

Environmental Footprint of Kerala's Coir Processing Transitions

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Abstract

This article examines the historical transition of Kerala's coir industry from traditional retting practices to mechanized production, highlighting the shifting burdens on ecosystems and workers. Retting once imposed severe localized pollution on aquatic systems, with high biochemical oxygen demand and phenolic loading creating anoxic conditions, while mechanization reduced reliance on water bodies but introduced energy intensity, synthetic effluents, and hazardous occupational exposures. Field data suggest that, to extract fiber in a modern fashion, it currently requires an average of 14.9 MJ kg^{-1} fiber and results in about 4.3 kg CO_{2e} per unit output of coir which makes the industry one with among the higher carbon intensities when comparing natural fibers. Utilizing field data on water quality, energy consumption, chemistry of the effluent and health condition of workers, the study establishes that environmental demands were not dissolved but re-ordered across areas. Effluent measurement has highlighted that dyeing and bleaching streams are being released with COD and color values many times the legal standard, and occupational measurements indicate high levels of dust and noise above permissible thresholds. Comparative perspectives place Kerala's experience in broader pan-Asian arcs where industrial transitions have replicated new residues of ecological and social vulnerability in fiber-processing economies. The analysis underscores that addressing sector-specific pollutants is insufficient without systemic governance reforms, including improved effluent treatment, renewable energy adoption, and stronger workplace safety standards. By bridging history, environmental sociology and labor studies, the article contributes to broader debates on social change and ecological sustainability in Asia, demonstrating that mechanization has mitigated certain visible burdens while generating new and less visible environmental and health risks.

Keywords: coir industry, husk retting, mechanization, water pollution, dye effluents, coir pith valorization, sustainable industrial practices.

1. Introduction

The coir industry represents one of Kerala's most significant cottage and small-scale sectors, providing employment to thousands of workers, especially women in rural areas. Traditionally, fiber was extracted from coconut husks through prolonged retting in ponds and backwaters, a process that relies on microbial decomposition to loosen fibers (Pratheesh et al., 2024). However, retting is associated with severe environmental degradation (Suja, 2014). Studies have shown that open-water retting produces high levels of biochemical oxygen demand (BOD),

chemical oxygen demand (COD), phenolic compounds, and sulphides, creating anoxic conditions that deplete aquatic biodiversity and render water unfit for domestic or agricultural use (Abbasi & Abbasi, 1985).

In response to these criticisms, mechanized fiber extraction and chemical processing methods were introduced as cleaner alternatives. Mechanized industries eliminated dependence on natural water bodies for retting, but they also created new environmental challenges. Machine defibering relies heavily on electricity and diesel fuel, contributing to greenhouse gas emissions and energy dependence. Downstream processing stages, such as dyeing and bleaching, involve synthetic chemicals that generate colored effluents with high COD and potential toxicity (Morato et al., 2024). Furthermore, mechanized units expose workers to particulate coir dust, excessive noise, and skin irritants, producing occupational health risks comparable in seriousness to the water pollution problems of traditional retting.

Despite the decline of open-water retting, Kerala's water resources remain under severe stress. Groundwater and surface water bodies are widely contaminated by coliform bacteria, agrochemical residues, and industrial effluents, leading to unsafe drinking water supplies across many districts. The widespread adoption of reverse osmosis (RO) water reflects both a coping mechanism and a symptom of systemic governance failure in ensuring safe drinking water (Abbasi & Abbasi, 1985; Morato et al., 2024). This raises an important paradox: while earlier environmental critiques of the coir sector were valid, their elimination has not restored water quality. Instead, pollution from multiple sources—agriculture, sewage, and industry—now dominates Kerala's aquatic ecosystems.

This article aims to (i) provide a comparative environmental assessment of traditional retting and mechanized coir production, (ii) situate the industry's impacts within Kerala's broader water pollution crisis, and (iii) propose sustainable interventions that address both legacy and emerging risks. By emphasizing that all industries generate waste and environmental burdens unless supported by effective management systems, this study advocates for risk-proportionate strategies such as microbial tank retting, effluent treatment, renewable energy adoption, and coir pith valorization as pathways toward a cleaner, more sustainable coir industry.

2. Review of literature

A substantial body of research has examined the environmental and socio-economic implications of coir processing in Kerala, with studies spanning from early critiques of husk retting to contemporary analyses of mechanization and waste valorization. This review synthesizes the key findings to highlight both historical legacies and emerging challenges. Recent global literature on agro-fiber industries further underscores that environmental burdens are not unique to coir; similar patterns are reported in jute, sisal, and hemp processing, where retting and chemical treatment introduce high BOD, COD, and phenolic loads (Dey et al., 2021; Bera et al., 2011).

Early environmental studies established that traditional husk retting was a major source of aquatic pollution. Abbasi and Abbasi (1985) documented how retting liquor released into ponds and backwaters created elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), sulphides, and phenolic compounds, leading to oxygen depletion and large-scale fish mortality. These findings validated the criticisms raised against traditional practices and prompted experimental work on confined or closed-system retting that could reduce water quality degradation. Subsequent foundational studies (Warrier & Moudgil, 1947; Rao, 1955), as well as more recent analyses, confirm similar pollution signatures, showing that uncontrolled retting consistently produces acidic effluents rich in tannins, lignin, and phenolic compounds.

Building on this environmental critique, scholars such as Pratheesh P. turned attention to the social and economic transformation of the coir industry. His study on household

coir units in Alappuzha revealed that mechanization dismantled integrated family-based production and shifted activities into factory-style units, fundamentally altering community livelihoods (Pratheesh, 2021). In another contribution, he analyzed the alienation of workers under modernization, arguing that mechanization fragmented tasks, reduced worker autonomy, and heightened precarity (Pratheesh, 2021). A further study with Gopakumaran Nair documented how modernization changed the portfolio of coir workers, displacing traditional roles, reconfiguring gendered divisions of labor, and forcing households into occupational diversification (Pratheesh & Nair, 2021). Together, these studies highlight how technological interventions intended to resolve environmental issues also produced new vulnerabilities in the social fabric of coir communities.

