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Design, development, and performance evaluation of a power-operated linseed fiber extraction machine

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Abstract
The extraction of linseed fiber using traditional manual methods is labor-intensive, time-consuming, and inefficient, limiting the effective utilization of linseed straw as a valuable agricultural resource. The present study focused on the design, development, and performance evaluation of a power-operated linseed fiber extraction machine (POLFEM) intended for small-scale and rural applications. Five linseed (*Linum usitatissimum* L.) varieties were used to assess machine performance under varying operating conditions. The developed prototype incorporated a four-roller system consisting of smooth feeding rollers for initial crushing and rasp-bar rollers for stem separation. Performance evaluation was carried out at different roller speeds (30, 40, and 50 rpm), feed rates (25, 30, and 35 kg h^{-1}), moisture content levels, and roller clearances. The results indicated that a roller speed of 40 rpm, feed rate of 30 kg h^{-1}, moisture content of 7-9%, and roller clearance of 30 mm were optimal for efficient operation. Under these conditions, the POLFEM achieved a maximum extraction efficiency of 98.51% with minimal fiber damage (1.3%). The economic analysis demonstrated the feasibility of the machine, with a fabrication cost of ₹75,000, total operating cost of ₹74.78 h^{-1}, and a payback period of 5.09 years. The machine significantly reduced human energy input, with mechanical and electrical energy contributing approximately 97% of the total energy requirement. Overall, the POLFEM provides an efficient and economically viable alternative to manual linseed fiber extraction methods and holds considerable potential for promoting mechanized processing and value addition of linseed straw in rural and small-scale industrial settings.

Keywords: Linseed fiber, fiber extraction machine, power-operated machine, bast fiber processing, agricultural mechanization

Introduction

Linseed (*Linum usitatissimum* L.) is an important multipurpose crop cultivated for its oilseed and bast fiber, with applications spanning food, textile, composite, and paper industries. While the economic importance of linseed seed and oil is well established, a substantial proportion of linseed straw generated after harvesting remains underutilized, particularly in major linseed-growing regions of India. In states such as Chhattisgarh, linseed straw is often treated as agricultural waste or used inefficiently, despite its potential as a valuable natural fiber resource (Assanova *et al.*, 2024) [2].

The extraction of fiber from linseed straw involves the separation of bast fibers from the woody core tissues, a process traditionally achieved through retting followed by mechanical separation. Conventional manual extraction methods, such as pit-hammering and hand-beating techniques, are labor-intensive, time-consuming, and characterized by low productivity and inconsistent fiber quality. These practices impose considerable physical drudgery on operators and limit the scale of fiber production, thereby reducing the economic viability of linseed fiber utilization at the farm and rural enterprise level (Karim *et al.*, 2021) [4].

The increasing demand for natural fibers in textiles, composites, and sustainable packaging has intensified the need for efficient and mechanized fiber extraction technologies. Natural bast fibers, including flax and linseed, are recognized for their favorable strength-to-weight ratio, biodegradability, and suitability as reinforcement materials in bio-composites (Ramachandran *et al.*, 2022) [5]. However, despite the availability of mechanized fiber extraction systems for crops such as jute, hemp, and flax, their adoption in linseed-growing regions has remained limited. Many existing machines are designed for large-scale industrial applications, are capital-intensive, and lack adaptability to the requirements of small-scale processors and rural entrepreneurs (Desai *et al.*, 2018; Soomro & Rossi, 2024) [3, 7].

The development of a power-operated linseed fiber extraction machine offers a practical solution to address these constraints. A suitably designed machine can significantly reduce manual labor, improve extraction efficiency, minimize fiber damage, and ensure uniform fiber quality. The performance of such machines is strongly influenced by operational parameters including roller speed, feed rate, moisture content of the straw, and roller clearance, which must be optimized to achieve efficient fiber separation without excessive damage (Selge *et al.*, 2024) [6].

Despite the recognized need for mechanization, limited research has been reported on the systematic design and performance evaluation of power-operated linseed fiber extraction machines under Indian agro-climatic conditions. In particular, experimental studies addressing the interaction between machine design parameters and performance indicators such as extraction efficiency, fiber damage, energy consumption, and economic feasibility remain scarce. This knowledge gap has restricted the development and adoption of efficient, low-cost extraction systems suitable for decentralized and rural applications.

