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Life cycle assessment of coir geotextiles for sustainable infrastructure applications

Krishnashree Achuthan [a,*], Vysakh Kani Kolil [a], S.U. Parvathy [a], Narayanan R. Nambiar [a], Vivek Prasad Shaw [b]

[a] School of Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, Kollam, 690525, Kerala, India
[b] Central Coir Research Institute, Kalavoor, Alappuzha, 688522, Kerala, India

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ABSTRACT

Recent years have witnessed a surge in demand for sustainable infrastructure materials, prompting increased scrutiny of natural fiber-based geotextiles as alternatives to synthetic counterparts. This study evaluates the environmental performance of coir geotextiles, derived from coconut husk fibers, through a cradle-to-grave life cycle assessment (LCA) using SimaPro v. 9.3.03, with inventory data sourced from Ecoinvent 3.7.1 and primary data from coir manufacturing facilities in India. The objective is to quantify the environmental impacts of 1 kg of woven coir geotextile (700 g/m^2 density) and compare it with synthetic geotextiles, focusing on 18 environmental impact categories. Results indicate that the manufacturing phase, particularly weaving, dominates environmental impacts, contributing ≈75% of global warming (GW) (1.17E−01 kg CO_2 eq out of 1.64E kg CO_2 eq), driven by fossil fuel-based electricity. Sensitivity analysis shows ±5% electricity variation significantly affects fossil resource scarcity and GW. Scenario analysis reveals renewable energy, especially hydropower, reduces impacts by 10%–50%. A comparative analysis of the three largest copra-producing countries reveals distinct environmental impact profiles: Indonesia experiences higher impacts primarily due to resource-intensive coconut cultivation; India's footprint is driven by its manufacturing processes; while the Philippines shows a more balanced profile, benefiting from the use of renewable energy. Compared to synthetic geotextiles, coir exhibits lower GW (≈ 34%–40% reduction) and toxicity burdens, largely due to its biodegradability, which eliminates energy-intensive disposal. These findings align coir geotextiles with Sustainable Development Goals (SDGs) 7, 9, 12, and 13, underscoring their potential as eco-friendly materials for erosion control and slope stabilization in tropical regions.

1. Introduction

The rapid expansion of infrastructure globally, especially in emerging economies, is generating an unparalleled need for sustainable engineering practices (Achuthan and Khobragade, 2025). Amidst growing concerns over climate change and the decline of biodiversity, this trend has prompted a thorough revaluation of material selection within the fields of civil and geotechnical engineering (Kallis et al., 2025; Alizadeh et al., 2024). As global efforts to achieve the UN Sustainable Development Goals (SDGs) intensify, there is an increasing expectation for the geotechnical sector to develop solutions that are not only technically robust but also environmentally sustainable and socially equitable (Thapa et al., 2025; MC et al., 2025; Kolil et al., 2026). A key area for such interventions lies in applications aimed at enhancing ground stability and managing surface water dynamics, particularly in regions vulnerable to soil degradation, mass movement, and hydrological stress (Amarasinghe et al., 2024; Alcántara-Ayala, 2025).

Geotextiles, engineered permeable fabrics used for filtration, separation, drainage, reinforcement, and erosion control, have become indispensable in a wide range of civil engineering applications, including road construction, embankment support, coastal protection, and other ground improvement strategies (Fan et al., 2025; Kumar and Das, 2018; Chatrabhuj, 2024). Synthetic geotextiles, predominantly made from fossil-derived polymers such as polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET), have long dominated the market due to their durability and mechanical performance (Tiwari et al., 2021). However, these advantages come at a significant environmental cost. The life cycle of synthetic geotextiles, from production

* Corresponding author.
E-mail addresses: krishna@amrita.edu (K. Achuthan), vysakh@am.amrita.edu (V.K. Kolil), parvathysu@am.amrita.edu (S.U. Parvathy), narayanann@am.amrita.edu (N.R. Nambiar), vshaw09@gmail.com (V.P. Shaw).

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to disposal, contributes to high greenhouse gas emissions and plastic pollution, particularly in regions lacking robust waste management infrastructure. Global estimates suggest that large volumes of plastic waste, especially in low and middle-income countries, are improperly disposed of, leading to environmental contamination, microplastic accumulation, and public health risks (Yannick Ngaba et al., 2025; Stevenson et al., 2025).

In light of these concerns, nature-based geotextiles derived from renewable plant fibers are gaining traction as sustainable alternatives (Morsy et al., 2025). One prominent example is coir, the fibrous material extracted from coconut husks. Coir is biodegradable, regionally abundant in tropical zones, and well-suited to geotechnical functions such as slope reinforcement, soil stabilization, and water management (Kampeerapappun et al., 2025; Guo et al., 2025b; Camilli et al., 2025).

Scientific advancements have further enhanced the viability of coir-based geotextiles. For instance, studies have shown that coating coir fibers with cashew nut shell liquid (CNSL), a plant-derived resin, significantly improves resistance to microbial degradation and extends service life. Sumi et al. (2016) reported that CNSL-treated coir geotextiles retained up to 76% of their tensile strength after 240 days of soil exposure, a stark contrast to the 19% retention in untreated samples. This work was expanded by Sumi et al. (2018), who demonstrated the effectiveness of CNSL modification across a variety of physical, chemical, and biological stress conditions. These findings emphasize the potential for natural geotextiles to match or exceed synthetic performance metrics, especially when enhanced through bio-based treatments.

Despite growing interest and promising results, the environmental performance of coir geotextiles has yet to be comprehensively assessed at a global scale. Life Cycle Assessment (LCA), a standardized framework for evaluating environmental impacts from raw material extraction through to end-of-life, offers a valuable lens to examine coir geotextiles in detail (Chavez et al., 2025). Through this lens, it becomes possible to identify environmental "hotspots" across various stages such as processing, distribution, and deployment, guiding more informed interventions aimed at reducing emissions and optimizing resource use (Hosamo et al., 2024).

This analysis is particularly relevant for both producing and consuming nations involved in the coir value chain. While production is concentrated in South and Southeast Asia, demand for sustainable infrastructure materials is global. Moreover, the decentralization of coir processing and reliance on fossil-based electricity in many manufacturing regions introduces a complex mix of challenges and opportunities for aligning with international climate targets (Bhatia and Smith, 2022; Bordoloi and Bordoloi, 2020).

Cumulative Energy Demand (CED), which encompasses both direct and indirect energy inputs across all life cycle stages, offers a comprehensive metric for assessing energy use associated with coir geotextiles. This approach facilitates rigorous comparisons with synthetic counterparts, particularly in evaluating energy intensity and overall resource efficiency (Borda et al., 2024; Zhao et al., 2025). Exploring the potential role of other energy scenarios in the coir production process also opens new possibilities for aligning the material with carbon-neutral infrastructure pathways, in support of long-term climate goals like India's 2070 net-zero commitment (Lakhouit et al., 2025).

