelial colonization and shortening the cultivation cycle. It also enhances the oxygenation of roots, improving nutrient absorption and overall mushroom health, making it a valuable technique in modern mushroom farming (Narasegowda et al., 2020; Grace 2023).

Additionally, innovative approaches like floating rafts and nutrient-channeled plastic bottle systems have yielded promising results, particularly for oyster mushrooms (Goh et al., 2016).

5. NUTRIENT SOLUTIONS IN HYDROPONIC MUSHROOM CULTIVATION

5.1. Macronutrients: Key carbon sources such as sucrose, glucose, and dextrose are used at optimal concentrations, alongside organic nutrients like yeast extract and peptone. Nitrogen, a crucial macronutrient, is often supplied in the range of 0.1-0.5% using urea, ammonium salts, or other nitrogenous extracts in submerged cultures (Mccoy et al., 1972). The ideal ratio of carbon to nitrogen is critical; for instance, a composition of 3% glucose, 0.072% KNO3, and 0.02% NaH2PO4, maintaining a pH of around 8.5, is found to be effective for mushroom growth (Chang-hong 2008).

5.2. Micronutrients: While required in smaller quantities, micronutrients such as potassium, calcium, magnesium, sulfur, iron, zinc, manganese, and copper play significant roles in the growth and quality of mushrooms (Jung et al., 2010). Calcium supplementation is crucial for maintaining the pH balance and cation exchange in the substrate. Studies have also highlighted the importance of freshly prepared compost, rich in zinc, sulfur, and iron, for the effective growth and yield of mushrooms, indicating the need for balanced micronutrient levels in hydroponic solutions (Sinha et al., 2020). Considering these requirements, it becomes clear that tailoring nutrient solutions to the specific needs of different mushroom varieties is key to successful hydroponic cultivation.

Comparison of Nutrient Solutions

Hydroponic nutrient solutions are formulated to optimize levels of key nutrients like carbon, nitrogen, and phosphorus, along with essential micronutrients, ensuring balanced nutrition for the mycelial growth and fruiting stages of mushrooms (Mccoy et al., 1972; Chang-hong 2008, Sinha et al., 2020,Jung et al., 2010).

6. HYDROPONICALLY TESTED MUSHROOM SPECIES

6.1. Oyster Mushroom (*Pleurotus ostreatus*): Renowned for its rapid growth and high nutritional value, the oyster mushroom has been extensively tested in hydroponic systems like DFT, NFT, and aeroponics. Notably, Nozzi et al. (2018) highlighted the suitability of oyster mushrooms for hydroponic cultivation.

6.2. Shiitake (*Lentinula edodes*) and Reishi (*Ganoderma lucidum*) cultivation: The Shiitake mushroom, another popular variety, has been successfully grown using the NFT system. Sousa et al. (2019) found that while hydroponic cultivation facilitates faster growth and harvesting, resulting in higher yields, there might be concerns regarding nutrient balance affecting quality compared to traditional wood log cultivation. Habijanic et al. (2013) reported the successful cultivation of Reishi mycelium on polyurethane foam, which served as a medium for producing valuable polysaccharides.

7. GROWTH PERFORMANCE COMPARISON BETWEEN HYDROPONIC AND CONVENTIONAL CULTIVATION

7.1. Mycelial Growth Rate: The growth rate of oyster mushroom mycelium has been observed to be 25% higher in the Deep Flow Technique (DFT) compared to traditional soil-based methods (Wenjie Yang et al., 2013). In aeroponic systems, mycelial proliferation saw an 11% increase over manual spraying methods, attributed to improved moisture and dissolved oxygen levels (Sharma et al., 2018).

7.2. Primordia Formation Time: In hydroponic systems using floating rafts, oyster mushroom primordia initiation occurred 2 days earlier compared to ground-based cultivation (Nadir et al., 2016). Shiitake mushrooms also showed a 3-5 day faster primordia development in Nutrient Film Technique (NFT) systems than in traditional soil cultivation (Ohta et al., 1994).

7.3. Fruiting Body Development Duration: The time from pinhead formation to harvest in oyster mushrooms was reduced by 4 days in aeroponic systems compared to manual mist spraying, due to better-controlled moisture (Ray et al., 2013).

8. YIELD

NFT System: Yielded total biomass of 427g, averaging 47.4g per trial, and 309g of edible biomass, averaging 34.3g per trial, demonstrating significant productivity (Re et al., 2021).

Ebb and Flow (E/F) System: Produced a total biomass yield of 424g, averaging 47.1g per trial, and 287g of edible biomass, averaging 31.9g per trial, slightly less than the NFT system.

Commercial Off-The-Shelf (COTS) Kit: Offered lower yields with 365g total mushroom biomass, averaging 40.6g per trial, and 262g of edible mushrooms, averaging 29.1g per trial. The NFT system showed numerically higher total and edible biomass yields compared to the E/F system, and both hydroponic methods outperformed the non-hydroponic COTS kit in terms of mushroom productivity.