In this context, the present study was undertaken to design, develop, and evaluate a power-operated linseed fiber extraction machine (POLFEM). The specific objectives were to design and fabricate a prototype suitable for small-scale use, evaluate its performance under varying operating conditions, and assess its economic feasibility. The findings of this study are expected to support the mechanization of linseed fiber extraction and promote the sustainable valorization of linseed straw as a value-added agricultural resource.

Materials and Methods

Raw Material Preparation

Five linseed (*Linum usitatissimum* L.) varieties, namely Sheela, Shekhar, Neelam, RLC-92, and RFC-2019, were selected for the study. Mature linseed plants were harvested, and the straw obtained after seed separation was used for fiber extraction experiments. The collected straw was initially sun-dried to reduce surface moisture and then subjected to wet retting for a period of 7-10 days to facilitate loosening of bast fibers from the woody core. After retting, the straw was washed thoroughly and partially dried to achieve moisture content levels suitable for mechanical extraction. During experimental trials, the moisture content of straw was maintained within the range of 25-40%.

Design and Fabrication of the POLFEM

The power-operated linseed fiber extraction machine (POLFEM) was designed and developed at the Department of Farm Machinery and Power Engineering, Indira Gandhi Krishi Vishwavidyalaya (IGKV), Raipur. The design objective was to develop a compact, low-cost, and efficient machine suitable for small-scale industries and rural applications.

The main frame of the machine was fabricated using mild steel sections to provide structural rigidity and support for all components. The fiber extraction unit consisted of a four-roller system arranged in two stages. The first stage comprised two smooth feeding rollers responsible for crushing the retted linseed straw and loosening the fiber bundles. The second stage consisted of two rasp-bar rollers designed to strip and separate the woody stem portion from the bast fibers.

Each roller had a radius of 60 mm and was mounted on a shaft supported by ball bearings to ensure smooth rotation. The surface of the rasp-bar rollers was provided with grooves to enhance frictional interaction between the rollers and straw material, thereby improving stem removal efficiency. The clearance between rollers was made adjustable to accommodate variations in straw thickness and moisture content. Front and side views of the power-operated linseed fiber extraction machine (POLFEM), showing the overall structural layout and arrangement of major components in Figure 1.

Power Transmission System

The machine was powered by a 1 hp single-phase electric motor. A speed reduction gearbox was employed to obtain the required operating speeds at the roller shafts. Power transmission from the motor to the rollers was achieved using a combination of belt and chain drives, ensuring efficient torque transfer and operational stability. The roller speeds could be varied between 30 and 50 rpm by adjusting the transmission system. A schematic representation of the power transmission system of the power-operated linseed fiber extraction machine (POLFEM) is shown in Figure 2 with components.