To ensure the reliability and applicability of insights, environmental outcomes are examined through sensitivity and uncertainty analyses. Sensitivity analysis helps identify the most critical variables affecting environmental outcomes, thereby guiding priorities for data refinement and methodological transparency (Chen et al., 2024; Singh et al., 2024). In parallel, uncertainty analysis addresses the inherent variability and data limitations within the life cycle inventory and impact assessment stages. Monte Carlo simulation, a widely adopted probabilistic method, is employed to propagate these uncertainties through the model, providing a statistical distribution of possible outcomes (Motevalli et al., 2024). This integrated approach ensures that the interpretation of results accounts for both data variability and model assumptions, thereby strengthening the reliability of conclusions drawn from the life cycle assessment.

This study makes a global contribution to sustainable materials engineering by rigorously evaluating coir geotextiles through the lens of life cycle sustainability. By addressing emissions, energy use, and renewable integration potentials, the study responds to the following research questions:

RQ1: What are the environmental impacts of coir geotextiles throughout their life cycle, and which stages in the manufacturing chain contribute most significantly to these impacts?
RQ2: How does the biodegradable nature of coir geotextiles influence their sustainability performance, particularly in comparison to synthetic alternatives in end-of-life scenarios?
RQ3: How does the environmental impact of coir geotextiles differ based on geographical variations?
RQ4: To what extent can the adoption of renewable energy systems and changes in manufacturing processes mitigate the environmental burdens associated with coir geotextile production?
RQ5: How does the overall environmental impact of coir geotextiles compare to synthetic counterparts across their life cycles?
RQ6: Which SDGs are most directly supported by the use of coir geotextiles, and through what mechanisms are these contributions realized?

By grounding the analysis in both engineering performance and environmental responsibility, this research aims to support a paradigm shift toward low-impact, nature-based infrastructure materials, particularly in the global tropics, where ecological restoration and erosion control are urgent priorities.

2. Methodology

LCA is a well-known and comprehensive tool for identifying and quantifying the environmental impacts of a product, service, or technology throughout its life cycle, from raw material extraction to disposal (Paul et al., 2024; Parvathy et al., 2025b). It is carried out in four distinct phases: goal and scope definition, inventory analysis, impact assessment, and interpretation, iteratively in accordance with the ISO 14040 and ISO 14044 standards (ISO 2006). Moreover, SimaPro software (Ver. 9.3.0.3) was used to prepare the LCA model.

2.1. Goal & scope

The first step of ISO14040 LCA involves setting out the assessment's goal, functional unit, and scope. Through scope definition, the boundaries of LCA are set (de Souza et al., 2024). This study's goal is to assess the environmental impacts of coir geotextile based on a cradle-to-grave LCA study, identify hotspots for improvement, and compare it with synthetic alternatives to enhance its sustainability. The functional unit used for calculating the share of environmental burden is 1 kg of woven coir geotextile. An average density of 700 GSM was assumed for the geotextile. Geotextiles made from coir fiber are expected to have a life of 5 years. The Fig. 1 illustrates the complete life cycle flow of coir geotextile production and application, beginning at the coconut farm and ending with biodegradation. The process starts at the coconut farm, where coconuts are harvested, and then the dehusked coconut is transported to the oil mill, and the husk is used for coir fiber extraction. At the dehusking area, the husk is separated from the coconut fruit using mechanical equipment. The dehusked coconuts are sent to the oil mill for oil extraction, while the coconut husks are transported to the geotextile manufacturing unit. Transportation to the oil mill is outside the scope of the study.

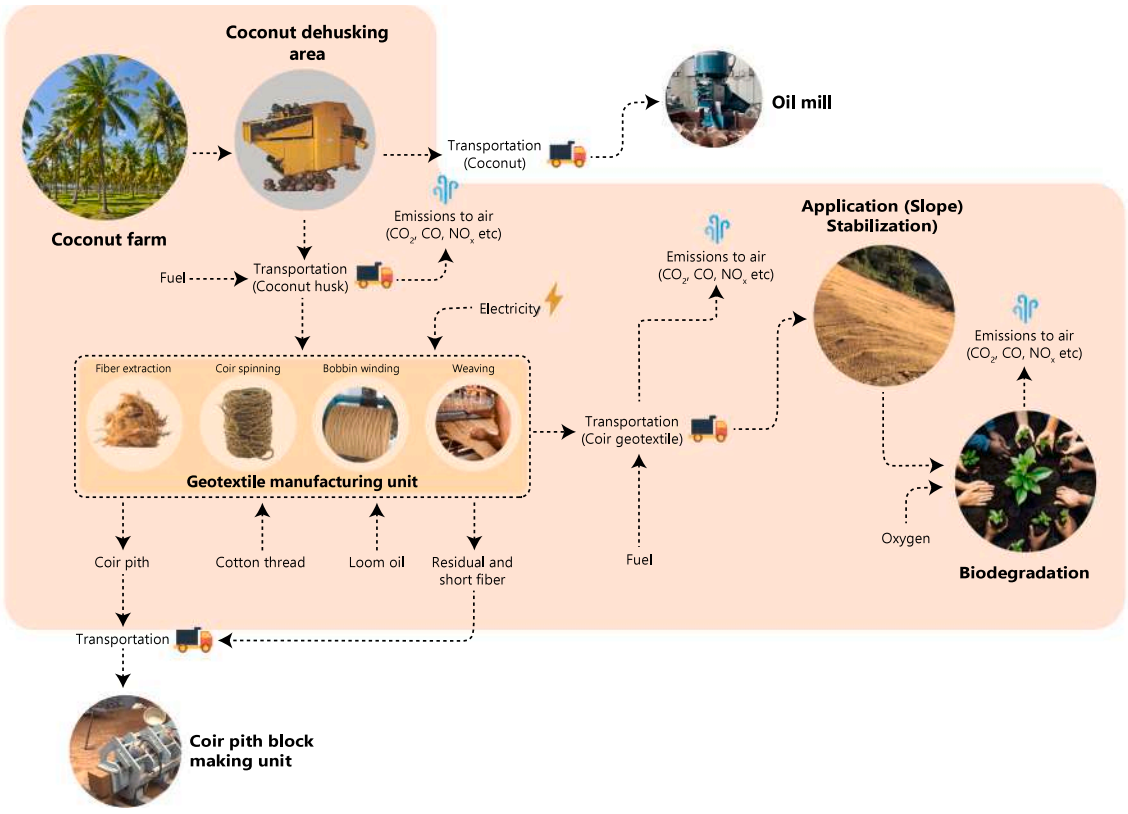


Fig. 1. Life cycle stages and activities involved in the coir geotextile.

In the geotextile manufacturing unit, the coconut husk undergoes several stages, fiber extraction, coir spinning, bobbin winding, and weaving, to produce coir geotextile. These operations require energy and materials. A by-product, coir pith, is simultaneously produced and sent to the coir pith block-making unit for further processing into blocks used in horticulture. The main product, coir geotextile, is then transported to the application site, consuming fuel and causing additional air emissions during transportation.

At the application stage, the coir geotextile is used for slope stabilization and erosion control. Over time, once its functional life is over, the material undergoes natural biodegradation in the soil. During this process, oxygen supports microbial decomposition, and gases such as carbon dioxide and methane are released back into the atmosphere. This completes the cradle-to-grave cycle of coir geotextile, showing the interconnected flow of materials, energy, and emissions across each phase of its life cycle. The factory built-up area was excluded due to its negligible contribution to the overall impact. Similarly, packaging was not involved in most cases as it was transported in bulk from the factory.

