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Abstract

Cordyceps militaris is a high-value medicinal mushroom with rapidly growing demand in functional food and nutraceutical markets, yet practical frameworks for small-scale household cultivation remain limited. This study presents an integrated technical and economic feasibility analysis of small-scale Cordyceps production, comparing two scenarios: Scenario 1, an entry-level household setup with one growth room and processing area; and Scenario 2, a larger configuration with two growth rooms and a shared processing area, with staggered scheduling. Both use consistent biological, operational, and market assumptions, with no hired labor. The analysis covers capital expenditure (CapEx), operating costs (OpEx), profitability metrics, payback period, and break-even thresholds, complemented by sensitivity analysis on key biological parameters. While both scenarios are technically and financially viable, Scenario 2 delivers substantially superior returns, faster payback, and stronger resilience to variation in biological efficiency and contamination, requiring only modest incremental CapEx. Gross margins remain consistent across scales, indicating that expansion's advantage lies in more efficient CapEx amortization rather than improved unit profitability. Beyond financial performance, the findings highlight Cordyceps cultivation as a family-centered enterprise that can strengthen household economic diversification, generate supplementary or primary income, and contribute to the livelihoods of urban and rural families. :

Keywords: *Cordyceps*; value-added products; extractives; dietary supplements; nutraceuticals

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1. Introduction

Cordyceps militaris is a well-known medicinal mushroom that has attracted growing scientific and commercial interest for its diverse bioactive compounds, including cordycepin, adenosine, polysaccharides, carotenoids, and other secondary metabolites with proven antioxidant, antimicrobial, immunomodulatory, and antitumor effects [1–4]. Unlike wild Ophiocordyceps species, which are ecologically limited and difficult to harvest sustainably, *Cordyceps* species demonstrate stable growth under artificial conditions, making them especially suitable for controlled cultivation systems [5]. Over the past two decades, significant advances have been made in cultivating *Cordyceps* under artificial conditions, especially in East Asia, where standardized production methods based on

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liquid culture, cereal-based substrates, and carefully regulated environmental conditions have been developed [6,7]. Many studies have shown that key factors, including the nutritional composition of the substrate, vitamin supplementation, temperature, and cultivation strategy, strongly affect outcomes such as mycelial growth rate, fruiting body development, and cordycepin accumulation, highlighting the importance of precisely controlling growth parameters [1,6,8].

Despite these advances, much of the literature focuses on laboratory-scale optimization or industrial production systems that rely on specialized equipment, advanced technical skills, and significant investment. These methods are often impractical for beginners, home growers, or small-scale farms. As a result, a clear gap remains between scientific research and cultivation processes that are accessible, affordable, and reproducible on a small scale. This gap is especially pronounced for family-owned agricultural businesses and small-scale enterprises, which often lack access to the sophisticated infrastructure and capital needed for industrial-scale production systems. Many family farms and artisanal producers seek to diversify their operations through mushroom cultivation but are constrained by the technical complexity and high startup costs of conventional approaches. Furthermore, the transfer of knowledge from academic research to practical application remains limited, with few resources specifically designed to bridge the gap between scientific optimization and real-world implementation in resource-constrained environments.

Developing simplified, cost-effective cultivation methods would not only democratize access, enabling family businesses to enter this growing market while maintaining sustainable practices. Closing this gap is essential to expand sustainable Cordyceps production beyond industrial settings while preserving biological performance and product quality [1,7]. Alongside cultivation, post-harvest processing of Cordyceps has attracted growing attention for its direct impact on product stability and bioactive compound retention, as well as its value in the nutraceutical market. Prior studies show that processing parameters, including temperature, drying time, and scale, significantly affect the preservation of key compounds such as cordycepin, polysaccharides, carotenoids, and protein-derived fractions [6,8–10]. These results underscore the importance of pairing optimized cultivation methods with appropriate drying and downstream processing techniques to support the economic viability of small-scale operations and enable family businesses [11].

This paper provides a practical, comprehensive guide for families and individuals seeking to establish a Cordyceps cultivation business at the household and small-farm level. It includes step-by-step cultivation procedures with detailed figures; guidance on required equipment and consumables; realistic cost estimates; post-harvest drying techniques; and basic processing methods. By translating existing scientific knowledge into accessible, economically feasible practices, this work seeks to reduce technical and financial barriers for families entering this market sector. The paper concludes with a comprehensive economic analysis that evaluates CapEx, OpEx, revenue projections, and profitability timelines, enabling families to make informed decisions about establishing consistent, high-quality Cordyceps cultivation enterprises suitable for small farms and cottage industries.

2. Materials and Methods

2.1. Study Organism

Cordyceps produces distinctive orange, club-shaped fruiting bodies that are usually 6–8 cm tall. It is distinguished from the wild-harvested *Cordyceps* by its ability to be reliably cultivated under controlled conditions on grain-based substrates [12]. Its main bioactive compounds, especially cordycepin and adenosine, are highly valued in the pharmaceutical and nutraceutical industries [13]. For laboratory maintenance, *Cordyceps* cultures are routinely preserved on agar plates (such as potato dextrose agar or similar media) and stored under refrigerated conditions (~4 °C) to preserve viability and genetic stability. Periodic subculturing keeps the cultures actively growing, and they can be revived by transferring mycelial plugs onto fresh agar plates and incubating at optimal temperatures (usually 20–25 °C) to promote vigorous mycelial growth for subsequent inoculation and production.

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2.2. Study Site and Infrastructure

For this study, *Cordyceps* cultivation was carried out at R&P Biotics in Chennai, India, in a dedicated grow room measuring 10 × 14 feet (140 ft²). The room was insulated with cross-linked polyethylene sheets and equipped with steel racks holding 18 rows of shelving, capable of holding ~4,880 cultivation cups. The growing room included a split air-conditioning unit with a voltage stabilizer, pink-spectrum LED grow lights on a timer-controlled 12-hour photoperiod, two exhaust fans for air circulation, an ultrasonic humidifier, and a digital thermometer/hygrometer for continuous environmental monitoring. A generator was kept as a backup to ensure an uninterrupted power supply. Laboratory equipment included a laminar airflow (LAF) cabinet, an autoclave (121 °C, 15 PSI), and a rotary shaker operating at 60-70 RPM.

As illustrated in Figure 1, Scenario 1 is directly based on the experimental setup described above, replicating the single-room configuration used at R&P Biotics, a substrate preparation area (14′ × 10′, 140 ft²) housing the autoclave, laminar flow hood, and associated laboratory equipment, and a single growing room (14′ × 10′, 140 ft²) with insulation panels and six shelving units (5′ × 2′, three rows each), yielding 18 shelf rows for bag placement. Scenario 2 is a modeled expansion beyond the experimental setup, adding a second independent growing room of the same dimensions to create a three-room configuration, doubling shelf capacity to 36 rows across both growing rooms. Each growing room operates as a self-contained unit with its own HVAC system, LED lighting, and exhaust fans, while the substrate preparation area is shared between the two rooms on a staggered schedule.

