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Original Article

Technological Integration, Mechanization and Innovation in the Coir Industry: Production Transformation, Sustainability and Socio-Economic Implications in India

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Abstract - *The coir industry remains one of India's most important agro-based rural industries, contributing to employment generation, export earnings, and the utilization of renewable natural resources, particularly in coconut-growing regions of southern India. For much of its history, production depended on labor-intensive practices such as manual fibre extraction, hand spinning, and conventional processing methods, which constrained productivity, product diversification, and technological advancement. While existing studies have examined mechanization, fibre technology, sustainability, labour conditions, and product development as separate themes, limited attention has been paid to the interconnected role of technological innovation, institutional support, and industrial transformation within a single analytical framework. This article examines the technological modernization of India's coir industry through an interdisciplinary analysis of mechanization, process engineering, product innovation, sustainability, and socio-economic change. The study is based on secondary sources, including engineering research articles, policy documents, institutional reports, doctoral theses, and technical studies relating to coir production and industrial development. Drawing on perspectives from industrial engineering, political economy, industrial sociology, and sustainable manufacturing, the analysis explores the changing technological foundations of the sector and their wider implications. The findings indicate that improvements in fibre extraction technologies, mechanized spinning systems, process optimization techniques, and coir-based composite applications have enhanced production efficiency, product quality, and industrial competitiveness. Technological advances have also broadened the range of coir products into geotextiles, biodegradable packaging, horticultural products, construction materials, and polymer composites. Institutional initiatives undertaken by the Coir Board and specialized research organizations have played a central role in facilitating modernization and product diversification. At the same time, financial constraints, uneven technological adoption, and fragmented production structures continue to limit the pace of transformation. By examining technological change, institutional support, sustainability, and socio-economic implications within a single analytical framework, the article contributes to a more comprehensive understanding of modernization processes in traditional rural industries and the challenges associated with achieving inclusive and environmentally responsible industrial transformation.*

Keywords *- Coir Industry, Mechanization, Technological Modernization, Coir Composites, Sustainability, Fibre Extraction, Innovation, Productivity, Industrial Transformation.*

1. Introduction

Natural fibre-based industries have acquired renewed importance in contemporary discussions on sustainable development, ecological industrialization, and environmentally responsible manufacturing. Growing concerns over climate change, plastic pollution, and resource-intensive production systems have encouraged the search for renewable and biodegradable alternatives to synthetic materials. Within this broader transition, coir fibre has emerged as a versatile natural resource with applications ranging from geotextiles and horticultural substrates to biodegradable packaging, erosion-control products, and composite materials. The increasing adoption of circular economy principles and green manufacturing practices has further enhanced the industrial relevance of coir in domestic and international markets.

In India, the coir industry occupies a distinctive position among agro-based rural industries. Concentrated primarily in coconut-growing regions, particularly Kerala, Tamil Nadu, and Karnataka, the sector has historically contributed to rural employment, export earnings, and decentralized industrial development. Kerala, and especially Alappuzha, evolved as the traditional centre of coir production owing to favorable ecological conditions, extensive coconut cultivation, and long-established trading networks. The industry has also played an important role in providing livelihoods for women and other socially and economically marginalized groups.

Despite its economic significance, the coir sector remained dependent for decades on labor-intensive production methods, including traditional retting, manual fibre extraction, and hand spinning. These practices were often associated with low productivity, inconsistent product quality, labour drudgery, and environmental concerns. Increasing global competition, changing market requirements, and growing environmental awareness created pressures for technological upgrading and industrial restructuring. In response, mechanization, process engineering innovations, product diversification, and institutional support initiatives gradually began to reshape production systems across the industry.

1.1. Research Problem

Although technological modernization has become an important feature of the contemporary coir sector, understanding its broader implications remains a challenge. Existing studies have examined mechanization, sustainability, labour relations, export performance, fibre technology, and product innovation as largely separate themes. As a result, the interconnected relationship between technological integration, industrial modernization, sustainability transitions, and socio-economic transformation has received comparatively limited attention. This fragmentation of knowledge constitutes the central research problem addressed in the present study.

1.2. Research Gap

Previous scholarship has generated valuable insights into individual dimensions of the coir industry, including production technologies, labour processes, environmental issues, composite materials, and industrial performance. However, relatively few studies have examined how technological innovation, institutional intervention, productivity enhancement, sustainability concerns, and socio-economic change interact within a single analytical framework.

Consequently, the broader implications of technological transformation for rural industrial development and long-term industrial sustainability remain insufficiently synthesized. The present study addresses this gap by bringing together these dimensions within an integrated interdisciplinary analysis.

1.3. Research Questions

The study is guided by the following questions.

1. How has technological integration transformed production systems within India's coir industry?
2. What socio-economic changes have accompanied mechanization and industrial modernization in the sector?
3. How have technological innovations influenced sustainability and the expanding industrial applications of coir?
4. What role have institutional interventions played in facilitating technological transformation and product diversification?

1.4. Novelty and Contribution

The originality of the study lies in its integrated examination of technological change within the coir industry. Rather than focusing exclusively on mechanization, labour, sustainability, or product innovation, the analysis brings together engineering, institutional, environmental, and socio-economic perspectives to explain the dynamics of industrial transformation. By examining technological change, institutional support, sustainability, and socio-economic implications within a single analytical framework, the article contributes to a more comprehensive understanding of modernization processes in traditional rural industries and the challenges associated with achieving inclusive and environmentally responsible industrial transformation.

The study draws upon engineering research, institutional reports, policy documents, and scholarly literature to examine the technological evolution of the coir sector and its wider developmental implications. The sections that follow discuss the methodological framework, technological modernization processes, institutional interventions, product diversification, sustainability dimensions, and socio-economic consequences of industrial transformation in India's coir industry.

2. Review of Literature

The coir industry has attracted scholarly attention from a wide range of disciplinary perspectives, including economic history, rural industrialization, labour studies, industrial engineering, environmental management, materials science and sustainable manufacturing. Early studies largely concentrated on the structural characteristics of the industry, identifying technological stagnation, low productivity, inadequate modernization and institutional constraints as major impediments to growth (Pylee, 1976; Isaac, 1991; Rammohan, 1999; Nayar, 2004). Research conducted during this period viewed the sector primarily as a labour-intensive rural industry whose competitiveness depended on improvements in production efficiency, technological upgrading, and market expansion. Subsequent analyses of production systems, export performance, and industrial restructuring reinforced these concerns while highlighting the growing pressures generated by globalization, trade liberalization, and changing international market conditions (Meipporul & Bhanumathy, 2010; Singaravelu & Kavitha, 2012; Praveenkumar, 2017; Raseena, 2018; Tanwani, 2020; Muneeswaran & Kesavan, 2022).

