Sustainable Food Technology

PAPER

View Article Online
View Journal

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Cite this: DOI: 10.1039/d6fb00006a

Financial analysis of shipping container-based mushroom cultivation

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Shipping-container mushroom farms offer a sustainable and scalable approach to year-round food production, enabling efficient resource use with minimal land and water requirements. This study presents a comprehensive financial assessment of container-based mushroom cultivation across four production scales (50, 100, 200, and 500 lb per day) using four commercially relevant species: Oyster, Enoki, Maitake, and Lion's Mane. Economic feasibility was evaluated over a 10-year project horizon using net present value (NPV), discounted cash flow, and payback period. Results show that small-scale systems (50 and 100 lb per day) are not financially viable for lower-value species such as Oyster, whereas medium and large-scale operations (200 and 500 lb per day) achieve positive NPVs and substantially shorter payback periods. At 200 lb per day, payback periods range from 4.4–4.6 years for Enoki and Maitake and 3.4 years for Lion's Mane, while Oyster requires 9.8 years to recover the initial investment. Financial performance improves further at 500 lb per day, with payback periods of 2.1–2.5 years for Lion's Mane, Maitake, and Enoki, and 3.4 years for Oyster. All reported payback periods include an additional one year for container installation, infrastructure setup, system commissioning, and ramp-up to steady production. Overall, Lion's Mane and Maitake deliver the highest returns due to substantial market value and efficient cost recovery. These results demonstrate that production scale and species selection are the dominant drivers of profitability in container-based mushroom cultivation, and the analytical framework provides a practical decision-support tool that can be extended to medicinal or specialty fungi.

Received 2nd January 2026
Accepted 20th April 2026

DOI: 10.1039/d6fb00006a

rsc.li/susfoodtech

Sustainability spotlight

Container-based mushroom cultivation represents a forward-thinking solution to sustainable food production, combining efficient resource use with minimal environmental impact. By enabling year-round growth in controlled environments, this approach significantly reduces land and water consumption while supporting local economies and enhancing food security. The scalable nature of container farming enables optimized production that meets market demand without the typical challenges associated with traditional agriculture. This study's financial analysis underscores how such innovative systems not only promote ecological sustainability but also present viable business opportunities, paving the way for broader adoption of sustainable, high-value crop production methods.

1 Introduction

The global mushroom farming industry has expanded significantly over the past few years due to rising demand for mushrooms as a sustainable protein alternative, driven by their versatility in fast food, rich flavor profiles, and nutritional benefits, creating profitable opportunities for farms of all sizes.[1,2] Major contributors to the mushroom industry include the United States, China, the Netherlands, Poland, and India.[3] In the U.S., Pennsylvania and California are the top two mushroom-producing states, which produce over 80% of the national mushroom production.[3] During the 2021–2022 season, U.S. mushroom crop sales totaled 702 million pounds, valued at $1.02 billion.[4] While 70–80% of domestic production consists of *Agaricus bisporus* (Button), demand is steadily increasing for other species such as *Pleurotus ostreatus* (Oyster), *Grifola frondosa* (Maitake), *Flammulina velutipes* (Enoki), *Hericium erinaceus* (Lion's mane), and *Lentinula edodes* (Shiitake).[5] This trend is fueled by consumer interest in culinary diversity, plant-based diets, and functional foods with medicinal and immune-boosting properties.

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Compared to most plant crops, domestic mushroom cultivation requires less space, has shorter growth cycles, and can be maintained year-round.[6] These advantages make mushroom production a high-margin opportunity for farmers and entrepreneurs. Mushroom cultivation is a multi-stage biological process that integrates mechanical operations with strict hygiene protocols to produce optimal yield and high-quality mushrooms. Densified biomass pellets undergo a series of steps, including storage, blending, jarred, sterilization, inoculation, incubation, fruiting, harvesting, packaging, and distribution. Brown and blue droplets denote the dirty and clean steps, respectively, to ensure proper sanitation flow (Fig. 1).

Large-scale mushroom farms benefit from advanced technologies, including automated climate-control systems, AI-based environmental monitoring, vertical farming structures, robotic harvesting, improved substrate processing, and blockchain-enabled supply-chain tracking. Small and medium-scale growers may lack access to high-tech innovations. Still, they can remain competitive by focusing on local markets, adopting eco-friendly practices to produce high-quality mushrooms, and selling directly to customers.[7] Small-scale mushroom farms can benefit from the growing consumer interest in organic, locally sourced products, which can also help them establish a strong brand identity and stand out in the market.[8,9] However, a significant challenge for small producers is maintaining the specific temperature and humidity ranges required by different mushroom species. Without a heating, ventilation, and air conditioning (HVAC) system, cultivation is constrained to seasons when ambient conditions are favorable. For example,

Fig. 1 Processing steps for producing mushrooms. Densified biomass pellets used as the substrate are first stored on pallets, then mixed in a ribbon blender, and finally filled into jars. These jars undergo steam sterilization before being inoculated with either solid or liquid spawn. Following inoculation, the jars are incubated to allow mycelial colonization, which eventually leads to the formation of mushroom fruiting bodies. The mature mushrooms are then harvested, packaged, and distributed. Brown and blue droplets represent dirty and clean steps, respectively, highlighting the importance of maintaining a sanitary flow throughout the process.

L. edodes (shiitake) and *P. ostreatus* (Oyster) thrive in cool, moist environments (55–65 °F), limiting production to spring and fall in many areas. *Calocybe indica* (milky white) prefers warm, humid conditions and is best cultivated in summer.[10] This seasonal dependency restricts year-round productivity and introduces variability in output, posing a challenge to the reliability and scalability of small-scale mushroom farming.[11] Traditional small-scale mushroom farming typically relies on regular rooms, basements, or barns with basic insulation, manual ventilation, and basic humidity control. They are low-cost and accessible, but they offer limited precision in maintaining environmental conditions, increasing the risk of contamination and yield loss.[12] In contrast, shipping containers are a promising option with superior insulation, a modular layout, and the easy integration of automated climate control systems, which enable consistent, year-round production despite the higher upfront cost. This setup is widely used for hydroponic microgreens.[13] Shipping containers are widely available, space-efficient, and stackable, and can be customized to provide specific environmental conditions for growing various mushroom species year-round. Their mobility and scalability make them suitable for rural or remote locations with limited infrastructure. Additionally, equipping container roofs with solar panels can reduce energy expenses, enhance sustainability, and make this approach more viable for small-scale farmers and agri-entrepreneurs.

To operate a profitable small-scale mushroom farm, producers must carefully evaluate both technological and economic variables, ranging from selecting the appropriate mushroom species and preparing the substrate to controlling the environment, implementing automation, managing capital expenditures (CapEx), operating costs (OpEx), understanding market demand, and devising a pricing strategy.[14] These factors are crucial for designing cost-effective and efficient operations that support financial sustainability. Financial feasibility is recognized as an essential tool for optimizing feasibility and profitability. However, outcomes may vary by region, mushroom type, and production scale.[15] Numerous studies emphasize the importance of financial analysis and TEA in ensuring sustainability and profitability. However, outcomes vary by region, species, and farm size. For example, larger farms often achieve better margins due to economies of scale and cost efficiency.[16–18] Keneni found that sourcing raw materials significantly reduced transport costs and boosted profitability.[19]

Despite growing interest in controlled-environment agriculture, a comprehensive financial analysis of shipping-container-based mushroom farming has been absent in the U.S. context. This study fills that gap by evaluating shipping container production systems for four scales: 50, 100, 200, and 500 pounds per day, with potential applications in other global settings.

CapEx, OpEx, NPV, and payback period are evaluated. In addition to financial modeling, this study offers practical insights through visual layouts, container configurations, and land-use estimates, supporting system design and planning. Results show the importance of production scale, a suitable mushroom strain, and a financing strategy for profitability and provide a decision-making framework for small-scale growers, investors, and policymakers. This approach is adaptable for cultivating a wide range of high-value edible and medicinal mushrooms, further enhancing its utility and potential impact on sustainable food systems.