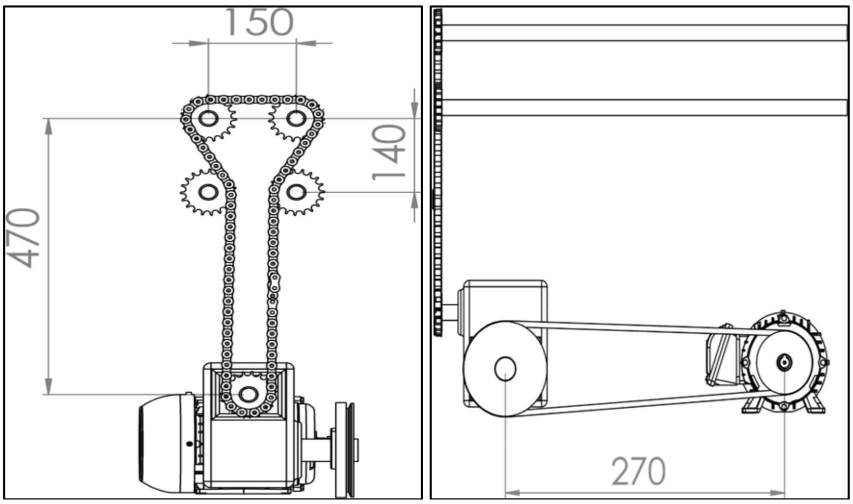

Fig 1: Front and side view of the machine

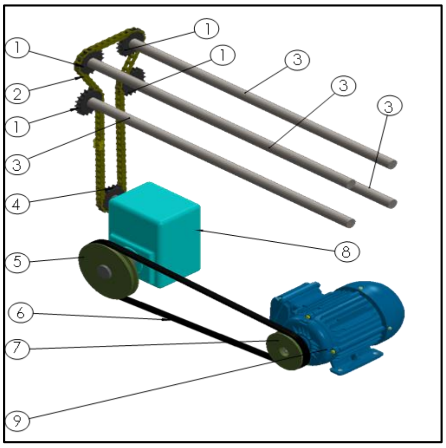

Fig 2: Schematic representation of the power transmission system of the power-operated linseed fiber extraction machine (POLFEM), showing the arrangement of motor (9), speed reduction gearbox (8), driver pulley (7), V-belt (6), follower pulley (5), driver gear (4), shaft gear/follower (1), chain (2), and roller shafts (3). All dimensions are in millimetres.

Working Principle of the POLFEM

The working principle of the POLFEM is based on mechanical crushing and scraping action. Retting-treated linseed straw is fed manually into the feeding rollers, where initial compression breaks the bonding between fibers and the woody core. The partially separated straw then passes to the rasp-bar rollers, where repeated impact and scraping actions remove the stem material and release the bast fibers. The extracted fibers are collected at the outlet, while the separated stem residues fall through the discharge section. The sequential roller action ensures continuous operation with minimal fiber damage when operated under optimal conditions. Prototype Figure 3, of the power-operated linseed fiber extraction machine (POLFEM) developed for experimental evaluation and Operational view also shown in Figure 4.

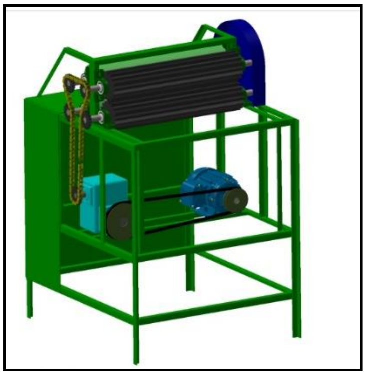

Fig 3: Prototype of machine

Fig 4: Operational view of the power-operated linseed fiber extraction machine during fiber extraction process.

Fig 5: Solid roller of the machine

Experimental Plan and Operating Parameters

Performance evaluation of the POLFEM was conducted by varying key operating parameters to assess their influence on machine efficiency and fiber quality. The experimental plan included the following independent variables:

- Roller speed: 30, 40, and 50 rpm
- Feed rate: 25, 30, and 35 kg h^{-1}
- Moisture content of straw: 25-30%, 30-35%, and 35-40%

Each experimental trial was conducted using a specific combination of these parameters, and observations were recorded after attaining steady-state operation. Figure 5, Solid roller used in the POLFEM, illustrating the construction and surface configuration employed for crushing and fiber separation. Figures 6, 7, and 8 show the effect of the moisture content of linseed straw on extraction performance at different roller clearances and roller speeds.

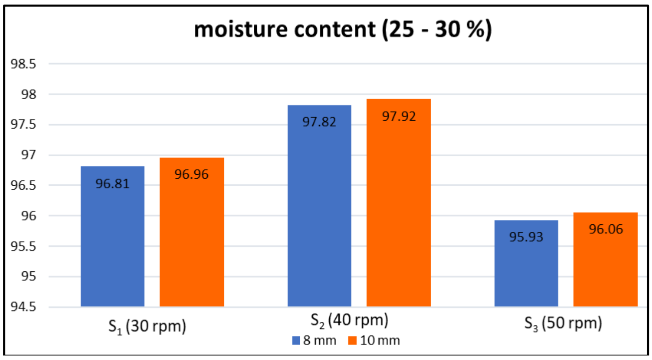

Fig 6: Effect of moisture content of straw (25-30 %) on different clearance and different roller speed