Growing attention to technological modernization produced a substantial body of research examining mechanization and productivity enhancement within the coir sector. Studies consistently indicate that the replacement of manual extraction, spinning, and processing systems with mechanized technologies contributes to higher productivity, improved fibre quality, and greater production efficiency (Rajpal, 2012; Joseph & Raseena, 2020; Raseena, 2020, 2024; Gopinath & Balaji, 2019; Ayodele & Omoniyi, 2020; Pavithran et al., 2024). Research undertaken by the Coir Board, CCRI, CICT, NCRMI, and other institutional agencies similarly emphasizes the role of machinery development, process optimization, technological diffusion, and modernization support programmes in enhancing industrial performance (Coir Board, 2017; Coir Board, n.d.; NCRMI, n.d.; Udyami Mitra, 2021; Ministry of MSME, 2021, 2023). These studies collectively suggest that technological upgrading has become a central determinant of competitiveness in the contemporary coir industry.

Parallel developments in industrial engineering and manufacturing research have expanded understanding of process innovation within coir production. Investigations into lean manufacturing, workflow synchronization, simulation-assisted production planning, and fibre extraction technologies demonstrate significant potential for improving resource utilization, reducing production costs, and enhancing operational efficiency (Ayodele & Omoniyi, 2020; Pavithran et al., 2024; Kumar & Shekar, 2022). Broader economic discussions concerning investment-specific technological change further reinforce the argument that technological modernization can fundamentally reshape productivity trajectories within traditional industries (Greenwood, Hercowitz & Krusell, 1995, 1996, 1997).

A rapidly expanding body of literature has also examined coir from the perspective of sustainability and environmentally responsible manufacturing. Earlier environmental studies identified traditional retting practices as a significant source of ecological degradation, particularly through water pollution, sediment contamination, and adverse impacts on aquatic ecosystems (Abbasi & Abbasi, 1985; Suja, 2014; Jose et al., 2019; Kasthuri et al., 2022). More recent investigations point towards cleaner extraction methods, pollution-abatement technologies, and environmentally improved processing systems capable of reducing ecological burdens associated with fibre production (Ravindaran & Singh, 2022; Rahman et al., 2022; Morato et al., 2024). Comparative environmental assessments further indicate that mechanized and technologically upgraded production systems may offer substantial environmental advantages over conventional retting-based methods (Pratheesh, 2026b).

At the same time, advances in materials science have transformed perceptions of coir from a traditional fibre product into a versatile industrial material with applications extending across construction, geotextiles, polymer engineering, packaging, automotive manufacturing, and sustainable infrastructure. Research on coir-based composites consistently demonstrates favourable mechanical, thermal, acoustic, and environmental properties, supporting its use as a renewable alternative to synthetic materials (Hasan, Horváth & Alpár, 2021; Wang et al., 2022; Elfaleh et al., 2023; Guruswamy et al., 2024; Ashok et al., 2025; Figueiredo et al., 2025; Ajayi et al., 2025). Similar conclusions emerge from studies examining natural fibre-reinforced composites, biodegradable materials, insulation systems, and circular-economy applications (Adeniyi et al., 2019; Maiti et al., 2022; Das & La Rosa, 2022; Hubbe, 2023; Krishnasamy et al., 2024; Karabacak et al., 2024).

The social dimensions of industrial transformation constitute another major strand within the literature. Research addressing labour relations, employment restructuring, gendered work patterns and occupational change demonstrates that modernization has produced both opportunities and tensions within traditional production systems (Heller, 1996; Pratheesh & Gopakumaran Nair, 2021a, 2021b; Pratheesh, 2021a, 2021b; Pratheesh & Nair, 2022; Pratheesh, 2024a; Chithra & Rajendran, 2021; Nair & Thomas, 2019; Ramachandran, 2021). Studies examining women's employment, livelihood adaptation, skill development, and rural economic empowerment similarly underscore the continuing socio-economic significance of the coir sector despite technological restructuring (Singh, 2015; Patel, 2017; Thangaraj, 2019; Srinivasan, 2020; Pandian & Kavitha, 2021; Pratheesh, Reema & Florence, 2024).

Table 1. Summary of Major Themes in Existing Literature and Identified Research Gaps

Theme	Representative Studies	Major Contributions	Gap Identified
Industrial History and Development	Pylee (1976); Isaac (1991); Nayar (2004); Rammohan (1999)	Documented historical evolution, production structures, and technological constraints	Limited attention to recent technological transformation
Mechanization and Productivity	Rajpal (2012); Joseph & Raseena (2020); Raseena (2024); Gopinath & Balaji (2019)	Established links between mechanization and productivity growth	Limited integration with sustainability and labour outcomes
Engineering and Process Innovation	Ayodele & Omoniyi (2020); Pavithran et al. (2024); Coir Board reports	Examined machinery development and production optimization	Focus largely restricted to technical efficiency.
Sustainability and	Abbasi & Abbasi (1985);	Evaluated the environmental	Limited connection with

Environmental Issues	Ravindaran & Singh (2022); Pratheesh (2026b)	impacts of retting and cleaner technologies	industrial modernization processes
Coir Composites and New Applications	Hasan et al. (2021); Wang et al. (2022); Ajayi et al. (2025); Figueiredo et al. (2025)	Demonstrated industrial applications in composites and green materials	Limited discussion of socio-economic implications
Labour and Rural Development	Heller (1996); Pratheesh et al. (2021–2025); Chithra & Rajendran (2021)	Analyzed labour transformation and rural livelihoods	Limited integration with engineering and sustainability perspectives
Institutional and Policy Interventions	Coir Board; NCRMI; MSME Reports	Highlighted modernization programmes and policy support	Absence of an integrated assessment of outcomes

Taken together, the existing body of scholarship has generated valuable knowledge on the historical evolution of the coir industry, mechanization processes, productivity enhancement, export performance, labour relations, environmental concerns, and the expanding range of coir-based industrial applications. These contributions have considerably improved the understanding of individual dimensions of the sector and have documented important developments in technology, production systems, and market expansion. Nevertheless, the available literature remains largely fragmented, with most studies concentrating on specific aspects of industrial change rather than examining their interconnections. Questions relating to how technological innovation, institutional support mechanisms, sustainability transitions, and socio-economic restructuring collectively shape the modernization of the coir industry have received comparatively limited attention. As a result, the broader implications of technological integration for productivity, labour transformation, and sustainable rural industrial development remain insufficiently synthesized. Addressing this gap, the present study adopts an integrated analytical approach that brings together mechanization, process engineering, sustainability transitions, institutional interventions, and socio-economic change in order to provide a more comprehensive understanding of the technological transformation of India's coir industry.

3. Materials and Methods

The present study is a secondary-data-based analytical investigation of the technological transformation of India's coir industry, drawing upon an interdisciplinary qualitative approach that brings together technical, institutional, environmental, and socio-economic perspectives. Rather than offering a descriptive review of existing literature, the analysis examines how mechanization, technological innovation, and industrial modernization have reshaped production systems and influenced broader processes of industrial change. The study considers the interrelationship between technological development, institutional support, sustainability transitions, and socio-economic restructuring, with particular attention to mechanized fibre extraction, process engineering, product diversification, composite material innovation, productivity improvement, and their implications for labour and rural industrial development. It further seeks to assess the extent of technological integration within the sector, evaluate its social and environmental consequences, and examine the role of institutional interventions in supporting modernization and long-term industrial transformation.