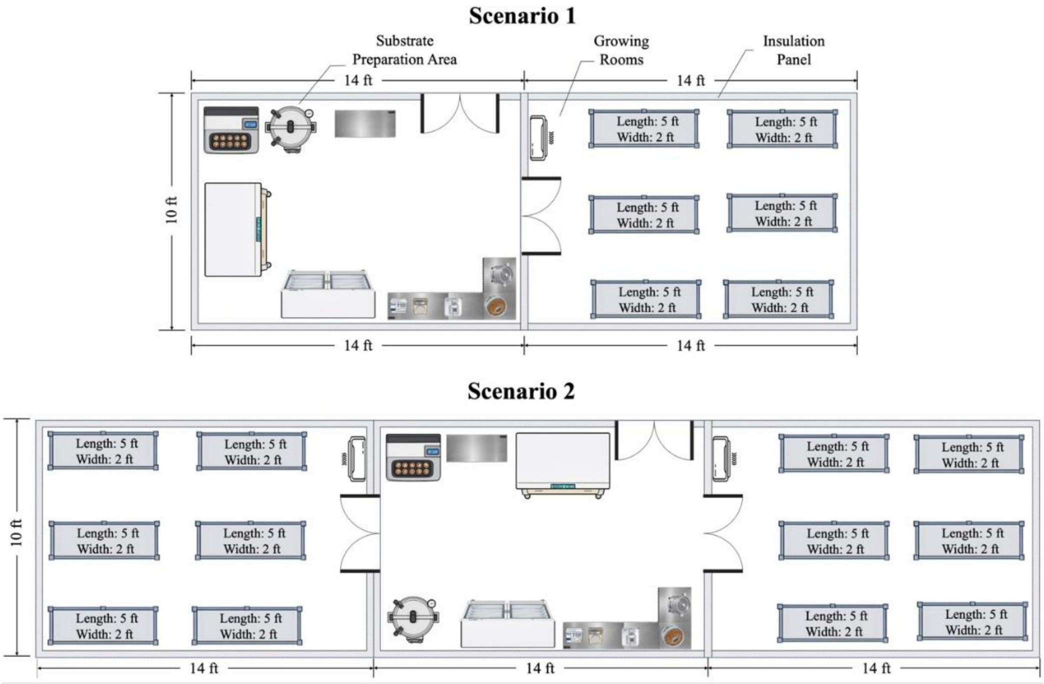


Figure 1. Facility floor plans for A: Scenario 1 and B: Scenario 2. Each growing room is fitted with six shelving units (5 ft × 2 ft, three rows each) and insulation panels. The substrate preparation area (14 ft × 10 ft) is shared between both rooms in Scenario 2 on a staggered schedule.

Both scenarios share identical assumptions for biological yield, contamination rate, substrate composition, selling price, and family-operated labor, with no hired workforce, ensuring that observed differences in financial performance arise solely from the scale and scheduling of production rather than from changes in underlying unit economics.

It should be noted that the experimental cultivation trials were conducted in polypropylene cups. However, for economic modeling in both scenarios, polypropylene fruiting bags are assumed as the production unit rather than cups. This substitution is justified on several grounds. First, reusable cups require repeated washing, sterilization, and handling between batches, adding labor, water, and energy costs that are particularly burdensome in a family-operated, no-hired-labor system. Second, bag cultivation provides superior moisture retention, better aeration, and more uniform mycelial colonization than rigid container systems, leading to higher yields and biological efficiency [14]. Third, at the production volumes modeled in this study, polypropylene fruiting bags represent a lower per-unit cost than reusable rigid containers. Bags are also the dominant cultivation vessel in small-scale specialty mushroom production globally, accounting for approximately 92% of worldwide output [15], and have been identified as a low-cost and economically viable cultivation strategy [14], ensuring that cost assumptions here are directly comparable to real-world commercial benchmarks.

2.3. Chemicals and Reagents

All chemicals were sourced from HiMedia Laboratories, India. The reagents were used across the three-culture media.

2.4. Equipment and Consumables

The glassware used included disposable Petri dishes, 250 mL and 500 mL conical flasks, test tubes, glass funnels, beakers, and measuring jars. Additional consumables included non-absorbent cotton for plugging, butter paper, aluminum foil, rubber bands, micropore tape (3 mm), disposable syringes, forceps, and surgical blades. A comprehensive visual inventory of all essential equipment, instruments, and consumables required for small-scale Cordyceps cultivation is provided in the supplementary materials (Supplementary Figures S1-S3). These detailed photographs illustrate major laboratory equipment, ancillary instruments, and complete lists of consumables, glassware, and laboratory tools necessary for successful cultivation operations. These comprehensive visual guides serve as practical reference materials for families and small-scale producers to systematically identify, procure, and organize all necessary components before initiating cultivation operations, ensuring complete preparation and minimizing setup delays.

2.5. Culture Medium

Medium 1 (for culture plates): About 32.5 g of PDA powder and 0.5 g of MgSO4 were mixed with 1,000 mL of preheated water at 70-80 °C and stirred continuously until homogeneous. The volume was then adjusted to 1,000 mL to compensate for evaporation. The medium was poured into test tubes (one-quarter capacity) or conical flasks for Petri dish preparation, sealed with non-absorbent cotton plugs covered with butter paper and aluminum foil, and autoclaved at 121 °C and 15 PSI for 30 minutes. It was then allowed to equilibrate at room temperature for 24 hours before inoculation. Medium 2 (for liquid culture) was prepared by dissolving potato dextrose broth (24 g/L), glucose (30 g/L), peptone (5 g/L), yeast extract (4 g/L), potassium dihydrogen orthophosphate (1 g/L), magnesium sulfate (0.5 g/L), and vitamin B1 (0.2 g/L) in 1000 mL of distilled water [16]. The medium was poured into conical flasks at 80% capacity, sealed with non-absorbent cotton plugs, wrapped in butter paper and aluminum foil, and autoclaved at 15 PSI for 30 minutes. Inoculation was performed within 24 hours of cooling to room temperature to prevent fermentation.

Medium 3 (nutrient solution for fruiting cup substrate): This basal nutrient solution was prepared at pH 7.5 by dissolving glucose (30 g/L), peptone (5 g/L), yeast extract (4 g/L), potassium dihydrogen orthophosphate (1 g/L), magnesium sulfate (0.5 g/L), ammonium citrate (1 g/L), vitamin B1 (0.2 g/L), and vitamin B12 (0.01 g/L) in 1,000 mL of distilled water [17–21]. For substrate preparation, 20 g of red rice was mixed with 32 mL of the nutrient solution at a ratio of 1 g to 1.6 mL per fruiting cup. The loaded fruiting bags were autoclaved at 121 °C for 30 minutes, then cooled to room temperature before inoculation.

2.6. Tissue Culture Initiation

Tissue culture was initiated by aseptically halving a healthy Cordyceps fruiting body and removing ~5 mm of the central medullary tissue. The tissue was transferred to PDA medium in a sterilized test tube or Petri dish. Petri dish rims were taped to prevent opening while allowing limited gas exchange. All cultures were incubated in darkness at 18-22 °C for 15 days. After the dark phase, cultures were exposed to ambient light for two to four days; successful isolation was confirmed by a color change in the mycelium from white to orange.

2.7. Liquid Spawn Preparation

Conical flasks containing sterilized Medium 2 were placed in the UV-treated LAF for 30 minutes before inoculation. A fragment of Cordyceps mycelium (0.5-1.0 cm) was aseptically transferred from the test tube culture into each Erlenmeyer flask, ensuring the forceps did not touch the inner flask walls. Inoculated flasks were closed using a cotton plug for air exchange, placed on a rotary shaker at 60-70 RPM, covered with opaque black polyethylene to block light, and incubated for five to seven days. Liquid-spawn cultures were considered ready when the mycelium was evenly distributed throughout the medium [17].

2.8. Fruiting Bag Inoculation

Sterilized fruiting bags were placed in the UV-treated laminar airflow cabinet for 30 minutes before inoculation. Five milliliters of liquid spawn were injected into each fruiting cup or bag containing 20 grams of red rice using a sterile disposable syringe. The bag was gently rotated to evenly distribute the inoculum across the rice substrate.

