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Improving labour efficiency and productivity in mushroom farming through mechanized straw cutter

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Abstract

Paddy straw mushroom (*Volvariella volvacea* (Bull.) Singer) cultivation is a labour-intensive enterprise where bed preparation directly affects yield quality and quantity. Fresh, disease-free paddy straw must be cut to precise dimensions. The conventional manual process achieves only 120-150 bundles per hour and demands at least two workers, resulting in physical fatigue and posing gender-specific ergonomic barriers. To address these constraints, an electrically operated dual-motor paddy straw cutter was developed through three iterative design phases. The machine was evaluated against manual and earlier mechanized methods using quantitative performance indicators: cutting capacity (bundles/hour), labour requirement (persons), specific energy consumption, and Operational Safety Risk (OSR), calculated using the Fine-Kinney risk assessment formula. Z-score standardization was applied to enable cross-variable comparison, and straightline depreciation was used for economic analysis. The final version (Version 3), equipped with dual 1 hp motors, feed guide bars, and a redesigned blade assembly, achieved a cutting capacity of 1,100 bundles per hour which signify an 8-fold increase over manual cutting while reducing labour to a single operator and lowering the total SEC to 0.00195 kWh/bundle. The operational safety risk declined from a High rating (OSR = 64) under manual operation to Low (OSR = 8) in the final design. Economic analysis demonstrated annual cost savings of Rs. 50,105, reducing the per-bundle cutting cost from Rs. 0.44 to Rs. 0.12. With over 1,600 units deployed across Odisha, Chhattisgarh, and Jharkhand, the technology demonstrates strong potential for scalable adoption in small and medium mushroom farming enterprises.

Keywords: Mechanization, paddy straw cutter, mushroom bed preparation, operational safety risk, specific energy consumption, labour efficiency

Introduction

Mushroom cultivation is a labour-intensive process where bed preparation plays a crucial role in determining both yield quality and quantity. The size and structure of the mushroom bed significantly impact growth conditions, while fresh, disease-free paddy straw serves as the ideal substrate [1]. Typically, around 10-15 kg of paddy straw is required per bed, and cutting the straw to precise dimensions (1.5-2 ft length × 1.5 ft width × 1.5 ft height) [2] is essential for uniform bed formation. Traditionally, straw cutting process for the bed preparation is performed manually using a manual straw cutter, which is the most labour intensive, time consuming operation for the mushroom cultivation [3]. This not only increases labour costs but also affects the efficiency of mushroom bed preparation [4].

In recent years, mushroom farming has shifted to controlled environments, such as plastic film houses, where cultivation is carried out under tropical conditions with varying temperatures (30-35 °C) and relative humidity (75-85%) to ensure optimal growth [5]. However, the manual process of straw cutting remains a bottleneck in large-scale production. In Odisha, where straw mushroom cultivation is widely practiced, the absence of mechanized processing has been identified as a major constraint increasing labour dependency, preparation time, and overall cost of production [6].

With the growing emphasis on productivity and efficiency, mechanization in small-scale mushroom farming has become increasingly important. The development of safe, efficient, and low-cost machinery can significantly enhance operational performance while reducing drudgery during bed preparation. Ergonomic evaluations of farm women have shown that the use of improved agricultural implements considerably minimizes physical strain and fatigue, resulting in greater comfort and higher work efficiency [7].

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Likewise, comparative assessments of manual and mechanized straw cutters revealed that mechanized units not only enhance cutting precision but also reduce labour effort and time, thereby improving overall efficiency in mushroom cultivation [8]. Furthermore, studies on small-scale agricultural mechanization in India have established that customized low-cost machinery significantly lowers production costs and reduces post-harvest losses, thereby strengthening farm-level profitability [9].

Custom hiring of farm machinery has also emerged as a cost-effective strategy in Indian agriculture, allowing smallholder farmers to access mechanized equipment without the burden of full ownership costs [10]. This model has gained particular relevance in mushroom farming clusters in eastern India, where shared machine utilization among 5-6 farmers reduces per-unit operational cost while increasing equipment utilization efficiency [11]. In light of these developments, the present study

documents the iterative design, performance evaluation, and economic assessment of a mechanized paddy straw cutter, with the objective of providing an evidence-based account of its impact on labour efficiency, occupational safety, and mushroom farming productivity.

Materials & Methods

Problem identification and need for mechanization

Prior to mechanization, a fully manual straw cutter (*Fig. 1* and *Fig. 2*) was employed for slicing paddy straw bundles used in mushroom bed preparation. While considered suitable for small-scale operations, this method was found to be inadequate as commercial straw mushroom cultivation expanded. Field observations and operator feedback identified several operational and ergonomic limitations associated with the traditional manual cutter, as summarized below:



Fig 1: Manual straw chaf cutting tool



Fig 2: Table type manual straw chaf cutter

- High physical effort: Each paddy straw bundle required approximately three to four strokes for complete cutting, resulting in considerable muscular strain.
- Low cutting capacity: The manual process achieved an average rate of only 120-150 bundles per hour, significantly limiting productivity.
- Reduced work sustainability: Continuous manual cutting was not feasible; operators required frequent pauses after every 15-20 minutes of operation due to fatigue.
- Health concerns: Prolonged repetitive motion led to joint and muscle pain, with some cases progressing to chronic discomfort.
- Gender limitations: The operation demanded substantial pulling force, making it unsuitable for most female workers engaged in mushroom cultivation.