3.1. Data Sources and Selection Criteria

The study relies exclusively on secondary data drawn from academic, technical, and institutional sources published between the early phases of mechanization research and the most recent studies on coir modernization. The database includes peer-reviewed journal articles, doctoral theses, engineering studies, project reports, policy documents, government publications, and institutional reports relating to technological development, mechanization, sustainability, and industrial transformation within the coir sector.

Data were collected from the following major sources:

- Coir Board of India publications and annual reports
- Central Coir Research Institute (CCRI)
- Central Institute of Coir Technology (CICT)
- National Coir Research and Management Institute (NCRMI)
- Ministry of Micro, Small and Medium Enterprises (MSME)
- Government of Kerala publications, including Economic Review reports
- Engineering and technology journals
- Doctoral theses and research dissertations
- Scholarly studies on coir composites, sustainability, and industrial modernization

The selection of source materials was guided by three criteria: (i) direct relevance to technological change and modernization within the coir industry; (ii) empirical, technical, or policy-based evidence relating to productivity, mechanization, sustainability, or labour transformation; and (iii) contribution to understanding long-term industrial restructuring within the sector. Particular emphasis was placed on studies published during the period 2000–2026, while selected earlier works were included to provide historical and institutional context.

3.2. Data Analysis and Analytical Approach

The analysis draws upon engineering studies, institutional records, and socio-economic research to examine the changing technological landscape of the coir industry. Information from these sources was reviewed and interpreted around key themes such as mechanization, production restructuring, sustainability and industrial development, enabling the identification of broader patterns of change across different stages of coir production.

Particular attention was given to the ways technological innovation has influenced productivity, product diversification, labour relations, environmental performance, and export competitiveness, while institutional policies and modernization initiatives were assessed in relation to their contribution to industrial transformation. By bringing together evidence from multiple sources, the study traces the major trends, challenges, and shifts that have shaped the contemporary coir sector.

3.3. Analytical Framework

The analytical framework integrates four complementary perspectives: process engineering, industrial sociology, political economy, and sustainable manufacturing.

The process engineering perspective is employed to examine developments in fibre extraction technologies, mechanized spinning systems, workflow optimization, lean manufacturing practices, and production efficiency. Industrial sociology provides a framework for understanding labour transformation, occupational restructuring, gendered work patterns, and the social consequences of mechanization within a traditionally labour-intensive industry.

The political economy perspective facilitates the examination of state intervention, institutional support, trade liberalization, export restructuring, and policy-driven modernization initiatives. Finally, the sustainable manufacturing perspective is used to assess the environmental dimensions of technological change, including biodegradable materials, waste utilization, coir composites, geotextiles, circular economy applications, and environmentally responsible production systems.

The integration of these perspectives enables technological modernization to be examined not only as an engineering process but also as a broader socio-economic and environmental transformation.

3.4. Thematic Areas of Analysis

To facilitate systematic interpretation, the study examines technological modernization through a set of interrelated thematic areas comprising fibre extraction technologies, mechanization and automation, productivity enhancement, product diversification, composite material innovation, labour transformation, sustainability indicators, institutional support mechanisms, and market restructuring. These thematic areas provide the basis for analyzing the interaction between technological change, industrial performance, and sustainable development within the coir industry.

3.5. Limitations of the Study

The study is based primarily on secondary sources, and therefore its findings reflect broader patterns of technological transformation in the coir industry, with particular relevance to major producing regions such as Kerala, rather than direct field-based evidence from all segments of the sector.

4. Results and Discussion

The analysis reveals that the technological transformation of the coir industry cannot be understood merely as a contemporary process of mechanization or industrial modernization. The present structure of the industry emerged through a historically layered process involving colonial commercial expansion, labor-intensive production systems, export-oriented restructuring, and later technological integration. The findings from institutional reports, mechanization studies, export analyses, and industrial process research indicate that the transition from traditional coir manufacturing to technologically integrated production systems was shaped by the interaction between global market pressures, state intervention, labour relations, and industrial innovation.

4.1. Historical Evolution and Industrial Transformation

The analysis indicates that the historical structure of the coir industry both enabled its early growth and constrained its technological development. Although regions such as Alappuzha emerged as major production and export centres through abundant raw materials, established trade networks, and a large labour force, production remained dependent for decades on manual retting, hand spinning, and household-based processing. Earlier studies consistently identified low productivity, technological stagnation, and fragmented production structures as major limitations affecting industrial competitiveness (Pylee, 1976; Isaac, 1991; Rammohan, 1999; Nayar, 2004). The findings suggest that these constraints became increasingly significant with the expansion of export markets and growing competition from mechanized producers.

Evidence from mechanization studies and institutional reports shows that technological upgrading altered both production processes and industrial performance. The introduction of fibre extraction machines, mechanized spinning systems, and process-optimization techniques reduced processing time, improved fibre quality, and increased throughput.

Performance assessments of modern extraction systems report crushing efficiencies exceeding 70–90 percent and substantial improvements in processing capacity compared with traditional methods. Similar observations were reported by Joseph and Raseena (2020), Raseena (2024), Ayodele and Omoniyi (2020), and Pavithran et al. (2024), who found positive associations between mechanization, productivity growth, and industrial competitiveness.

The transformation was not confined to production efficiency alone. Technological modernization facilitated the expansion of coir into geotextiles, horticultural substrates, biodegradable packaging, composites, and construction materials, broadening market opportunities beyond conventional mats and ropes. Research on coir composites and sustainable materials similarly points to growing industrial demand for coir-based products in environmentally conscious markets (Hasan et al., 2021; Ajayi et al., 2025). At the same time, modernization generated uneven social outcomes. While productivity and export performance improved, labour displacement, occupational restructuring, and skill adaptation emerged as recurring concerns, particularly in traditional production clusters. The experience of Kerala illustrates this dual transition, where institutional support from the Coir Board, CCRI, and CICT accelerated technological adoption while simultaneously reshaping long-established patterns of employment and production.

Table 2. Industrial Transformation in the Coir Sector

Indicator	Traditional System	Modernized System
Fibre extraction	Manual/retting-based	Mechanized extraction
Processing time	Several weeks/months	Hours to days
Productivity	Low	Significantly higher
Product range	Mats, ropes	Geotextiles, composites, packaging, construction materials
Labour demand	High manual labour	Lower manual labour, higher skill requirement
Environmental impact	Retting-related pollution	Reduced environmental burden

4.2. Coir Fibre Properties and Industrial Potential

The industrial versatility of coir is rooted in the distinctive characteristics of the fibre itself. Extracted from the husk of the coconut, coir possesses a combination of strength, flexibility, and durability that distinguishes it from many other natural fibres. Its relatively high lignin content enhances resistance to moisture, microbial degradation, and mechanical wear, enabling longer service life under demanding environmental conditions. These characteristics have contributed significantly to its continued use in both traditional and modern industrial applications. Chemical composition studies indicate that coir contains substantial proportions of lignin and cellulose, along with smaller quantities of hemicellulose, pectin compounds, and water-soluble substances. In physical terms, the fibre exhibits moderate density, high elongation capacity and good resilience, properties that support its suitability for reinforcement, insulation and protective applications. Unlike synthetic alternatives, coir is renewable, biodegradable, and derived from an agricultural by-product, making it increasingly attractive within resource-efficient production systems.