2.2. Inventory analysis

Life cycle inventory analysis (LCI) is the second phase of life cycle assessment (LCA). In this phase, all of the inputs and outputs that make up the LCA's purview are gathered from databases and other sources. This process involves data collection, analysis, validation, and data linkage to the functional unit in accordance with ISO 14040–14044 standards (Guo et al., 2025a). The foreground data regarding material requirements (supplementary document Table S1) and energy consumption (supplementary document Table S2) were collected from geotextile manufacturing industries located in Alappuzha district, Kerala (India). Additional inputs on manufacturing process and process flow were provided Central Coir Research Institute, Alappuzha (India) (Table 1). Supplementary processes and emission factors were modeled using the Ecoinvent 3.7.1 database. The LCI reflects a cradle-to-grave perspective, capturing all resource flows up to the delivery of 1 kg of woven coir geotextile to the warehouse. Particular attention was given to the electricity inputs, as they were later substituted by renewable sources in scenario modeling.

2.2.1. Raw material collection and transportation

Coconut husk, the primary raw material for coir geotextile production, is generally sourced from multiple locations based on local availability. In this study, it is assumed that the husk is transported by truck over an average distance of 20 km to the manufacturing unit, particularly in regions like Kerala, where coconut cultivation is widespread. Coconut husk is considered a co-product of coconut farming and is therefore assigned a proportional share of the environmental impacts associated with the cultivation process.

2.2.2. Geotextile manufacturing

In this study, all manufacturing processes were modeled as occurring within a single hypothetical facility, despite the typically decentralized nature of production. This approach was adopted to ensure methodological consistency and facilitate accurate data integration. The manufacturing phase consists of the following four stages:

Fiber Extraction: Coconut husks are mechanically processed using a coir fiber extraction machine to separate coir fiber from husk. The fiber yield varies between 30%–35%, depending on the quality of the husk. Coconut husk typically contains about 30% coir fiber and 70% pith by weight (Van Dam et al., 2004); however, this ratio can vary depending on the coconut variety and the efficiency of the defibring process. In this study, we assumed a husk with relatively higher fiber content and an efficient defibring process to reflect optimized production conditions commonly reported in industrial practice (Ali et al., 2022; Wang et al., 2023). Coir pith is the by-product and gets transported to the pith block-making unit.

Table 1
Summary of LCI data.

LCA stage	Input/Output	Value	Unit
Raw material	Coconut husk production	3.200	kg
Material transportation	Transportation of husk to manufacturing unit	20.00	km
Manufacturing			
(a) Fiber extraction	Coconut husk	3.200	kg
	Electricity	0.076	kWh
	Coir fiber	1.120	kg
	Coir pith	2.080	kg
(b) Coir spinning	Coir fiber	1.120	kg
	Cotton thread	0.020	kg
	Electricity	0.452	kWh
	Coir yarn	1.010	kg
	Residual and short fibers	0.103	kg
(c) Bobbin winding	Coir yarn	1.010	kg
	Electricity	0.024	kWh
	Coir spool	1.010	kg
(d) Weaving	Coir spool	1.010	kg
	Loom oil (Lubricant)	3.59E−3	kg
	Electricity	0.085	kWh
	Coir geotextile	1	kg
	Residual yarn	0.010	kg
Product transportation	Transportation of coir geotextile to the site of application	300	km
Use	No input or output of material or energy.		
End-of-Life (EoL)	Biodegradation of coir geotextile	1	kg

Coir Spinning: The extracted fibers are spun into yarn using semi-automatic spinning machines. To improve the tensile strength and flexibility of the yarn, cotton thread is incorporated during spinning, with an input ratio ranging from 1%–3% per kilogram of yarn.

Bobbin Winding: The spun yarn is wound onto bobbins or spools. This stage involves no material transformation or mass change.

Weaving: The coir yarn, in spool form, is woven into geotextiles using power looms. The environmental impacts associated with the production of coir fiber and pith were allocated based on the mass of each product (i.e., 35% for coir fiber and 65% for coir pith). Electricity consumption across all manufacturing stages was modeled using the medium voltage electricity supply scenario specific to India (IN) to reflect regional energy profiles.

2.2.3. Product transportation, installation, and use

The final product is distributed to both domestic and international markets based on demand. For domestic transportation, road and rail are the primary modes, while international shipments are typically handled via air or sea freight. However, for the purpose of this study, only the domestic use of coir geotextiles is considered.

Given the frequent occurrence of landslides in Kerala, primarily due to inadequate slope management in hilly regions, coir geotextiles have been employed as an effective intervention. Accordingly, the transportation scenario modeled in this study assumes delivery of the product to a hilly region located approximately 300 km from the manufacturing facility.

Installation is carried out manually by labor sourced locally from the application site. Once installed, the geotextile is expected to function effectively for a service life of approximately five years, during which no additional material or energy inputs are required.

2.2.4. End-of-life

Natural fiber-based products are biodegradable. Hence, coir geotextiles have an advantage over synthetic geotextiles in the market. Unlike its synthetic alternatives, it does not need to be disposed of separately. We have used a breakdown of biowaste in an open dump scenario to represent. The EoL scenario occurs at the site of installation, avoiding the need for a separate disposal site.

2.3. Life cycle impact assessment

Impact assessment is the third step of LCA. This phase quantifies the potential environmental impacts of the inputs and outputs identified in the Life Cycle Inventory (LCI) (Rosenbaum et al., 2018). This stage is crucial as it provides impact information of the product under study; during this stage, impact categories are selected. Characterization, normalization, and weighing are the substeps for impact assessment. This study utilizes the ReCiPe 2016 Midpoint (H) method (Ver. 1.05) to develop the LCA model in SimaPro. This method offers a scientifically balanced and policy-aligned approach with 18 midpoint indicators, enabling comprehensive and less uncertain environmental impact assessment. It is widely used, software-compatible, and aligns well with SDG-related evaluations. Additionally, it is fully compatible with the SimaPro v9.3.03 software and the Ecoinvent 3.7.1 database, facilitating seamless integration into the life cycle modeling process.

2.4. Interpretation

Interpretation is the last stage of LCA; it is an extensive process to find, quantify, validate, and evaluate data from the results of the impact assessment and inventory analysis. The results of the interpretation step are a compilation of the research's conclusions and recommendations (de Visser et al., 2025).

2.5. Scenario analysis

2.5.1. Modeling geographical scenarios

Apart from India, Indonesia and the Philippines are other top producers of coconut and manufacturers of coir-based products (Pham, 2016). To study the regional variation in environmental impacts, a scenario analysis was done by substituting the coconut husk and electricity mix data specific to India with those of Indonesia and the Philippines. Sri Lanka, though the largest coir producer, was excluded from this study due to the lack of standardized coir geotextile production data. The transportation and EoL data used for the baseline scenario were not specific to any region. Hence, that data was retained in two other scenarios.

Table 2
Summary of inventory data used for 1 kg of geosynthetics.