2.9. Cultivation Conditions

After inoculation, 54 fruiting bags were placed on shelves and covered with opaque black polythene to block all light. Temperature was maintained between 19 and 21 °C with no added humidity. Colonization was monitored by visual inspection through the container walls. When the red rice substrate was fully covered with white mycelium, usually within 7-10 days after inoculation, it signaled readiness to move to the light phase. After full colonization, fruiting bags were transferred to shelves fitted with pink-spectrum LED lights operating on a 12-hour light:12-hour dark cycle, controlled by timer switches. The temperature was kept between 16-20 °C, and the relative humidity was maintained at 90-95% using an ultrasonic humidifier [22]. The change in mycelium color from white to orange, which usually occurs within 2 days of light exposure, served as a key developmental indicator. Primordia were expected to appear between days 17 and 20 post-inoculation, with visible fruiting bodies developing from day 25 onward.

2.10. Fruiting Body Harvest

Fruiting bodies were harvested between days 56 and 60 post-inoculation, once they reached full maturity. Alcohol sprayed gloves were used during harvesting. Mushrooms were carefully hand-picked to minimize mechanical damage. Any fruiting bags showing signs of contamination at any stage of growth were immediately removed from the grow room and discarded [23].

2.11. Post-Harvest Drying and Storage

Harvested fruiting bodies were dried in a food-grade vegetable dehydrator at 40 °C until reaching a final moisture content of ~5%. Drying method significantly influences the retention of bioactive compounds in Cordyceps: freeze-drying preserves the highest cordycepin content, sun-drying maximizes adenosine retention, and hot-air and vacuum drying achieve the best balance for other thermolabile metabolites [24]. Hot-air dehydration was selected for this study as a practical compromise between cost, accessibility, and bioactive compound preservation, making it well-suited for household-scale operations. The dried mushrooms were then vacuum sealed in airtight pouches to prevent moisture reabsorption

2.12. Growth Monitoring and Quality Control

Development was monitored daily in accordance with the timeline outlined in Table 1. Fruiting bags were discarded if mycelium did not turn from white to orange within three days of moving to the light phase or if any visible contamination was present, and bags were kept sealed until harvest to avoid moisture loss.

Table 1. Growth Monitoring Timeline for *Cordyceps* Cultivation.

Day / Stage	Observation and Action
Day 0	Inoculation: bags transferred to dark phase
Days 7-10	Assess mycelial colonization; transfer to the light phase upon full coverage
Day 9 (approx.)	Mycelium color shift from white to orange (key quality indicator)
Days 17-20	Emergence of primordia (pin heads)
Day 25	Visible early-stage fruiting bodies
Days 26-55	Progressive fruiting body development
Days 56-60	Harvest window; monitor daily for maturity

Beyond visual inspection, contamination monitoring was conducted throughout the cultivation cycle by examining bags daily for abnormal coloration, unusual odor, or visible mold growth; any compromised bags were immediately removed from the grow room and discarded to prevent cross-contamination. At harvest, microbial quality of the fruiting bodies is recommended to be further assessed using ATP (adenosine triphosphate) bioluminescence assay kits, which provide a rapid and sensitive measure of total microbial load by quantifying cellular ATP as a proxy for viable microbial biomass. The ATP assay was not performed in our study; however, ATP assay results will help verify that harvested mushrooms meet acceptable microbiological standards prior to packaging [25–27]. This dual approach, combining continuous visual monitoring during cultivation with quantitative biochemical assessment at harvest, ensured consistent quality control across all production batches and supported the 15% contamination rate assumption used in the calculations.

2.13. Techno-Economic Analysis (TEA)

TEA was conducted to assess the financial viability of small-scale Cordyceps production under two scenarios. Scenario 1 represents the baseline configuration operated by one family member. Scenario 2 represents a scaled-up configuration operated by two family members. Both scenarios assume no hired labor, the same cultivation cycle, market pricing, and financial parameters. All financial values are reported in United States Dollars (USD). Production assumptions, CapEx, OpEx, and 5-year projections were modeled in a purpose-built spreadsheet to estimate return on investment (ROI), net present value (NPV), internal rate of return (IRR), payback period, and break-even analysis. The key production parameters used are shown in Table 2.

Table 2. Production and Financial Assumptions for Scenario 1 and Scenario 2.

Parameter	Scenario 1	Scenario 2	Unit
Production parameters			
Fruiting bags per batch	1,250	2,500	bags
Bag size	500	500	ml
Red rice per batch	55	110	lb/bag
Liquid spawn per bag	5	5	ml/bag
Moisture content (fresh mushroom)	90	90	%
Dark period	10	10	days

Light period	50	50	days
Total cycle duration	94	94	days
Batches per year	5	9	batches
Yield parameters			
Fresh yield per batch	55	110	lb/batch
Contamination risk	15	15	%/batch
Operator	1 family member	2 family members	—
Market assumptions			
Selling price — low	80	80	USD/lb
Selling price — average	90	90	USD/lb
Selling price — high	100	100	USD/lb
Financial assumptions			
Total CapEx (shared)	32,180	44,654	USD
Loan portion of CapEx	80	80	%
Bank loan interest rate	8	8	%
Discount rate	8	8	%
Tax rate	30	30	%
Annual escalation rate	2.5	2.5	%

In this model, mushroom yield is assumed to be 55 lb/batch (Scenario 1) and 110 lb/batch (Scenario 2) at 90% moisture. Pricing benchmarks were established at \$80/lb (wholesale low), \$90/lb (average), and \$100/lb (retail high), based on prevailing US market rates for organic Cordyceps fresh fruiting bodies. An 8% discount rate, a 30% tax rate, an annual cost escalation of 2.5%, and loan financing covering 80% of CapEx expenses were applied consistently across the financial models. CapEx included all one-time investments required to set up the growth rooms and major/ancillary equipment, totaling \$32,180 for Scenario 1 and \$44,654 for Scenario 2, as shown in Table 3.

Equipment was grouped into four categories: (a) major laboratory instruments, (b) ancillary equipment, (c) grow room infrastructure, and (d) glassware and lab tools. A 5% contingency was added to the subtotal. OpEx was evaluated on a per-batch basis and categorized into three components: substrate and growth media, consumables, and utilities. Labor costs were excluded from both scenarios because the operation is family-owned and has no hired labor.

Table 3. CapEx for *Cordyceps* Small-Scale Production Unit for the two scenarios.

Item	**Qty (1)**	**Cost (1)**	**Qty (2)**	**Cost (2)**
A. Major Instruments				
Autoclave/pressure sterilizer	1	\$2,250	2	\$4,500
Laminar flow hood (LAF)	1	\$1,500	1	\$1,500
Incubator/rotary shaker	1	\$2,250	2	\$4,500
Spectrophotometer	1	\$1,150	1	\$1,150
Refrigerator/freezer	1	\$1,400	2	\$2,800
Subtotal A		**\$8,550**		**\$14,450**
B. Ancillary Equipment				
HVAC system	2	\$6,000	3	\$9,000
Dehydrator	1	\$1,250	1	\$1,250
Moisture analyzer	1	\$1,000	1	\$1,000
Weighing machine	1	\$450	1	\$450
Magnetic stirrer	1	\$275	1	\$275
pH meter	1	\$200	1	\$200
Humidifier	1	\$200	1	\$200
Digital thermometer/hygrometer	1	\$100	1	\$100
Light meter	1	\$140	1	\$140
CO_2 meter	1	\$400	1	\$400

Vacuum sealer	1	$350	1	$350
Package sealer	1	$400	1	$400
Sticker maker/label printer	1	$400	1	$400
Stabilizer (voltage regulator)	1	$350	1	$350
Subtotal B		**$11,515**		**$14,515**
C. Grow Room Infrastructure				
XLPE insulation panels (incl. labor)	2	$2,000	3	$3,000
Steel racks (18 rows)	2	$2,300	3	$3,450
LED lights (wiring and labor included)	2	$1,200	3	$1,800
Exhaust fans (2 per room)	4	$460	6	$690
Generator/UPS backup	1	$2,750	1	$2,750
CCTV monitoring system	1	$550	1	$550
Subtotal C		**$9,260**		**$12,240**
D. Glassware and Lab Tools				
Glassware set, magnetic bars, spirit lamp, trays, mother culture (×2), and stationery	—	$1,323	—	$1,323
Subtotal D		**$1,323**		**$1,323**
Contingency and miscellaneous (5%)		$1,532		$2,126
Total CapEx		**$32,180**		**$44,654**

Note. CapEx differs between scenarios: $32,180 for Scenario 1 and $44,654 for Scenario 2. Equipment lifespan was assumed to be 10 years for depreciation purposes, with annual straight-line depreciation of $3,218 and $4,466 for Scenarios 1 and 2.