Table 3. Chemical and Physical Properties of Coir Fibre

Property	Value
Lignin	45.84%
Cellulose	43.44%
Hemicellulose	0.25%
Pectin compounds	3.00%
Water-soluble substances	5.25%
Density	1.40 g/cc
Fibre length	6–8 inches
Breaking elongation	30%

Source: Compiled from coir fibre property studies.

The fibre is generally classified into white and brown varieties. White coir, obtained from relatively immature coconuts, is finer and more pliable, making it suitable for yarn and rope production. Brown coir, derived from mature husks, possesses greater rigidity and tensile strength and is therefore widely used in mats, brushes, geotextiles, and erosion-control products. This variation in fibre characteristics has enabled manufacturers to tailor products to different industrial requirements.

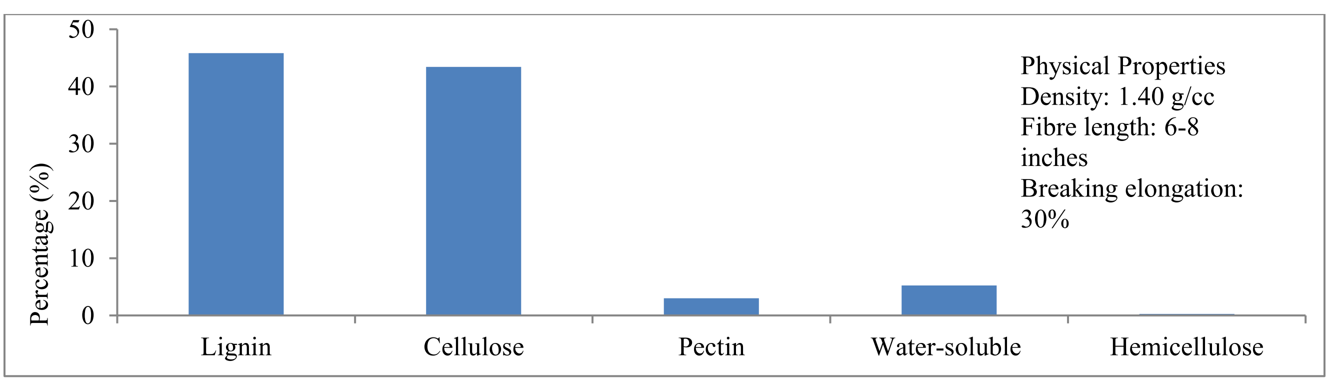

Fig. 1 Chemical Composition and Selected Physical Properties of Coir Fibre

Source: Compiled from Hasan et al. (2021), Mishra et al. (2022), and coir fibre characterization studies.

Figure 1 illustrates the chemical composition and key physical characteristics that contribute to the industrial utility of coir fibre. Lignin (45.84%) and cellulose (43.44%) constitute the major components, indicating a fibre structure characterized by durability, resilience, and resistance to biological degradation. The comparatively high lignin content distinguishes coir from many other natural fibres and contributes to its suitability for geotextiles, erosion-control materials, and outdoor applications. The fibre also exhibits a moderate density (1.40 g/cc), considerable elongation at break (30%) and lengths ranging from 6–8 inches, properties that support its use in composite materials, insulation products and engineering applications. Collectively, these characteristics explain the growing adoption of coir in sustainable manufacturing, biodegradable products, and natural fibre-reinforced composite technologies.

Research in materials engineering has further demonstrated the potential of coir as a reinforcement material in polymer composites, lightweight construction products, insulation panels, and biodegradable packaging. Experimental studies report improvements in strength, impact resistance, and thermal performance when coir fibres are incorporated into composite materials. Equally significant has been the growing commercial utilization of coir pith, once regarded as a processing residue, as a horticultural substrate because of its water-retention capacity and biodegradability. These developments illustrate how the intrinsic properties of coir have expanded its industrial relevance well beyond its traditional uses and positioned it as a valuable material within emerging sustainable manufacturing systems.

4.3. Mechanization in Fibre Extraction Systems

Fibre extraction represents one of the most significant areas of technological change within the coir industry. Traditional production depended on retting and manual fibre separation, a process that often required several months before usable fibre could be obtained. Besides limiting production capacity, prolonged retting contributed to inconsistent fibre quality and environmental stress in water bodies used for husk processing. The introduction of mechanized extraction systems fundamentally altered this stage of production by reducing processing time, improving fibre uniformity, and enabling continuous large-scale operations.

Table 4. Comparison of Traditional and Mechanized Fibre Extraction Systems

Parameter	Traditional System	Mechanized System
Extraction process	Retting and manual beating	Mechanical disintegration and decortication
Processing period	3–12 months	A few hours to 2 days
Labour requirement	High	Moderate
Fibre quality	Variable	More uniform
Production scale	Small and dispersed	Continuous industrial production
Environmental impact	Significant water pollution	Comparatively lower
Productivity	Low	Substantially higher

Source: Compiled from engineering studies, Coir Board reports, and mechanization research.

Table 5. Selected Productivity Indicators in Mechanized Fibre Extraction

Indicator	Performance
Crushing efficiency	72–96%
Sieving efficiency	81–82%
Crushing throughput	14.5 kg/hr
Sieving throughput	13.9 kg/hr
Processing duration	Reduced from months to hours/days
Fibre consistency	Improved standardization

Source: Compiled from machine evaluation and process optimization studies.

The evidence suggests that mechanization has improved both efficiency and output. Machine-performance studies report crushing efficiencies ranging between 72 and 96 percent, while fibre separation efficiencies exceed 80 percent. Throughput levels of approximately 14–15 kg per hour represent a considerable improvement over the manual extraction method. Similar findings have been reported in studies on mechanization and productivity in Kerala, where technological adoption was associated with higher production efficiency, better quality control, and improved industrial competitiveness (Joseph & Raseena, 2020; Raseena, 2024; Ayodele & Omoniyi, 2020).

Beyond machinery alone, modernization involved changes in workflow organization, material handling, and production planning. Process-optimization studies show that lean manufacturing practices and simulation-assisted layout redesign reduced bottlenecks, improved workflow coordination, and increased operational efficiency.

The experience of modernization programmes implemented through the Coir Board and allied research institutions illustrates how technological upgrading extended beyond equipment replacement to encompass broader improvements in production management, productivity, and environmental performance. Collectively, these developments point to a gradual shift from labor-intensive extraction systems towards more efficient and technologically integrated production structures.