LCA stage	Input/Output	Value	Unit
Raw material	Polyethylene granulate production	0.75	kg
	Polyethylene terephthalate granulate production	0.28	kg
Material sourcing	Transportation of materials to manufacturing unit	100	km
Manufacturing	Polyethylene granulate	0.75	kg
	Polyethylene terephthalate granulate	0.28	kg
	Electricity	0.73	kWh
	Water	0.86	kg
	Heat	1.24	MJ
	Lubricant	0.000073	kg
	Synthetic geotextile	1	kg
Product transportation	Transportation of synthetic geotextile to the site of application	300	km
Use	No input or output of material or energy.		
End-of-Life (EoL)	Landfilling of geosynthetics	1	kg

2.5.2. Modeling renewable energy integration

Adoption of renewable energy (e.g., hydro, solar, or wind power) is expected to enhance the sustainability of both the product and process. The baseline electricity scenario is dominated by coal-based power (>50%), a nonrenewable source of energy. Hence, energy consumption is expected to contribute significantly to the overall environmental impact of coir geotextiles. The renewable energy integration scenario was modeled to reduce the impact of the coir geotextile over its life cycle compared to the baseline scenario. Data on energy production from hydro, solar, and wind were taken from the database.

2.5.3. Sensitivity and uncertainty analysis

Energy consumption plays a crucial role in determining the sustainability of coir geotextiles. A sensitivity analysis was carried out to assess how changes in energy use affect the product's overall environmental impact. Two primary factors influencing energy consumption during manufacturing are motor capacity and process throughput. To evaluate the effect, electricity consumption was adjusted by ±5% from the baseline scenario.

Furthermore, a Monte Carlo simulation was employed to analyze uncertainty in the LCA results by accounting for the probability distributions of key input parameters. This analysis was performed using SimaPro software with a range of input datasets. The uncertainty assessment helped identify the most influential variables, contributing to a more precise and meaningful evaluation.

2.5.4. Comparison of coir geotextile with geosynthetics

For the comparative analysis, life cycle inventory data for geosynthetic production were sourced from the LCA study conducted by European Association for Geosynthetic Manufacturers (EAGM). The transportation and use phases were excluded from the comparison, as their contribution to the overall environmental impact was found to be negligible. To ensure methodological consistency, the life cycle assessment of the geosynthetic material was performed using the same approach and SimaPro software as applied to the coir geotextile. The inventory data corresponding to 1 kg of geosynthetic material are presented in Table 2 and supplementary document Table S3. The end-of-life stage was modeled using data for both sanitary and unsanitary landfill scenarios.

2.6. SDG mapping

Evaluating the environmental impact of goods and services is vital for reaching the SDGs. This study used the framework developed by Castellani et al. (2019) to ensure a more complete and robust evaluation of the impacts, addressing SDGs. To understand the effects on the impact category on SDGs for the product considered, a scenario analysis was conducted. The purpose of the scenario analysis is to present multiple potential future development paths that yield different outcomes and associated implications, and to evaluate the effects of possible future events on system performance by considering various alternative scenarios. Similarly, we considered four scenarios and conducted the analysis.

3. Results & discussion

3.1. Hotspot analysis

3.1.1. Baseline environmental impacts

The baseline impacts associated with the life cycle of 1 kg of woven coir geotextile are in Fig. 2. The baseline scenario uses a conventional electricity mix grid during the manufacturing stage. The manufacturing phase emerged as the predominant contributor to environmental burdens across most impact categories, such as global warming, human carcinogenic toxicity, water consumption, and eutrophication. This dominance is primarily attributed to the high energy demand of operations such as spinning, weaving, and processing, which are energy-intensive and heavily reliant on coal-based grid electricity in India. Similar trends have been reported in previous studies, such as by Sharma and Kumar (2023), who emphasized the significant environmental burden from coal-dependent power in Indian manufacturing sectors. Specifically, GW is estimated at 1.637 kg CO_2 eq per kg of product, of which approximately (4.50E−01 kg CO_2 eq) originates from manufacturing, largely due to fossil fuel-based energy use. This aligns with findings by Kong et al. (2025), who identified electricity consumption as the primary driver of carbon emissions in fiber processing industries.

A breakdown of manufacturing stages (Table 3) shows that weaving is the most environmentally intensive process. It contributes the highest to categories such as global warming, acidification, resource scarcity, particulate matter formation, ozone formation, and both human carcinogenic and non-carcinogenic toxicity. For instance, weaving alone accounts for 1.17E−01 CO_2 eq (global warming), 3.84E−04 kg SO_2 eq (acidification), and 3.97E−04 m^3 (water consumption). This highlights the energy burden of mechanized weaving in the coir sector (Padath et al., 2024).

These high impacts are driven by fossil-based grid electricity, inefficiencies such as yarn waste and frequent maintenance, and auxiliary energy demands (lighting, ventilation, heat control) (Cheng et al., 2024). The reliance on fossil-based power amplifies impacts across several categories, including ionizing radiation (3.83E−03kg U235 eq) and fine particulate matter formation (2.93E−04 kg PM2.5 eq). The raw material acquisition stage also contributes significantly to specific impact categories. Land use impact is estimated at 1.39E m^2a crop eq, primarily due to the cultivation of coconut trees. Although coconut husk is treated as a co-product, it shares a portion of the cultivation-related burdens, including land occupation, agrochemical

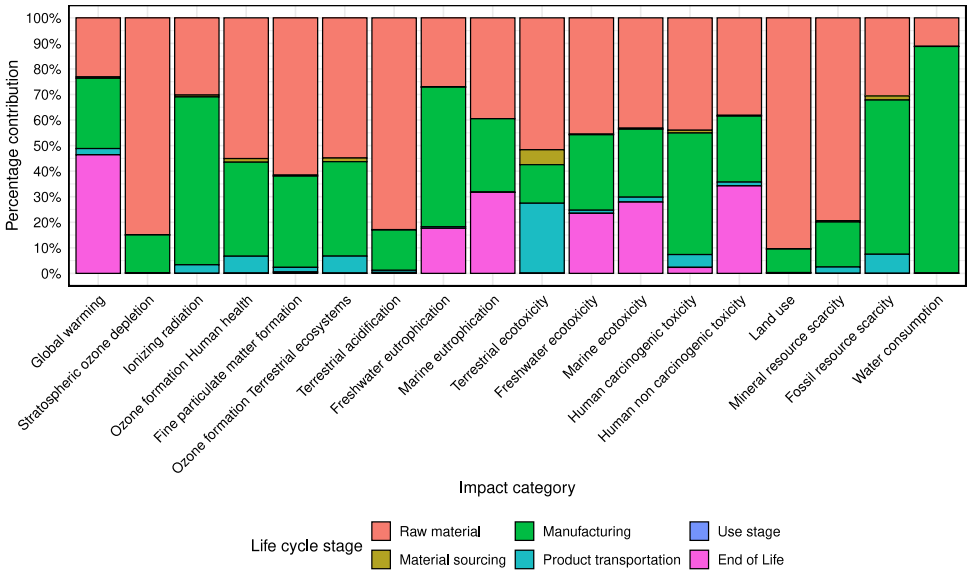


Fig. 2. Environmental impacts (baseline) of coir geotextile.

use, and irrigation. Stratospheric ozone depletion (7.32E−06 kg CFC-11 eq) and terrestrial acidification (1.30E−02SO_2 eq) also see notable contributions from upstream agricultural activities, including biomass burning and chemical retting (Provin et al., 2021).