2 Methods and assumptions

2.1. Substrates and conditioning assumptions for mushroom production

In commercial mushroom production, several substrate formulations vary by species and are a critical determinant of yield and quality. Oyster, Maitake, Lion's mane, and Enoki mushrooms can all be cultivated on a range of lignocellulosic or nutrient-supplemented substrates. Typical formulations include hardwood sawdust amended with bran, Master's mix (50 : 50 hardwood sawdust and soy hulls), and pasteurized or pelleted straw. Oyster mushrooms are exceptionally adaptable and can utilize a wide range of agricultural residues, including corncobs, wheat straw, rice straw, cottonseed hulls, sugarcane bagasse, and soybean hulls, making them among the most flexible in terms of substrate selection.[20] Maitake mushrooms, while more selective, perform well on hardwood sawdust supplemented with bran or gypsum, on oak-based sawdust blends, and in soy hull-enriched formulations that support dense, uniform mycelial colonization.[21]

Lion's mane cultivation typically relies on hardwood sawdust supplemented with bran, with oak-based sawdust fortified with wheat bran and calcium sources being especially effective. The species can also grow on beech or maple sawdust, soy-hull-rich mixes, and, in some cases, pelleted straw blends, although yields are generally lower on non-wood substrates.[22] Enoki mushrooms are traditionally produced on hardwood sawdust supplemented with wheat bran and calcium carbonate. Still, they are also compatible with oak- or beech-based sawdust, Master's mix, and finely processed straw or corncob substrates when properly sterilized.[23]

These substrate formulations are widely adopted in commercial mushroom production due to their reliability, balanced nutrient profiles, broad availability, and consistently high biological efficiency. In this study, all substrates are assumed to be purchased in pre-processed, pelletized form to standardize input quality and facilitate transparent cost estimation.[24] The pellets are hydrated in a paddle mixer to achieve a target moisture content of approximately 65–70%, which is optimal for fungal growth.[25] Following hydration, the substrate is filled into bags or bottles and autoclaved to eliminate contaminants and establish a sterile environment for mycelial colonization.[26]

After sterilization and cooling, grain spawn is added at an inoculation rate of 5–20% (w/w), depending on the mushroom species, growth characteristics, substrate composition, and desired colonization speed. Higher spawn rates are commonly applied to species with slower mycelial expansion or when using denser substrates. In this analysis, a 10% spawn rate is assumed for Oyster and Enoki, reflecting their rapid and efficient colonization under standard production conditions. In contrast, Lion's mane and Maitake are modeled using a 15% spawn rate, acknowledging that these species typically benefit from higher inoculation levels to ensure uniform and reliable colonization, particularly in substrates that are more resistant to mycelial penetration. The equipment used for substrate conditioning and container filling is illustrated in Fig. S1.

After inoculation, the sealed substrate bags or bottles enter the incubation phase, during which fungal mycelium colonizes the substrate. Incubation is typically carried out in a dark or

Table 1 Species-specific incubation and fruiting conditions assumptions

Mushroom species	Incubation conditions	Fruiting conditions	Reference
Oyster (*Pleurotus ostreatus*)	Temperature: 25–30 °C Humidity: 65–75% Light: dark/low light Air exchange: minimal	Temperature: 20–25 °C Humidity: 85–95% Light: moderate diffuse light CO_2: <1000 ppm Air exchange: high fresh-air flow	27
Maitake (*Grifola frondosa*)	Temperature: 15–20 °C Humidity: 60–70% Light: dark	Temperature: 12–18 °C Humidity: 85–95% Light: low-moderate light CO_2: <800 ppm Air exchange: moderate	28
Lion's Mane (*Hericium erinaceus*)	Temperature: 20–25 °C Humidity: 65–70% Light: dark	Temperature: 18–24 °C Humidity: 90–95% Light: low diffuse light CO_2: <1000 ppm Air exchange: gentle ventilation to avoid elongated spines	29
Enoki (*Flammulina velutipes*)	Temperature: 18–25 °C Humidity: 60–70% Light: dark	Temperature: 15–18 °C Humidity: 85–95% Light: very low light CO_2: <800 ppm Air exchange: controlled, low airflow	30

Table 2 Biological efficiency and substrate requirements and average market price for Oyster, Enoki, Maitake, and Lion's Mane mushrooms

Type of mushroom		BE (%)	Assumed substrate	Average price ($ per lb)	Reference
Oyster		80–150	Corncobs, wheat straw, rice straw, cottonseed hulls, sugarcane bagasse, and soybean hulls	6–8	20
Enoki		70–100	Hardwood sawdust, oak-based sawdust blends	8–12	23
Lion's Mane		60–150	Hardwood sawdust, wheat bran	20–30	22
Maitake		35–45	Hardwood sawdust, wheat bran	18–22	21

low-light condition under controlled temperature, humidity, and fresh-air exchange to promote rapid mycelial expansion. While optimal parameters vary by species, incubation generally requires elevated CO_2 concentrations, high relative humidity (60–75%), and minimal ventilation. Upon complete substrate colonization, the system transitions to the fruiting phase, characterized by reduced temperatures, higher humidity, and increased air exchange to promote primordia formation and fruit-body development. Species-specific environmental requirements for both phases are summarized in Table 1.

In this study, both incubation and fruiting are assumed to occur within a climate-controlled shipping container, where species-specific environmental conditions are maintained using integrated HVAC, humidification, and ventilation systems. Mature mushrooms are harvested manually, packaged, and prepared for distribution to buyers and end users. Details regarding substrate volume capacity within the shipping container and corresponding mushroom yields are provided in Table S1.

2.2. Mushroom variety, growth conditions, and market value

The mushroom varieties evaluated in this study are Oyster, Enoki, Maitake, and Lion's mane, and were selected based on their commercial relevance, cultivation feasibility, and market demand. Each species exhibits specific biological and environmental requirements that influence its suitability for small and medium-scale farming. Mushroom yield is demonstrated with biological efficiency percentage (BE), which is a measure of how effectively a mushroom crop converts substrate into mushrooms. It is calculated as the fresh weight of the harvested mushroom divided by the substrate's dry weight. For Oyster mushrooms, BE ranges from 80–150% on straw-based substrates, while Enoki mushrooms achieve 70–100% BE on sawdust. Maitake mushrooms can be grown on wood chips, have a lower BE of 35–45%, but command high market prices. Lion's mane is priced for their flavor, reaching a BE of 40–60%.[19,31–33] Optimal temperature and humidity requirements differ by species and can substantially impact both yield and production costs (Table 1).

Oyster, Enoki, Lion's mane, and Maitake mushrooms are tolerant of standard indoor conditions. Market prices reflect consumer demand and production cost, with Lion's mane priced at ∼$20–30 per lb, Maitake at $18–22 per lb, Enoki at $8–12 per lb, and Oyster mushrooms at ∼$6–8 per lb (Table 2).

By analyzing mushrooms with diverse growth parameters and economic values, this study aims to identify the most profitable and sustainable container-based cultivation method.

2.3. Organization of a shipping container mushroom farm

The shipping container mushroom farm will use standard 40 ft × 8 ft × 8.6 ft containers (320 ft^2 each), with layouts precisely modeled in AutoCAD to optimize spatial organization. Each container is equipped with HVAC systems, circulation fans, humidifiers, and full-spectrum LED lighting, enabling precise control of temperature, humidity, airflow, and lighting conditions. The system is designed to accommodate four production scales, with the corresponding number of containers indicated in parentheses: 50 lb per day (7 containers), 100 lb per day (11 containers), 200 lb per day (17.5 containers), and 500 lb per day (33 containers). A minimum clearance of 15 feet is maintained around the installation for vehicle access and maneuverability. Each container is subdivided into growing chambers. These

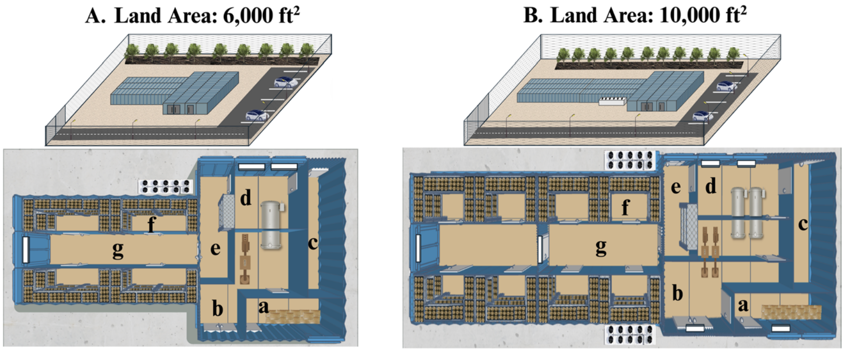

Fig. 2 Layout of shipping container-based mushroom farms at small production scales. (Panel A) Illustrates a system designed for 50 lb per day production, while (Panel B) depicts a system for 100 lb per day production. The shipping container farm is divided into different sections. These areas include: area (a) storage area for densified biomass in pellet form; (b) substrate conditioning and mixing area for materials such as straw, bran, corn flour, lime, and gypsum (c) station for spent substrate disposal and equipment cleaning; (d) clean room for aseptic spawn inoculation; (e) storage area for the sterilized substrate bags or bottles; (f) growth chambers for mushroom fruiting and harvesting, (g) walkway area, (h) Spawn incubation area.

chambers are designed to operate in staggered cycles, allowing simultaneous cultivation of multiple species or growth stages. Additional containers are designed for specific functions such as substrate preparation, sterilization, inoculation, and harvesting, as well as walkways to provide smooth operational flow.