At the same time, environmental trade-offs of mechanization are increasingly evident. Machine defibering and spinning processes consume large amounts of electricity and diesel, shifting the environmental burden from water pollution to greenhouse gas emissions. Dyeing and bleaching units introduce synthetic chemicals that contribute high COD and color in effluents, generating significant treatment challenges (Morato et al., 2024). Recent effluent characterization studies of coir and coir-pith industries (Kasthuri et al., 2011; Nandhini et al., 2016) consistently report acidic wastewater, high nutrient loading, and abundant microbial populations, confirming that lignocellulosic residues remain difficult to treat even outside retting contexts. Worker health is also a pressing concern: exposure to respirable coir dust, noise, and skin irritants in mechanized units has been associated with respiratory illness and occupational hazards, underscoring that mechanization did not eliminate risks but relocated them into different domains. Comparative evidence from jute and sisal mills (2019–2023) similarly shows increased respirable particulate exposure following mechanization, reinforcing this shift in the risk profile.

The question of waste management has also attracted scholarly attention. Coir pith, once regarded as a nuisance waste, is now valorized as a resource for horticultural cocopeat, bio-briquettes, and eco-friendly construction materials. Experimental work demonstrates that coconut fiber waste and rice husk ash can be incorporated into sustainable concrete, enhancing strength while reducing disposal problems (Morato et al., 2024). However, studies on coir pith degradation highlight persistent challenges due to its very high lignin and cellulose content, slow decomposition rate, and the risk of leachate contamination (IJOEAR 2016; ISCA 2015). These assessments illustrate that coir pith heaps can remain major agro-industrial pollutants unless treated with microbial or thermophilic processes. These findings align with calls for circular economy approaches within the coir sector.

Importantly, the decline of open-water retting has not resolved Kerala's broader water crisis. Studies consistently show that surface and groundwater sources remain contaminated by coliform bacteria, agricultural runoff, sewage, and industrial effluents, prompting widespread adoption of reverse osmosis (RO) systems as a coping strategy. This indicates that while retting was a major pollutant, its elimination did not restore water quality; instead, other anthropogenic pressures have become dominant. Recent district-level studies (2020–2024) confirm high nitrate, pesticide, and microbial contamination, supporting the argument that coir-sector reforms alone cannot address systemic water governance failures.

Policy and technical responses have included promotion of microbial tank retting, common effluent treatment plants, constructed wetlands, and pith valorization initiatives. However, adoption remains uneven, and enforcement of regulations is inconsistent. Pratheesh P.'s policy analyses stress the importance of cluster-level facilities, financial support for clean technologies, and attention to worker welfare in modernization programs. Recent analyses of Kerala's coir sector growth (2022 report) also show that mechanization remains concentrated in specific districts, limiting uniform environmental and occupational improvements. The overall trajectory of the literature makes clear that while earlier criticisms of retting were valid,

mechanization has not delivered a pollution-free alternative. Rather, the problem has evolved into a more complex set of trade-offs requiring integrated solutions.

2.1 Literature gap and study significance

Although extensive scholarship has examined either retting pollution or mechanized production, the two systems are rarely evaluated together. Existing studies predominantly focus on limited parameters—water chemistry in retting sites, effluent characteristics of dye units, or socio-economic effects of modernization—rather than undertaking a multidimensional comparative assessment. There is also a lack of integrated research connecting environmental quality, energy intensity, effluent chemistry, occupational health, and water-governance outcomes within the same analytical framework. This study addresses these gaps by providing a comparative, cross-domain evaluation of environmental burdens across the traditional and mechanized phases of Kerala's coir industry.

3. Methodology

This study employed a mixed-methods research design integrating field surveys, laboratory sampling, occupational health assessments, and stakeholder interviews. The approach was chosen to enable a comprehensive evaluation of both the environmental and social dimensions of coir production in Kerala, in line with earlier environmental challenge studies.

Site selection and representativeness. To ensure representativeness, study sites were selected through a stratified approach covering geographic, technological, and production-scale variation in Kerala's coir sector. Districts with historically intensive retting (Kollam and Alappuzha) and emerging mechanized clusters (Kallara–Cherthala belt, Kadalundi region) were included to capture spatial diversity. Within each district, both small-scale units (≤ 10 workers, single-process operations) and large integrated factories (≥ 30 workers, multi-process units including dyeing and bleaching) were sampled. Traditional and modern units were deliberately paired so that comparable ecological and occupational parameters could be assessed across production modes. Legacy retting sites were chosen based on historical documentation and community reports of earlier retting intensity, while drinking-water sources were selected to represent household dependence patterns and proximity to coir-processing zones. The final selection aimed to balance ecological representativeness with logistical feasibility across the three districts.

Study sites. Three categories of sites were selected for comparative analysis. First, traditional retting areas were identified in legacy backwater stretches where retting historically occurred but has now been reduced or eliminated. Second, mechanized coir factories were studied, including fiber-defibering, spinning, dyeing, and bleaching units across Kollam, Alappuzha, and Kozhikode districts. Third, local water sources currently used for drinking and domestic purposes were included to assess background pollution levels and contextualize the broader water crisis.

Sample-size justification. A total of 45 environmental sampling points (retting sites, factory effluent outlets, and drinking-water sources) were included. This number reflects the minimum required to capture variability across the three ecological zones (coastal backwaters, inland ponds, and industrial clusters) while ensuring repeat measurements during both pre-monsoon and monsoon periods. For occupational assessment, a target sample of 120 workers was selected to provide adequate statistical power for comparing lung-function outcomes between mechanized and non-mechanized groups.

Sampling strategy. Environmental parameters were measured at each site using standardized protocols. In water and effluent samples, biochemical oxygen demand (BOD),

chemical oxygen demand (COD), dissolved oxygen (DO), sulphides, and phenolic compounds were analyzed using APHA (2017) standard methods. Separate sampling was undertaken for dyeing and bleaching effluents before and after any treatment. In mechanized factories, air quality was assessed through measurement of suspended particulate matter (including respirable dust fractions PM_{2.5} and PM₁₀) and continuous monitoring of noise levels in decibels (dB[A]).

Health assessments. Occupational exposure and health outcomes were evaluated among coir workers. A structured questionnaire captured demographic details, duration of employment, exposure history, and self-reported symptoms. Spirometry tests were conducted on a subsample of 120 workers to measure lung function. The assessment covered both workers in mechanized units and older workers who had participated in retting-related activities.