Transportation impacts are minimal under the baseline assumptions. Transport contributes only 4.03E−02 CO_2 eq to global warming, due to the use of short-distance, efficient transport modes. However, these impacts could rise substantially if the product is exported internationally, especially via air or maritime routes (Liang et al., 2025).

The use phase of the coir geotextile is considered environmentally neutral in this study. The EoL phase has a minimal environmental impact due to the natural biodegradability of coir under aerobic conditions (Maraveas, 2020). During degradation, the material breaks down into carbon dioxide and biomass without leaving toxic residues or requiring energy-intensive treatment, providing a distinct advantage over synthetic alternatives that necessitate complex disposal processes. Consequently, the study identifies the weaving operation during the manufacturing phase as the primary environmental hotspot, consistent with the conclusions of similar LCA studies in the natural fiber sector (Shamsuzzaman et al., 2023). The critical role of electricity source and process efficiency in shaping the environmental performance of coir geotextile highlights the potential for impact mitigation through renewable energy integration and process optimization.

The impacts from transportation, both upstream and downstream, are relatively low in the current scenario. For instance, the global warming impact from downstream transport is only 0.027 kg CO_2 eq, due to the short distances and efficient transport modes assumed in the study. However, if the product is exported to international markets, especially via air or maritime transport, transportation impacts could increase considerably, particularly in climate change-related categories (Ravikumar et al., 2023). The use phase does not contribute to the environmental impacts in this study, and hence it was excluded. The end-of-life (EoL) stage shows very low environmental impact, mainly due to the natural biodegradation of coir under aerobic conditions. During this process, the material primarily releases CO_2 and reduces in mass without generating harmful residues or solid waste. During this process, the material breaks down into smaller particles with a reduction in its overall mass without generating any waste products (Prambauer et al., 2019). This gives coir geotextile a significant environmental advantage over synthetic alternatives that require energy-intensive disposal.

3.1.2. Cumulative energy demand

The CED for producing 1 kg of woven coir geotextile is categorized into renewable and non-renewable energy sources, as shown in Fig. 3. The predominance of renewable biomass energy in the raw material phase demonstrates the environmental merit of coir geotextile as a bio-based product. Derived from coconut husks, an agricultural by-product, coir fibers inherently carry a renewable energy footprint, contributing significantly to the total CED (Atapattu et al., 2024). This characteristic offers a distinct comparative advantage over geotextiles manufactured from fossil or petrochemical sources. Similar findings were reported by Islam et al. (2024) in their LCA of natural fiber textiles, where raw material stages in plant-based products were largely renewable in energy terms, contributing positively to overall sustainability.

A modest contribution to renewable energy also arises during the manufacturing phase, primarily due to the incorporation of cotton threads in the spinning process. As a naturally derived fiber, cotton supplements the renewable energy share. However, this is relatively minor compared to the total energy requirements of processing operations such as spinning and weaving. Duarte et al. (2025) observed that mechanical processing stages in fiber-based products often shift the energy profile toward non-renewable sources due to electricity-intensive operations.

Conversely, the manufacturing stage accounts for a substantial share of non-renewable energy consumption, largely due to its dependence on electricity from fossil fuel-dominated grids, particularly coal-based sources. These energy-intensive steps considerably increase the non-renewable fraction of CED, which in turn heightens the environmental burden through emissions and resource use. Imran et al. (2023) highlighted similar energy burdens in textile processing, pointing out that power grid dependence significantly affects the total CED in natural fiber value chains.

The end-of-life stage exhibits negligible energy demand, attributable to the biodegradable nature of coir. Unlike synthetic materials that often require energy-intensive disposal or recycling, coir degrades passively, eliminating the need for additional energy input during disposal (Ravichandran et al., 2024).

Overall, the CED profile of coir geotextile reveals a favorable sustainability performance, driven by the high share of renewable energy content in the upstream stages. Nevertheless, reducing the non-renewable share, especially during manufacturing, remains critical.

Table 3
Relative contribution of each specific manufacturing step to the impact categories.

Impact category	Unit	Total	I	II	III	IV
Global warming	kg CO_2 eq	4.50E−01	3.47E−02	2.68E−01	3.13E−02	1.17E−01
Stratospheric ozone depletion	kg CFC11 eq	1.28E−06	8.38E−09	1.23E−06	7.56E−09	3.10E−08
Ionizing radiation	kBq Co-60 eq	1.53E−02	1.10E−03	9.41E−03	9.93E−04	3.83E−03
Ozone formation, Human health	kg NOx eq	1.21E−03	7.77E−05	7.83E−04	7.01E−05	2.79E−04
Fine particulate matter formation	kg PM2.5 eq	1.11E−03	8.82E−05	6.49E−04	7.96E−05	2.93E−04
Ozone formation, Terrestrial ecosystems	kg NOx eq	1.23E−03	7.84E−05	7.91E−04	7.07E−05	2.91E−044
Freshwater eutrophication	kg P eq	2.47E−03	1.12E−04	1.87E−03	1.01E−04	3.84E−04
Marine eutrophication	kg N eq	2.87E−04	2.07E−05	1.80E−04	1.87E−05	6.76E−05
Terrestrial ecotoxicity	kg 1,4-DCB	1.03E−03	1.28E−06	1.02E−03	1.16E−06	4.20E−06
Freshwater ecotoxicity	kg 1,4-DCB	4.16E−01	2.04E−02	2.99E−01	1.84E−02	7.75E−02
Marine ecotoxicity	kg 1,4-DCB	1.97E−02	7.82E−04	1.54E−02	7.06E−04	2.76E−03
Human carcinogenic toxicity	kg 1,4-DCB	2.05E−02	1.06E−03	1.47E−02	9.59E−04	3.74E−03
Human non-carcinogenic toxicity	kg 1,4-DCB	2.25E−02	1.80E−03	1.29E−02	1.63E−03	6.17E−03
Land use	m2a crop eq	5.01E−01	3.37E−02	3.24E−01	3.04E−02	1.13E−01
Mineral resource scarcity	kg Cu eq	1.41E−01	4.01E−04	1.39E−01	3.62E−04	1.39E−03
Fossil resource scarcity	kg oil eq	1.12E−01	9.26E−03	5.97E−02	8.36E−03	3.51E−02
Water consumption	m^3	1.06E−01	1.10E−04	1.05E−01	9.96E−05	3.97E−04

I: Fiber extraction, Coir fiber; II: Coir spinning, Yarn
III: Bobbin winding, Coir spool; IV: Weaving, Coir geotextile