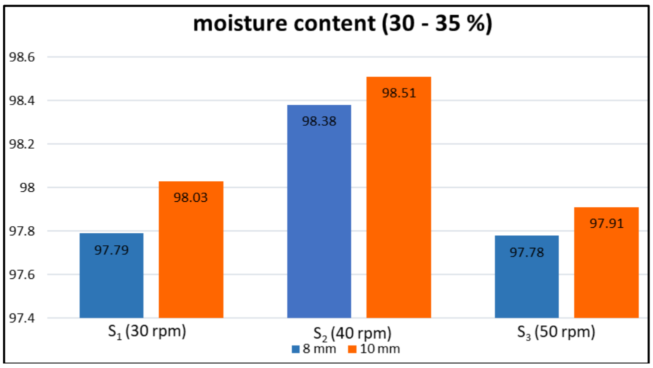

Fig 7: Effect of moisture content of straw (30-35 %) on different clearance and different roller speed

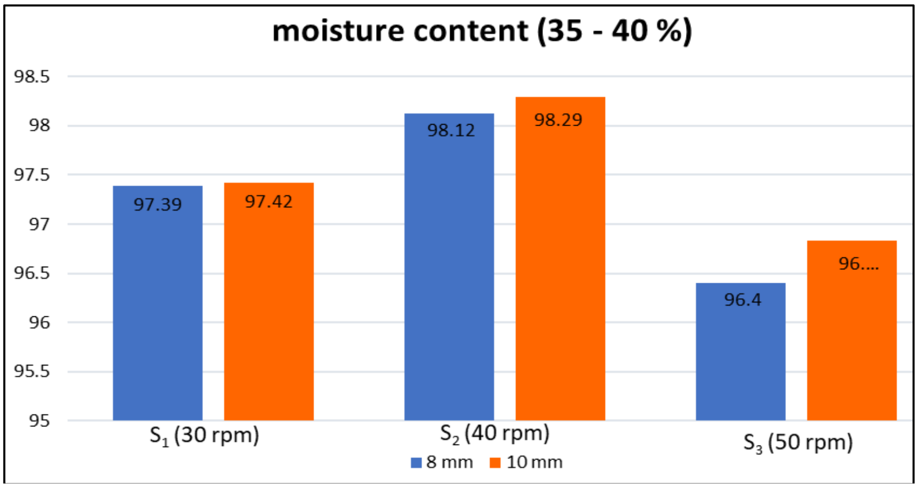

Fig 8: Effect of moisture content of straw (35-40 %) on different clearance and different roller speed

Performance Evaluation Parameters

The performance of the POLFEM was evaluated using the following dependent parameters:

- **Extraction efficiency (%):** Ratio of mass of fiber extracted to the total fiber present in the input straw.
- **Fiber damage (%):** Proportion of broken or excessively shortened fibers relative to total extracted fiber.
- **Energy consumption:** Electrical energy consumed during operation, measured using a power meter.

Each experiment was replicated to ensure reliability of the results, and average values were used for analysis. Figure 9, effect of roller speed and feed rate on the extraction efficiency of the power-operated linseed fiber extraction machine and Figure 10, show the effect of roller speed and feed rate on fiber damage during linseed fiber extraction using the POLFEM.