The illustrated facility layout offers a scalable and efficient framework for container-based mushroom cultivation, designed to accommodate four production capacities: 50 and 100 pounds per day (Fig. 2A and B) and 200 and 500 lb per day (Fig. 3A and B).

The cultivation facility is organized into distinct functional zones to streamline workflow and optimize productivity. Each production scale corresponds to a defined number of shipping containers and land footprint, as detailed in Table S2: 50 lb per day (7 containers, 6000 ft^2), 100 lb per day, (11 containers, 10 000 ft^2), 200 lb per day (17.5 containers, 15 000 ft^2) and 500 lb per day (33 container, 25 000 ft^2). All containers are aligned along a central walkway, with side doors to provide smooth access for staff, equipment, and harvest trays. This ergonomic layout facilitates efficient loading and unloading, routine cleaning, and continuous environmental monitoring.

Each container is outfitted with standardized infrastructure to maintain optimal growing conditions including: (i) ventilation system with intake, exhaust, and auxiliary air handling fans; (ii) 1-ton mini-split HVAC unit with dual-zone temperature control; (iii) ultrasonic or fogging humidifiers for precise humidity regulation; (iv) full-spectrum LED grow lights for consistent illumination; (v) water pump (0.3–0.5 HP) for automated misting or irrigation; and (vi) Wi-Fi-enabled smart controllers integrated with temperature, humidity, and CO_2

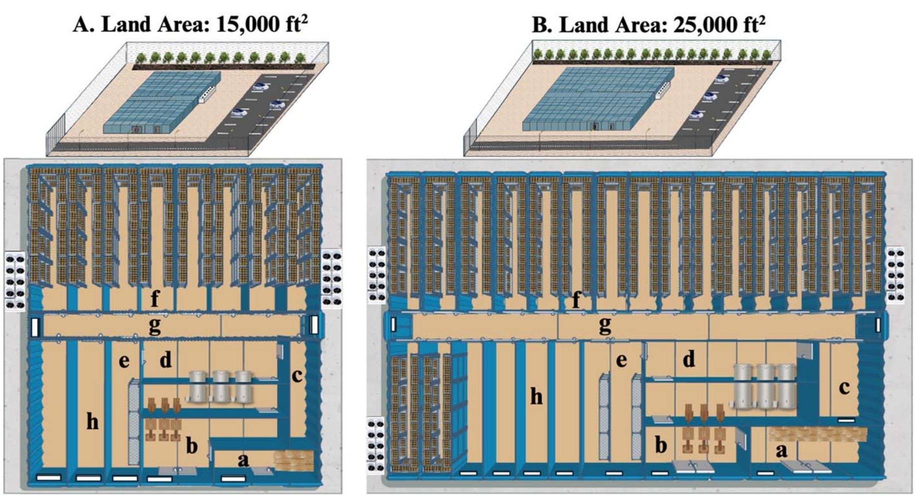

Fig. 3 Layout of shipping container-based mushroom farms at medium production scales. (Panel A) Illustrates a system designed for 200 lb per day production, while (Panel B) depicts a system for 500 lb per day production. For medium-scale systems (200 and 500 lb per day), an additional area h is incorporated to accommodate auxiliary containers for extended incubation, overflow management, or cultivation of experimental strains. These areas include: area (a) storage area for densified biomass in pellet form; (b) substrate conditioning and mixing area for materials such as straw, bran, corn flour, lime, and gypsum (c) station for spent substrate disposal and equipment cleaning; (d) clean room for aseptic spawn inoculation; (e) storage area for the sterilized substrate bags or bottles; (f) growth chambers for mushroom fruiting and harvesting, (g) walkway area, (h) Spawn incubation area.

sensors. Shared zones, such as the central walkway and substrate preparation area, are also climate-controlled to ensure consistent air quality and environmental stability across the entire facility.

An efficient contamination-control system is critical for reliable container-based mushroom production. To minimize the introduction of airborne spores, microorganisms, and dust, the container design incorporates a HEPA-filtered air intake and maintains a controlled positive-pressure environment. HEPA filtration removes fine particulate contaminants before air enters the cultivation chamber. At the same time, positive pressure ensures that airflow is directly outward through any small openings, thereby preventing infiltration of unfiltered ambient air. Together, these measures substantially reduce contamination risks during both substrate colonization and fruiting, supporting consistent yields and hygienic production conditions.[34]

2.4. Capital expenditure computation assumptions

CapEx refers to the long-term investments required to establish infrastructure and equipment before production and revenue generation.[15,16,35,36] Major CapEx components include specialized growing systems, indoor production machinery, land acquisition or leasing, and the conversion of shipping containers into climate-controlled fruiting chambers. Essential equipment, such as autoclaves, industrial balances, filling machines, ribbon mixers, and pallet lifters, is scaled according to the production capacity, with the types and numbers of containers tailored to support daily outputs of 50, 100, 200, or 500 pounds. The specific equipment requirements and assumed cost at each scale are detailed in Tables S2 and S3, respectively. Estimated land requirements, including space for containers and vehicle access, are 6000 ft^2, 10 000 ft^2, 15 000 ft^2, and 25 000 ft^2 for respective production capacities. To account for unforeseen needs, a 20% markup is applied to the initial investment for additional supplies, and a 15% markup is applied to ongoing maintenance costs. Installation costs, including container retrofitting and system integration, are estimated at 30% of the initial investment. All cost estimations are based on 2025 market data, using average prices for equipment, containers, materials, and variable inputs.

2.5. Operating expenditure computation assumptions

OpEx for daily mushroom cultivation constitutes a significant portion of total production costs and scales with output volume.[7,37] These expenses include labor, substrates and spawn (assumed purchased ready-made), utilities, packaging, and distribution. In this study, OpEx is categorized into five main components: substrate and spawn, electricity, packaging, water, and labor.

2.5.1. Substrate requirements and cost calculation. For each production scale, the required dry substrate quantity is first estimated using eqn (1), based on the target BE.[38]

$$\text{BE (\%)} = (\text{weight of fresh mushrooms})/(\text{dry weight of substrate}) \quad (1)$$

Substrate costs, including shipping fees, are calculated. Total wet substrate and its associated water content are then determined using eqn (2):

$$\text{Wet weight of substrate} = (\text{dry weight of substrate})/(1 - \text{moisture content \%}) \quad (2)$$

To account for spawn, 10–15% of the total wet substrate is allocated for spawn preparation, and the associated cost is calculated accordingly.

2.5.2. Water use estimation. Water use includes adjusting the substrate's moisture content, cleaning, and maintaining appropriate environmental conditions. Moisture in the substrate is calculated to achieve the desired water content, which is a percentage of the total wet substrate weight. First, the total wet weight is estimated (eqn (2)), then the wet weights of individual solid ingredients are calculated based on their initial moisture contents. The total water requirement is then the difference between the total wet substrate weight and the combined wet weights of these ingredients, as shown in eqn (3).

$$\text{Water required} = \text{wet weight} - \text{wet mass of ingredients} \quad (3)$$

In this paper, the average of 2–4 gallons of water per pound of mushrooms is assumed for all calculations.[39]

2.5.3. Electricity consumption. Electricity demand for the containerized mushroom production system was estimated using a physics-based thermal–electrical model that accounts for both fixed equipment loads and the cooling energy required to maintain species-specific growth temperatures. Energy consumption was scaled as a function of production capacity (50–500 lb per day), the number of containers (growing chambers, substrate preparation units, and walkway containers), and the container thermal properties (insulated *vs.* non-insulated). Species-specific temperature requirements were incorporated directly into the thermal load calculations: Oyster (20–25 °C), Maitake (12–18 °C), Lion's mane (18–24 °C), and Enoki (15–18 °C). Species requiring lower temperature setpoints relative to ambient conditions (25 °C) exhibit higher cooling-related energy demand.

Total electrical energy consumption (E_{Total}) is calculated as the sum of all non-HVAC electrical loads and the electricity consumed by the cooling system using eqn (4):

$$E_{\text{Total}} = E_{\text{Equipment}} + \left(\frac{Q_{\text{Thermal}}}{\text{COP}}\right) \times h \quad (4)$$

This formulation distinguishes electrical power that is converted to heat (from lighting, fans, pumps, and environmental monitoring systems) from electrical power required to move that heat *via* cooling. The HVAC electricity demand is governed by the system's coefficient of performance (COP), which represents cooling efficiency (*e.g.*, a COP of 3 indicates that 1 kWh of electricity removes 3 kWh of heat). This two-term approach allows accurate assessment of how biological heat generation, ventilation rates, and insulation levels influence total facility energy demand.