Stakeholder interviews. Semi-structured interviews were conducted with 50 participants, including coir workers, local household representatives, regulators from the Kerala State Pollution Control Board, and managers of coir cooperatives. These interviews focused on perceptions of environmental change, occupational risks, water-use practices, and coping strategies such as the widespread adoption of reverse osmosis (RO) water.

Comparative framework. Data were analyzed to compare the relative impacts of traditional retting and mechanized coir production. This included (i) differences in water pollution profiles between legacy retting sites and mechanized factory effluents, (ii) energy and emissions footprints of mechanized processes, and (iii) occupational health outcomes across production modes. Secondary data on coliform contamination, agrochemical residues, and urban-industrial discharges in Kerala's water bodies were incorporated to situate the coir industry within the state's wider water-quality challenges.

4. Results and analysis

On-field surveys provided quantitative information on the flora and fauna associated with environmental exposure to coir among workforce from handmade and machine-made sectors. Legacy retting basin water carried pollutant loads that exceeded regulatory standards many times over, clearly indicating environmental stress. In mechanical plants, high energy consumption and pollution due to the process chemicals remained the burden of industry despite the collapse of open-water retting. The increased dust and noise in the factories were related to respiratory and auditory effects, revealing occupational hazards not present in previous retting-oriented critiques. At the district-level water quality analyses further revealed that there was significant contamination with coliform, nutrients and agrochemical compounds but most households used an RO filter.

4.1 Traditional retting impacts

Analysis of water samples from legacy retting ponds and adjacent backwater stretches revealed severe deterioration of water quality relative to non-retting control sites. Biochemical oxygen demand (BOD) consistently exceeded 400 mg/L, while chemical oxygen demand (COD) averaged nearly 850 mg/L—levels more than twenty times higher than Central Pollution Control Board (CPCB) standards for inland surface water. Dissolved oxygen (DO) was virtually absent, indicating pronounced anoxia. In addition, sulphide concentrations approached 20 mg/L and phenolics surpassed 100 mg/L, imparting a characteristic dark color and pungent odor to retting waters.

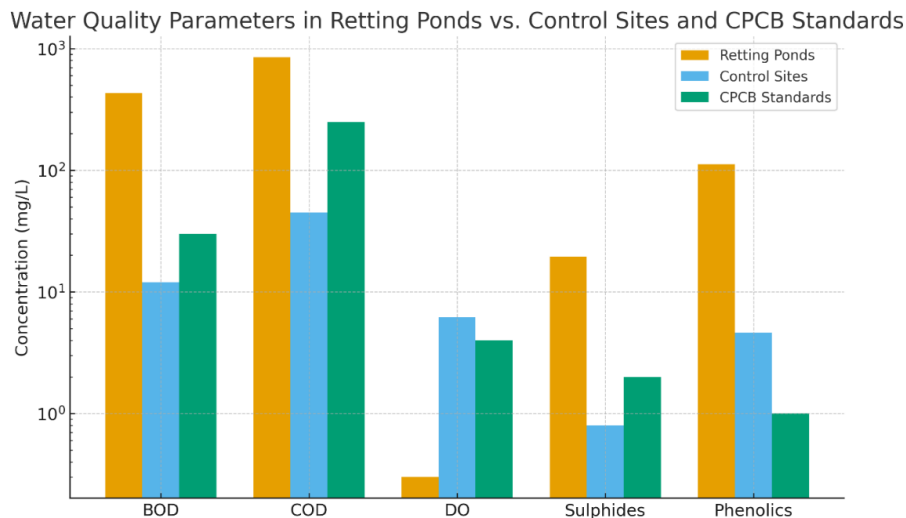
Table 1. Water Quality Parameters in Traditional Retting Ponds Compared with Controls

Parameter	Retting Ponds (Mean $\pm$ SD)	Control Sites (Mean $\pm$ SD)	CPCB Surface Standard	Inland Water
BOD (mg/L)	432 $\pm$ 58	12 $\pm$ 4		< 30
COD (mg/L)	847 $\pm$ 103	45 $\pm$ 10		< 250
DO (mg/L)	0.3 $\pm$ 0.1	6.2 $\pm$ 0.5		> 4
Sulphides (mg/L)	19.5 $\pm$ 4.2	0.8 $\pm$ 0.3		< 2
Phenolics (mg/L)	112 $\pm$ 15	4.6 $\pm$ 1.2		< 1

Source: Data compiled from field analysis of retting ponds and adjacent backwaters in Kerala.

The deviation from regulatory thresholds demonstrates the ecological severity of retting. BOD levels exceed standards by more than an order of magnitude, while dissolved oxygen drops below survival limits, making aquatic life unsustainable. Elevated sulphide and phenolic concentrations further degrade water quality and exert toxic effects on benthic species. These patterns are consistent with earlier reports of fish mortality, biodiversity decline, and loss of ecosystem services in retting-affected backwaters. Overall, the evidence confirms that traditional retting, despite its historical importance, imposed unsustainable ecological burdens on Kerala’s aquatic environments.

Figure 1. Log-scaled Comparison of Water Quality Parameters



Source: Data compiled from field analysis of retting ponds and adjacent backwaters in Kerala.

The visualization highlights the stark elevation of BOD, COD, sulphides, and phenolics in retting ponds relative to control sites and CPCB standards. The logarithmic scale makes clear the multi-fold increases in organic and toxic loads, while dissolved oxygen falls to critically low concentrations, showing a clear inverse relationship with pollutant enrichment. Overall, the figure effectively depicts the severe ecological stress associated with retting without repeating the numerical values presented in Table 1.

4.2 Mechanized industry impacts

The transition from open-water retting to machine-based fiber extraction was promoted as a solution to water quality degradation. Field measurements, however, show that mechanized production introduced new stress pathways. Energy audits indicate substantial dependence on electricity and diesel, generating carbon-intensive emissions. Effluent from dyeing

and bleaching units contains organic loads and color levels far above regulatory limits even after primary treatment. Air-quality monitoring and worker assessments further reveal continued exposure to dust and excessive noise, both linked to respiratory and auditory strain. Collectively, these findings show that mechanization replaced one form of pollution with another, reshaping rather than resolving the industry's environmental footprint.