Total OpEx per batch was $1,683 for Scenario 1, and $3,309 for Scenario 2. The detailed per-batch OpEx breakdown for both scenarios is presented in Table 4.

Table 4. OpEx breakdown for Scenario 1 and Scenario 2.

Item	**Qty/batch (S1/S2)**	**Unit price (USD)**	**S1 (USD)**	**S2 (USD)**
A. Substrate and growth media				
Red rice	55 / 110 lb	$0.4	$23	$47
Growth media / PDA	0.1 / 0.2 lb	$90	$8	$16
DI water	46 / 92 L	$0.8	$35	$69
Potato Dextrose Broth	2.5 / 4.9 lb	$80	$196	$392
Glucose	4.7 / 9.4 lb	$60	$281	$563
K_2HPO_4	0.2 / 0.4 lb	$15	$3	$6
Peptone	1.0 / 2.0 lb	$70	$73	$143
Yeast extract	0.5 / 1.0 lb	$18	$9	$18
$MgSO_4$	0.1 / 0.2 lb	$70	$7	$14
Ammonium citrate	0.1 / 0.2 lb	$50	$5	$10
B1/B12 vitamins	0.04 lb / 0.08	$23	$0.1	$0.2
Subtotal A			**$634**	**$1,280**
B. Consumables				
PPE supplies	1 set	$45	$45	$90
Petri dish pack	1 pack	$28	$28	$55
Disposable syringes	1 pack	$20	$20	$40
Assay kit	2 kits	$300	$300	$600
Vacuum bags and labels	1 batch	$28	$28	$56
Mushroom bags	1,250 / 2,500	$0.4	$500	$1,000
Subtotal B			**$948**	**$1,840**
C. Utilities (91-day batch)				
Electricity (kWh)	1,270 / 2,519	$0.08	$95	$189
Water (gal)	111 / 222	$0.002	$0.2	0.3

Subtotal C	**$95**	**$189**
Total OpEx per batch	**$1,683**	**$3,309**

Note. All costs are in USD per batch. Electricity consumption was calculated using a bottom-up equipment model that accounted for system losses. PDA = potato dextrose agar; PPE = personal protective equipment.

2.14. Economic Modeling and Cost Analysis

The economic viability of small-scale Cordyceps production was evaluated using a 5-year discounted net return (DNR) model built in Microsoft Excel. The model calculated earnings before tax (EBT), net return after tax, NPV, IRR, payback period, ROI, and break-even points. Each analytical component and its governing equations are described in the following subsections. In developing the DNR, the annual EBT was first calculated by subtracting total annual OpEx, maintenance expenses, depreciation, and loan interest from the gross return. Depreciation was computed using the straight-line method over 10 years with zero salvage value, and loan interest was fixed at 8% of the remaining loan balance for all projection years. All financial metrics were computed using standard engineering economic methods [28] and managerial cost accounting principles [29]. EBT thus reflected the operation's true economic EBT, as shown in Equation (1).

$$EBT = Gross\ return - depreciation - loan\ Interest \tag{1}$$

where,

$$Gross\ return = Total\ revenue - total\ operating\ costs - maintenance\ cost$$

Income tax was applied at 30% of EBT in each projection year (Equation (2)), consistent with the applicable corporate tax rate. Net return after tax was then calculated as EBT plus depreciation minus the income tax charge (Equation (3)). Annual revenue and OpEx increased by 2.5% each year from Year 2 onward to reflect inflationary effects on prices and input costs.

$$Income\ Tax = EBT \times income\ tax\ rate \tag{2}$$

$$Net\ Return\ After\ Tax = EBT \times (1 - income\ tax\ rate) + depreciation \tag{3}$$

Adding annual depreciation back to EBT is necessary because depreciation is a non-cash accounting charge that reduces reported return but does not involve any actual cash outflow from the business. Net return (from this point forward, net return after tax is referred to simply as net return) thus represents the actual return generated by operations each year, available to cover CapEx. Cumulative net return was calculated as the running total of annual net return values, with the full CapEx outlay recorded as a negative value at Year 0 (Equation (4)). This allowed the payback period to be defined as the point at which cumulative net return first crossed zero.

$$Cumulative\ Net\ Return = -CAPEX + \sum_{n} net\ return(n) \tag{4}$$

NPV was calculated by discounting each year net return to its present value at an 8% discount rate, then summing over all 5 projection years and subtracting the CapEx (Equation (5)). Discounting adjusts future returns to reflect the time value of money; a dollar received in the future is worth less than a dollar received today. A positive NPV indicates that the project is expected to generate returns that exceed its total cost over the projection period.

$$NPV = -CAPEX + \sum n[(Net\ return(n))/((1 + r)\hat{}n\ )]\ , where\ n = 1\ to\ 5\ years \tag{5}$$

IRR is the discount rate at which the NPV of the project equals zero (Equation (6)). Unlike NPV, which evaluates project viability at a fixed discount rate, IRR expresses the project's inherent return as a single percentage, independent of any assumed rate. IRR was calculated iteratively using Microsoft Excel's built-in IRR function applied to the full net return series, including the Year 0 CapEx outflow. A project with an IRR exceeding the CapEx (8% in this study) is considered financially viable.

$$0 = -CAPEX + \sum\_n[(Net\ return(n))/((1 + r)\hat{}n\ )]\ , where\ n = 1\ to\ 5\ years \quad (6)$$

The discounted payback period is the first year in which the cumulative present value of DNR becomes non-negative (Equation (7)), indicating the complete recovery of the initial CapEx, adjusted for the time value of money. By discounting each year's free cash flow at the 8% rate, this metric provides a more conservative measure of investment recovery than the simple payback period, as it reflects the opportunity cost of CapEx over the entire recovery horizon.

$$Discounted\ Payback = first\ n\ where\ Cumulative\ PV(n) >= 0 \quad (7)$$

where

$$Cumulative\ PV(n) = \sum_n \left[\frac{Net\ return(n)}{(1 + r)^n}\right]$$

ROI was calculated as the ratio of the total cumulative net after-tax return over the full 5-year projection period to the total CapEx, expressed as a percentage (Equation (8)). This metric provides a simple, single-period measure of capital efficiency, with CapEx of $32,180 in Scenario 1 and $44,654 in Scenario 2.

$$\text{ROI (\%)} = [\Sigma_1^n \text{ Net Return}/\ Total\ CAPEX]\ x\ 100 \quad (8)$$