2.5.3.1. Fixed electrical loads. All devices operating within the container, excluding the active refrigeration cycle, were treated as fixed electrical loads, and their daily energy consumption was calculated as the sum of each component's rated power and operating time (eqn (5)).

$$E_{\text{Equipmet}} = \sum_i P_{i,\text{rated}} t_i \tag{5}$$

These loads include LED grow lights, whose energy use varies with shelf configuration, species-specific lighting requirements, and photoperiod, and which convert nearly all the electricity they consume into heat within the chamber. Additional contributors include humidifiers, circulation fans, and HEPA or laminar-flow units that operate for extended periods to maintain target humidity and air quality, as well as environmental sensors, automated valves, and control systems that draw continuous low-power loads. Pumps used for irrigation and misting add intermittent heat gains, while substrate-processing equipment (*e.g.*, ribbon mixers) contributes additional thermal load on preparation days. Autoclaves and steamers represent the largest single electrical load (3–18 kW during sterilization); when operated inside the container, they introduce substantial internal heat that can exceed biological and environmental heat sources. Consequently, autoclave operation is preferably isolated in a separate, externally vented module to avoid oversizing of the HVAC system and excessive cooling demand.

2.5.3.2. HVAC thermal load. The total thermal load that the HVAC system must remove was modeled as the sum of four distinct heat sources, each representing a different physical mechanism contributing to temperature rise within the container (eqn (6)):

$$Q_{\text{thermal}} = Q_{\text{trans}} + Q_{\text{vent}} + Q_{\text{internal}} + Q_{\text{product}} \tag{6}$$

Q_{thermal} is the total heat load that the HVAC system must manage, consisting of heat transfer through the container envelope (Q_{heat}), heat from ventilation air exchange Q_{vent}, heat generated by internal equipment Q_{internal}, and metabolic heat produced by the growing mushrooms (Q_{product}).

2.5.3.2.1. Transmission heat load. Transmission heat is conductive heat transfer through the container walls, ceiling, and floor, driven by temperature differences between the external environment and the controlled interior. It is calculated as (eqn (7)):

$$Q_{\text{trans}} = U \times A \times (T_{\text{amb}} - T_{\text{set}}) \tag{7}$$

where U is the overall heat-transfer coefficient (W m^{-2} K^{-1}), A is the total exposed surface area of the container (m^2), T_{amb} is the ambient temperature (°C), and T_{set} is the species-specific internal setpoint temperature (°C). Calculations assumed a high-performance, insulated (reefer-grade) container with a low heat-transfer coefficient ($U = 0.07$ W m^{-2} K^{-1}) and a total exposed surface area (A = 138 m^2). The ambient temperature was fixed at 25 °C to represent typical warm-climate operating conditions. Under these assumptions, the transmission heat load was relatively small compared with internal electrical and biological heat sources; however, it increased for colder-growing species such as Enoki and Maitake due to a larger temperature gradient, even within a well-insulated structure.[40]

2.5.3.3. Internal electrical heat gain. Nearly all electrical devices operating within the container dissipate most of the energy they consume as heat, resulting in a substantial internal heat load. The internal electrical heat generation was estimated as (eqn (8)):

$$Q_{\text{internal}} = \eta_{\text{heat}} \times E_{\text{equipment}} \tag{8}$$

where η_{heat} is assumed to be 0.9, representing the fraction of electrical energy converted to heat, $E_{\text{equipment}}$ is the daily fixed electrical energy consumed by lighting, fans, pumps, sensors, and control system (kWh per day). Because LEDs, circulation fans, and humidifiers operate for extended periods, this term often constitutes the dominant contributor to overall cooling demand.

2.5.3.4. Biological product heat. Actively growing mushrooms and colonized substrate continuously release metabolic heat through cellular respiration, representing a significant component of the total thermal load within the growing chamber. This heat generation was quantified as (eqn (9)):

$$Q_{\text{product}} = W_{\text{rasp}} \times M_{\text{bio}} \tag{9}$$

where M_{bio} is the mass of biologically active substrate or biomass (kg), and W_{resp} is the species- and growth-stage-specific respiration heat rate (7.08 W kg^{-1} for actively colonizing substrate under controlled cultivation conditions).[41] Because biological heat generation scales directly with substrate mass, larger, higher-density production systems generate proportionally greater heat loads, thereby increasing cooling demand. Consequently, Q_{product} often becomes a dominant heat source in container-based farms when multiple shelves of colonizing substrate are used simultaneously. Neglecting this contribution would substantially underestimate HVAC cooling requirements, highlighting the importance of explicitly accounting for biological heat production in energy models.

2.5.3.5. Ventilation heat load. Ventilation is essential in mushroom cultivation because fungal respiration generates substantial CO_2, requiring a continuous supply of fresh air to maintain proper gas exchange and avoid growth inhibition. However, this necessary airflow imposes a thermal penalty, as outside air, typically warmer than the growing chamber, is introduced into the container and must be cooled to the species-specific setpoint temperature. The resulting ventilation heat load is computed as (eqn (10):

$$Q_{\text{vent}} = V \times \rho \times C_{\text{p}} \times \Delta T \tag{10}$$

where V is the airflow rate (0.08 m^3 s^{-1}), ρ is the density of air (1.2 kg m^{-3}), C_{p} is the specific heat capacity of air (1.006 kJ kg^{-1} K^{-1}), and ΔT is the temperature difference between ambient and setpoint conditions. Because air has a relatively high heat capacity, even moderate ventilation rates can introduce substantial heat that the HVAC system must remove. This contribution is significant for species with high CO_2 production or rapid air-exchange requirements during fruiting, such as Oyster and Lion's mane mushrooms. Warm-climate conditions (*e.g.*, ambient temperatures of 25–30 °C) further amplify this effect by increasing the temperature gradient between incoming and conditioned air. Consequently, Q_{vent} can rival or exceed transmission heat loads in highly ventilated or poorly insulated systems, making airflow controls critical for minimizing cooling energy demand in container-based mushroom farms.[42]

To convert the total thermal load into electrical energy consumption, the sum of the heat sources was divided by the HVAC system's coefficient of performance (COP) to determine the required cooling power. A COP of 3 was assumed, indicating that the HVAC system removes 3 kW of heat per 1 kW of electricity consumed. Daily cooling energy use (kWh) was then calculated by multiplying the cooling power by the system's daily operating hours, thereby directly converting the thermal load to refrigeration energy demand.[43]

2.5.4. Impact of outdoor climate on monthly ventilation and heat exchange demand. To assess the influence of outdoor climate on the system thermal performance, a month-by-month sensitivity analysis was conducted for both ventilation and transmission energy. These components are strongly governed by the temperature difference between ambient conditions and the species-specific chamber setpoint; consequently, seasonal variability can substantially affect cooling requirements. Houston, TX, was selected as the reference climate, and monthly temperature data were obtained from US Climate Data, as shown in Fig. 4.[44]

For each month, the ambient temperature was represented by the average of the monthly high and low temperatures. Species-specific temperature differentials were then calculated using these monthly ambient temperatures and the required cultivation setpoints. These temperature differences were used to update monthly ventilation and transmission heat loads. To isolate the effect of climate alone, all other system parameters, including container insulation, surface area, airflow rate, HVAC coefficient of performance, and operating hours, were held constant, and the analysis was performed for a single growing container.

2.5.5. Labor cost. This study assumes labor requirements of 3, 6, 8, and 10 workers for daily production capacities of 50, 100, 200, and 500 lb, respectively, within shipping container farms. At the 50 lb per day scale, one worker handles substrate preparation, another manages cleaning and monitoring, and a third oversees harvesting and packaging. As production increases to 100 lb per day, tasks are divided among six workers covering substrate preparation, sanitation, growth monitoring, harvesting, and packaging. The 200 lb per day scale introduces further specialization, with eight workers assigned to substrate processing, environmental control, harvesting, labeling, and inventory. On the 500 lb per day scale, 10 workers are designated for specific roles, including inoculation, environmental monitoring, logistics, and documentation. Each production level reflects a more structured division of labor, optimizing workflow and resource use. Labor costs increase with capacity, allowing for streamlined operations and improved productivity.

2.5.6. Final OpEx estimations. The complete breakdown of variable OpEx by production scale is detailed in the SI. Labor cost estimates for different shipping container sizes are scaled by production volume, with labor hours allocated to substrate preparation, inoculation, monitoring, harvesting, and post-harvest handling. Total OpEx is calculated by summing the five cost components over the number of working days, as described in eqn (11).

$$\text{OpEx} = \Sigma(C_{\text{Sub}} + C_{\text{L}} + C_{\text{P}} + C_{\text{W}} + C_{\text{E}}) \times (\text{working days}) \quad (11)$$

where: C_{Sub} = substrate and spawn costs, C_L = labor costs, C_P = packaging costs, C_W = water-related expenses, and C_E = electricity consumption costs.