9. ADVANTAGES OF HYDROPONICS IN MUSHROOM FARMING

9.1. Optimal Nutrition: Hydroponic systems offer precise control over nutrient levels, enabling customization to meet the specific nutritional needs of mushrooms, leading to improved yields and product quality (Nozzi, V. et al. 2018). This precision helps prevent the nutrient deficiencies often seen in soil-based cultivation, and mushrooms grown hydroponically benefit from a higher bioavailability of essential nutrients (Rashid et al., 2021; Upadhyay et al., 2019).

9.2. Controlled Microclimate: Hydroponics allows for complete control over environmental conditions such as temperature, light, and humidity, optimizing them for enhanced mushroom growth (Pandey et al., 2014). This control also facilitates year-round production, unaffected by external weather changes (Rashid et al., 2021; Upadhyay et al., 2019).

9.3. Reduced Contamination Risk: Hydroponic cultivation significantly reduces the risk of soil-borne diseases, common in traditional farming, and lowers contamination risks from pests and pathogens (Kumar, R. et al., nd; Rashid et al., 2021). Integrated pest management practices are more straightforward to implement in a controlled hydroponic environment (Pandey et al., 2014).

9.4. Increased Productivity: Mushrooms grown in hydroponic systems exhibit faster growth rates due to optimal and stable growing conditions, leading to higher yields per unit area compared to traditional soil-based methods (Rashid et al., 2021; Kumar, R. et al., nd). The ability to maintain continuous production cycles throughout the year further enhances productivity (Upadhyay et al., 2019).

9.5 Reduced Labor Requirements: Hydroponics simplifies cultivation by eliminating labor-intensive soil preparation tasks. Automation of irrigation and lighting reduces labor needs, and the standardized setup facilitates easier harvesting (Rashid et al., 2021; Pandey et al., 2014; Kumar, R. et al., nd).

9.6. **Free from Heavy metals and Toxicity:** The wild edible mushrooms and mushrooms cultivated in conventional substrates system has risks of heavy metals like lead, cadmium, molybdenum, arsenic and mercury. (Mccoy et al., 1972; Chang-hong 2008, Habijanic et al. (2013). The hydroponic and arenumponic system can lower the risks or can be eliminated because of precise and careful choice of inorganic salts and organic nutrients without those toxic metals.

10. CHALLENGES IN HYDROPONIC MUSHROOM FARMING

10.1. Technical Challenges

Moisture Management: Proper moisture level management is crucial to prevent mushroom sogginess, a common issue in hydroponic systems (Re, 2021).

Optimal Conditions for Fruiting: Providing the ideal moisture, nutrient, and gas exchange conditions required for the development of the fruiting body is challenging (Bechara et al., 2006).

Yield Consistency: There is a lack of long-term yield data over multiple harvest cycles, which is necessary to establish the reliability of hydroponic methods (Re, 2021).

Contamination Risks: Inadequate control over moisture and environmental factors can increase the risk of microbial contamination, affecting mushroom growth (Bechara et al., 2006; Re, 2021).

10.2. Economic Analysis:

Return on Investment (ROI): A comprehensive economic analysis, including ROI across the commercial viability of hydroponic mushroom cultivation, is needed (Gurung et al., 2020; Nozzi et al., 2018). Studies should include the cost-benefit analysis of various hydroponic techniques, tailoring nutrient solutions to specific mushroom species, and developing scalable, user-friendly hydroponic system designs.

10.3. Lack of Familiarity and Adoption Challenges:

Grower Exposure: Mushroom growers are often unfamiliar with hydroponic systems and their operation compared to traditional methods (Zhu et al., 2021, Re, 2021; Bechara et al., 2006).

11. PROOF OF CONCEPT

Hydroponic and arenumponic mushroom cultivation system was established at the Science Business Research and Innovation Center (SciBRIC) at HICAST.

11.1. Selection of Mushroom Species: The project involved cultivating various mushroom species, such as oyster mushroom (*Pleurotus ostreatus*), king oyster mushroom (*Pleurotus eryngii*), and Padke chyau (*Schleroderma* spp.). The Padke chyau was collected from the wild at Dandagaun, Patlekhet, Kavrepalnchowk District, Nepal. Padke chyu is edible mushroom popular among Tamang Ethic community in the subtropics and Tharu community of the tropics of Nepal.

11.2 Adaptation of Hydroponic System: Originally designed for plant hydroponics, the system was modified for mushroom cultivation. This involved adding an air diffuser with the help of aquarium air pump to the nutrient water circulation system.

11.3 Nutrient Solutions: A specific nutrient composition was used in the hydroponic system. This included various chemicals and nutrients such as Sucrose, Potassium Phosphate, Ammonium Phosphate, Potassium Nitrate, MgSO4, CaCl2 (substituted with CaCO3 Lime), MnSO4, ZnSO4, FeSO4, NaMoO4, and Thiamine. These nutrients were essential for the growth of mushrooms in a hydroponic setup.

12. ARENUMPONIC SYSTEM DEVELOPMENT AT SCIBRIC LAB: Besides hydroponics, an arenumponic system using sterilized sand as an inert substrate was also developed. This method, known as arenumponic, facilitated uniform moisture distribution, crucial for the mycelium's growth and spread.