Design and development methodology

The mechanized straw cutter was developed through a series of iterative modifications aimed at improving performance, safety, and user comfort. Three successive versions were designed,

fabricated, and evaluated before arriving at the final working model.

First version: single-blade motorized straw cutter

The first prototype was designed as a single-blade, motor-operated cutting unit aimed at enhancing cutting capacity over the traditional manual method. With the introduction of a powered blade and straw feeding tray, the hourly output was significantly increased in comparison to manual cutting. However, field evaluation identified several shortcomings that limited its practical acceptance.

Limitations of first version

- The straw bundles needed to be rotated after each cut to achieve complete separation from both sides.
- The cutting capacity of the machine was recorded at 400-450 bundles per hour.
- The exposed high-speed blade (operating at approximately 1200 rpm) posed serious safety concerns.
- Female operators were hesitant to use the machine due to the risk associated with the uncovered rotating blade.



Fig 3: First version of the straw cutter (single-blade motor-operated)

Second version: safety-enhanced model with manual feeding mechanism

To address the safety concerns identified in the earlier version, a second model was developed, incorporating a manual feeding system supported by a movable tray and handle. This design arrangement was intended to ensure that a safe operating distance from the cutting blade could be maintained by operators. While safety and operational comfort were greatly improved, some new challenges were identified.

Limitations of Second Version

- The effective cutting capacity decreased to 350-400 bundles per hour due to the added feeding mechanism
- The adjustment of straw bundle length was complicated, requiring frequent mechanical adjustments.
- After extended operation, there was a high chance of interference between the blade and the moving tray, creating potential hazards.



Fig 4: Second version of the straw cutter with manual feeding tray and safety housing

Third version: improved high-capacity model

In the third and final version, the feeding system was restructured and key components were redesigned to achieve higher productivity and safer operation. The straw feeding

arrangement was redesigned with a flat metal feed sheet supported by two horizontal columns, allowing simultaneous feeding of multiple straw bundles.



Fig 5



Fig 6



Fig 7

Fig 5, Fig 6, and Fig 7 collectively showing Third and final version of the straw cutter having improved feeding tray, guiding bars, and motor assembly

Description

The developed straw cutter is an electrically operated machine designed for high-capacity, uniform cutting of paddy straw bundles for mushroom bed preparation. The machine incorporates a rotating dual-blade assembly, an ergonomically designed feeding system, and enclosed safety components, making it suitable for continuous operation by both male and female operators. The final version enables simultaneous feeding of more than eight straw bundles per pass, with adjustable cutting length to suit different mushroom bed sizes.

The overall design prioritises mechanical stability, operator safety, and ease of use under on-farm conditions.

Construction

The machine is constructed on a rectangular mild steel base frame supported by vertical columns that provide structural rigidity. Four wheels fitted to the base facilitate easy portability between work areas. Two electric motors, each rated at 1 hp and operating at 1,440 rpm, are mounted symmetrically on either side of the frame and drive counter-rotating cutting blades via a

shaft assembly supported on bearings. The bearing supports minimise vibration and reduce friction during operation, extending the service life of the cutting components. A motor holding assembly with parallel slots is incorporated to enable lateral adjustment of each motor, thereby allowing the blade-to-blade gap to be controlled in accordance with the required cutting length.

A safety cover encloses the rotating blade assembly above the cutting zone, and the straw output channel is kept open for unhindered outflow of the precisely cut straw bundles. The feeding assembly, consisting of a flat metal feed sheet supported by two horizontal columns, is equipped with two parallel guiding rods through which straw bundles are channelled in a controlled and aligned manner toward the blades. An electric control panel with an on-off switch is mounted on the frame to facilitate convenient operation. All rotating and moving components are enclosed within protective mufflers, thereby eliminating direct contact between the operator and hazardous parts.

The major components of the machine are shown in Fig. 8, with all major parts identified in the component legend.

Working and operation

Prior to operation, the blade-to-blade distance is adjusted through the motor adjustment slots to match the target mushroom bed length of 1.5-2 ft. Upon energising the control panel, both motors are activated simultaneously, and rotational force is transmitted through the shaft assembly to the cutting blades. Shear force is thereby generated by the counter-rotating blades, by which paddy straw bundles are cut cleanly and uniformly to the desired length.

Straw bundles are placed on the feeding platform and advanced beneath the guiding rods, through which bundle alignment is maintained as the material is directed into the cutting zone. More than eight bundles are capable of being fed simultaneously, enabling high throughput to be achieved without compromising cut quality. Smooth, vibration-free rotation is ensured throughout the cycle by the bearing-supported shaft assembly. All moving parts remain enclosed within the safety covers and protective mufflers, thereby ensuring safe operation in accordance with basic ergonomic standards for agricultural machinery.