2.6. Financial analysis and discounted returns

In this model, revenue is generated from the sale of fresh mushrooms and spent mushroom substrate (SMS). Fresh

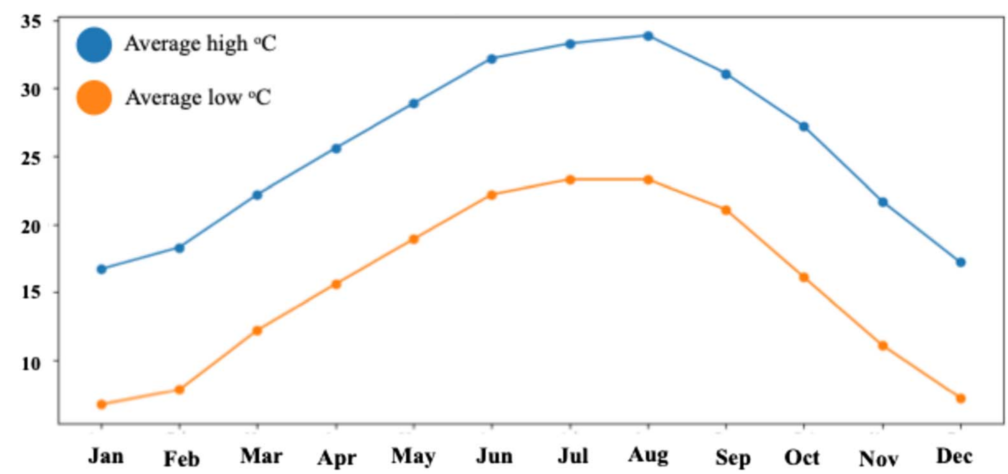

Fig. 4 Average monthly high and low temperatures for Houston, Texas, expressed in degrees Celsius. Values were converted from historical climate data.[44]

mushrooms are assumed to be sold at the average market price, while SMS is sold at $0.01 per pound (wet weight). In the first year, the number of harvesting days is reduced due to the initial cultivation period. The financial analysis of the mushroom farm uses a 10-year discounted cash flow analysis that incorporates both CapEx and OpEx.[45] The farm design includes four production scales: 50, 100, 200, and 500 lb per day, each requiring equipment appropriate to its scale, with associated costs. Equipment depreciation, representing the reduction in asset value due to wear and tear over time, is calculated using the straight-line method over a 10-year lifespan with no salvage value and is included in annual OpEx (eqn (12)).

$$\text{Depreciation} = (\text{purchase price} - \text{salvage value})/\text{useful life} \quad (12)$$

The financing structure assumes an 80 : 20 debt-to-equity ratio. Interest rates of 8% on debt and 10% on equity were considered based on market conditions and the relative risk of debt *versus* equity financing. A 30% corporate tax rate was applied, consistent with standard government tax regulations. Taxable income is determined by subtracting allowable deductions, such as annual depreciation and loan interest, from gross income.[46] The income tax is calculated using eqn (13):

$$\text{Income tax} = (\text{gross income} - \text{depreciation} - \text{loan interest}) \times 0.30 \quad (13)$$

To evaluate investment feasibility, future cash flows are discounted to present value using the Weighted Average Cost of Capital (WACC), which reflects the minimum return investors expect. WACC is a composite rate based on the cost of equity and the cost of debt, adjusted for their respective capital-structure weights and tax savings on interest (eqn (14)).[47]

$$\text{WACC} = (\text{equity wt.} \times \text{cost of equity}) + (\text{debt weight} \times \text{cost of debt}) \times (1 - \text{tax rate}) \quad (14)$$

The key indicator used includes NPV, which measures profitability by subtracting the initial investment from the present value of projected returns. A positive NPV indicates financial viability.[48] Additionally, the payback period was calculated to estimate the time required to recover the initial investment, providing insight into investment risk and capital recovery.[46,49]

3 Results and discussion

3.1. Processing substrate and producing mushrooms in a shipping container

Mushroom cultivation in shipping containers follows a modular, controlled process designed to optimize space, hygiene, and yield. The process begins in the "dirty zone", where densified lignocellulosic biomass pellets are loaded into a hopper, conveyed to a ribbon blender, and mixed with supplements and water to moisten the substrate. The blended substrate is dispensed into bottles or bags using automated loaders, then sterilized in a double-door steam sterilizer. After sterilization, the bottles or bags are moved into the "clean zone", where they are inoculated with mushroom spawn (solid/liquid) under aseptic conditions (Fig. 5).

These inoculated substrates are then incubated at regulated temperatures, with low humidity (70%) and high CO_2 levels, in dark conditions, to promote mycelial colonization. Once colonization is complete, environmental conditions are carefully adjusted to control lighting, airflow, and CO_2 levels, promoting fruit body formation. Bottles (used for Enoki and Lion's mane mushrooms) are placed on racks, while polythene bags (used for Oyster and Maitake mushrooms) are suspended from rods. Mature mushrooms are then harvested, packed, and prepared for distribution within the container's compact, climate-controlled environment, enabling scalable, year-round production.

Fig. 6 illustrates the internal configuration of a standard 40 ft. long high-cube shipping container, divided into two independent growing chambers. Each chamber can accommodate either substrate bags or jars and is accessible *via* insulated doors. Fig. 6A depicts a jar-based system in which mycelium-inoculated jars are placed in trays and stacked on three-tier shelving. Fig. 6B illustrates a bag-based system in which inoculated substrate bags are vertically hung from rods, making it ideal for high-fruiting species.

The modular design supports flexible batch management and species-specific environmental control, minimizing cross-contamination and enabling continuous, high-efficiency mushroom cultivation. The container interior features a washable surface, allowing each chamber to be washed and sanitized between cultivation cycles to reduce the risk of contamination.

3.2. CapEx analysis

CapEx for establishing container-based mushroom farms was estimated across four production scales—50, 100, 200, and 500 pounds per day. CapEx includes costs for equipment, container procurement, land acquisition, and installation/construction, all of which scale with production capacity (Table 3).

Equipment costs encompass autoclaves, industrial balances, filling machines, ribbon mixers, and stackers, scaled to match operational throughput. Equipment costs begin at $106 140 for the 50 lb per day system and increase to $199 140 for 100 lb per day, $305 280 for 200 lb per day, and $307 320 for 500 lb per day.

Container costs rise with production capacity and are divided into two categories: insulated, climate-controlled growing containers, and standard containers for substrate preparation, incubation, and logistics. For 50 lb per day, two growing containers and five regular containers are required. This increases to 4 and 7 for 100 lb per day, 10 and 7.5 for 200 lb per day, and 21 and 12 for 500 lb per day, respectively. Total container costs range from $65 000 (50 lb per day) to $358 500 (500 lb per day).

Assuming an average land price of $2.50 per ft^2, land acquisition costs range from $15 000 (50 lb per day) to $62 500 (500 lb per day), with intermediate scale requiring $25 000 (100 lb per day) and $37 500 (200 lb per day). Installation and construction expenses, including retrofitting the container, HVAC setup, plumbing, and electrical work, range from $55 842

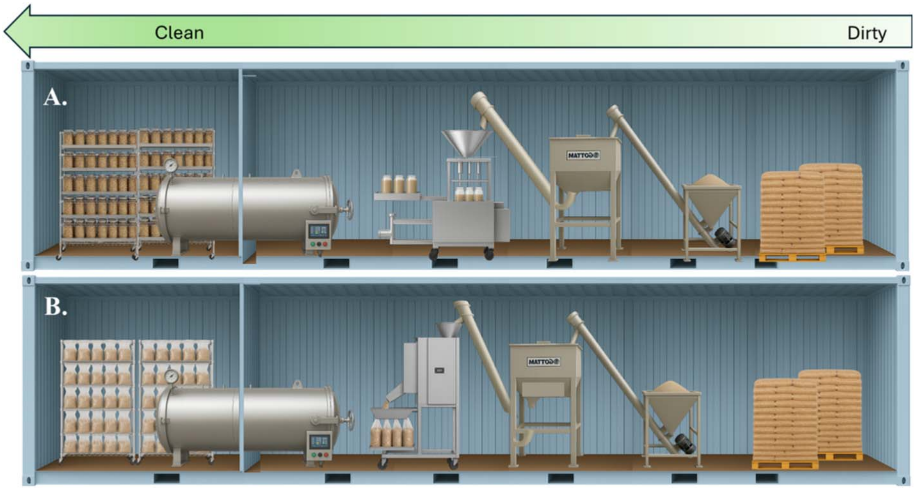

Fig. 5 Detailed layout of the substrate processing and packaging area for the two methods. The dirty zone includes sections for substrate storage, milling, mixing, and packing into either bottles or bags. The clean zone is designated for inoculating sterilized substrates with liquid or solid mycelium. (Panel A) Depicts the bottling method, while (Panel B) illustrates the bagging method.

to \$218 496. The total estimated CapEx by scale is: 50 lb per day (\$241 982); 100 lb per day (\$429 182); 200 lb per day (\$686 114); 500 lb per day (\$946 816). These estimates highlight the direct relationship between production scale and capital investment, consistent with the existing literature emphasizing the need for proportionally scaled infrastructure to ensure operational efficiency and financial viability.[45]