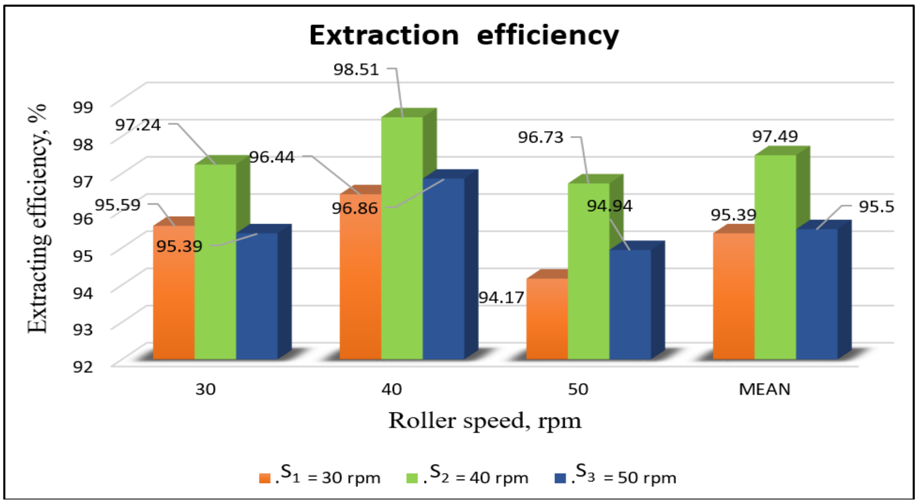

Fig 9: Effect on extracting efficiency at different roller speed and feed rate

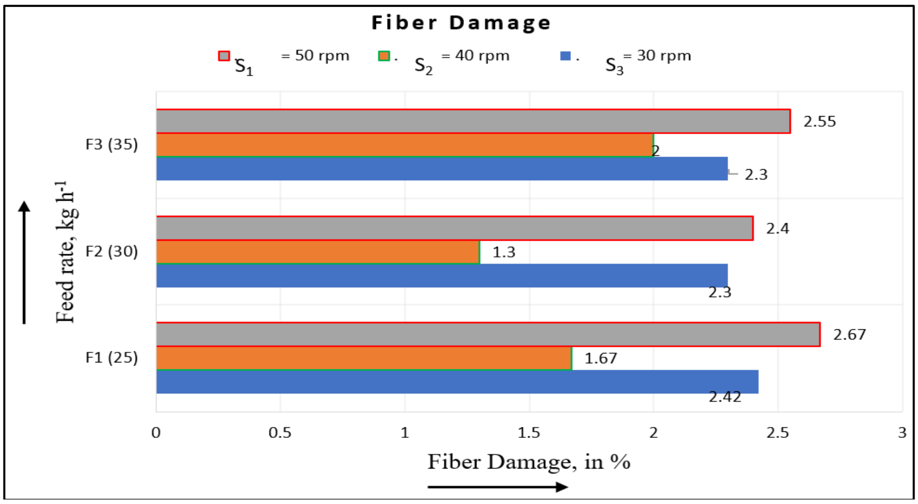

Fig 10: Effect on fiber damage at different roller speed and feed rate

Economic Analysis

An economic evaluation of the POLFEM was carried out to assess its feasibility for small-scale adoption. Fixed costs included depreciation, interest, housing, and insurance, while variable costs comprised electricity consumption, labor charges, and maintenance. Break-even point and payback period were calculated based on standard agricultural machinery cost analysis procedures.

Results and Discussion

Performance Evaluation of the POLFEM

The performance of the power-operated linseed fiber extraction machine (POLFEM) was evaluated under different combinations of roller speed, feed rate, and moisture content to determine optimal operating conditions. The results demonstrate that machine performance is strongly influenced by the interaction between these parameters, particularly roller speed and moisture content of the straw.

Effect of Roller Speed on Extraction Efficiency

Roller speed had a pronounced effect on fiber extraction efficiency. Among the tested speeds (30, 40, and 50 rpm), a roller speed of 40 rpm resulted in the highest extraction efficiency, as shown in Table 1, reaching a maximum value of 98.51%. At this speed, the crushing and rasping actions were sufficient to effectively separate bast fibers from the woody core without excessive fiber breakage.

At 30 rpm, the extraction efficiency was comparatively lower due to insufficient crushing and scraping action, resulting in incomplete stem separation. Conversely, increasing the roller speed to 50 rpm led to higher mechanical aggressiveness, which increased fiber breakage and reduced overall fiber quality. These findings indicate that moderate roller speeds provide an optimal balance between effective fiber release and controlled mechanical stress.

Similar observations have been reported in bast fiber extraction systems, where excessive roller speed increases impact forces and fiber damage, while lower speeds result in incomplete separation (Selge *et al.*, 2024) [6].

Table 1: Effect of roller speed and feed rate on extraction efficiency (%) of the power-operated linseed fiber extraction machine.