Key features and improvements in third version

- 1 Cutting capacity increased substantially to 1000-1200 straw bundles per hour.
- 2 A safety muffler was installed to cover the upper portion of the blade, reducing the risk of accidental contact.
- 3 Guiding bars were introduced to hold straw bundles parallel and stable during cutting.
- 4 The cutting-length adjustment mechanism was simplified through a dual nut-bolt arrangement, enabling quick calibration.
- 5 The electric motor holding assembly was redesigned with parallel slots, allowing easy adjustment of the motor's base position and enabling control of the blade-to-blade distance as required.

Analytical methods and formulae

Performance evaluation was carried out using five quantitative indicators. The following formulae were applied consistently across all machine versions and comparative analyses.

1. Specific Energy Consumption (SEC): SEC quantifies the total energy consumed per unit of output, encompassing both

mechanical (electrical) and human energy inputs, thereby providing a comprehensive measure of energy efficiency independent of machine size or operating duration.

$$\text{SEC (kWh/bundle)} = (\text{Electrical Energy} + \text{Human Energy}) / \text{Cutting Capacity (bundles/hour)}$$

Where: Electrical Energy (kWh) = connected motor load (kW) × operating hours; Human Energy (kWh) = Number of workers × 0.544 kWh/person-hour^[12]; Cutting Capacity = bundles per hour.

2. Operational Safety Risk (OSR) — Fine-Kinney Method:

The Fine-Kinney risk assessment method^[12] was used to quantify operational risk at each design stage. Risk is expressed as a composite score of three independent factors.

$$\text{OSR} = S \times L \times E$$

Where S = Severity of potential harm, L = Likelihood of occurrence, and E = Exposure frequency. Risk levels were classified as: High (OSR > 20), Medium (OSR = 10-20), and Low (OSR < 10).

3. Z-Score Standardization: Since labour requirement and OSR are measured on different scales, z-score normalization was applied to enable cross-variable comparison while preserving relative differences^[13].

$$Z = (X - \mu) / \sigma$$

Where Z = standardized score, X = observed value, μ = mean of the dataset, and σ = standard deviation. A negative Z-score indicates a value below the mean (improvement), while a positive score reflects abovemean values (higher risk or labour demand).

4. Depreciation — Straight-Line Method: Annual depreciation was calculated using the standard straightline method^[14], which distributes the cost of an asset uniformly over its useful life.

$$D = (C - S) / L$$

Where D = Annual depreciation (Rs.), C = Initial capital cost (Rs. 25,000), S = Salvage value at end of life (10% of C = Rs. 2,500), and L = Expected operational lifespan (5 years). Annual Depreciation = Rs. 4,500.

5. Pearson Correlation Coefficient: Pearson's correlation coefficient (r) was used to determine the strength and direction of linear relationships between pairs of performance variables (cutting capacity, SEC, OSR, and labour requirement)^[15].

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

Where r = Pearson's correlation coefficient ($-1 \leq r \leq +1$), x and y = individual data points for the two variables and n = number of observations (machine versions evaluated). Values of r close to ± 1 indicate strong correlation; values near 0 indicate weak or no linear relationship.

6. Simple Payback Period (SPP)

The Simple Payback Period was used to determine the duration required for the initial capital investment to be recovered through annual cost savings generated by replacing the manual method. The SPP is a widely adopted economic indicator for evaluating the financial viability of agricultural machinery investments [16]. $SPP \text{ (years)} = C / S$; Where: SPP = Simple Payback Period (years); C = Initial capital investment (Rs.); S = Annual net cost savings = Annual cost of manual method - Annual cost of mechanized method (Rs./year). A lower SPP indicates faster recovery of investment and higher financial

attractiveness for the adopting farmer.

Results

Performance evaluation and operational efficiency

Performance evaluation of the developed straw cutter was conducted to assess improvements in cutting capacity, labour requirement, power consumption, and operational safety across successive versions of the machine. Comparative trials were performed between the manual process and three mechanized prototypes under similar operating conditions. The observations are summarized in Table 1.

Table 1: Comparative operational data for the different versions of the straw cutter

Mode	Cutting Capacity (Bundles/hr)	Labour Required (Persons)	Electrical Energy (kWh)	Human Energy (kWh)	Total Energy (kWh)	SEC = Total Energy / Capacity (kWh/bundle)
Manual	140	1	0.00	0.544	0.544	0.00389
Version 1	430	2	1.20	1.089	2.289	0.00532
Version 2	380	2	1.40	1.089	2.489	0.00655
Version 3 (Final)	1,100	1	1.60	0.544	2.144	0.00195

Cutting capacity and efficiency

A cutting capacity of 140 bundles/hour was recorded for the manual method, requiring approximately with one worker per operation. The first motorized version was found to yield a capacity of approximately 430 bundles/hour, representing a threefold increase in productivity. A marginal decline in capacity to 380 bundles/hour was observed in the second version, attributable to the added safety tray and manual feeding mechanism.

The present version (Version 3), equipped with dual 1 hp motors, feed guide bars, and a redesigned blade assembly, was found to achieve a cutting capacity of 1,100 bundles/hour; representing an 8-fold improvement over the manual process. This enhancement was found to reduce the time required for mushroom bed preparation, thereby enabling larger cultivation volumes to be handled per working shift. (Refer to Fig 8 for comparative chart of cutting capacity across versions.)