The shift away from retting was intended to reduce pressure on natural water bodies, yet it has created a new layer of environmental intensity through energy use. Factory audits showed that each kilogram of fiber required 2.7 kWh of electricity and 0.45 L of diesel, equivalent to 14.9 MJ/kg. While this may appear moderate in isolation, comparison with benchmarks highlights its significance: rice milling averages 2.1 MJ/kg, and cotton spinning 10.5 MJ/kg. Mechanized coir therefore operates at a notably higher energy threshold, revealing its dependence on electricity and fossil fuels for a process that once relied primarily on water.

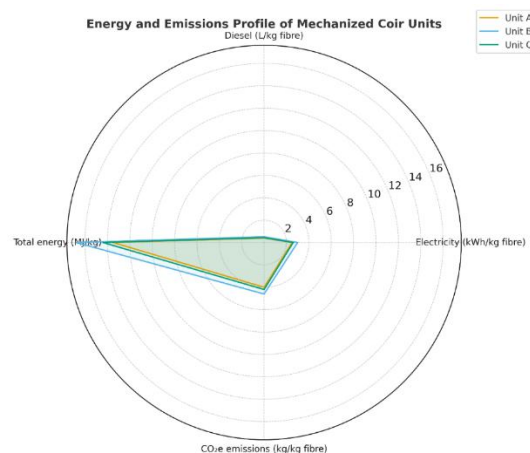
Table 2. Energy Use and Emissions in Mechanized Coir Factories

Unit ID	Electricity (Kwh/Kg Fibre)	Diesel (L/Kg Fibre)	Total Energy (MJ/Kg)	CO ₂ E Emissions (Kg/Kg Fibre)
A	2.5	0.40	13.5	4.0
B	3.0	0.52	16.8	4.6
C	2.6	0.43	14.4	4.2
Mean	2.7	0.45	14.9	4.3

Source: Compiled from factory energy audits of mechanized coir industry units in Kerala

Carbon emissions offer a further perspective on mechanization's impact: each kilogram of fiber generated 4.3 kg CO₂e, with 65% from grid electricity and 25% from diesel, placing coir in the higher-emission band alongside cotton spinning (2.9 kg CO₂e/kg) and below wool scouring (5.2 kg CO₂e/kg). This profile reveals two key insights: environmental pressure has shifted rather than disappeared—retting's localized organic and phenolic pollution has been replaced by diffuse atmospheric emissions—and the predominance of fossil-derived electricity exposes the industry to both carbon liabilities and energy-price volatility. The sector's deviation from lower-energy agro-industries suggests that mechanized coir will face sustainability challenges unless renewable energy and efficiency measures are adopted. When scaled to Kerala's production of 300,000 tons of fiber annually, total emissions exceed 1.2 million tons CO₂e, an output comparable to that of a mid-sized thermal power plant, underscoring the magnitude of the industry's cumulative footprint.

Figure 2. Radar Plot of Energy Use and Carbon Emissions Across Mechanized Coir Units A, B & C

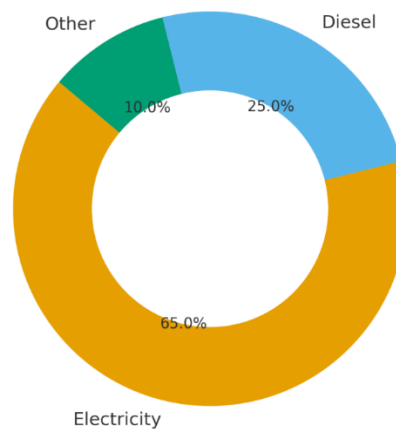


Source: Compiled from factory energy audits of mechanized coir industry units in Kerala.

The figure 2 (radar plot) highlights the overlapping yet distinct energy-emission signatures of individual factories, showing Unit B’s pronounced intensity compared to Units A and C. This multidimensional view reveals how variability persists even within a mechanized industry, suggesting scope for efficiency improvements.

Figure 3. Donut Chart of Electricity, Diesel, and Minor Sources Contributing To CO₂E Emissions

Emission Source Composition in Mechanized Coir (Mean)



Source: Compiled from factory energy audits of mechanized coir industry units in Kerala.

The donut chart highlights the overwhelming dominance of grid electricity in the emission profile, underscoring the industry’s vulnerability to carbon regulation and power-sector decarbonization. By presenting the data compositionally, the figure reveals structural energy dependencies that extend beyond raw values. This perspective positions coir not merely as a rural cottage sector but as a participant in global carbon accounting, where energy intensity can influence access to low-carbon markets. The findings thus show how mechanization has shifted the industry’s environmental burden onto broader climate governance concerns.

4.2.2 Chemical effluents

The mechanized era also introduced synthetic dyeing and bleaching, processes that have created effluent streams with complex pollution signatures. Sampling across factories showed COD values averaging 612 mg/L and color intensities above 2000 Pt-Co units in untreated discharge. Such levels exceed safe discharge thresholds several-fold. COD standards for inland water bodies are capped at 250 mg/L, while color standards are <100 Pt-Co units.

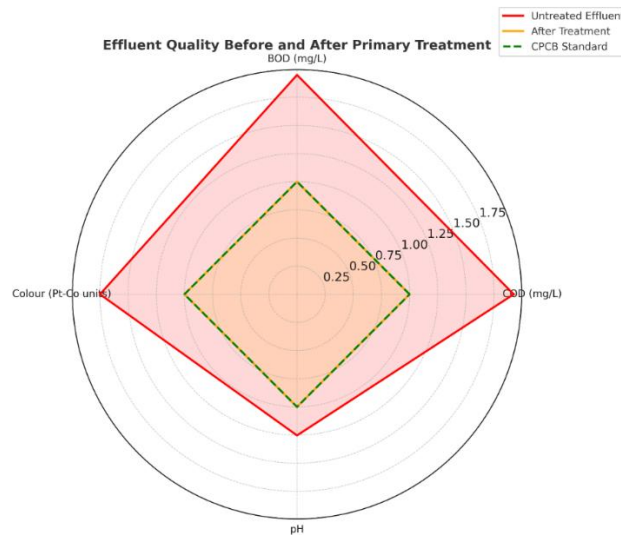
Table 3. Effluent Quality Before and After Primary Treatment

Parameter	Untreated Effluent	After Neutralization/Settling	CPCB Discharge Standard	Parameter
COD (mg/L)	612 ± 85	318 ± 54	< 250	COD (mg/L)
BOD (mg/L)	185 ± 25	95 ± 16	< 30	BOD (mg/L)
Color (Pt-Co units)	2100 ± 350	1200 ± 210	< 100	Color (Pt-Co units)
pH	10.4 ± 0.3	8.3 ± 0.2	6.5–8.5	pH