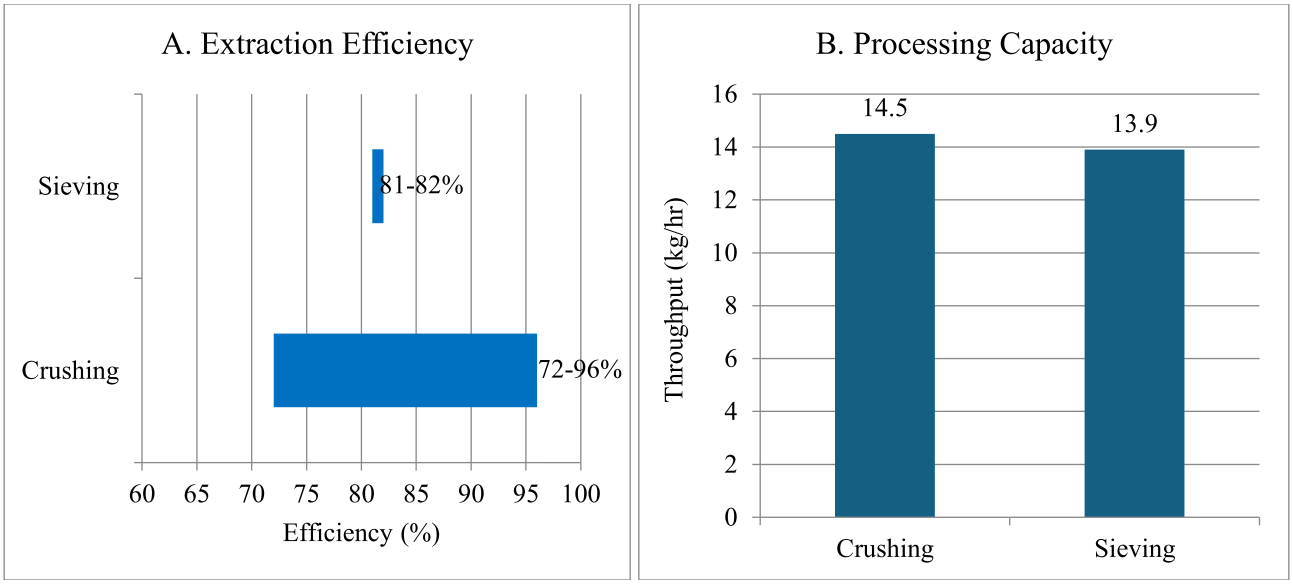

Fig. 2 Operational Performance of Mechanized Coir Fibre Extraction Systems

Source: Compiled from fibre extraction machine performance evaluation studies (Ayodele & Omoniyi, 2020; Coir Board technical reports).

The figure presents the operational performance of mechanized coir fibre extraction systems using two key indicators: extraction efficiency and processing capacity. Crushing efficiency ranged from 72–96%, while sieving efficiency remained above 81%, indicating effective fibre recovery and separation. Processing capacities of 14.5 kg/hr and 13.9 kg/hr for crushing and sieving operations, respectively, demonstrate the ability of mechanized systems to sustain continuous industrial production. Compared with traditional retting-based extraction, which typically requires several months for fibre separation, mechanized extraction reduces processing time to a few hours or days while improving fibre uniformity and process standardization. These performance gains explain the growing adoption of mechanized extraction technologies within modern coir manufacturing.

4.4. Process Optimization and Lean Manufacturing in Coir Production

The modernization of the coir industry has involved not only the adoption of machinery but also significant changes in production organization and workflow management. Evidence from industrial engineering studies shows that inefficiencies in conventional coir units were often linked to fragmented production layouts, excessive material movement, poor synchronization between operations, and prolonged waiting periods during retting and drying. Time–motion analyses indicate that while several processing activities could be completed within minutes, drying and related handling operations frequently extended production cycles by four to five days, reducing continuity and overall plant efficiency.

Studies on lean manufacturing and process engineering demonstrate that production performance improved when workflow design was integrated with technological modernization. Techniques such as Value Stream Mapping (VSM), layout redesign, and simulation-assisted planning reduced unnecessary movement of materials, improved machine utilization, and minimized production bottlenecks. Similar observations were reported in process-optimization studies by Pavithran et al. (2024), where synchronized workflows and revised plant layouts contributed to smoother production flow and lower operational delays.

Table 6. Effects of Process Optimization in Coir Manufacturing Units

Operational Area	Conventional System	Optimized System
Material movement	Excessive	Reduced
Workflow coordination	Fragmented	Integrated
Machine utilization	Uneven	Improved
Lead time	High	Lower
Space utilization	Inefficient	Better organized
Production continuity	Frequently interrupted	More consistent
Worker safety	Limited safeguards	Improved conditions

Source: Compiled from lean manufacturing and industrial process studies.

A practical example can be seen in modernization initiatives undertaken in Kerala-based coir units, where simulation tools and layout planning software were used to evaluate alternative production arrangements before implementation. These interventions helped identify bottlenecks, reduce idle time, and improve coordination between extraction, drying, grading, and baling operations. Similar approaches have been widely adopted in manufacturing sectors seeking to improve productivity without substantial increases in labour or capital inputs. The findings suggest that process optimization contributes to industrial performance in ways that extend beyond output growth alone. Improved workflow coordination reduces waste, lowers handling costs, and supports more efficient use of labour, machinery, and floor space. In this respect, lean manufacturing has emerged as an important complement to mechanization, enabling coir enterprises to improve competitiveness while making production systems more efficient and resource conscious.

4.5. Mechanization and Productivity Enhancement

The impact of mechanization on the coir industry becomes most visible when examined through productivity indicators. Evidence from Kerala's coir sector shows that technological adoption was accompanied by substantial improvements in output, labour productivity, and production efficiency.

Firms operating with higher levels of mechanization consistently recorded greater production volumes than traditional units dependent on manual spinning, weaving, and processing systems. Statistical analysis undertaken by Raseena (2024) demonstrates a positive relationship between mechanization and industrial performance, indicating that productivity gains were not merely incidental outcomes but were closely associated with the degree of technological integration within production processes.

Table 7. Average Daily Production across Mechanization Categories

Mechanization Category	Average Daily Production (₹)
Traditional Units	37,422.98
Low Mechanized Units	130,704.00
Medium Mechanized Units	1,130,696.50
Highly Mechanized Units	536,076.00

Source: Adapted from Research Works of the Author (2024-26).

The differences become even more pronounced when output is measured on a per-worker basis. While traditional firms generated an average per-capita production of 1,914.82, highly mechanized firms recorded more than seven times that level. Statistical tests confirmed that these variations were significant, suggesting that mechanization exerted a measurable influence on productivity performance across production units.