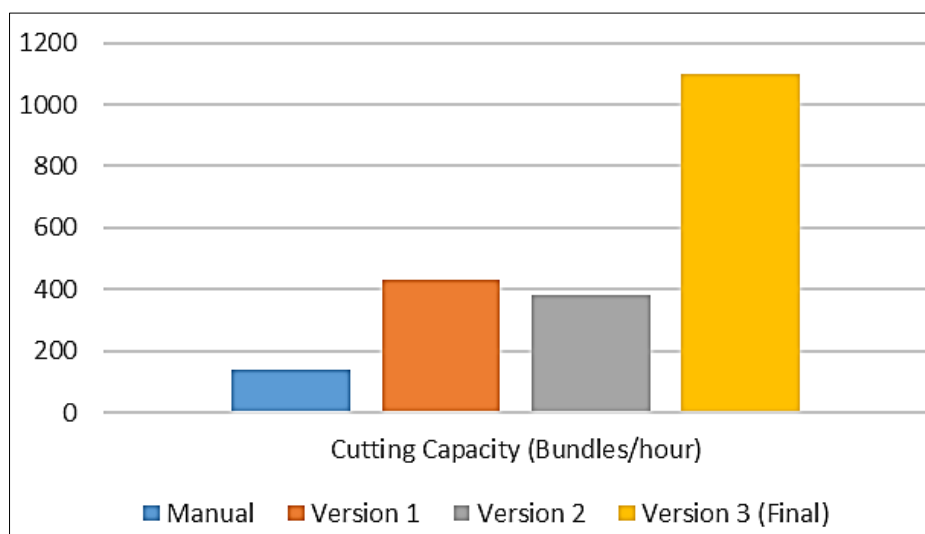


Fig 8: Comparison of cutting capacity of different versions

Labour requirement and operational safety

Reduction in labour dependency was achieved through mechanization in the final version. The inclusion of safety

covers, guide bars, and ergonomic controls resulted in improvement of the safety.

Table 2: Fine-Kinney Operational Safety Risk (OSR) analysis for each version of the straw cutter [13]

Machine	Severity (S)	Likelihood (L)	Exposure (E)	OSR = S×L×E	Risk Level	Safety rating
Manual	4	4	4	64	High	1
Version 1	3	3	4	36	High	3
Version 2	2	2	2	8	Low	4
Version 3	2	2	2	8	Low	4



Fig 9: OSR score trend across design versions. The dashed red line marks the High Risk threshold (OSR = 20). Manual operation and Version 1 fall in the High Risk zone; Versions 2 and 3 achieve Low Risk status (OSR = 8)

Since labour requirement and OSR are expressed on different scales, z-score standardization was applied as described in Section 2.4 (Equation 3) to enable cross-variable comparison. The standardized results are presented in Table 3.

$$Z = \frac{X - \mu}{\sigma}$$

Table 3: Z-score standardized values of labour requirement and OSR across versions

Mode	Labour Required (Persons)	OSR	Standardized Labour	Standardized OSR
Manual	1	64	-1	1.50
Version 1	2	36	1	0.30
Version 2	2	8	1	-0.90
Version 3 (Final)	1	8	-1	-0.90

The reduction in standardized labour requirement and OSR in the final version indicates improved ergonomics and operational safety. These findings are corroborated by user feedback, which reported reduced operator fatigue and enhanced comfort during extended operation, demonstrating

that the machine can be effectively operated by both male and female workers without physical strain. (Refer to *Fig 10* for the relationship between labour requirement and safety improvement.)

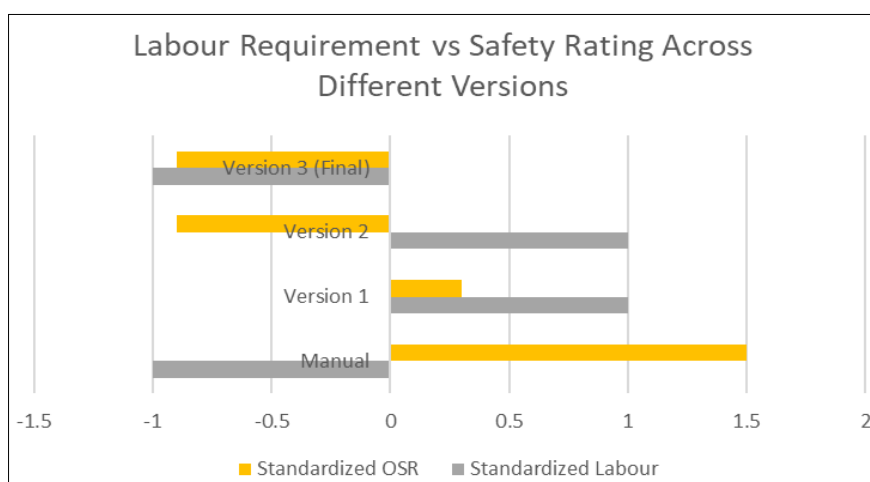


Fig 10: relationship between labour requirement and safety improvement across versions safety improvement across versions

Specific Energy Consumption: As computed Capacity), and incorporating human energy at 0.544 kWh per person-hour^[17], the net SEC values reflect total energy demand across all versions. The manual process recorded an SEC of 0.00389 kWh/bundle, representing the baseline. Version 1 and Version 2 exhibited higher SEC values of 0.00532 and 0.00655 kWh/bundle respectively, attributed to increased human energy input from two-operator requirements alongside elevated electrical consumption.