Feed rate, (kg h^{-1})	Extracting efficiency, %			Mean
	Speed, rpm			
	S_1 (30 rpm)	S_2 (40 rpm)	S_3 (50 rpm)	
F_1 (25)	95.59	97.24	95.39	96.04
F_2 (30)	96.44	98.51	96.86	97.09
F_3 (35)	94.17	96.73	94.94	95.25
Mean	95.39	97.49	95.5	96.12

Effect of Feed Rate on Machine Performance

The POLFEM was tested at feed rates of 25, 30, and 35 kg h^{-1}. The machine was able to handle feed rates up to 35 kg h^{-1} without operational instability. However, a feed rate of 30 kg h^{-1} was found to be optimal for stable operation and uniform fiber extraction.

At lower feed rates (25 kg h^{-1}), machine capacity was underutilized, reducing productivity. At higher feed rates (35 kg h^{-1}), congestion at the roller interface occasionally occurred, leading to uneven crushing and marginal increases in fiber damage. The optimal feed rate ensured continuous material flow, consistent roller engagement, and minimal operator intervention.

Influence of Moisture Content on Fiber Extraction

Moisture content of linseed straw significantly affected extraction efficiency and fiber damage. Straw moisture content in the range of 7-9% (after retting and partial drying) produced the best fiber quality with minimal damage. At lower moisture levels, straw became brittle, increasing fiber breakage during crushing. At higher moisture levels, excessive flexibility reduced the effectiveness of rasping action, resulting in incomplete stem removal.

These results confirm that moisture conditioning is a critical pre-processing step for linseed fiber extraction and must be carefully controlled to ensure optimal machine performance.

Effect of Roller Clearance

Roller clearance plays a vital role in controlling crushing intensity and fiber separation. An optimum clearance of 30 mm between the inner and outer rollers allowed smooth passage of retted straw while preventing excessive stress on machine components. Smaller clearances increased fiber damage and machine vibration, while larger clearances resulted in incomplete separation of the stem from fibers. The adjustable clearance mechanism of the POLFEM therefore provides operational flexibility for handling variations in straw thickness and moisture content.

Fiber Damage Assessment

Fiber damage was found to be minimal under optimal operating conditions, as shown in Table 2. At a roller speed of 40 rpm and feed rate of 30 kg h^{-1}, fiber damage was limited to 1.3%, indicating effective separation with minimal degradation of fiber quality. Higher damage levels were observed at elevated roller speeds due to increased mechanical impact and abrasion.

Low fiber damage is a critical performance indicator, as it directly affects the suitability of fibers for downstream applications such as textiles and composite reinforcement.

Table 2: Effect of roller speed and feed rate on fiber damage (%) during linseed fiber extraction.

Feed rate, (kg h^{-1})	Fiber damage, %			Mean
	Speed, rpm			
	S_1 (30 rpm)	S_2 (40 rpm)	S_3 (50 rpm)	
F_1 (25)	2.42	1.67	2.67	2.25
F_2 (30)	2.3	1.3	2.4	2.00
F_3 (35)	2.3	2	2.55	2.25
Mean	2.34	1.65	2.54	2.16

Energy Consumption and Human Effort Reduction

Energy analysis revealed that approximately 97% of the total energy input was supplied through mechanical and electrical sources, while only 3% was attributed to human effort. This demonstrates the effectiveness of the POLFEM in significantly reducing manual drudgery compared to traditional extraction methods. The reduced reliance on human labor enhances productivity and improves working conditions, particularly for rural operators.

Economic Performance of the POLFEM

The fabrication cost of the POLFEM prototype was approximately ₹75,000, making it economically accessible for small-scale industries and rural entrepreneurs. The total operating cost was estimated at ₹74.78 h^{-1}, with a calculated break-even point of 188.89 h $year^{-1}$ and a payback period of 5.09 years.

These economic indicators suggest that the POLFEM is a financially viable solution for decentralized linseed fiber processing, offering substantial reductions in labor cost and improvements in processing efficiency.