Break-even analysis was performed using the contribution margin method to determine the minimum production volume and minimum selling price at which the operation covers all costs. The contribution margin per pound is the portion of the selling price remaining after variable costs, available to recover CapEx (Equation (9)). The break-even volume is the annual output at which total contribution exactly matches total CapEx (Equation (10)). The break-even selling price at the current annual production volume was found by rearranging the cost-coverage condition (Equation (11)). Finally, the safety margin is measured as the percentage by which the actual selling price exceeds the break-even price, indicating the buffer before the operation starts incurring losses (Equation (12)).

$$Contribution\ Margin\ (\$/lb) = Selling\ Price - Variable\ Cost\ per\ lb \quad (9)$$

$$Break - Even\ Volume\ (lb/yr) = Fixed\ Costs\ per\ Year\ /\ Contribution\ Margin \quad (10)$$

$$Break - Even\ Price\left(\frac{\$}{lb}\right) = \left(\frac{Fixed\ Costs}{Annual\ Volume}\right) + Variable\ Cost/lb \quad (11)$$

$$Margin\ of\ Safety\ (\%) = [(Selling\ Price - Break - Even\ Price)/Selling\ Price]\ x\ 100 \quad (12)$$

3. Results and Discussion

The complete small-scale cultivation workflow for *Cordyceps* used in this study is summarized in Figure 2. The production cycle comprises four consecutive stages: (A) liquid culture preparation, in which nutrient media are prepared, sterilized, and inoculated to produce liquid spawn; (B) substrate inoculation and fruiting body development, involving grain substrate preparation, sterilization, inoculation, and incubation through dark and light phases until harvest-ready fruiting bodies form; (C) harvesting and quality control, including collecting fresh mushrooms, conducting microbiological assessment, performing compositional analysis, and measuring moisture and water activity; and (D) post-harvest processing and development of value-added products, such as dehydration, packaging, and powder production. Each stage is explained in detail in the following subsections.

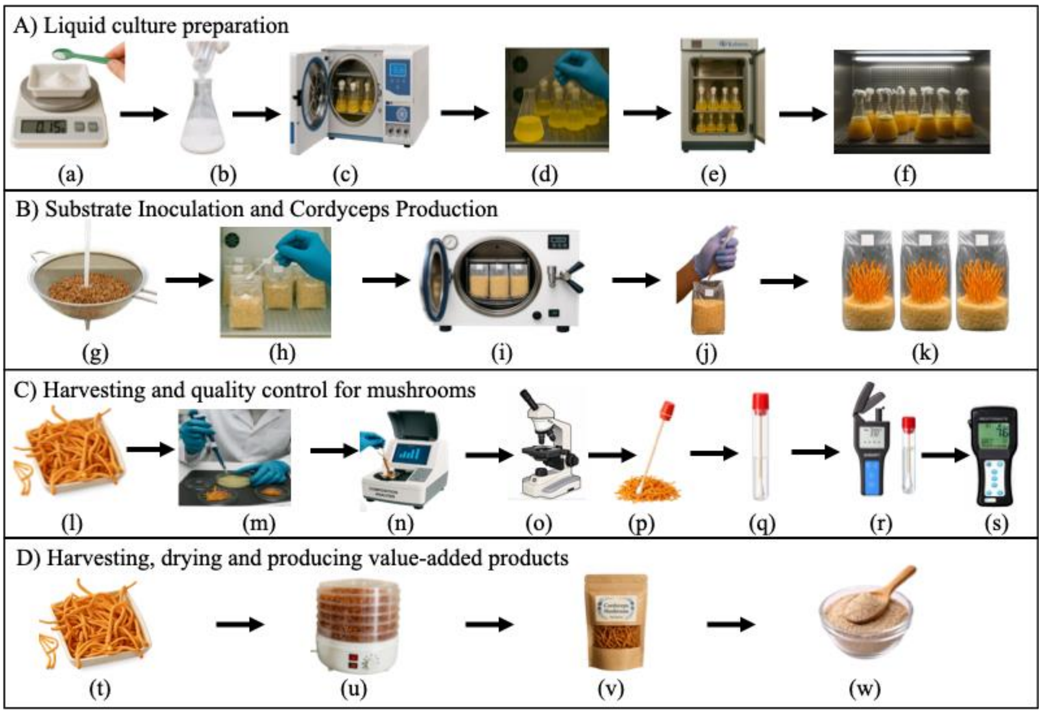


Figure 2. Process of producing cordyceps products. Here, a) media weighing, b) adding water, c) autoclaving media, d) inoculating media, e) incubating media, f) liquid culture, g) substrate preparation, h) adding chemical and nutrition, i) substrate sterilization, j) substrate inoculation, k) growth stage, l) harvested cordyceps, m) quality check, n) composition analysis, o) checking by microscope, p) preparing sample for APT assays, q) mixing with test solution, r) analyzing amount of microbe, s) reading results t) harvested cordyceps, u) drying mushroom, v) packaging mushroom, w) ground powder.

3.1. Production Scheduling and Batch Cycle Management

The production cycle spans 91 active days per batch, covering the full process from culture preparation through harvest, followed by 3 days of room cleaning at the end of each cycle, bringing the total cycle duration to 94 days. The phase sequence per batch is as follows: PDA preparation and inoculation (15 days), liquid media preparation (2 days), liquid spawn incubation in a rotary shaker (7 days), grain preparation and autoclaving (5 days), dark colonization period (10 days), pinning and fruiting body development (50 days), and harvest (2 days). Room fumigation and cleaning are conducted for 3 days immediately after harvest to prepare the space for the next batch.

In Scenario 1, the single growing room operates sequentially, with all preparatory stages completed in the substrate preparation area before each batch enters the dark colonization phase. Because only one room is available, a new batch cannot begin until the previous cycle, including room cleaning, is fully completed, limiting annual throughput to five production cycles within 365 days (Figure 3-Scenario 1).

In Scenario 2, two independent growing rooms operate with a 29-day offset between them. From the second batch onward, the preparatory stages for the incoming batch, including PDA preparation, media preparation, liquid spawn incubation, and grain preparation, are initiated in the shared substrate preparation area while the previous batch is still in its fruiting stage in the other room. The 29-day offset precisely matches the total substrate preparation duration of 29 days, ensuring that each incoming batch is ready to enter the dark phase exactly when the preparation area becomes available. This staggered two-room scheduling eliminates idle time between consecutive cycles, maintains physical separation between concurrent batches to minimize cross-contamination risk, and increases annual throughput to nine production cycles within 365 days (Figure 3).