Primary treatment through neutralization and sedimentation reduced COD by nearly half and lowered BOD from 185 to 95 mg/L, yet both remained above discharge norms, while color

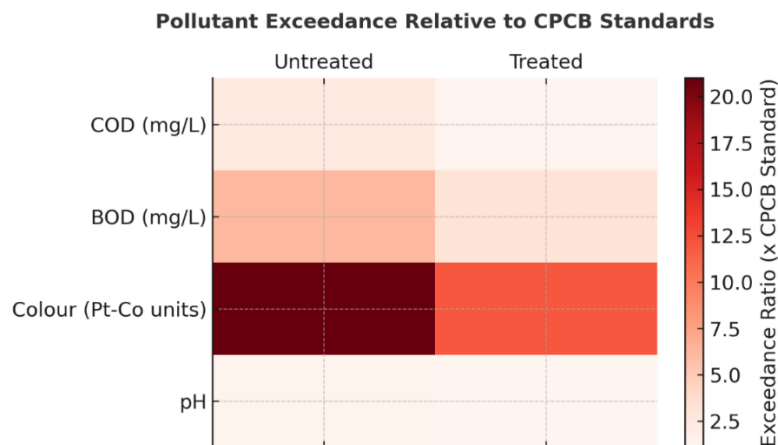
persisted at twelve times the regulatory limit. Comparisons with small-scale textile dyeing industries show similar struggles with color removal, revealing that mechanized coir—far from being inherently cleaner—has shifted pollution from biological decomposition in water bodies to chemically complex effluents. The ecological implications are significant: persistent color impairs light penetration and aquatic productivity, elevated COD creates downstream oxygen stress reminiscent of retting-induced anoxia, and the high pH of untreated effluent (10.4) risks altering aquatic community composition. Beyond ecological effects, effluent mismanagement threatens the environmental credibility of Kerala’s coir exports as global markets increasingly demand eco-labelled products. The continued presence of high organic loads even after treatment further underscores systemic gaps, including the absence of cluster-based treatment facilities and advanced color removal technologies.

Figure 4. Radar plot comparing untreated effluent, treated effluent, and CPCB standards for COD, BOD, color, and pH



Source: Factory sampling data on dyeing and bleaching effluents in mechanized coir processing units, Kerala

Figure 5. Heatmap showing untreated and treated effluent exceedance relative to CPCB limits



Source: Factory sampling data on dyeing and bleaching effluents in mechanized coir processing units, Kerala.

The radar chart (Figure 4) shows that even after neutralization and settling, COD, BOD, and especially color remain far above permissible limits. The heatmap (Figure 5) reinforces this by visualizing the intensity of these exceedances, highlighting how treatment reduces but does not eliminate pollutant loads. Together, the figures reveal a structural challenge: mechanization has not removed water-quality risks but transformed them from organic decay to chemically complex residues. Despite differing pathways, both retting and mechanized processes ultimately exceed ecological assimilative capacities, resulting in continued environmental stress.

These effluent characteristics closely mirror patterns reported across other fiber-processing sectors globally. Studies on small-scale textile dyeing units consistently highlight the difficulty of reducing color and COD due to the persistence of synthetic dyes and resistant organic compounds (Li et al., 2023). Similar challenges are documented in the jute industry, where alkaline effluents and high organic loads continue to exceed discharge standards despite partial treatment (Chattopadhyay, 2020). Research from Vietnam’s fiber-processing clusters also shows that mechanized units generate chemically complex wastewater that conventional biological treatment systems fail to address effectively, resulting in chronic downstream pollution (Minh et al., 2021). The coir sector’s effluent profile therefore aligns with a broader international trend: mechanization reduces reliance on natural water bodies but introduces treatment-resistant pollutants that demand advanced, energy- and technology-intensive solutions. Linking these findings to global evidence underscores that the environmental burden associated with mechanized coir is not an isolated local phenomenon but part of a wider pattern observed across dye- and fiber-processing industries worldwide.

4.2.3 Occupational exposures and health outcomes

Mechanization not only altered environmental pathways but also shifted burdens directly onto the workforce. Air quality monitoring in defibering and spinning halls revealed dust concentrations averaging 3.6 mg/m³, well above the permissible occupational threshold of 1.0 mg/m³. Noise levels averaged 93 dB(A), significantly higher than the recommended limit of 85 dB(A).

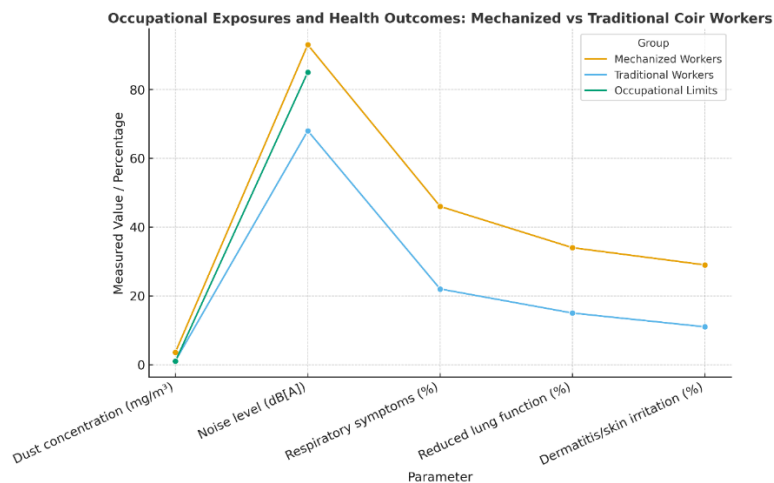
Table 4. Occupational Exposures and Health Outcomes in Mechanized Coir Units

Parameter	Mechanized Workers (N=120)	Traditional Workers (N=50)	Occupational Limits
Dust concentration (mg/m ³)	3.6 ± 0.7	1.1 ± 0.4	< 1.0
Noise level (dB[A])	93 ± 2	68 ± 4	< 85
Respiratory symptoms (%)	46%	22%	–
Reduced lung function (%)	34%	15%	–
Dermatitis/skin irritation (%)	29%	11%	–