The final version (Version 3) achieved the lowest total SEC of 0.00195 kWh/bundle, demonstrating a 50% reduction over the manual baseline, driven by the combined effect of singleoperator operation and the substantially higher cutting throughput of 1,100 bundles per hour. Bearings and precision alignment were incorporated to minimize vibration losses, ensuring smooth mechanical operation and enhancing durability.

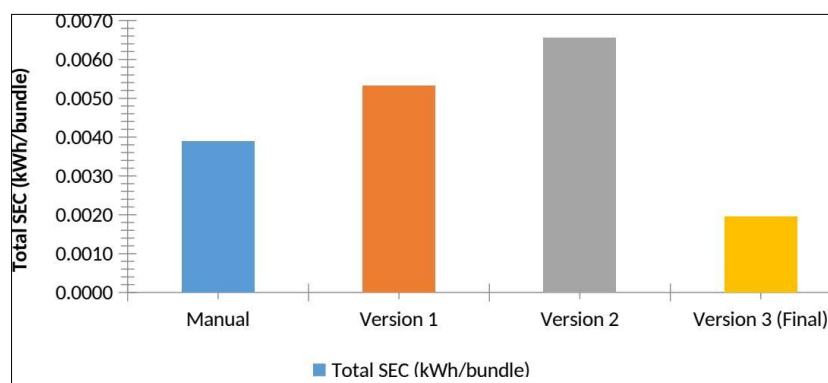


Fig 11: Total Specific Energy Consumption (Electrical + Human Energy) comparison across all versions (kWh/bundle). Lower SEC indicates higher overall energy efficiency per unit output

Correlation Analysis of Performance Parameters

To understand the interrelationships among the measured performance variables, a correlation analysis was conducted using four key indicators: cutting capacity, labour requirement, Specific Energy Consumption (SEC), and Operational Safety Risk (OSR). Pearson correlation coefficients for all six variable pairs computed using Equation (5), are presented in *Fig 12*.

A strong design trend was observed between cutting capacity and OSR, which exhibited a strong negative relationship ($r = -0.70$). Since lower OSR values indicate lower operational risk and therefore safer operation, this trend suggests that successive design improvements increased productivity while simultaneously enhancing operator safety. The incorporation of safety covers, feed guide bars, controlled feeding arrangements enabled the final version to achieve a cutting capacity of 1100 bundles/hour while reducing the OSR from 64 in manual operation to 8 in the final design.

A similarly strong negative trend was observed between cutting capacity and specific energy consumption (SEC) ($r = -0.66$), indicating that improvements in machine productivity were accompanied by improved energy utilization efficiency. Dual motor configuration and continuous feeding mechanism enabled the machine to process a larger quantity of straw without a proportional increase in energy consumption, thereby reducing the energy requirement per bundle processed..

The strongest positive relationship in the matrix was observed between labour requirement and SEC ($r = 0.88$), indicating that machine configurations associated with greater labour dependency also exhibited higher energy consumption per unit output. Earlier versions required greater operator involvement for feeding and handling operations, leading to intermittent feeding and reduced utilization of the cutting mechanism. The final version, equipped with guide bars and an improved feeding arrangement, enabled smoother material flow and reduced idle machine time, resulting in improved energy utilization and reduced labour dependency.

A moderate negative trend was observed between labour requirement and OSR ($r = -0.30$), indicating that reductions in labour dependency were accompanied by reductions in operational risk. The transition from manual operation to the final version reduced the workforce requirement from two operators to a single operator while simultaneously reducing OSR values from 64 to 8. This improvement was primarily attributable to the introduction of safety guards and ergonomic operating arrangements, which reduced direct interaction between the operator and moving components.

Similarly, the moderate negative relationship between cutting capacity and labour requirement ($r = -0.30$) suggests that the substantial increase in throughput was not solely a consequence of reduced manpower requirements. Instead, the productivity gains were largely driven by engineering modifications which enabled higher output while maintaining lower labour dependency.

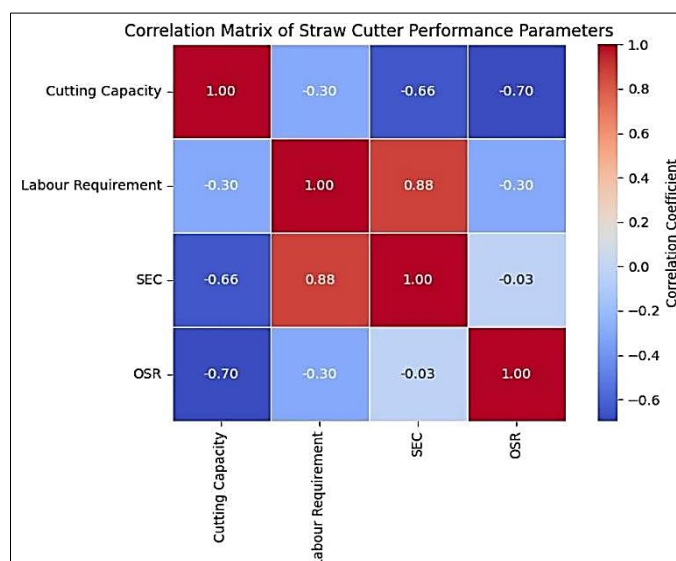


Fig 12: Correlation Matrix of Diferent Performance Parameters

Finally, the correlation between SEC and OSR was negligible ($r = -0.03$), suggesting that energy utilization efficiency and operational safety evolved largely independently during the machine development process. This indicates that the safety improvements introduced in successive versions did not adversely affect energy performance, allowing the machine to achieve lower operational risk without compromising energy efficiency.