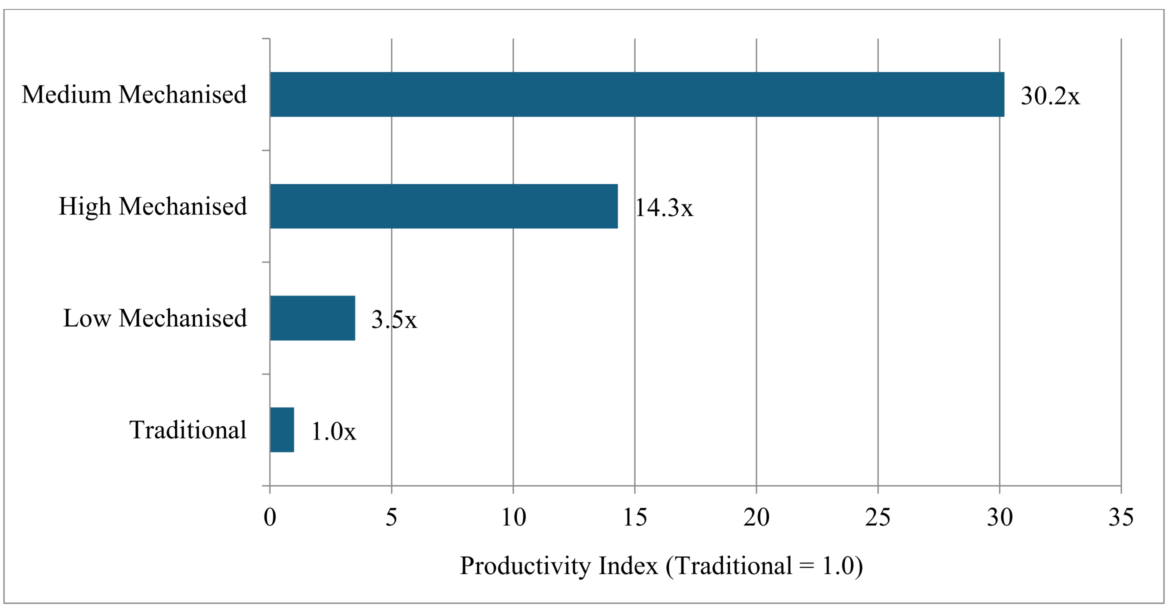

Fig. 3 Relative Productivity Index across Mechanization Categories in the Coir Industry

Source: Calculated from average daily production data reported in the author's research (2024–2026), with traditional units indexed to 1.0.

The figure presents productivity performance relative to traditional production units. Low-mechanized enterprises recorded productivity levels approximately 3.5 times higher than traditional units, while highly mechanized firms achieved productivity levels exceeding fourteen times the traditional benchmark. Medium-mechanized firms exhibited the highest production performance, reaching a productivity index of 30.2. The substantial variation across mechanization categories indicates a strong association between technological adoption and production outcomes, suggesting that mechanization has been a major factor influencing productivity growth and industrial expansion within the coir sector.

Table 8. Per-Capita Production and Statistical Significance

Mechanization Category	Average Per-Capita Production
Traditional Units	1,914.82
Low Mechanized Units	2,359.18
Medium Mechanized Units	11,243.81
Highly Mechanized Units	14,155.51

Statistical Test	Value	Significance (p)
Independent Samples Median Test	10.19	.017
Kruskal–Wallis Test	14.07	.003

Source: Adapted from the research works of the author (2025-26).

Further analysis revealed a statistically significant positive correlation between the Extent of Mechanization (EM) score and daily production ($r = 0.31$, $p < .01$), indicating that production levels generally increased as technological adoption intensified.

Similar conclusions were reported by Joseph and Raseena (2020), Gopinath and Balaji (2019), Anitha and Kumar (2022), and Pratheesh and Florence (2024), who found that mechanized units achieved greater output stability, improved product quality, and stronger export competitiveness than conventional production systems.

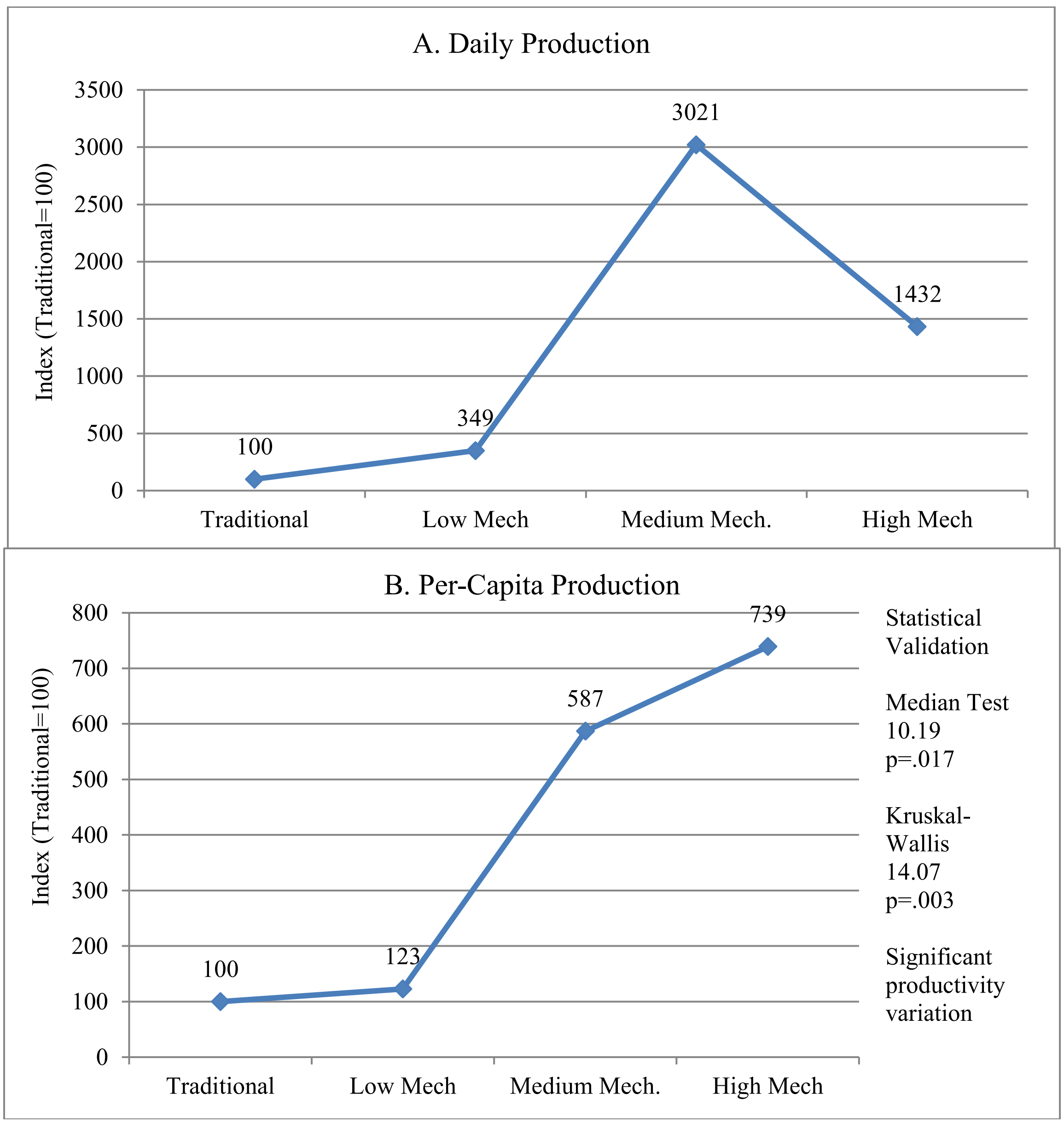

Fig. 3 Productivity Effects of Mechanization in the Coir Industry

Source: Adapted from Research Works of the Author (2024–2026). Daily production and per-capita production values are indexed to traditional units (Traditional = 100) to facilitate comparison across mechanization categories

The figure shows a clear and statistically significant relationship between mechanization and productivity, with both daily production and per-capita output increasing substantially across mechanization categories. The significant results of the Median Test (10.19, p = .017) and Kruskal–Wallis Test (14.07, p = .003) indicate that technological adoption has been a key factor driving productivity growth and industrial competitiveness in the coir sector.