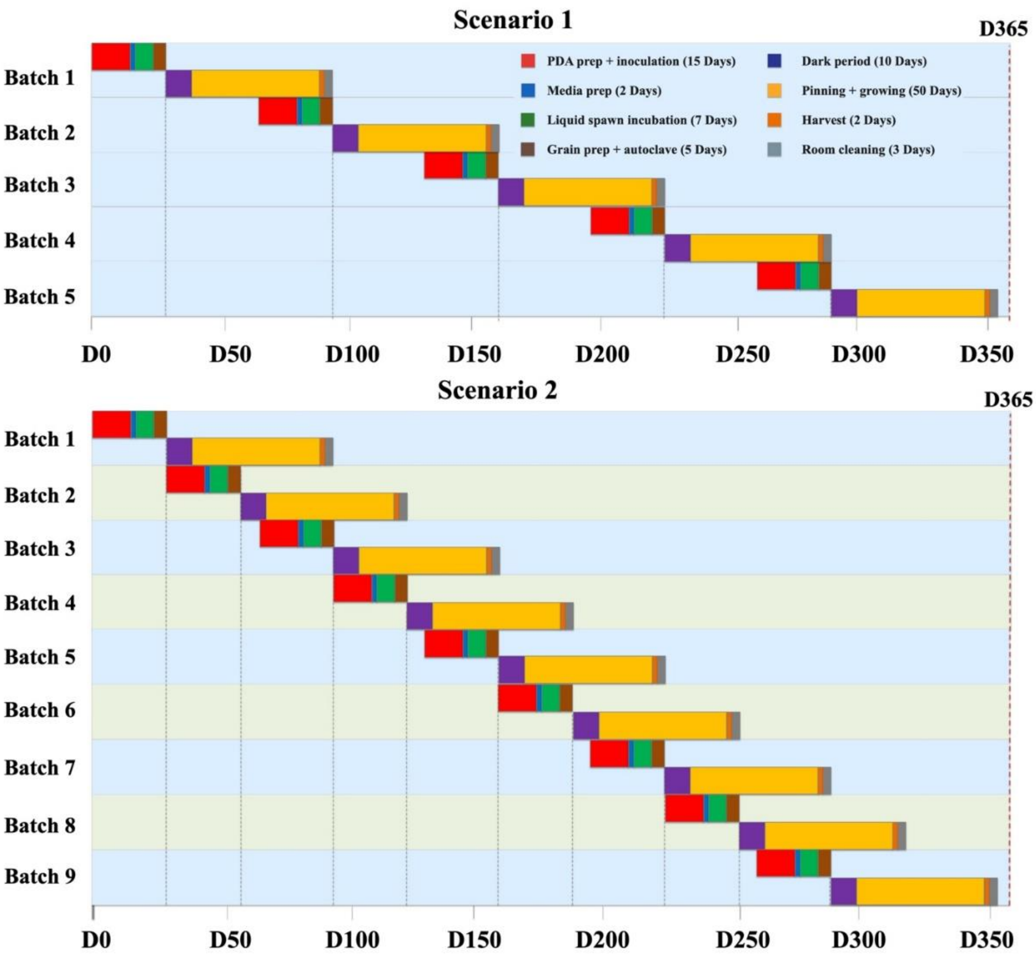


Figure 3. Gantt charts of the production schedules for Scenarios 1 and 2 over 365 days. Each batch follows a 94-day cycle comprising eight sequential phases. In Scenario 2, batches alternate between Grow Room 1 and Grow Room 2 with a 29-day offset, enabling continuous production throughout the year. The dashed red line marks Day 365, confirming all batches are completed within a single calendar year.

3.2. Cultivation Yield and BE

BE, defined as the ratio of fresh fruiting body weight to the dry weight of the substrate used, was calculated as follows. With a substrate loading of 0.04 lbs. of red rice per bag and 54 bags per batch, the total dry substrate weight was 2.4 lbs. BE ranged from 90% at the lower yield boundary to 110% at the upper boundary, averaging 100% after accounting for contamination losses. The relatively high BE achieved in this study may be attributed to the optimized nutrient solution formulation used in Medium 3, particularly the inclusion of vitamin B12, ammonium citrate, and a balanced carbon-to-nitrogen ratio, all of which have been reported to enhance fruiting body biomass accumulation in Cordyceps [23].

Fresh fruiting body yield per batch of 1,250 fruiting bags was estimated at 55 lbs., based on optimistic small-scale production benchmarks. After accounting for a 15% contamination rate, consistent with contamination risks reported under small-scale aseptic conditions, the adjusted average fresh yield was 47 lbs. per batch from ~1,063 effective bags. Dry yield, calculated at 90% moisture content, averaged 5 lbs. per batch for Scenario 1 and 10 lbs. per batch for Scenario 2. Across 5 production cycles per year for Scenario 1, annual fresh and dry yields were estimated at 234 lbs. and 23 lbs., respectively. For Scenario 2, operating 9 production cycles per year across 2 growing rooms, the annual fresh yield reached 842 lbs., with a corresponding dry yield of 84 lbs., reflecting the combined effect of doubled bag capacity and increased batch frequency.

3.3. OpEx and CapEx

The per-batch OpEx for Scenario 1 totaled $1,683, distributed across three categories (Table 4 and Figure 4a). Consumables accounted for the largest share at $948 (56%), driven primarily by the assay kit ($300) and mushroom packaging bags ($500). The dominance of consumable costs reflects the quality-assurance-intensive nature of medicinal mushroom production, where ATP assay kits, PPE, and sterile packaging are unavoidable per-batch expenditures.

Substrate and growth media accounted for $640 (38%), while utilities contributed $95 (6%), reflecting electricity consumption of 1,270 kWh per batch based on a bottom-up equipment model. Detailed electricity consumption calculations for both scenarios, including a bottom-up equipment-level breakdown of power ratings, operating hours, efficiency factors, and system losses, are provided in Tables S1 and S2. These findings suggest that cost-reduction strategies should primarily target consumable procurement through bulk purchasing or reusable PPE components, rather than substrate formulation, where ingredient costs are already low relative to total OpEx. Under Scenario 2, per-batch OpEx increased to $3,309, with consumables remaining the dominant category at $1,840 (55%), followed by substrate at $1,280 (39%) and utilities at $189 (6%) (Table 4 and Figure 4d).

Total CapEx was $32,180 for Scenario 1 and $44,654 for Scenario 2 (Table 3, Figures 4b and 4e). The composition of CapEx differs notably between the two scenarios. In Scenario 1, ancillary equipment formed the largest share at 36%, followed by grow room infrastructure at 29%, major laboratory instruments at 27%, glassware and lab tools at 4%, and contingency at approximately 5%. In Scenario 2, ancillary equipment and major laboratory instruments became nearly equal at 33% and 32%, respectively, followed by grow room infrastructure at 27%, glassware, and lab tools at 3%, and contingency at ~5%.

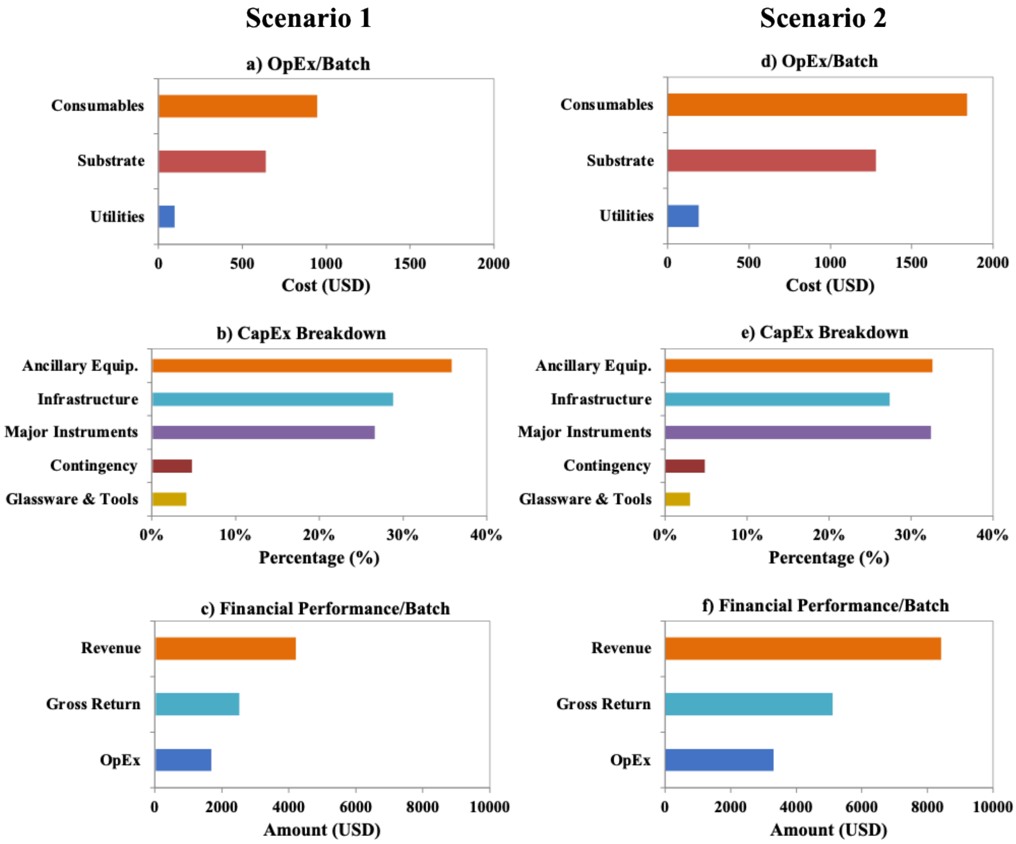


Figure 4. Breakdown of operational, capital costs, and financial performance per batch for the small-scale *Cordyceps* production system.