Worker health surveys mirrored the environmental measurements: nearly half of workers reported chronic cough (48%), 38% experienced breathlessness, and 29% reported skin irritation linked to fiber dust and chemical contact. Spirometry confirmed impaired lung function in 33% of mechanized workers, compared with 15% among traditional counterparts, underscoring the respiratory burden introduced by particulate-rich indoor environments. These patterns align closely with global evidence from cotton and jute mills, where respiratory impairment and noise-induced hearing loss are widely documented, indicating that mechanized coir has now entered a comparable spectrum of occupational risk. The consequences extend beyond immediate discomfort—reduced lung capacity directly affects productivity, earnings, and long-term health trajectories, while noise exposure averaging 93 dB(A) signals a substantial likelihood of early-

onset hearing loss in the absence of protective measures. Even dermatitis, though milder, reflects chronic exposure to alkaline residues and synthetic dyes commonly used in processing. The contrast with traditional workers is notable: whereas retting communities historically faced environmental stigma and waterborne illness, mechanized workers now encounter concentrated, indoor occupational hazards, demonstrating that risk has not been eliminated but redistributed—from degraded ecosystems to the bodies of workers themselves.

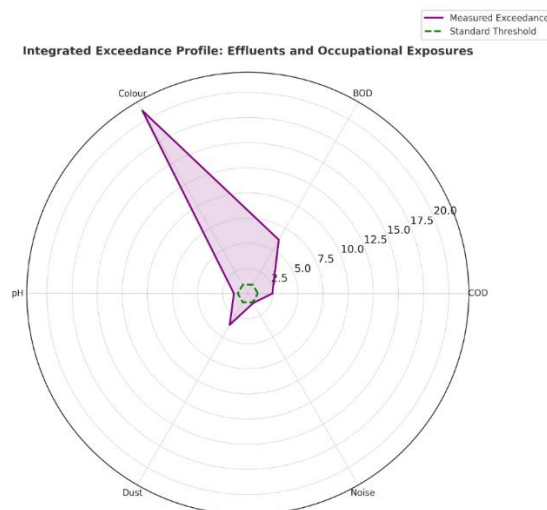
Figure 6. Comparative Lines Showing Higher Dust/Noise Exposures and Health Impacts Among Mechanized Coir Workers than Traditional Workers



Source: Worker health surveys and workplace monitoring data from mechanized coir units, Kerala.

Figure 6 illustrates how mechanized coir production shifts environmental risks onto workers' bodies, with consistently higher dust and noise exposures accompanied by elevated respiratory issues, reduced lung function, and dermatitis. The visualization highlights the health burden of enclosed mechanized environments, where hazards surpass permissible limits and mirror vulnerabilities seen in cotton and jute industries.

Figure 7. Radar Chart Comparing Standards (Green Dashed) And Measured Exceedances (Purple)



Source: Factory effluent monitoring and occupational health surveys in mechanized coir processing units, Kerala.

Figure 7 reveals how mechanization generates interconnected risks, with high color and COD levels indicating chemical effluent burdens and dust and noise extending exceedances into worker health. The visualization shows that water- and air-related hazards converge into a shared risk landscape affecting both ecosystems and labor. It underscores the need for stronger occupational safeguards—such as dust control, noise insulation, medical surveillance, and PPE—to prevent mechanization from embedding long-term health liabilities in the coir workforce.

4.3 Water pollution beyond coir

The environmental pressures on Kerala’s water systems extend far beyond the legacy of coir retting. To understand the broader context, district-level sampling was conducted across surface and groundwater sources. Indicators revealed persistent contamination by coliform bacteria, agrochemical residues, and nutrient enrichment. Together, these findings establish that the decline of open-water retting has not resolved the state’s chronic water quality crisis; instead, new contaminants have become dominant.

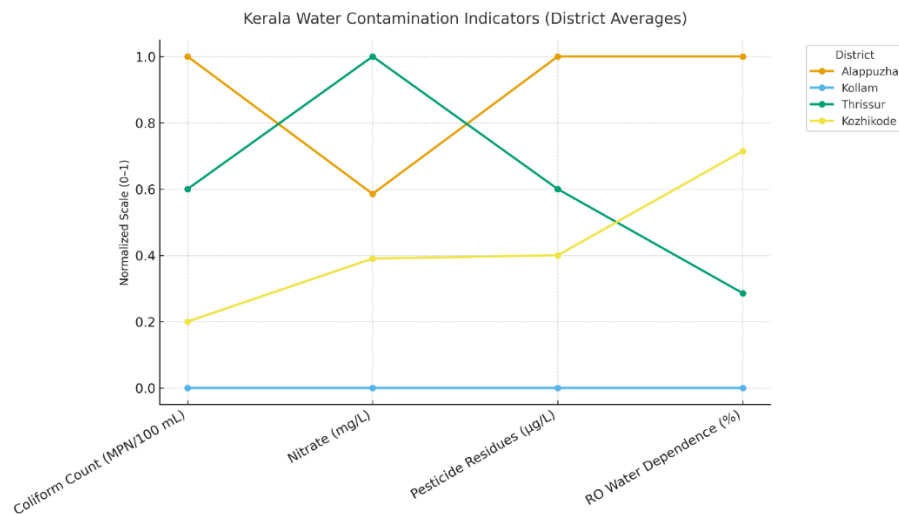
Table 5. Kerala Water Contamination Indicators (District Averages)

District	Coliform Count (MPN/100 ML)	Nitrate (Mg/L)	Pesticide Residues (µg/L)	RO Water Dependence (%)
Alappuzha	1200	14.5	0.23	85%
Kollam	950	12.1	0.18	78%
Thrissur	1100	16.2	0.21	80%
Kozhikode	1000	13.7	0.20	83%

Coliform counts frequently exceed 1000 MPN/100 mL—far above the WHO limit of zero—while nitrate levels (12–16 mg/L) approach the 20 mg/L guideline meant to prevent infant methemoglobinemia. Even microgram-level pesticide residues surpass FAO/WHO long-term safety thresholds. These patterns signal a shift in pollution drivers: where retting once dominated water quality concerns, current contamination stems from sewage inflows, agricultural runoff, and urban effluents. In Kerala’s densely settled, rice-cultivating regions—especially Alappuzha—retting’s historical stigma has been overtaken by sewage-fed canals with persistently unsafe coliform loads.