3.3. OpEX analysis

The total OpEx for container-based mushroom cultivation was estimated across four production scales 50, 100, 200, and 500 lb per day to account for variability in substrate and spawn inputs, electricity usage, packaging, water, and labor costs (Fig. 7). A breakdown in electricity consumption and associated fees is provided in SI Table S4. These OpEx estimates align with earlier studies highlighting the importance of scalability assessments in mushroom production, particularly in resource-sensitive regions such as India, where output expansion significantly increases input demand.[36]

The operating expenditure (OpEx) analysis across production scales of 50, 100, 200, and 500 lb per day reveals clear scale-dependent trends and species-specific differences in resource requirements. At the most minor scale (50 lb per day), daily OpEx remains relatively modest, totaling \$253 for Oyster, \$307 for Lion's mane, \$301 for Maitake, and \$257 for Enoki. These lower costs reflect reduced substrate throughput, limited environmental loads, and minimal labor and material-handling demands. As production increases to 100 lb per day, OpEx

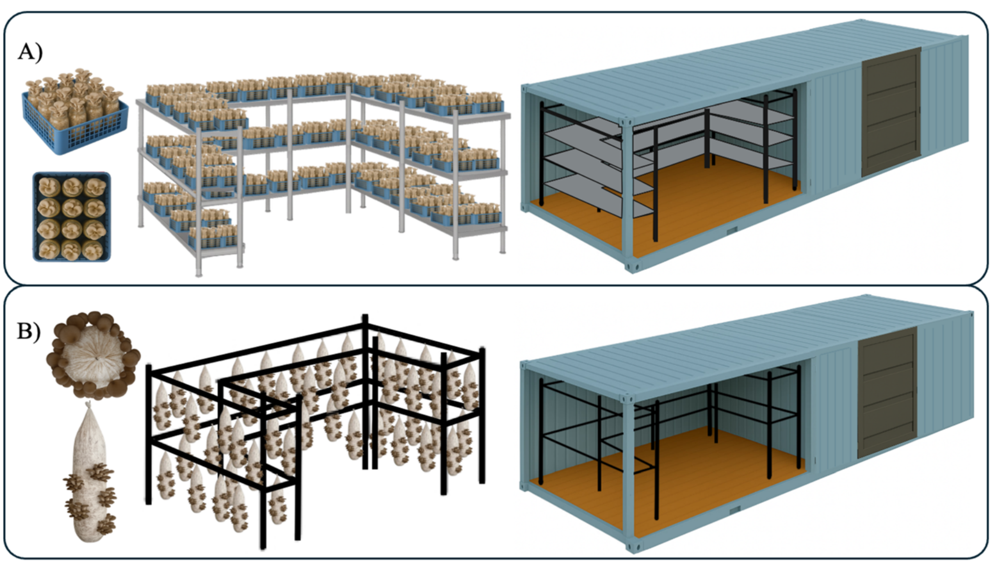

Fig. 6 Arrangement of substrate batches inside a shipping container partitioned into two chambers for optimized storage. (Panel A) Shows the layout of trays containing small plastic bottles, while (Panel B) shows the arrangement of plastic bags. For better visualization, both the top and side views of the shipping container are provided in each panel.

Table 3 Initial investment cost in equipment, land, installation, and construction of a small and medium-sized shipping container-based mushroom farm

	Mushroom farm's production capacity			
Items	50 lb per day ($)	100 lb per day ($)	200 lb per day ($)	500 lb per day ($)
Autoclave	60 000	120 000	180 000	180 000
Industrial balance	1700	1700	3400	5100
Filling machine	3000	3000	6000	6000
Ribbon Mixer	17 500	35 000	52 500	52 500
Industrial stacker	7500	7500	15 000	15 000
Other cost	16 440	31 940	48 380	48 720
Refrigerated container	25 000	50 000	125 000	262 500
Regular container	40 000	56 000	60,000	96 000
Land	15 000	25 000	37 500	62 500
Installation and construction	55 842	99 042	158 334	218 496
Total	241 982	429 182	686 114	946 816

rises proportionally with greater substrate volumes, higher spawn consumption, and increased energy demand, reaching $477 for Oyster, $583 for Lion's mane, $568 for Maitake, and $480 for Enoki. At 200 lb per day, daily operating costs increase further to $691 for Oyster, $902 for Lion's mane, $870 for Maitake, and $695 for Enoki, driven by more frequent substrate preparation cycles, expanded labor requirements, and intensified HVAC operation.

At the largest production scale (500 lb per day), OpEx peaks at $1062 for Oyster, $1590 for Lion's mane, $1506 for Maitake, and $1070 for Enoki, reflecting substantial increases in energy consumption, packaging needs, and overall process throughput associated with high-volume production. Across all scales, Lion's mane and Maitake consistently exhibit higher operating costs due to stricter environmental control requirements and more labor-intensive handling. In contrast, Oyster and Enoki remain comparatively less costly to produce.

Examination of individual operating cost components reveals clear scale-dependent trends and, in some cases, species-independent behaviors. Water costs increase proportionally with production volume, as higher substrate throughput, greater humidification demand, and more frequent sanitation activities require increased water use. Daily water expenses rise from $2.8 at 50 lb per day to $27.8 at 500 lb per day, reflecting the combined contributions of misting, substrate hydration, soaking, and routine cleaning.

Labor costs also scale upward with increasing production capacity, as additional time is required for substrate preparation, inoculation, environmental monitoring, harvesting support, and general chamber maintenance. Total labor expenses increase from $180.0 per day at 50 lb per day to $600.0 per day at 500 lb per day. However, labor cost per unit of production declines with scale, demonstrating clear economies of scale. Harvesting and packaging costs increase nearly linearly with output because each unit of production requires manual harvesting, trimming, and packaging. These costs rise from $18.5 per day at 50 lb per day to $185.0 per day at 500 lb per day, reflecting the direct relationship between production volume and packaging material consumption and handling effort.

Substrate costs vary across species due to differences in substrate composition, bulk density, and moisture requirements. At the smallest production scale (50 lb per day), daily substrate expenses range from $5.2 for Oyster to $11.3 for Maitake, with Enoki remaining comparatively low at $5.3. As production increases to 500 lb per day, substrate costs scale accordingly, reaching $51.8 for Oyster, $90.0 for Lion's mane, $112.5 for Maitake, and $52.9 for Enoki. Spawn costs exhibit the most significant species-specific variation because they are directly influenced by biological efficiency. Species with higher biological efficiency require less substrate to achieve the same output; because spawn is applied at a fixed inoculation rate (10% w/w), lower substrate requirements translate directly into reduced spawn demand. Consequently, Oyster and Enoki exhibit relatively low spawn costs across all scales ($16.8–$171.6), whereas Lion's mane and Maitake, characterized by lower biological efficiency require greater substrate input and therefore incur substantially higher spawn costs ($65.6–$656.3).

Electricity costs vary across species because of differences in temperature setpoints, humidity control, and ventilation requirements. At the smallest production scale (50 lb per day), daily electricity expenses range from $30.2 for Oyster to $33.6 for Maitake. As production increases to 500 lb per day, electricity costs rise substantially to $150.3–$166.0 per day, reflecting the greater HVAC demand associated with larger cultivation volumes and intensified environmental control. Overall, Lion's mane and Maitake incur higher substrate, spawn, and electricity costs due to their lower biological efficiency and more stringent climate requirements. In contrast, Oyster and Enoki consistently remain the most cost-effective species across all production scales.[39,50] The estimated energy consumption of 4 kWh per lb at the 500 lb per day scale is reasonable and consistent with literature values, as container-based mushroom cultivation requires additional HVAC, humidification, and environmental control energy compared with conventional systems. Robinson *et al.* reported total primary energy use of approximately 2.8 kWh per lb, with electricity as the dominant