The high combined share of instrumentation and infrastructure costs reflects the precision-controlled environment required for consistent Cordyceps production, in which the HVAC system, autoclave, LAF cabinet, and dehydrator are indispensable investments regardless of production scale. In Scenario 2, doubling key equipment to support two concurrent growing rooms increased the share of major laboratory instruments in total CapEx from 27% to 32%. Despite this, the incremental CapEx of $12,474, representing ~39% additional CapEx above Scenario 1, yielded more than a fivefold improvement in Year 1 net return, confirming that physical expansion costs remain highly justified relative to the financial gains achieved.

3.4. Per-Batch Financial Performance

Per-batch financial performance for Scenario 1 (Figure 4c) showed strong unit economics. Revenue per batch was $4,208 at an average selling price of $90/lb, with OpEx of $1,683, yielding a gross return of $2,525 and a gross margin of 60%. These results indicate that the primary financial challenge for small-scale operators is not per-batch profitability but rather the recovery of initial CapEx over repeated production cycles.

Per-batch financial performance for Scenario 2 (Figure 4f) showed substantially stronger unit economics. Revenue per batch was $8,415 at an average selling price of $90/lbs., with OpEx of $3,309, yielding a gross return of $5,106 and a gross margin of 61%. This margin is consistent with Scenario 1 at 60%, reflecting that while bag count doubled, consumable and substrate costs scaled proportionally. The result confirms that scaling production volume substantially increases absolute return even as gross margin percentage remains similar, because the CapEx structure means the primary financial gain comes from throughput rather than unit cost reduction.

3.5. TEA Summary and Financial Feasibility Assessment

The comprehensive TEA of both production scenarios is summarized in Figure 5, with a full comparative breakdown of financial and operational parameters in Table 5. For Scenario 1, the variable cost per pound of fresh mushrooms was $36/lb, calculated as total OpEx divided by the fresh yield per batch. The resulting contribution margin was $54/lb. Break-even analysis showed that the operation required a minimum of 107 lbs. of fresh mushrooms per year, equivalent to 2.3 of five batches completed annually, to cover all CapEx and OpEx. This represents ~46% of annual production capacity, confirming that the system operates above its break-even threshold under normal conditions.

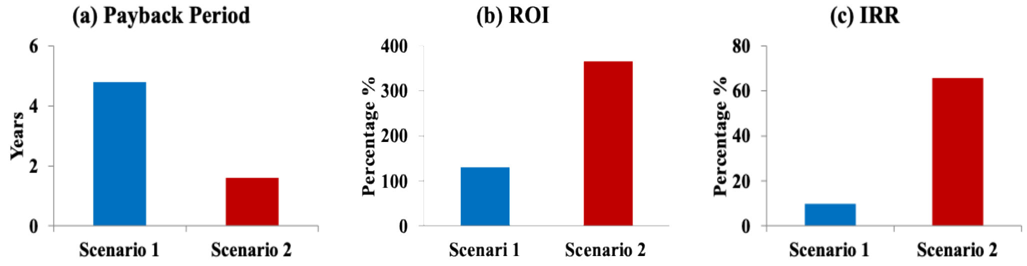


Figure 5. Comparative financial performance of the Scenario 1 and Scenario 2 *Cordyceps* production scenarios across four key metrics: (a) discounted payback period (years), (b) return on investment (ROI %), (c) internal rate of return (IRR%).

The break-even selling price at full annual production volume was $61/lb, yielding a margin of safety of 33%, indicating a price buffer above the cost-recovery threshold. These findings are consistent with prior economic evaluations of small-scale specialty mushroom production in the Northeastern United States, which similarly report favorable break-even thresholds and strong contribution margins when premium-priced gourmet and medicinal mushrooms are produced on small-scale grain- or log-based substrate systems [30], with comparable IRR-based feasibility outcomes reported for integrated small-scale mushroom production systems in the United States [31] and similar break-even and margin-of-safety patterns observed across small, medium, and large *Cordyceps* enterprise scales in India [32].

The broader financial indicators further confirmed the economic viability of Scenario 1. The IRR of 10% over the 5-year projection exceeded the 8% discount rate, and the 5-year NPV of $1,456 at an 8% discount rate was positive, collectively confirming that the project generates economic value above its cost of capital. The discounted payback period of 4.8 years indicates that full capital recovery is achievable within 5 years of operation (Figure 5a). The 5-year cumulative ROI of 131% (26% average annual) (Figure 5b) and gross margin per batch of 60% collectively reinforce the conclusion that *Cordyceps* cultivation is a financially sound enterprise model for small-scale producers operating with modest capital and a single family member.

Table 5. Comparative Financial and Operational Parameters for Scenario 1 and Scenario 2.

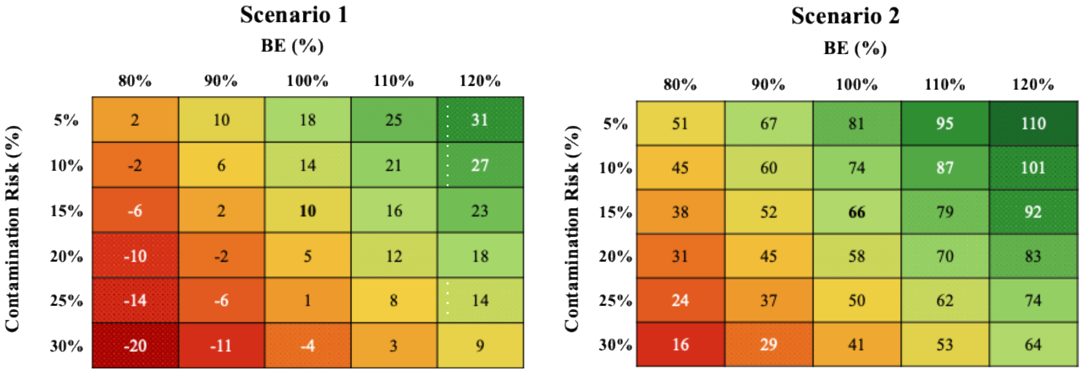
Parameters	Unit	Scenario 1	Scenario 2
Production Parameters			
Fruiting bags per batch	bags	1,250	2,500
Batches per year	batches/yr	5	9
Growing rooms	rooms	1	2
Cultivation cycle	days	94	94
Fresh yield per batch (contamination adjusted)	lb/batch	47	94
Annual fresh yield	lb/yr	234	842
Dry yield per batch	lb/batch	5	9
Cost Structure (per batch)			
Total OpEx	USD	$1,683	$3,309
Substrate & growth media	USD	$640	$1,280
Consumables	USD	$948	$1,840
Utilities	USD	$95	$189
Total CapEx	USD	$32,180	$44,654
Variable cost per lb fresh	USD/lb	$36	$35
Contribution margin per lb	USD/lb	$54	$55
Revenue & Returns (per batch)			
Revenue per batch	USD	$4,208	$8,415
Gross return per batch	USD	$2,525	$5,106
Gross margin	%	60%	61%
Break-Even Analysis			
Break-even volume	lb/yr	107	146
Break-even batches per year	batches	2.3	1.6
Break-even selling price	USD/lb	$61	$45
Margin of safety	%	33%	50%
5-Year Financial Indicators			
Net Present Value (NPV @ 8%)	USD	$1,456	$85,257
Internal Rate of Return (IRR)	%	10%	66%
Discounted payback period	years	4.8	1.6
Return on Investment	%	131%	366%