Economic analysis and cost estimation

Economic feasibility was assessed through a cost analysis covering depreciation, electricity, maintenance, and labour. Progressive mushroom growers in eastern India typically operate in batches of 120-150 beds, adding 25-30 beds daily to sustain an output of 20-25 kg/day across the 12-14-day crop cycle. This necessitates the cutting of 400-500 straw bundles per day, yielding an annual straw bundle requirement of 140,000-150,000 bundles. All economic calculations were carried out based on this annual workload of 150,000 bundles.

Depreciation (straight-line method)

Depreciation was computed using the standard straight-line method [14]. The straight-line depreciation schedule over the 5-year operational life of the machine was computed. This method distributes the asset cost uniformly and provides a transparent basis for financial planning in mushroom cultivation mechanization.

$$D = \frac{C - S}{L}$$

Where:

- C = Initial capital cost of the machine = Rs. 25,000
- S = Salvage value (10% of C) = Rs. 2,500
- L = Expected lifespan = 5 years
- Annual Depreciation = Rs. 4,500

Electricity Cost: Electricity cost was estimated based on the total connected load and the annual operating hours of 150 hours, at the prevailing rate of Rs. 6.2 per unit.

- Motor Load: 2 HP (1 HP for each motor) $\approx$ 1.5 kW
- Annual Use: 150 hours $\Rightarrow 1.5 \times 150 = 225$ kWh
- Thus, Annual Electricity Cost (@ Rs. 6.2/kWh) = Rs. 1,395.00

Repair and maintenance cost: Annual repair and maintenance costs (covering lubrication, blade replacements, and minor adjustments) were estimated at Rs. 1,000.

Labour Cost: Based on an annual requirement of 150,000 straw bundles and the hourly cutting capacity of the manual process, approximately 1,072 working hours were required for the annual cutting workload.

It was estimated that approximately 134 working days (8 hours per day) are required to complete the annual cutting workload the manual method, whereas the same workload was accomplished in 19-20 days using the mechanized machine. Hence the mechanization achieves an approximate 85% reduction in time commitment.

Labour cost was estimated based on the prevailing wage rate for unskilled workers in Odisha (Rs. 500/man day for an 8-hour workday). Annual labour costs for each method were computed as follows:

- Manual Method: 1 worker $\times$ Rs. 500/man day $\times$ 134 man days = Rs. 67,000/year
- Machine Use: 1 operator $\times$ Rs. 500/man day $\times$ 20 man days = Rs. 10,000/year

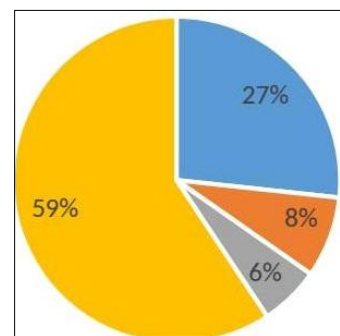


Fig 13: Cost Component Distribution Depreciation Electricity (Mechanized Method)

Table 4: Annual operating cost comparison — Manual vs Mechanized straw cutting methods

Cost Component	Manual Process	Mechanized Process
Depreciation	0	Rs. 4,500
Electricity	0	Rs. 1,395
Maintenance	0	Rs. 1,000
Labour	Rs. 67,000	Rs. 10,000
Total Annual Cost	Rs. 67,000	Rs. 16,895

Annual Cost Savings = Rs. 67,000 - Rs. 16,895 = Rs. 50,105 per year

The cost component distribution presented in Table 4 and highlights the relative contribution of each operational cost element in the mechanized method of straw cutting. The labour component accounts for the largest share (59%), followed by depreciation (27%), electricity (8%), and maintenance (6%) which is visually presented in fig 13.

This distribution indicates that even though labour costs remain the dominant component, they are substantially lower compared to the manual method (Rs. 67,000 per year). Depreciation forms a moderate share due to the low capital investment of Rs. 25,000. Electricity and maintenance together contribute less than 15% of total annual expenditure, demonstrating that the machine is cost-efficient and inexpensive to operate.

Overall, the cost structure reflects a low-recurring-expense model, which is considered favourable for small and medium-scale mushroom growers considering mechanization of bed preparation.

Cost per Unit and Economic Efficiency

Table 5: Per-bundle cost and economic efficiency — Manual vs Mechanized methods

Mode	Annual Output (Bundles)	Annual Cost	Cost per Bundle
Manual	150,000	Rs. 67,000	Rs. 0.44
Mechanized	150,000	Rs. 16,895	Rs. 0.12

As shown in Table 5, the per-bundle cutting cost under the mechanized method was computed at Rs. 0.12, representing a reduction to approximately 27% of the manual method cost (Rs. 0.44). Labour dependency was reduced by approximately 85%, while processing reliability was improved and timely bed preparation was ensured which is a critical requirement for consistent mushroom production cycles.