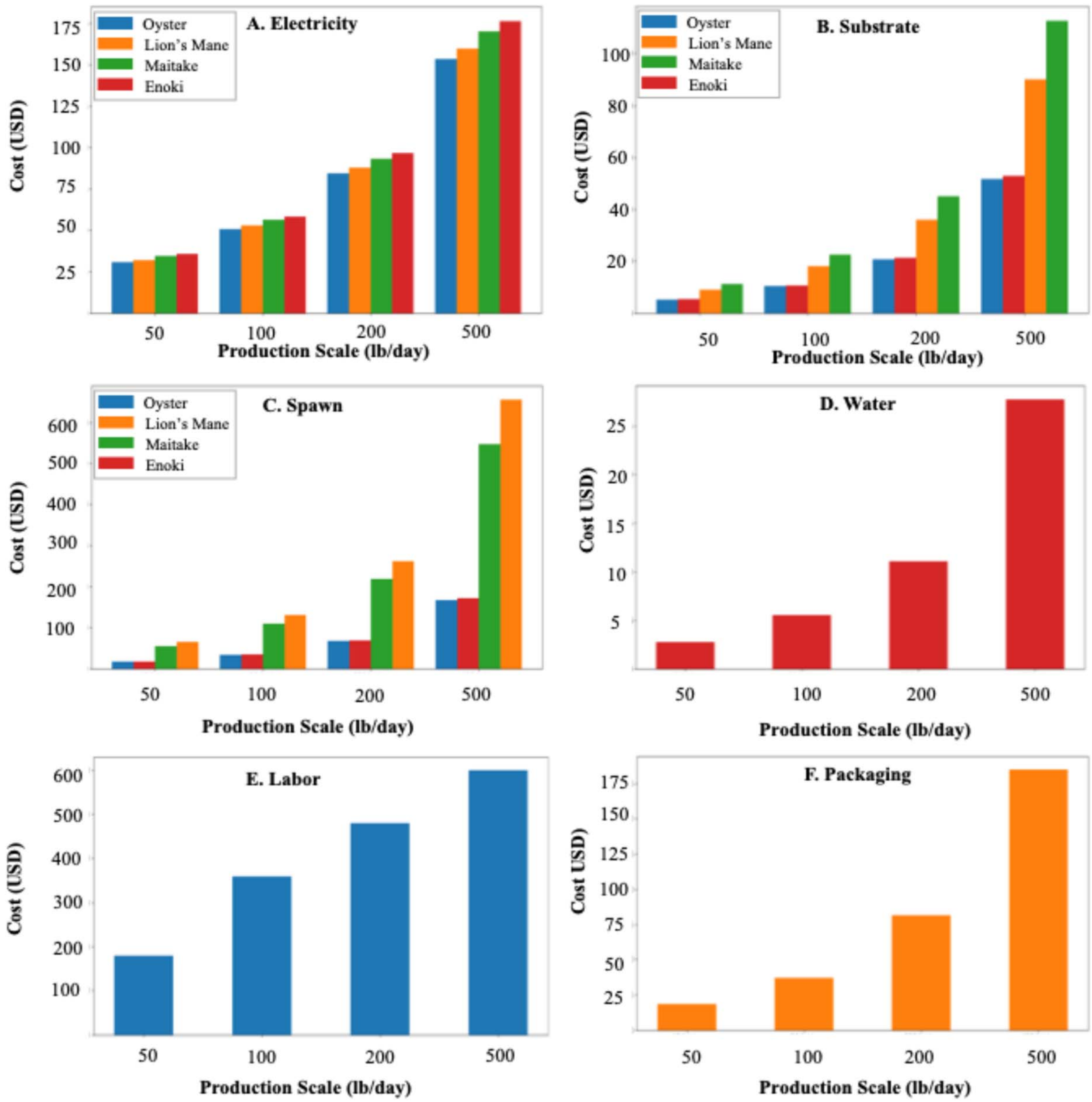

Fig. 7 Cost breakdown of production inputs across mushroom types and production scales. (Panels A–C) Show the costs of electricity, substrate, and spawn for four mushroom types—Oyster, Maitake, Enoki, and Lion's Mane—across four production scales (50, 100, 200, and 500 lb per day). (Panels D–F) Present the costs of water, labor, and packaging, which remain consistent across all mushroom types.

contributor, supporting the plausibility of higher energy intensity in more tightly controlled production systems.[39]

3.4. Sensitivity analysis of ventilation and transmission loads

To assess the impact of seasonal climate variability on container energy performance, a month-by-month temperature sensitivity analysis was conducted for both ventilation energy (E_{vent}), and transmission energy (E_{trans}) across four cultivated mushroom species. For each month, the effective ambient temperature was defined as the average of the monthly high and low temperatures, representing typical outdoor operating conditions for the container. These monthly ambient temperatures range from approximately 12 °C in the winter months (January and December) to 28–29 °C in the summer months (July and August), producing pronounced seasonal variability in thermal loading (Fig S2).

Using these ambient conditions, a monthly temperature difference ΔT was calculated for each species based on its species-specific growing temperature (setpoint). The four mushrooms evaluated (Oyster, Maitake, Lion's mane, and Enoki), exhibit distinct thermal preferences, with Oyster requiring the warmest conditions and Enoki the coldest. Consequently, ΔT varies substantially across species and seasons. Oyster shows small or near-zero ΔT values during warmer months (May–September) and, in some cases, slightly positive values, reflecting minimal cooling requirements. In contrast, Maitake and Enoki exhibit consistently large positive

ΔT values during summer because their cultivation temperatures must be maintained well below outdoor conditions. During winter months, Oyster and Lion's mane experience negative ΔT values, indicating net heat loss to the environment and a corresponding need for space heating rather than cooling.

These monthly ΔT values directly govern the ventilation energy (E_{vent}) and transmission energy (E_{trans}) requirements associated with air exchange and conductive heat transfer through the container envelope. When $\Delta T < 0$, heat is lost from the container to the surroundings, resulting in negative values of E_{vent} and E_{trans} and indicating a heating demand. Conversely, when $\Delta T > 0$, the HVAC system must remove excess heat, resulting in positive energy values associated with cooling demand. Oyster mushrooms, which grow at temperatures close to ambient conditions, require little to no cooling during spring and fall but exhibit substantial heating demand in winter (*e.g.*, $E_{vent} = -8.3$ in January, −7.3 in February, and −7.9 in December). Lion's mane follows a similar trend, with pronounced winter heating requirements ($E_{vent} = -7.1$ in January and −6.8 in December) and only moderate cooling demand during summer, peaking at approximately 5.8 in August.

In contrast, Maitake and Enoki, which require significantly cooler growing conditions, experience sustained and elevated cooling loads during warm months. Maitake's cooling demand increases sharply from late spring into summer, reaching approximately 6.8 in May, 9.4 in June, 10.2 in July, and peaking at 10.5 in August. Enoki displays a comparable seasonal pattern, with cooling demand rising from 5.7 in May to 8.2 in June, 9.1 in July, and 9.3 in August. Elevated cooling requirements persist into early autumn for both species (*e.g.*, 7.4 for Enoki and 8.5 for Maitake in September). Collectively, these results highlight that warm-climate conditions impose minimal cooling burdens for warm-growing species such as Oyster and Lion's mane, while generating substantial HVAC energy demand for colder-growing species, particularly Maitake and Enoki.

Transmission energy (E_{trans}) exhibits a seasonal pattern similar to ventilation energy but remains smaller in magnitude due to the container's high insulation ($U = 0.07$ W m^{-2} K^{-1}). As outdoor temperatures exceed species-specific setpoints, $E_{(trans)}$ becomes increasingly positive, reflecting additional cooling demand. Warm-growing species such as Oyster experience modest summer transmission loads, rising from 0.1–0.5 kWh between May and August, peaking at 0.5 kWh in August. Colder-growing species, including Maitake and Enoki, show larger midsummer values due to greater temperature differentials: Maitake increases from 0.7 kWh in May to 1.1 kWh in August, while Enoki ranges from 0.6 kWh in May to 0.9 kWh from June through August. Lion's mane follows a similar trend, increasing from 0.2 kWh in May to 0.6 kWh in July and August (Fig S3).

During winter, all species exhibit negative transmission energy, indicating heating demand rather than cooling demand. For example, Oyster reaches 0.8 kWh in January and December, Lion's mane −0.7 kWh in January and 0.3 kWh in December, and Enoki −0.4 kWh in January and 0.3 kWh in December. Although transmission contributes less to total thermal load than ventilation, it responds strongly to monthly temperature fluctuations, reinforcing the pattern of high cooling demand in summer and heating demand in winter. Overall, the combined climate data, species-specific ΔT, and resulting $E_{(vent)}$ and $E_{(trans)}$ values demonstrate that ambient temperature strongly governs heating and cooling requirements. Species cultivated at lower setpoints (Enoki, Maitake) are considerably more sensitive to warm climates than those grown near ambient conditions (Oyster, Lion's mane).

3.5. Production cost analysis

The cost analysis across four production scales (50, 100, 200, and 500 lb per day), reveals clear economies of scale for all mushroom species evaluated. As production volume increases, the unit cost per pound declines substantially, highlighting the economic advantage of scaling controlled-environment mushroom operations. Oyster and Enoki exhibit the highest cost efficiency, with per-pound costs dropping from \$5.1 at 50 lb per day to \$2.1 at 500 lb per day, a nearly 59% reduction. Lion's mane, the most resource-intensive species, also shows significant cost savings, decreasing from \$6.1 to \$3.2 per pound (48% reduction), while Maitake follows a similar trend, falling from \$6.0 to \$3.0 per pound (50% reduction). These reductions result from more efficient utilization of substrate, spawn, electricity, and labor, as well as better amortization of fixed infrastructure, including climate-control systems, environmental sensors, and automated handling equipment.