13. GROWTH PERFORMANCE IN MUSHROOM HYDROPONICS AND ARENUMPONICS

We cultured and got mycelium growth of oyster and king oyster mushrooms in both hydroponic and arenumponic system. The mycelium growth was better than the traditional methods of cultivation in rice straw for both types of oysters. There is fruiting body formation in one net cup. Because of closures of lab for some reasons the experiment was halted and could not run satisfactorily and the trials are going on. The different figures (1-4) of the photographs show the hydroponic and arenumponic system setup, the growth of mycelium and fruiting stage of oyster and king mushrooms.

Photograph plate-1. Figure-1&2. Hydroponic and arenumponic system setup. Figure-3. Mycelium growth of king oyster in the hydroponic system. Figure-4. Oyster mushroom fruiting.

14. FUTURE PERSPECTIVE ON HYDROPONIC AND ARENUMPONIC MUSHROOM FARMING

14.1. Testing and Refinement of Hydroponic Systems: The exploration of alternative systems such as the Deep Flow Technique should be continued to improve moisture regulation and the quality of mushrooms (Re, 2021). This includes conducting microbiological safety tests over multiple harvests to ensure consistent quality and safety (Re, 2021).

14.2. Economic Analysis and Optimization: Determining the economic viability of hydroponic mushroom cultivation is crucial. This involves optimizing technologies and automation processes to enhance efficiency and reduce costs

(Bechara et al., 2006; Gurung et al., 2020). This research will help quantify the benefits of hydroponic methods over traditional farming (Nozzi et al., 2018).

14.3. Optimization of Hydroponic Formulations: Tailoring nutrient solutions and environmental conditions in hydroponic systems to maximize yields is another important area of research (Bechara et al., 2006). This includes fine-tuning nutrient formulations to meet the specific needs of different mushroom species.

15. ECONOMIC ASPECTS

Gilmour et al. (2019) examined consumer responses and found that while hydroponically grown products didn't garner a price premium, consumer preferences were significantly influenced by the information provided about hydroponic practices. Kholis et al. (2022) discovered that hydroponic ventures, especially small-scale home industries, are quite profitable. The concept of Open Field Hydroponics, despite being traced back to the early '90s, has only begun gaining substantial attention in scientific discourse since the 2000s, as evidenced by the work of Rubio-Asensio et al. (2020, Malik et al. 2018).

In assessing the economic aspects of hydroponic systems in mushroom cultivation, employing robust econometric methods is crucial to quantitatively analyze their financial viability and efficiency. One such approach is the Cost-Benefit Analysis (CBA), which can be used to compare the total costs (including setup, operation, and maintenance) against the benefits (such as increased yield, quality, and market price of mushrooms). Additionally, models like the Cobb-Douglas production function could be applied to understand the relationship between inputs (such as nutrients, water, and labor) and output (mushroom yield), which aids in optimizing resource allocation for maximum economic return. Implementing these econometric analyses will not only offer insights into the economic efficiency of these methods compared to traditional farming but also guide future investments and policy decisions in sustainable mushroom agriculture.

16. EMPIRICAL METHODS

For analyzing the economic aspects of hydroponic systems in mushroom cultivation, an appropriate econometric model should address the specificities of cost structures, revenue streams, and productivity factors associated with this type of agriculture. A suitable model for this context would be the Stochastic Frontier Analysis (SFA). By using Stochastic Frontier Analysis, stakeholders in the hydroponic mushroom industry can gain valuable insights into the efficiency of their operations, identify areas for improvement, and make data-driven decisions to enhance profitability and sustainability.

17. CONSUMER AWARENESS AND PREFERENCES

Despite these benefits, hydroponic mushroom farming faces challenges such as the need for detailed moisture management and the development of economically viable systems (Re, 2021; Bechara et al., 2006). Furthermore, the unfamiliarity of mushroom growers with hydroponic systems indicates a need for more extensive research and training (Zhu et al., 2021, (Gurung et al., 2020; Rubio-Asensio et al., 2020). By employing econometric models such as Cost-Benefit Analysis (CBA) and the Cobb-Douglas production function, researchers can effectively analyze and optimize the financial viability and efficiency of these systems (Malik et al., 2018; Gilmour et al., 2019). Studies like those by Gilmour et al. (2019) and Kholis et al. (2022) have shown that while hydroponic products may not command a premium price, consumer preferences are highly influenced by information about hydroponic cultivation.

18. CONCLUSION

In conclusion, the study highlights that hydroponic and arenumponic systems in mushroom cultivation provide promising alternatives to traditional farming, addressing issues like inconsistent substrate quality and contamination risks (Ferdousi et al., 2019; Easin et al., 2017). These advanced methods offer precise nutrient control, improved microclimate management, and increased productivity (Gume et al., 2013; Re et al., 2021; Nozzi et al., 2018; Rashid et al., 2021; Kumar et al., nd). However, realizing their full potential in the agricultural sector requires further research into scaling, commercialization, technological innovation, and economic feasibility, including market analysis and regulatory considerations.

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- The submitted article presents original research findings.
- The submitted article offers a comprehensive critical review and evaluation of key literature sources for a given topic; and
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