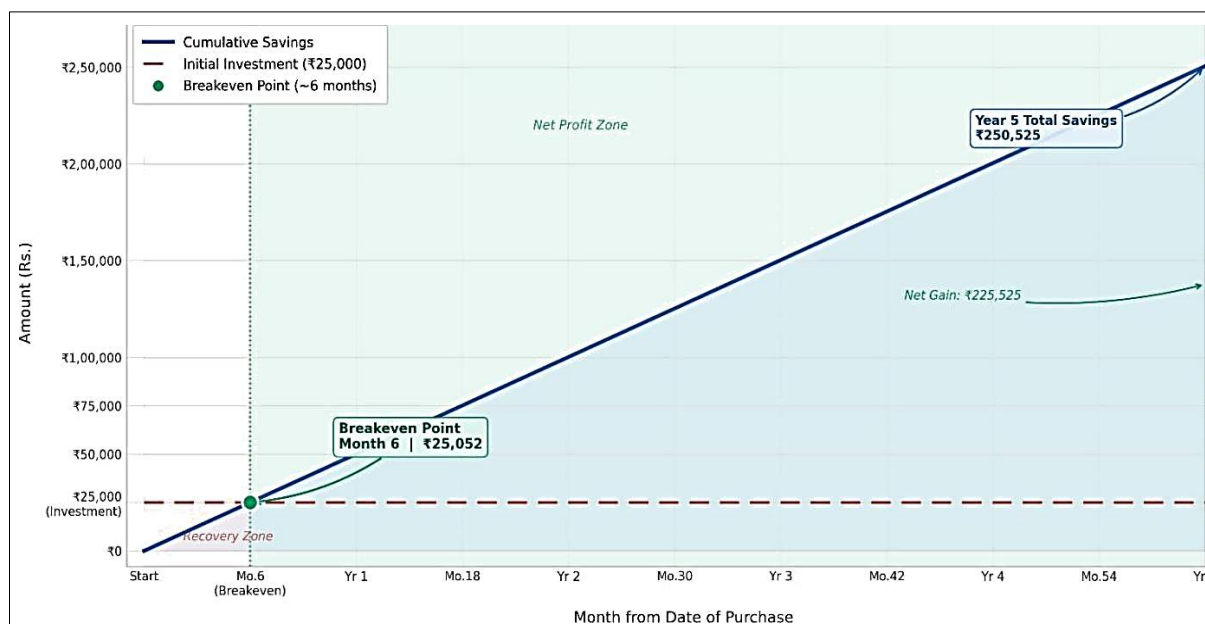
Simple Payback Period

Based on the economic data presented in Table 4, the Simple Payback Period was computed as follows:

$$SPP = C / S = 25,000 / 50,105 = 0.499 \text{ years } (\approx 6 \text{ months})$$

Table 6: Simple Payback Period analysis for the mechanized straw cutter

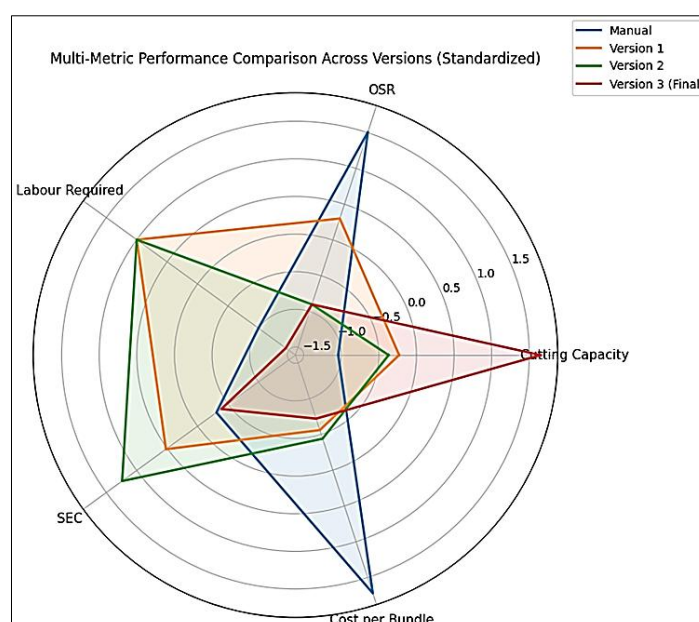
Parameter	Value
Initial Investment (C)	Rs. 25,000
Annual Cost in Manual Method	Rs. 67,000
Annual Cost in Mechanized Method	Rs. 16,895
Annual Net Savings (S)	Rs. 50,105
Simple Payback Period (SPP)	0.499 years ($\approx$ 6 months)
Machine Operational Lifespan	5 years
Remaining Profit Period after Payback	$\approx$ 4.5 years

**Fig 14:** Simple Payback Period (SPP) breakeven chart for the mechanized straw cutter. The green dot marks the breakeven at Month 6 (SPP = 0.499 years); the shaded region represents the net profit period over the 5-year machine lifespan

The SPP of approximately 6 months confirms that the initial investment of Rs. 25,000 is fully recoverable within the first season of operation, well within the 5-year machine lifespan. This is significantly lower than comparable agricultural machinery investments reported in similar contexts [16],

confirming the high financial attractiveness of the mechanized straw cutter, particularly under custom-hiring or shared-use arrangements where multiple farmers benefit from the same unit.