The experience of Kerala illustrates these changes clearly. Programmes implemented through the Coir Board, CCRI, and CICT encouraged the adoption of motorised ratts, mechanized extraction units, and improved weaving technologies, reducing dependence on labour-intensive production methods. At the same time, modernization remained uneven. Small household enterprises often lacked the financial capacity to invest in machinery, creating substantial productivity differences between technologically upgraded firms and traditional units. Consequently, while mechanization strengthened production efficiency and industrial competitiveness, its benefits were concentrated among enterprises with better access to capital, technology, and institutional support. The findings therefore suggest that technological modernization has reshaped productivity structures within the coir industry by increasing output per worker, improving production efficiency, and enabling larger-scale operations. However, the uneven distribution of technological resources continues to influence the extent to which these gains are realized across different segments of the sector.

4.6. Research, Development, and Institutional Innovation

Institutional research has been a major driver of technological change within the coir industry. The modernization of fibre extraction, spinning, product development, and environmental management was supported largely through interventions led by the Coir Board, CCRI, CICT, NCRMI, and allied research centres. Their contribution is reflected not only in machinery development but also in the expansion of value-added products and technology-transfer programmes that facilitated industrial adoption.

Table 9. Institutional Contributions to Technological Modernization

Institution	Major Contribution	Industrial Outcome
CCRI	Fibre extraction technologies, coir pith utilization, and eco-friendly processing	Improved productivity and reduced waste
CICT	Product diversification and composite applications	Expansion into the engineering and construction sectors
Coir Board	Technology transfer, modernization schemes, and incubation support	Wider technology adoption
NCRMI	Research coordination and innovation support	Strengthened industry–research linkages
CIPET–CBPST	Coir-polymer composite development	High-value industrial applications

Source: Compiled from Coir Board, CCRI, CICT, NCRMI, and CBPST project reports.

The impact of these initiatives is evident in the industry's shift from traditional mat and rope production toward geotextiles, horticultural substrates, biodegradable packaging, and composite materials. Research on coir-reinforced polypropylene composites demonstrated improvements in tensile strength, flexural performance, and thermal stability following fibre treatment and process optimization (Hasan et al., 2021; CBPST-CIPET, 2020). Similar studies have shown that coir-based composites are increasingly being used in construction materials, insulation products, and environmentally sustainable packaging systems. Institutional support also accelerated technology diffusion. Under the Science and Technology components of the Coir Vikas Yojana, modernization programmes promoted improved extraction machinery, mechanized spinning technologies, and cleaner processing methods aimed at reducing labour drudgery and enhancing product quality. Coir Board reports indicate that these interventions contributed to higher production efficiency, wider product diversification, and stronger export orientation within the sector. The evidence, therefore, suggests that research and development activities functioned as a catalyst linking scientific innovation with industrial application. By strengthening technology generation, commercialization, and product development, institutional initiatives helped reposition the coir industry from a predominantly traditional manufacturing sector toward a more diversified and technology-intensive industrial system.

4.7. Coir Composite Technology and Sustainable Material Innovation

Coir composite technology represents one of the most important shifts in the industry's technological trajectory, extending the use of coir from traditional products to high-value engineering and industrial applications. Research undertaken during the last two decades demonstrates that coir fibre possesses several characteristics favourable for composite production, including high lignin content (45.84%), low density (1.40 g/cc), good impact resistance, and natural biodegradability. These properties have increased its suitability as a reinforcement material in construction products, automotive components, insulation materials, and biodegradable packaging.

A major challenge in composite production has been the hydrophilic nature of untreated coir fibre, which weakens bonding with polymer matrices. Experimental studies show that alkali and silane treatments significantly improve fibre–matrix adhesion, resulting in better tensile strength, flexural performance, thermal stability, and moisture resistance (Hasan et al., 2021; Shah et al., 2021; CBPST-CIPET, 2020). As a result, treated coir composites increasingly meet the performance requirements of commercial manufacturing applications.

Table 10. Performance Advantages of Coir-Based Composites

Indicator	Observed Outcome
Fibre density	1.40 g/cc
Lignin content	45.84%
Component weight	Approximately 10% lower than glass-fibre systems
Manufacturing energy requirement	Up to 80% lower than conventional synthetic composites
Moisture resistance	Improved through fibre treatment
Mechanical performance	Enhanced tensile and flexural properties
Environmental profile	Renewable and biodegradable material-based

Source: Compiled from Hasan et al. (2021), CBPST-CIPET (2020), Ajayi et al. (2025), Maiti et al. (2022), and related composite studies.

The commercial significance of these developments is reflected in the diversification of end-use applications. Recent studies report the growing use of coir-based composites in automotive interior panels, acoustic and thermal insulation boards, lightweight construction materials, geotextiles, and moulded packaging products (Figueiredo et al., 2025; Guruswamy et al., 2024; Karabacak et al., 2024). Research on coir-fibre-reinforced concrete and hybrid composites has likewise demonstrated improvements in crack resistance, insulation performance, and material sustainability compared with conventional alternatives.

The transition towards composite-based applications has also altered the value structure of the coir industry. Whereas traditional products were concentrated in low-value segments such as mats and ropes, composite technologies have enabled entry into higher-value manufacturing markets linked to construction, transport, and sustainable materials. The evidence, therefore, suggests that composite innovation has become a major avenue through which the coir industry has enhanced product value, expanded market opportunities, and aligned itself with emerging trends in green manufacturing and circular-economy production systems.

4.8. Product Diversification and Sustainable Industrial Applications

Product diversification has been one of the most visible outcomes of technological modernization in the coir industry. While the sector traditionally depended on mats, mattings, and ropes, advances in mechanization, composite technology, and applied research enabled the development of higher-value products serving agriculture, construction, automotive, and environmental engineering markets. This shift reduced dependence on conventional product segments and strengthened export competitiveness.

A notable example is the emergence of coir geotextiles, which are increasingly used for soil stabilization, slope protection, and erosion control owing to their biodegradability, durability, and moisture-retention capacity. Similar value addition occurred through the commercial utilization of coir pith. Once treated as a processing residue, coir pith became an important horticultural input because of its high water-holding capacity, aeration properties, and suitability for greenhouse cultivation. The conversion of coir pith into export-oriented grow bags, pith blocks, and horticultural substrates created an additional revenue stream while reducing industrial waste.

Table 11. Major Diversified Coir Products and Industrial Applications

Diversified Product	Principal Application
Coir Geotextiles	Soil stabilization and erosion control
Coir Pith Blocks	Horticulture and agriculture
PP–Coir Composites	Automotive and moulded products
Thermal Insulation Boards	Construction and acoustic applications
Biodegradable Packaging	Sustainable packaging systems
Rubberized Coir Products	Furniture and cushioning materials

Source: Compiled from Coir Board reports, composite studies, and industrial product-development research.