The steepest unit-cost reduction occurs between 200 lb per day and 500 lb per day, marking the production scale at which the benefits of scaling outweigh the added operational complexity. As output increases, fixed costs are distributed over a larger production volume, lowering per-pound costs without a proportional rise in inputs. Across all scales, Lion's mane remains the costliest to produce due to its strict environmental requirements and slower growth cycle. In contrast, Oyster and Enoki remain the most economical, suitable for both small- and large-scale cultivation. These results underscore that scaling production capacity is a key strategy for improving economic performance and achieving competitive unit costs in container-based mushroom farming. Consistent with Dushyant Kumar *et al.*, larger-scale mushroom farms achieve lower per-unit production costs due to economies of scale, as fixed costs are spread over higher output and bulk purchasing reduces the unit costs of compost, spawn, labor, and energy.[51]

3.6. NPV analysis

Net Present Value (NPV) is a key metric for evaluating the financial feasibility of an investment, comparing the present value of projected cash inflows with the discounted value of capital and operating expenditures over the project lifetime. In this study, NPV was used to assess the profitability of container-based mushroom cultivation for four species Oyster, Enoki, Maitake, and Lion's mane under an 80% loan and 20% equity financing structure with a 30% corporate tax rate. All capital equipment and container infrastructure were depreciated using the straight-line method over a 10-year useful life (Fig. 8).

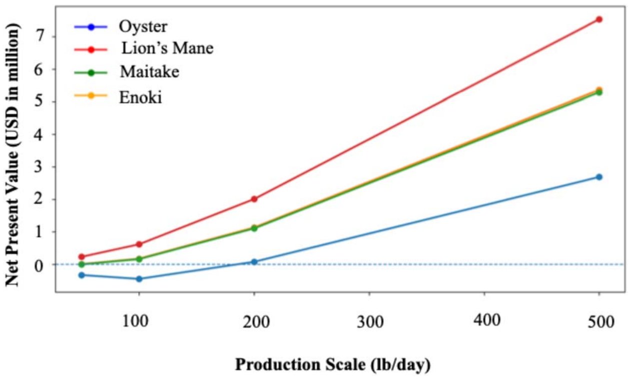

Fig. 8 Net Present Value (NPV) of mushroom production for different mushrooms and scales. NPVs are shown for four mushroom strains—Oyster, Maitake, Enoki, and Lion's Mane at production capacities of 50, 100, 200, and 500 lb per day. The dashed line at NPV = 0 indicates the break-even point.

Fig. 9 Payback period for mushroom production at different scales. The figure illustrates the payback period (years) for four mushroom varieties across multiple production scales under a financing structure of 80% debt and 20% equity. Darker green shades indicate longer payback periods, whereas lighter green shades indicate shorter ones. Red cells indicate payback periods exceeding 10 years, suggesting financial infeasibility. The analysis excludes the time required for facility setup and ramp-up to steady-state production, which may take up to one year.

At the smallest scale of 50 lb per day, only Maitake, Enoki, and Lion's mane achieve positive NPVs ($1686, $14 746, and $235 297, respectively). At the same time, Oyster remains unprofitable (−$322 758), reflecting the difficulty of covering fixed infrastructure and operational costs at low volumes. At 100 lb per day, profitability improves for all species except Oyster, with Lion's mane showing the strongest performance ($619 195), followed by Enoki ($181 765) and Maitake ($164 066). Oyster's NPV remains negative (−$441 563), though the deficit is smaller, signaling early benefits of scale.

At 200 lb per day, all species achieve positive NPVs for the first time, marking this as the minimum scale for universal financial viability. Lion's mane leads with $2 011 248, followed by Enoki ($1 140 062), Maitake ($1 106 910), and Oyster ($81 229). This scale demonstrates effective amortization of fixed costs and improved operational efficiency. At the largest scale (500 lb per day), profitability is maximized. Lion's mane remains the most lucrative ($7 538 331), followed by Enoki ($5 365 878), Maitake ($5 284 834), and Oyster ($2 688 702). High output volumes, optimized energy use, reduced per-unit labor, and efficient substrate handling drive strong positive cash flows. Detailed revenue and discounted net cash flow data for the four species are presented in Tables S5–S8.

Production scale is the dominant driver of profitability in container-based mushroom cultivation. High-value species such as Lion's mane and Maitake consistently yield superior financial returns, whereas lower-margin species like Oyster become financially attractive only at larger scales. Annual revenues and discounted net cash flows across scales (50–500 lb per day) demonstrate clear economies of scale, with the most substantial gains observed at 200 and 500 lb per day. These results highlight the importance of both production scale and species selection in achieving sustainable, long-term financial performance.

3.7. Payback period evaluation

Payback period analysis demonstrates a strong dependence of financial feasibility on production scale for container-based mushroom farming (Fig. 9). At the smallest scale (50 lb per day), Oyster, Maitake, and Enoki mushrooms do not achieve payback within the 10-year project horizon, indicating high financial risk, whereas Lion's Mane reaches a payback period of 5.8 years. At 100 lb per day, Oyster remains unprofitable within the project timeframe, while payback periods improve to 8.0 years for Maitake, 7.7 years for Enoki, and 4.9 years for Lion's Mane, reflecting gradual cost recovery but continued capital constraints at small scales. At 200 lb per day, financial performance improves substantially across all species, with payback periods of 9.8 years for Oyster, 4.6 years for Maitake, 4.4 years for Enoki, and 3.4 years for Lion's Mane, demonstrating more efficient utilization of fixed infrastructure and operational scaling. The most favorable outcomes occur at 500 lb per day, where all species achieve rapid capital recovery, with payback periods of 3.4 years for Oyster, 2.5 years for Maitake, 2.4 years for Enoki, and 2.1 years for Lion's Mane.

Importantly, all reported payback periods already include an additional one year to account for container installation, infrastructure setup, system commissioning, and ramp-up to steady mushroom production, providing a realistic estimate of time to profitability. The results highlight the economic advantage of scaling production, as larger systems distribute capital and operating costs over higher output, while small-scale farms remain financially vulnerable unless supported by premium pricing, external funding, or targeted efficiency improvements.

4 Conclusion and future directions

This study demonstrates that container-based mushroom farming offers a scalable, hygienic, and efficient platform for year-round production. The modular design enables flexible species selection, batch scheduling, and environmental zoning, while standardized infrastructure ensures consistent climate control and reduces the risk of contamination. Production scale was identified as the primary driver of financial performance. Small-scale systems (50–100 lb per day) incur high per-unit costs and long payback periods, particularly for low-margin species such as Oyster, making them financially challenging without subsidies, premium markets, or technological support. In contrast, larger systems (200–500 lb per day) benefit from economies of scale, achieving lower operating costs, positive NPVs, and faster capital recovery. High-value species such as Lion's mane consistently deliver quicker returns, highlighting their commercial viability.

Beyond economics, containerized farms provide a controlled, climate-resilient solution that can operate independently of location or season. Future work should explore renewable energy integration (*e.g.*, solar-assisted HVAC), location-specific energy optimization, automation of harvesting and substrate handling, and the application of artificial intelligence for real-time climate control. Incorporating life-cycle assessment and carbon footprint analysis would further elucidate environmental sustainability. Additional opportunities include cultivating medicinal fungi and vertical stacking to increase yield density. With appropriate technological and financial support, container-based mushroom cultivation has strong potential as a robust, scalable, and climate-resilient strategy for sustainable global food production.

Author contributions

Mahsa Alian: methodology, visualization, resources, writing – original draft, review & editing. Sunil P. Dhoubhadel: techno-economic analysis, editing; Sandesh Risal and Pratikshya Tiwari: setting up the model, calculations, and techno-economic analysis; Weihang Zhu: editing, and funding acquisition; Venkatesh Balan: conceptualization, methodology, resources, writing original draft, review & editing, and funding acquisition.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Abbreviations

NPV	Net Present Value
CapEx	Capital Expenditure
OpEx	Operational Expenditure
BE	Biological Efficiency
WACC	Weighted Average Cost of Capital
HVAC	Heating, Ventilation, and Air Conditioning

Data availability

All data supporting the findings of this article are presented in the manuscript's tables and figures. No restrictions apply to the availability of these data.

Supplementary information (SI) is available. See DOI: https://doi.org/10.1039/d6fb00006a.

Acknowledgements

This project was supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, under award numbers 2021-67022-34889 and 2023-51300-40853. We also acknowledge the University of Houston Energy Transition Institute, supporting two undergraduate students (Mr Ayush Patel and Mr Viet-Joseph Dinh) who contributed to specific components of the project. Thanks to Mr Shiresh Bhatnagar from Netventix, Sugarland, Texas, and his team for drafting some of the figures for this manuscript.

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