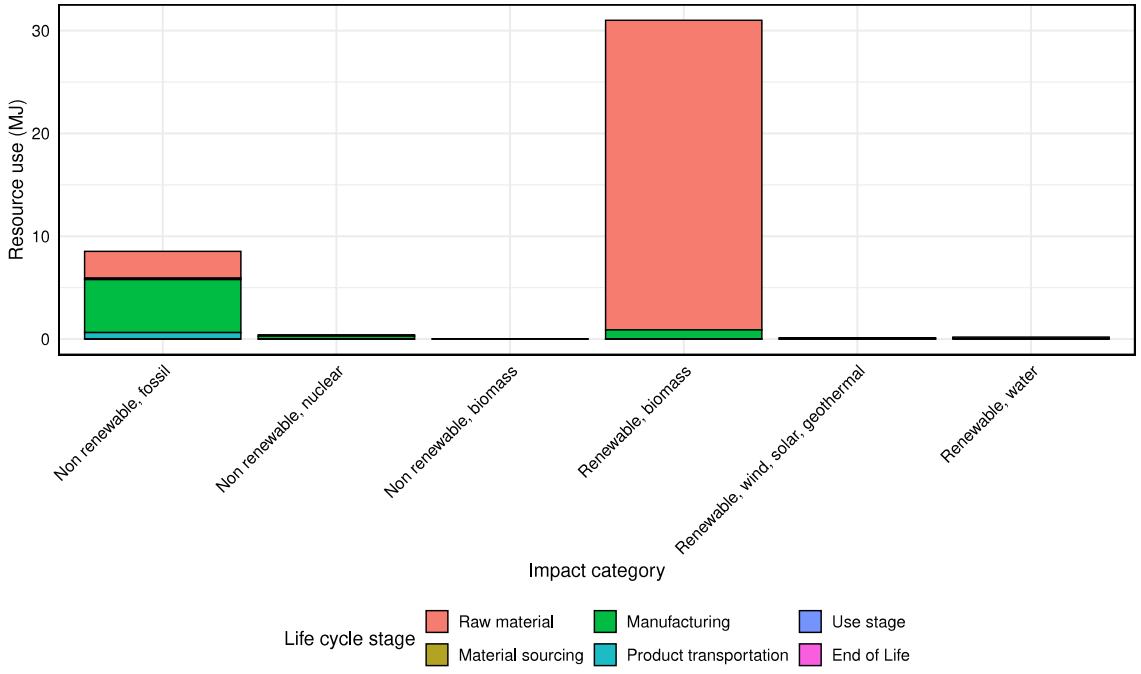


Fig. 3. Cumulative energy demand in the life cycle stages of coir geotextile.

Improvements such as upgrading to energy-efficient machinery, integrating renewable electricity, and streamlining production could meaningfully lower the total CED, thereby reinforcing coir geotextile's potential as a sustainable solution in geotechnical and civil infrastructure applications.

3.2. Scenario analysis

3.2.1. Geographical impacts

While coir geotextiles are increasingly recognized as a biodegradable, renewable, and eco-friendly alternative to synthetic geotextiles, their life cycle sustainability is not uniform across production regions. Instead, it is significantly shaped by local agricultural practices, resource efficiency, and energy infrastructure (Abedi et al., 2023). In particular, the cultivation of coconuts, the primary feedstock for coir fibers, and the energy mix used during fiber processing play critical roles in determining the environmental performance of coir geotextile systems.

A recent comparative LCA of coir geotextile supply chains in Indonesia, the Philippines, and India reveals that Indonesia consistently exhibits the highest environmental impacts across most mid-point categories, with values ranging from 0.9 to 5.6 times higher than those reported for India (Table 4). These elevated impacts are predominantly driven by the resource-intensive nature of coconut cultivation in Indonesia. The country, as the world's largest producer of coconut, heavily relies on extensive, low-efficiency farming systems often characterized by large land footprints, high water demand, and minimal mechanization (Utomo et al., 2016). These practices, coupled with limited implementation of agroecological methods and poor integration of circular farming models, result in substantial contributions to land use change, water depletion, and greenhouse gas (GHG) emissions, particularly methane and nitrous oxide from manure and fertilizer use.

In contrast, India's coconut production systems demonstrate a relatively lower environmental burden, largely due to the higher productivity per hectare, more diverse intercropping systems, and wider adoption of rainfed agriculture in southern coastal states like Kerala

Table 4
Environmental impacts of India, Indonesia, and the Philippines.

Impact category	India	Indonesia	Philippines
Global warming	1.64E+00	3.54E+00	2.42E+00
Stratospheric ozone depletion	8.62E−06	1.08E−05	9.42E−06
Ionizing radiation	2.33E−02	2.62E−02	2.41E−02
Ozone formation, Human health	3.29E−03	4.68E−03	4.07E−03
Fine particulate matter formation	3.11E−03	1.75E−02	4.29E−03
Ozone formation, Terrestrial ecosystems	3.33E−03	4.89E−03	4.19E−03
Terrestrial acidification	1.57E−02	1.44E−02	1.35E−02
Freshwater eutrophication	5.26E−04	1.58E−03	8.69E−04
Marine eutrophication	3.57E−03	1.01E−02	6.19E−03
Terrestrial ecotoxicity	2.75E+00	2.68E+00	3.06E+00
Freshwater ecotoxicity	6.66E−02	1.07E−01	1.06E−01
Marine ecotoxicity	7.69E−02	1.25E−01	1.18E−01
Human carcinogenic toxicity	4.73E−02	9.79E−02	6.86E−02
Human non-carcinogenic toxicity	1.94E+00	3.41E+00	3.61E+00
Land use	1.54E+00	3.70E+00	4.26E+00
Mineral resource scarcity	3.05E−03	3.25E−03	3.29E−03
Fossil resource scarcity	1.86E−01	3.04E−01	2.52E−01
Water consumption	1.19E−01	3.71E−01	6.31E−01

and Tamil Nadu (Kumar and Kunhamu, 2022). In these regions, traditional coconut farming has evolved to include multi-tier cropping, organic manuring, and minimal tillage, all of which help in reducing emissions, erosion, and nutrient loss (Nayak et al., 2021). However, this agricultural advantage is substantially offset by the high environmental impacts observed during the manufacturing phase, particularly those associated with energy consumption in fiber processing and geotextile fabrication. India's electricity grid is still dominated by fossil fuels, especially coal, which accounted for over 70% of total electricity generation in 2023 (Singh et al., 2023; Bhatia, 2023). As coir fiber production involves mechanical decortication, drying, spinning, and weaving, all energy-intensive steps, the use of coal-based electricity leads to a significantly higher carbon footprint at this stage (Chandra et al., 2025). In fact, according to Ramachandran et al. (2023), electricity is often the largest single contributor to life cycle GHG emissions in fiber-processing systems, especially in countries with carbon-intensive grids.

The Philippines, meanwhile, occupies an intermediate position. Although its coconut cultivation systems are less efficient than India's and may still be susceptible to monoculture-related impacts, the environmental pressures from this phase remain lower than in Indonesia. More importantly, the electricity mix in the Philippines features a higher share of renewables, including geothermal, hydro, and solar power, which contributes to lower emissions during manufacturing (del Barrio Alvarez et al., 2025). The Philippine grid in 2022 derived over 29% of its power from renewable sources, compared to only 20% in India and 14% in Indonesia (Castro et al., 2022). As a result, the manufacturing-stage environmental impacts of coir geotextiles in the Philippines are markedly lower than those in India or Indonesia, leading to a more balanced life cycle impact profile across the cultivation and processing phases.