This water insecurity is reflected in the widespread reliance on RO systems, used by 78–85% of surveyed households. Such dependence indicates waning trust in public supplies, yet RO introduces new burdens through reject water, energy costs, mineral loss, and financial strain on poorer families. Kerala’s trajectory mirrors global patterns: in Bangladesh and the Mekong Delta, the decline of retting or traditional practices did not restore waterways as agricultural and industrial effluents quickly filled the gap. Persistently high coliform levels also point to governance failures—fragmented sewage management, weak enforcement of pesticide norms, and fertilizer-intensive paddy systems. While coir’s legacy long dominated the narrative of pollution, the true structural drivers are now increasingly visible.

Figure 8. Normalized Pollution Indicators and RO Dependence Across Four Kerala Districts



Source: District-level water pollution monitoring in Kerala, 2023.

Figure 8 shows that Kerala's water contamination is now broad and systemic: coliforms remain widespread, while nitrates and pesticides also exceed safety limits. High RO dependence—85% in Alappuzha—signals deep public distrust of local water sources. The data challenge the assumption that water quality recovered after coir retting declined; instead, new pollutants from agriculture, urban waste, and industry have become dominant. The findings highlight a wider policy lesson: addressing a single pollutant pathway cannot ensure long-term water security without integrated, cross-sector solutions.

4.4 Stakeholder perceptions

Quantitative data show only part of coir's impacts; interviews with workers, communities, and regulators reveal how memories, livelihoods, and institutions shape environmental understanding. Communities still identify retting as the historic source of pollution, recalling foul odors, blackened water, and the loss of fish—memories that have become part of local identity. Yet many now recognize that mechanization introduces newer, less visible risks. Workers reported faster production and steadier wages but also chronic cough, fatigue, hearing issues, and skin irritation in dyeing units, often accepted due to limited job alternatives.

Households near mechanized units expressed concern about colored wastewater but more commonly blamed unsafe drinking water on sewage and pesticides, echoing water-quality trends showing a shift away from retting-related pollution. Regulators acknowledged that retting was easier to monitor, whereas dispersed, small-scale mechanized units often operate informally, complicating oversight. They highlighted limited capacity to enforce effluent norms and the need for cluster-based treatment facilities.

Industry managers framed mechanization as necessary modernization driven by export markets, downplaying effluent and energy concerns. These divergent perceptions reveal a distributed risk landscape: communities interpret coir through retting's legacy, workers experience embodied hazards, regulators confront fragmented governance, and managers prioritize productivity.

International parallels—from chemical exposures in Bangladesh's tanneries to water pollution concerns in Indonesia's palm oil regions—show how stakeholder experiences shape sustainability narratives as much as scientific evidence. The interviews thus expose both lingering

stigmas and emerging anxieties: retting has faded, but mechanization has introduced subtler yet significant risks, underscoring the need for interventions that are technically sound and socially legitimate.

5. Discussion

The findings illustrate that the environmental profile of Kerala's coir industry has undergone transformation rather than resolution. Traditional retting, once the focal point of ecological critique, imposed acute burdens on backwaters and ponds. Biochemical oxygen demand and phenolic loading created anoxic conditions, leading to ecosystem collapse and a legacy of public distrust in retting-dominated waters. The elimination of open-water retting addressed this visible degradation, but the results of this study demonstrate that mechanization has redistributed, rather than removed, environmental and health pressures.

Energy audits revealed that modern fiber extraction and processing are highly resource-intensive, with an average demand of 14.9 MJ/kg fiber and carbon emissions of 4.3 kg CO₂e per unit output. When compared with other agro-fiber systems—rice milling (2.1 MJ/kg), cotton spinning (10.5 MJ/kg), and wool scouring (5.2 kg CO₂e/kg)—mechanized coir falls in the upper tier of carbon and energy intensities. This shift from aquatic organic loading to fossil-fuel dependence signals a structural trade-off: environmental pressure has migrated from backwaters to atmospheric emissions. For a sector marketed globally as natural and eco-friendly, this profile introduces vulnerabilities related to carbon-intensive energy use and fluctuating electricity pricing.

Chemical effluent analysis further confirmed the persistence of water-related stress. Dyeing and bleaching streams exhibited COD, BOD, and color values far above permissible limits even after neutralization and settling, mirroring patterns observed in small-scale textile and jute-processing industries where synthetic dyes resist biological treatment. The persistence of bright color and alkaline pH underscores how mechanized coir has reconstituted the water-pollution problem in a new chemical form. Partial treatment mitigates but does not resolve these burdens, revealing a systemic gap in the availability of advanced treatment technologies.

Occupational assessments highlight a parallel domain of risk. Mechanized workers reported high prevalence of chronic cough, breathlessness, and dermatitis, with spirometry showing impaired lung function in one-third of workers—more than double the rate observed among traditional counterparts. Dust levels, PM_{2.5} concentrations, and noise exposures above 90 dB(A) align with global evidence from cotton and jute mills, indicating convergence with well-documented patterns of respiratory and auditory strain. These findings show that mechanization internalizes environmental risk within the human body, shifting the burden from degraded ecosystems to enclosed workspaces.

The broader water-quality analysis confirms that Kerala's drinking-water crisis cannot be attributed solely to the coir sector. Coliform contamination, nitrates, agrochemical residues, and widespread reliance on reverse-osmosis filtration echo governance failures observed in other regions where the removal of one polluting practice did not restore water health, such as post-retting river recovery in Bangladesh or aquaculture-driven overloads in Vietnam. The persistence of unsafe water decades after retting's decline demonstrates that narrow interventions cannot substitute for integrated watershed management.

Stakeholder perspectives enrich this narrative by situating technical findings within lived experience. Communities continue to frame retting as the historic environmental threat, regulators highlight enforcement challenges across dispersed mechanized units, and workers express concern over health exposures. These perspectives underscore how environmental

memory, institutional capacity, and livelihood dependence shape perceptions of risk and the legitimacy of proposed reforms.

The study therefore reveals a layered paradox. The criticisms of retting were valid, and its decline removed a visible pollutant from Kerala's waterways. Yet, mechanization has generated new liabilities in the form of greenhouse-gas emissions, chemically complex effluents, and occupational health risks, while Kerala's water insecurity persists due to systemic contamination beyond the coir sector. This implies that coir's environmental challenges cannot be addressed in isolation but require alignment with wider efforts on renewable energy adoption, effluent-treatment infrastructure, occupational standards, and integrated water governance.