The expansion of coir composites further widened industrial applications. Studies conducted by CICT, CBPST-CIPET, and other research institutions demonstrated the suitability of coir-reinforced polypropylene composites for injection-moulded products, including flower pots, utility items, and automotive interior components. Composite research also reported reductions in component weight of nearly 10 per cent and manufacturing energy requirements of up to 80 per cent when compared with conventional synthetic-fibre systems, highlighting both economic and environmental advantages.

The diversification process reflects broader changes in global markets, where demand for biodegradable materials, sustainable packaging, and environmentally responsible construction products has expanded steadily. By converting agricultural residues into commercially valuable products and extending applications into multiple industrial sectors, the coir industry has moved beyond its traditional product base and positioned itself within emerging green-manufacturing and circular-economy markets. This transition has enhanced value addition, improved resource utilization, and expanded opportunities for long-term industrial growth.

4.9. Socio-Economic Implications of Technological Modernization

Technological modernization has reshaped the labour structure of the coir industry as much as its production systems. Historically, the sector depended on a large workforce engaged in spinning, weaving, retting, and fibre processing, with Kerala alone accounting for nearly 3.75 lakh workers, many of whom were women from economically disadvantaged communities. While this labor-intensive structure generated extensive rural employment, low productivity and limited earnings constrained long-term industrial growth.

Evidence from mechanization studies shows that technological adoption increased output and labour productivity while reducing dependence on physically demanding manual operations.

Per-capita production rose from 1,914.82 in traditional units to 14,155.51 in highly mechanized firms, while daily production increased from ₹37,423 in traditional enterprises to more than ₹11.3 lakh in medium-mechanized units.

Statistical tests confirmed significant productivity differences across mechanization categories (Kruskal–Wallis $\chi^2 = 14.07$, $p = .003$), indicating that technological upgrading substantially altered production performance.

Table 12. Major Socio-Economic Effects of Technological Modernization

Technological Change	Socio-Economic Outcome
Mechanized extraction	Reduced labour-intensive processing
Motorised spinning and weaving	Higher worker productivity
Process integration	Lower idle time and production delays
Composite manufacturing	Growth of skilled technical employment
Product diversification	Expansion of market opportunities
Industrial modernization	Shift towards organized production systems.

Source: Compiled from mechanization and labour studies.

The benefits of modernization, however, have not been evenly distributed. Larger firms adopted technology more rapidly, whereas many household and small-scale units continued to rely on conventional production methods because of financial constraints and limited access to modernization support. Studies on labour restructuring in Kerala similarly report declining dependence on household-based spinning and the emergence of machine operation, maintenance, quality control, and logistics as new areas of employment. Rather than eliminating labour altogether, modernization altered occupational composition and skill requirements. The evidence, therefore, points to a process of labour reorganization rather than simple labour displacement. Productivity gains, higher-value production, and improved export competitiveness have expanded economic opportunities, but they have also increased the importance of skill formation, technology access, and institutional support in determining who benefits from industrial transformation.

4.10. Constraints and Future Trajectories of Technological Transformation

The evidence presented across the preceding sections suggests that technological modernization has substantially improved productivity, processing efficiency, and product diversification within the coir industry, but the transition remains uneven across production segments. Statistical evidence indicates significant productivity differences between traditional and mechanized enterprises, with per-capita production increasing from 1,914.82 in traditional units to 14,155.51 in highly mechanized firms, while daily production levels rose from ₹37,423 to more than ₹11 lakh in medium-mechanized units. Despite these gains, technological adoption remains concentrated among larger and better-capitalized enterprises.

One of the principal constraints concerns the fragmented structure of the industry. A large proportion of production continues to be undertaken by small and household-based units that face difficulties in accessing machinery, institutional finance, and technical support. Studies on mechanization in Kerala consistently identify capital costs, technology awareness gaps, and uneven institutional outreach as major barriers to modernization. These factors contribute to persistent productivity differentials between technologically advanced firms and traditional producers.

The findings also indicate that future growth is likely to depend less on conventional products and more on value-added sectors linked to sustainable manufacturing. Coir composites, geotextiles, horticultural substrates, and biodegradable packaging have emerged as the most dynamic segments of the industry, supported by growing international demand for renewable and low-carbon materials. Research on composite applications further demonstrates reductions of nearly 10 per cent in component weight and up to 80 per cent in manufacturing energy requirements compared with conventional synthetic-fibre systems.

Table 13. Technological Transformation: Major Gains and Continuing Constraints

Dimension	Observed Gains	Continuing Constraints
Productivity	Significant increase in output and labour productivity	Uneven adoption across firms
Production Systems	Faster processing and improved quality control	Persistence of traditional units
Employment	Growth of skilled and technical occupations	Occupational displacement in manual activities
Product Structure	Expansion into composites, geotextiles, and horticultural products	Limited commercialization among smaller producers
Environmental Performance	Reduced dependence on retting and improved resource utilization	Continued ecological concerns in conventional processing

Source: Compiled from mechanization, productivity, environmental, and institutional studies.

The broader implication is that future competitiveness will depend on strengthening the link between technological innovation and industrial diffusion. Expanding technology access for small producers, promoting cleaner extraction technologies, improving research-commercialization linkages, and investing in skill development are likely to determine whether modernization remains confined to a limited segment of the industry or evolves into a more inclusive process of industrial transformation. The trajectory of the coir sector therefore points toward increasing integration with green manufacturing and circular-economy markets, although the realization of this potential remains contingent upon addressing persistent structural inequalities in technology adoption.

5. Conclusion

The findings of the study demonstrate that the coir industry has undergone a significant transition from a labor-intensive traditional agro-based sector to a technologically evolving and sustainability-oriented manufacturing industry. Mechanization in fibre extraction, process optimization, and machine-assisted production systems substantially improved productivity, fibre quality, and industrial efficiency. Research and institutional interventions led by the Coir Board, CCRI, and CICT accelerated modernization through technological innovation, machinery development, and product diversification. The study further reveals that coir composite technology and sustainable material applications expanded the industrial relevance of coir beyond conventional products into geotextiles, biodegradable packaging, horticultural products, and polymer composites. These developments strengthened the industry's export competitiveness and aligned the sector with global green manufacturing and circular economy transitions.

However, modernization within the coir industry remains uneven due to financial limitations, technological awareness gaps, environmental concerns, and fragmented production structures. Small-scale and traditional units continue to face difficulties in adopting advanced technologies and sustainable production systems. So, the study establishes that the future competitiveness of the coir industry depends upon integrated technological modernization supported by institutional research, sustainable manufacturing practices, and inclusive industrial policies. Strengthening research-commercialization linkages, promoting eco-friendly processing technologies, and expanding modernization support for small-scale units are essential for ensuring long-term industrial sustainability and rural economic development.

Conflicts of Interest

"The authors declare that there is no conflict of interest regarding the publication of this paper."

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