The analysis indicates that coir geotextiles, while inherently sustainable in material terms, are not universally low-impact unless regional agricultural and energy system dynamics are addressed. To ensure genuinely sustainable production, context-specific interventions are needed. These include promoting sustainable coconut farming practices (agroforestry, integrated pest management), increasing the use of renewable energy in processing units, and encouraging regionalized LCA modeling to inform policy decisions. Without such integrated approaches, the climate and resource savings potential of natural fiber-based geotextiles may be compromised by upstream inefficiencies and downstream emissions.

3.2.2. Mitigation of impacts

The manufacturing stage is the major hotspot in the life cycle of coir geotextile. Electricity consumption is identified as the key factor contributing to the higher impact of the manufacturing process. Hence, there is an urgent need to explore alternative sources of energy that can reduce the overall life cycle impact of the product. To address this, scenario analysis replaced the baseline energy with renewable sources: hydro, solar, and wind. The results, shown in Fig. 4, indicate that renewable energy integration reduced environmental impacts by 10%–50% compared to the baseline scenario, supporting the expected drastic impact reduction from a complete transition to renewable power. Among these alternatives, the integration of hydro-based electricity showed the least impact across all categories. Hydropower generation offers higher conversion efficiency compared to coal-based and solar-based systems (Xue et al., 2023; Østergaard et al., 2023; Rahman et al., 2022), confirming its status as a superior renewable option. However, its application is regionally restricted to areas with perennial river systems, limiting its global feasibility.

3.3. Sensitivity and uncertainty analysis

The sensitivity analysis was performed by varying the major contributor to explore the overall environmental impact of the coir geotextile. The variation in environmental impacts due to changes in electricity consumption is shown in Fig. 5. The impact scale ranges from −0.7 to 0.7, where 0 represents the baseline scenario corresponding to a median process throughput configuration.

The results show that a 5% variation in electricity consumption leads to significant changes in environmental impacts across most categories. Notably, fossil resource scarcity (±0.1378), fine particulate matter formation (±0.001), human carcinogenic toxicity (±0.0262), and global warming (±0.5138) exhibit the highest sensitivity, with deviations exceeding 50% from the baseline. In contrast, categories such as stratospheric ozone depletion (±1.2306E−07), water consumption (±0.0016), show minimal or no sensitivity to electricity consumption changes.

These results indicate a linear and symmetrical relationship between electricity consumption and environmental impact within the ±5% range. The most sensitive categories are directly linked to energy use, particularly from fossil-based sources, while the least sensitive categories are influenced by other factors in the manufacturing process.

The energy consumption per unit mass of output is influenced by the process throughput of the machinery used (Sheppard and Rahimifard, 2019). Large-scale geotextile manufacturing units typically operate with high-throughput machines to meet market demand, resulting in lower energy consumption per unit mass of product. Conversely, machines with lower throughput consume more electricity per unit mass, increasing the environmental burden (Łach and Svyetlichnyy, 2025; Rajendran et al., 2025). Thus, process throughput plays a critical role in determining the environmental performance of the manufacturing system.

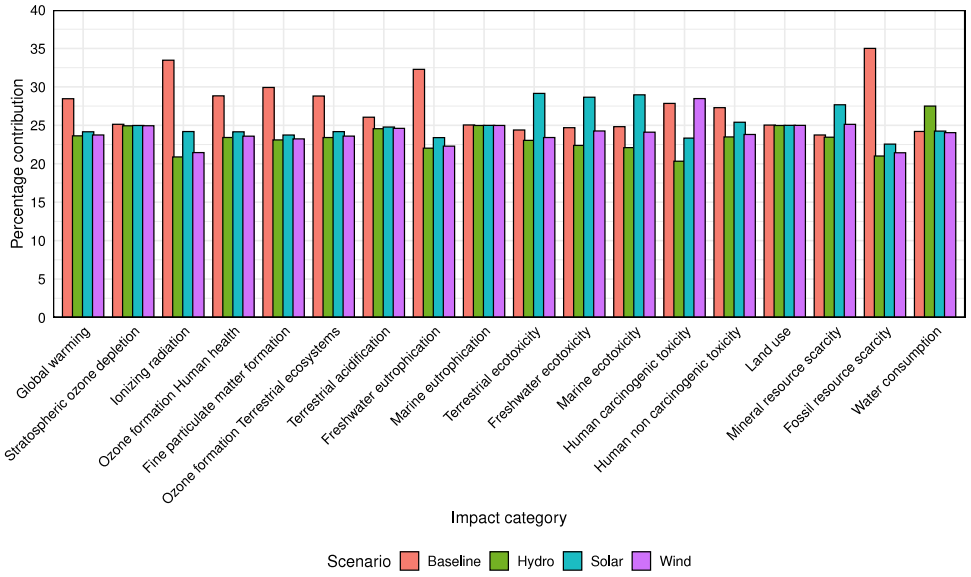


Fig. 4. Relative impacts of manufacturing stage under different energy scenarios.

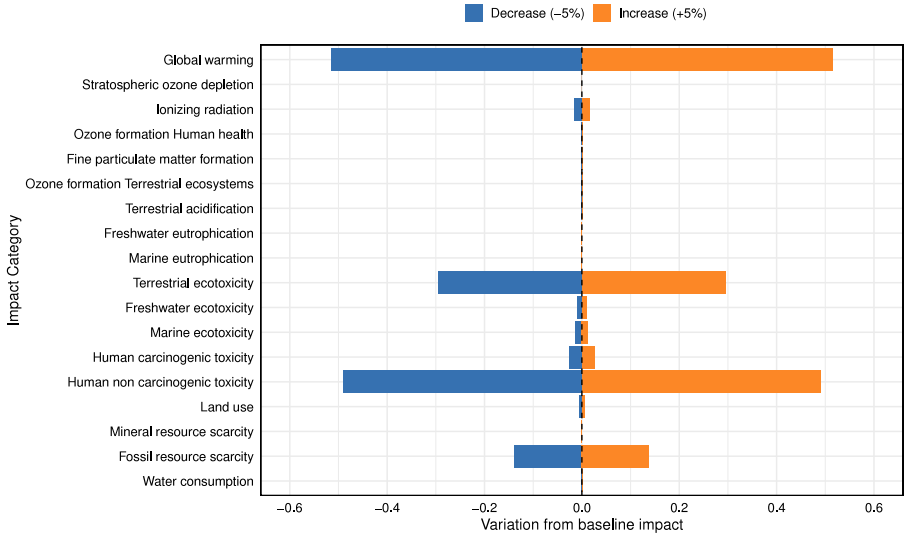


Fig. 5. Variation in environmental impact with change in process throughput.

Table 5
Uncertainty analysis.