Overall Performance Assessment

The combined results indicate that the POLFEM performs optimally at a roller speed of 40 rpm, feed rate of 30 kg h^{-1}, moisture content of 7-9%, and roller clearance of 30 mm. Under these conditions, the machine achieved high extraction efficiency, low fiber damage, reduced energy expenditure, and favorable economic returns. The findings demonstrate the technical feasibility and practical applicability of the POLFEM for small-scale linseed fiber extraction.

Economic Analysis

An economic evaluation of the power-operated linseed fiber extraction machine (POLFEM) was carried out to assess its financial feasibility for small-scale processors and rural entrepreneurs. The analysis included estimation of fixed and variable costs, total operating cost, break-even point, and payback period using standard farm machinery cost evaluation procedures. The objective was to determine whether the developed prototype could offer an economically viable alternative to manual fiber extraction methods.

The total fabrication cost of the POLFEM was approximately ₹75,000, indicating its affordability for decentralized and small-scale applications. Fixed costs comprised depreciation, interest, housing, and insurance, while variable costs included electricity consumption, labor charges, and routine maintenance. Based on these components, the total operating cost of the machine was calculated as ₹74.78 h^{-1}. The economic indicators showed a break-even point of 188.89 operating hours per year and a payback period of 5.09 years, demonstrating the long-term economic viability of the machine.

The economic performance of the POLFEM is summarized in Table 3, which presents key cost components and financial indicators relevant to decision-making for adoption at the farm and rural enterprise level.

Table 3: Economic analysis of the power-operated linseed fiber extraction machine (POLFEM)

Economic parameter	Value (Rs)
Fabrication cost of machine (₹)	75,000
Fixed cost (₹ h^{-1})	22.70
Variable/operating cost (₹ h^{-1})	54.04
Total operating cost (₹ h^{-1})	74.78
Cost of operation (₹ kg^{-1} h^{-1})	24.90
Break-even point (h $year^{-1}$)	188.89
Payback period (years)	5.09
Mechanical and electrical energy contribution (%)	97
Human energy contribution (%)	3

Discussion of Economic Feasibility

The economic analysis clearly indicates that the POLFEM offers a cost-effective solution for linseed fiber extraction, particularly in comparison to labor-intensive manual methods. The low dependence on human labor (3%) significantly reduces operational drudgery while improving productivity. The moderate fabrication cost and reasonable payback period make the machine suitable for adoption by farmer groups, self-help groups, and small rural enterprises. Overall, the POLFEM demonstrates strong potential for enhancing the economic value of linseed straw through mechanized processing.

Conclusion

The present study successfully designed, developed, and evaluated a power-operated linseed fiber extraction machine (POLFEM) suitable for small-scale and rural applications. The machine effectively addressed the limitations of traditional manual extraction methods by significantly reducing labor intensity while achieving high extraction efficiency and improved fiber quality. Performance evaluation revealed that the machine operated optimally at a roller speed of 40 rpm, feed rate of 30 kg h^{-1}, moisture content of 7-9%, and roller clearance of 30 mm. Under these conditions, the POLFEM achieved a maximum extraction efficiency of 98.51% with minimal fiber damage (1.3%).

The results demonstrated that roller speed, feed rate, moisture content, and clearance exert a significant influence on extraction performance, highlighting the importance of parameter optimization for efficient fiber separation. The machine's design, incorporating a four-roller system with smooth feeding rollers and rasp-bar extraction rollers, ensured effective separation of bast fibers from the woody core while minimizing mechanical stress on the fibers.

Economic analysis confirmed the financial feasibility of the developed prototype, with a moderate fabrication cost of ₹75,000, a total operating cost of ₹74.78 h^{-1}, and a payback period of 5.09 years. The high contribution of mechanical and electrical energy (97%) and minimal reliance on human effort (3%) further emphasized the machine's potential to reduce manual drudgery and improve productivity in rural settings.

Overall, the POLFEM represents a viable mechanized solution for linseed fiber extraction and offers significant potential for promoting the value addition of linseed straw. The adoption of this machine can enhance income generation for farmers and rural entrepreneurs while supporting the sustainable utilization of linseed biomass in textile and allied industries.

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