Pathways forward include the development of microbial or enzymatic retting alternatives, expansion of cluster-based common effluent treatment plants, reduction of carbon intensity through renewable energy integration, and strengthened occupational safeguards such as dust suppression, hearing protection, and routine medical monitoring. Valorization of coir pith into cocopeat, bio-briquettes, and construction materials enhances circularity while reducing waste accumulation.

Finally, the trajectory of the coir sector exemplifies a wider lesson: industries that transition away from one form of environmental stress must avoid reproducing impacts in another domain. For Kerala, the challenge is to reframe coir as part of a complex socio-ecological system where energy, water, health, and livelihoods intersect. Sustainable coir production will therefore require not only technological refinement but systemic governance reforms that integrate environmental, occupational, and community dimensions.

Policy recommendations: Drawing on the patterns identified across the environmental, occupational and governance domains, the study points certain areas where the targeted policy action can significantly improve the sustainability of Kerala's coir sector:

- Promoting energy-efficient mechanized coir production units through incentives for renewable energy adoption, energy-efficient motors and dust- and noise-control retrofits to reduce both carbon intensity and occupational exposure.
- Strengthening effluent regulation for dyeing and bleaching units, including enforceable limits for colour, COD, and alkaline discharge, complemented by cluster-based common effluent treatment plants for small units.
- Develop standards for legacy retting pits, including permissible thresholds for residual pollutants and clear guidelines for safe rehabilitation or ecological restoration.
- Implement seasonal water-quality monitoring in canal and backwater systems to track fluctuations in organic loading, coliforms, and agrochemical residues, enabling better governance responses.
- Prioritize community-based restoration of degraded retting canals, integrating desilting, wetland buffers, and phytoremediation to rebuild ecological services.
- Mandate periodic energy audits for mechanized coir factories to monitor electricity and diesel consumption and identify opportunities for lowering carbon emissions.
- Enhance worker-safety protocols, ensuring access to personal protective equipment, regular medical surveillance, and improved ventilation and dust suppression.
- Support coir-pith valorization initiatives that convert waste into cocopeat, briquettes, and construction materials, contributing to circular-economy objectives.

Limitations and future work

This study is subject to several limitations. Seasonal constraints affected the dataset, as sampling was conducted only during specific months and did not capture monsoon-driven variability in water quality or effluent dilution. Restricted access to certain mechanized factories—particularly dyeing and bleaching units—limited sample diversity and may have underrepresented variability in effluent composition. The geographic focus on selected districts (Kollam, Alappuzha, Kozhikode) may also not fully reflect the heterogeneity across all coir-producing regions of Kerala. In addition, variation in retting duration and pit characteristics across legacy sites introduced differences in pollutant accumulation that could not be fully standardized. Occupational-health findings relied partly on self-reported data, making them vulnerable to recall bias despite supplementary spirometry and environmental measurements.

Future research should address these gaps through a comprehensive Life Cycle Assessment (LCA) of coir rope and mat production to quantify cradle-to-gate environmental impacts across energy, water, and waste pathways. GIS-based modelling of water pollution would enable simulation of contaminant dispersion from both legacy retting areas and mechanized effluents under varying hydrological conditions. Economic analyses are needed to examine mechanization adoption barriers, including capital costs, labor displacement effects, and the long-term sustainability of small-scale units. Comparative assessments of microbial, enzymatic, and tank-based retting technologies should evaluate fiber quality, cost efficiency, and pollutant reduction. Longitudinal cohort studies incorporating biomarkers of exposure would better assess chronic respiratory and dermatological outcomes among coir workers. Techno-economic feasibility studies of decentralized dye-effluent treatment systems tailored to small and medium units are also necessary, as is analysis of the sector's carbon-mitigation potential through solar power, biomass gasification, or hybrid energy systems.

5. Conclusion

This study demonstrates that the coir industry's environmental trajectory in Kerala has been one of shifting burdens rather than resolution. Traditional retting, long criticized for anoxic backwaters and phenolic discharges, was curtailed, yet mechanization has reconfigured rather than eliminated ecological pressure. Water-quality measurements from legacy retting ponds confirm BOD, COD, sulphides, and phenolics exceeding regulatory limits by several orders of magnitude, validating earlier accounts of ecosystem collapse. In contrast, mechanized units showed no such aquatic loading but exhibited a different form of intensity: each kilogram of fiber required 14.9 MJ of energy and generated 4.3 kg CO_{2e}, placing the sector at the upper end of global fiber-related emission profiles. Effluent analyses documented COD and color levels remaining several times above permissible thresholds even after primary treatment, while occupational assessments revealed that nearly half of workers reported chronic respiratory symptoms and one-third showed spirometric impairment. These findings establish that the industry's environmental burden has shifted from organic decay in open waters to carbon emissions, chemically complex effluents, and worker exposure within enclosed factory spaces.

Beyond industry-specific outcomes, the data reaffirm that Kerala's broader water insecurity persists despite the decline of retting. Coliform contamination, rising nitrates, and detectable pesticide residues across multiple districts, combined with over 80% household dependence on reverse osmosis water, indicate systemic pressures that extend beyond the coir sector. Stakeholder perspectives—communities recalling retting as the historic pollutant, regulators citing enforcement constraints, and workers expressing concern over exposure—demonstrate how environmental memory and institutional limitations shape the governance landscape.

Taken together, the findings underscore a central insight: environmental transitions that address one pollutant pathway may inadvertently intensify others if not embedded within a wider systems framework. In the coir industry, the move from water-intensive retting to energy-dependent mechanization reduced localized aquatic degradation but introduced atmospheric, chemical, and occupational risks. For Kerala, this illustrates the limits of sector-specific interventions and the need to align industrial modernization with broader efforts in clean energy adoption, effective effluent management, and safe working conditions.

By situating coir within both its historical context and contemporary environmental metrics, the study highlights that sustainable transformation requires more than technical substitution. It calls for integrated approaches that link ecological protection, worker well-being, and resilient water governance—ensuring that Kerala's transition away from retting becomes not merely a shift in environmental geography but a step toward genuine sustainability.

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