Note. All financial values are in USD. Yields are adjusted for a 15% contamination rate. CapEx = capital expenditure; OpEx = operating expenditure; NPV = net present value; IRR = internal rate of return. Discount rate = 8%; tax rate = 30%; annual escalation = 2.5%; loan financing = 80% of CapEx. Electricity consumption was estimated using a bottom-up equipment model (1,270 kWh/batch for 1A; 2,519 kWh/batch for Scenario 2), inclusive of system losses. No hired labor was assumed for either scenario.

Scaling production to Scenario 2 substantially improved all financial metrics, as detailed in Table 5. The variable cost per pound was $35/lb, and the contribution margin was $55/lb. Break-even volume was 146 lbs. per year, equivalent to 1.6 batches, accounting for a slightly higher cost of the larger operation. The break-even selling price was $45/lb, lower than in Scenario 1, and the safety margin was 50%, higher than in Scenario 1. The IRR was 66% (Figure 5c), and the 5-year NPV reached $85,257, confirming that the scaled model generates substantially greater long-term value. The discounted payback period declined to 1.6 years (Figure 5a), indicating that full capital recovery is achievable within approximately the first two years of operation. The 5-year cumulative of 366% (73% average annual) (Figure 5b) further underscores the financial leverage achieved by doubling production volume and increasing batch frequency under a partially CapEx structure, confirming that both production scale and scheduling intensity are critical levers for improving financial performance in this cultivation system.

3.6. Effect of Biological Efficiency (BE) and Contamination Rate on Financial Viability

A two-dimensional sensitivity analysis was conducted to quantify the combined influence of BE and contamination rate on the IRR for both production scenarios (Figure 6). BE was varied across five levels (80%, 90%, 100% base, 110%, 120%) and contamination across six (5–30%), yielding a 5 × 6 IRR matrix per scenario. Scenario 1 produced a base case IRR of 10% (100% BE, 15% contamination), just above the 8% hurdle rate, with values ranging from −20% at the worst combination (80% BE, 30% contamination) to 31% at the best (120% BE, 5% contamination). BE was the stronger driver: at 15% contamination, raising BE from 80% to 120% improved IRR by 29% (−6% to 23%), versus 21.3% (−4% to 18%) from reducing contamination from 30% to 5% at 100% BE. A substantial portion of the matrix (contamination ≥ 10% and BE ≤ 100%) fell below the hurdle rate, indicating that Scenario 1 requires near-optimal performance on both parameters to remain viable. Scenario 2 was markedly more robust, with IRR ranging from 16% to 110% and a base case of 66%. Even the worst-case combination yielded 16%, roughly twice the hurdle rate, confirming financial viability across every tested condition. BE remained the dominant driver, contributing a 54 percentage-point gain at 15% contamination (38% to 92%) compared with 40% from contamination reduction at 100% BE (41% to 81%).



Scenario 1

BE (%)

Contamination Risk (%)	80%	90%	100%	110%	120%
5%	2	10	18	25	31
10%	-2	6	14	21	27
15%	-6	2	**10**	16	23
20%	-10	-2	5	12	18
25%	-14	-6	1	8	14
30%	-20	-11	-4	3	9

Scenario 2

BE (%)

Contamination Risk (%)	80%	90%	100%	110%	120%
5%	51	67	81	95	110
10%	45	60	74	87	101
15%	38	52	**66**	79	92
20%	31	45	58	70	83
25%	24	37	50	62	74
30%	16	29	41	53	64

Figure 6. Sensitivity of internal rate of return (IRR, %) to biological efficiency (BE, %) and contamination rate for Scenario 1 and Scenario 2. The base case (BE = 100%, contamination = 15%) is outlined in bold. Color scale: red = IRR below the 8% cost-of-capital hurdle rate; yellow = near-hurdle (8–20%); green = viable (>20%). IRR was computed over a 5-year discounted cash flow (DCF) horizon, assuming a $90/lb selling price, an 8% discount rate, and a 30% tax rate.

These results confirm that production scale is the decisive determinant of financial resilience, while BE optimization and contamination control remain operationally critical, particularly for the smaller Scenario 1 configuration.

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5. Conclusions

This study presented a comprehensive technical and economic framework for small-scale Cordyceps cultivation across two production scenarios. Both scenarios demonstrated strong financial viability, with Scenario 2 substantially outperforming Scenario 1 across all metrics. Scenario 1 delivered an IRR of 10% and a discounted payback period of 4.8 years, with Capex of $32,180. Scenario 2 achieved an IRR of 66% and full capital recovery within 1.6 years, with a capital increment approximately 39% above Scenario 1, driven by the addition of a single growing room, duplication of key instruments, and staggered scheduling. Sensitivity analysis confirmed that biological efficiency is the dominant operational risk factor, with Scenario 2 remaining financially viable across all tested combinations of biological efficiency and contamination rate. The break-even prices of $61/lb and $45/lb for Scenarios 1 and 2, respectively, provide a substantial cushion relative to the $90/lb average selling price. Beyond financial performance, both configurations function as viable family-centered enterprises, with Scenario 1 generating supplementary household income and Scenario 2 approaching a substantial secondary or near-primary livelihood at cottage-industry scale. This work provides an integrated, evidence-based guide to support consistent, profitable Cordyceps cultivation at household and cottage-industry scales, with future work needed to validate projections using longitudinal farm-level data and to explore direct-to-consumer pricing and substrate optimization strategies

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Author Contributions: Mahsa Alian: Conceptualization, methodology, formal analysis, investigation, data curation, writing, original draft, writing, review & editing, visualization. **Yiyi Zhang:** writing, review, and editing. **Ruth Prashant:** Investigation. **Sunil P. Dhoubhadel:** data analysis, methodology, validation, supervision, writing, review, and editing. **Hemen Hosseinzadeh:** drafting figure. **Venkatesh Balan:** conceptualization, supervision, funding acquisition, resources, writing, review, and editing. **Srividya Raja:** drafting figures.

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Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Cordyceps	*Cordyceps militaris*
BE%	Biological Efficiency (Percentage)
PDA	Potato Dextrose Agar
LAF	Laminar Air Flow
PPE	Personal Protective Equipment
ATP	Adenosine Triphosphate
RPM	Revolutions Per Minute
PSI	Pounds per Square Inch
RH	Relative Humidity
DI water	Deionized Water
HVAC	Heating, Ventilation, and Air Conditioning
LED	Light-Emitting Diode
UV	Ultraviolet
TEA	Techno-Economic Analysis
CapEx	Capital Expenditure

OpEx	Operating Expenditure
NPV	Net Present Value
IRR	Internal Rate of Return
ROI	Return on Investment
EBT	Earnings Before Tax
DNR	Discounted Net Return
USD	United States Dollar

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