Multi-Metric Performance Comparison Across Machine Versio

**Fig 15:** Multi-metric performance radar chart comparing all versions across five normalized dimensions: Cutting Capacity, Safety Rating, Labour Efficiency, Energy Efficiency, and Cost Efficiency. Version 3 shows dominant performance across all axes

The standardized radar chart presented in Fig. 15 illustrates the progressive improvement in machine performance through successive design iterations. The manual operation exhibited the least favourable performance profile, characterized by low cutting capacity, high operational safety risk (OSR), high cost per bundle, and poor energy utilization efficiency.

Version 1 achieved a substantial increase in cutting capacity and a reduction in cost per bundle compared with the manual method. However, labour dependency and specific energy consumption remained relatively high due to the continued requirement for operator involvement in feeding and material handling operations.

Version 2 primarily focused on improving operational safety and ergonomics. The incorporation of safety trays, feed guide bars, and controlled feeding arrangements significantly reduced OSR, although these modifications resulted in a temporary reduction in cutting capacity and an increase in specific energy consumption.

The final version (Version 3) exhibited the most balanced and optimized performance profile, achieving the highest cutting capacity while simultaneously maintaining low labour dependency, low operational risk, reduced specific energy consumption, and the lowest cost per bundle processed. The integration of dual motors, optimized blade geometry, and an improved feeding mechanism enabled higher throughput with reduced operator effort and improved energy utilization.

Discussion

Broader Implications and Adoption Potential

Due to the high-quality protein content and the presence of dietary fibres, vitamins, amino acids, and carbohydrates [2, 18] paddy straw mushroom is gaining popularity as a protein-rich dietary option. With increasing commercial demand, paddy straw mushroom farming is becoming the first choice for many farmers as an alternative livelihood [11]. As the popularity of paddy straw mushroom continues to rise, the need for mechanisation and automation in the associated cultivation steps is becoming essential for farmers.

Bed preparation is a fundamental step in straw mushroom cultivation and has been associated with significant labour requirements. To overcome this challenge, a preference for mechanised cutting of paddy straw bundles has been increasingly observed among farmers. With the introduction of the paddy straw cutting machine, extensive adoption among farmers has been observed.

The developed machine has been demonstrated to enhance both productivity and operational safety. Owing to its lightweight construction and portability, a single machine is typically shared among 5-6 farmers within a village cluster through renting or custom hiring arrangements. This practice reduces the initial acquisition cost for individual farmers and enables the machine owner to utilise the equipment more efficiently, facilitating cost recovery in a timely manner.

Conclusion

The mechanized paddy straw cutter, developed through three iterative design phases with direct input from mushroom-growing clusters across Odisha, Chhattisgarh, and Jharkhand, achieved a final cutting capacity of 1,100 bundles per hour which is an 8-fold increase over the 140 bundles per hour recorded for the manual baseline. Labour requirement was reduced from two operators to one, and the Operational Safety Risk score declined from 64 (High) under manual operation to

8 (Low) in the final version. Total Specific Energy Consumption fell from 0.00389 kWh/bundle under the manual method to 0.00195 kWh/bundle in the final version, reflecting a 50% improvement in energy utilization efficiency.

Economic analysis established an annual cost saving of Rs. 50,105 against a capital investment of Rs. 25,000, yielding a Simple Payback Period of 0.499 years i.e. 6 months of operation [16]. Over the 5-year machine lifespan, the net gain amounts to Rs. 2,25,525, confirming financial viability for smallholder operators. Per-bundle cutting cost was reduced from Rs. 0.44 to Rs. 0.12, a 73% reduction. These figures are attainable through the shared-use model already practised in surveyed clusters, where one machine serves 5-6 growers through custom-hiring arrangements, further distributing acquisition costs [11].

The correlation analysis revealed that successive design improvements followed a consistent trade-off trajectory: cutting capacity and OSR were negatively correlated ($r = -0.70$), as were cutting capacity and SEC ($r = -0.66$), confirming that engineering modifications increased throughput while simultaneously reducing both risk and energy demand per unit processed. The positive correlation between labour requirement and SEC ($r = 0.88$) identifies operator involvement in feeding as the primary driver of energy inefficiency which is an insight that should guide future design decisions.

Deployment data, with over 1,600 units in operation across three states [11], substantiates field acceptance at scale. The machine's suitability for operation by a single female worker is evidenced by the Low OSR rating and ergonomic feeding design [7] which has supported the participation of women farmers in bed preparation, an operation previously constrained by physical load requirements. Mushroom cultivation is an established livelihood activity for rural women in eastern India [19], and mechanization of this preparatory step reduces the physical barrier to their participation [20].

The primary limitation of the current design is its dependence on grid electricity, which restricts use in offgrid cultivation sites common in tribal districts of Odisha and Jharkhand, where mushroom farming has been identified as a key income source for smallholder communities [6]. Adaptation for battery or solar operation, and an investigation of blade geometry optimisation for uniform straw length control, represent the most productive directions for future work.

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