Impact category	Mean	Median	SD	CV	2.5%	97.5%
Global warming	9.29E−01	9.23E−01	9.23E−02	9.93E+00	7.72E−01	1.13E+00
Stratospheric ozone depletion	1.39E−06	1.38E−06	1.41E−07	1.01E+01	1.15E−06	1.71E−06
Ionizing radiation	3.19E−02	1.71E−02	5.32E−02	1.67E+02	4.15E−03	1.50E−01
Ozone formation, Human health	2.29E−03	2.27E−03	2.02E−04	8.81E+00	1.92E−03	2.72E−03
Fine particulate matter formation	2.33E−03	2.31E−03	2.31E−04	9.89E+00	1.94E−03	2.81E−03
Ozone formation, Terrestrial ecosystems	2.32E−03	2.30E−03	2.03E−04	8.79E+00	1.95E−03	2.75E−03
Terrestrial acidification	4.03E−03	3.94E−03	4.65E−04	1.15E+01	3.41E−03	5.13E−03
Freshwater eutrophication	5.81E−04	5.11E−04	2.97E−04	5.11E+01	2.39E−04	1.40E−03
Marine eutrophication	1.05E−03	1.04E−03	7.54E−05	7.20E+00	9.10E−04	1.21E−03
Terrestrial ecotoxicity	6.91E−01	6.82E−01	9.01E−02	1.30E+01	5.52E−01	8.95E−01
Freshwater ecotoxicity	2.67E−02	2.56E−02	2.87E−02	1.07E+02	−2.78E−02	8.57E−02
Marine ecotoxicity	3.10E−02	2.84E−02	2.70E−02	8.70E+01	−1.16E−02	8.66E−02
Human carcinogenic toxicity	4.58E−02	3.42E−02	3.16E−01	6.91E+02	−5.27E−01	6.77E−01
Human non-carcinogenic toxicity	−5.14E+00	−7.03E+00	2.18E+02	−4.25E+03	−4.61E+02	4.03E+02
Land use	1.46E−01	1.46E−01	5.31E−03	3.63E+00	1.37E−01	1.58E−01
Mineral resource scarcity	6.29E−04	6.26E−04	6.08E−05	9.67E+00	5.22E−04	7.74E−04
Fossil resource scarcity	2.40E−01	2.38E−01	2.73E−02	1.14E+01	1.94E−01	2.97E−01
Water consumption	1.07E−01	1.09E−01	4.59E−02	4.28E+01	1.21E−02	1.94E−01

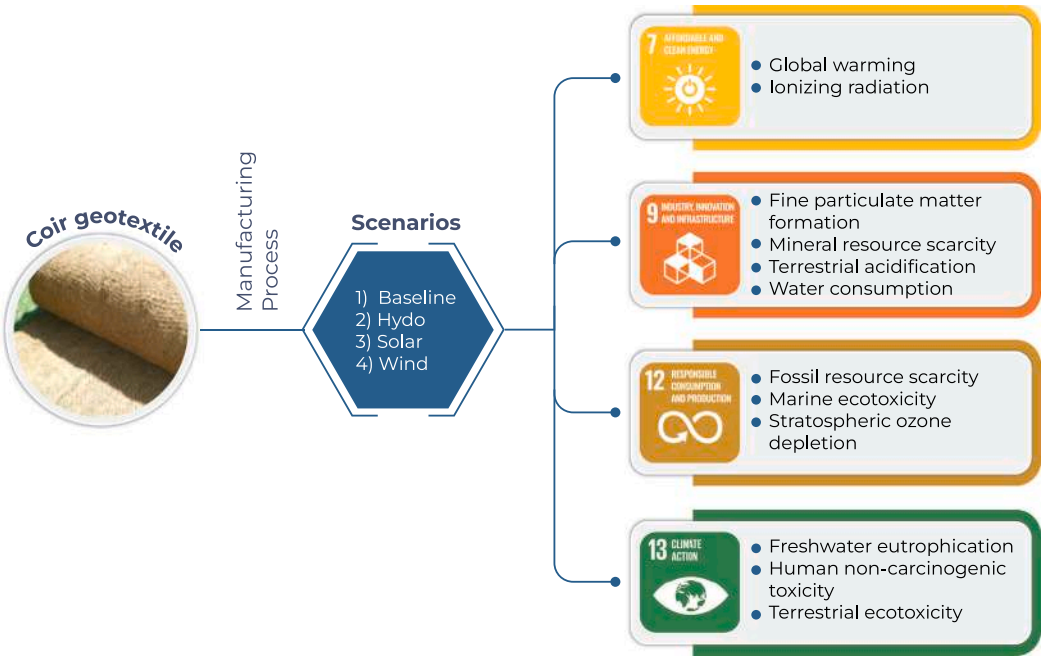


Fig. 6. Mapping of impact categories to SDGs.

To assess the robustness of the results, a Monte Carlo simulation with 1000 iterations was conducted. The simulation outputs include the mean, standard deviation (SD), 2.5th and 97.5th percentiles, and the coefficient of variation (CV) for each impact category (Table 5). The results indicate that global warming, fossil resource scarcity, and fine particulate matter formation categories have low uncertainty (CV < 10%), making them reliable indicators for decision-making. On the other hand, freshwater eutrophication, human carcinogenic toxicity, and marine eutrophication exhibit moderate uncertainty. Categories such as freshwater ecotoxicity and ionizing radiation show high uncertainty, suggesting that results in these categories should be interpreted with caution.

3.4. Contributions to SDGs

To assess comprehensive sustainability, impact categories were mapped to relevant SDGs (Parvathy et al., 2025a), specifically SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (Fig. 6). Scenario results demonstrate that transitioning to renewable energy significantly reduces environmental impacts across most impact categories, aligning with global sustainability objectives.

3.4.1. SDG 7: Affordable and clean energy

SDG 7 emphasizes clean, sustainable energy systems. The impact categories of GW (measured in kg CO_2 eq) and IR (kBq Co-60 eq) are directly relevant to this goal (Fig. 7a). The fossil-based baseline has the highest GQ potential (1.64E+00 kg CO_2 eq). In contrast, renewable energy scenarios (hydro: 1.36E+00 kg CO_2 eq, solar: 1.39E+00 kg CO_2 eq, wind: 1.37E+00 kg CO_2 eq) achieve a notable 15%–17% reduction in GW potential (see Fig. 7).

Similarly, ionizing radiation impacts are reduced by 27%–37% in renewable scenarios (hydro: 1.46E−02, solar: 1.69E−02, and wind: 1.50E−02 kBq Co-60 eq) compared to the baseline (2.33E−02 Co-60 eq). These reductions demonstrate that renewables mitigate risks from radiative emissions, supporting cleaner energy adoption and international climate goals (Meinshausen et al., 2022). Hydro and wind show slightly superior performance to solar, likely due to lower material and energy life cycle inputs (Meinshausen et al., 2022). Hydro and wind show slightly superior performance to solar, likely due to lower material and energy life cycle inputs.

3.4.2. SDG 9: Industry, innovation, and infrastructure

SDG 9 fosters sustainable industrialization and resilient infrastructure, with impact categories such as fine particulate matter formation (kg PM2.5 eq), terrestrial acidification (kg SO_2 eq), water consumption (m^3), and mineral resource scarcity (kg Cu eq) being relevant. The baseline shows the highest impacts (Fig. 7b), with fine particulate matter formation at 3.11E−03 kg PM2.5 eq and terrestrial acidification at 1.57E−02 kg SO_2 eq. Renewables reduce fine particulate matter by 21%–23% and terrestrial acidification by 5%–6%, supporting sustainable industrial practices and improving air quality (Jaiswal et al., 2022).

However, water consumption presents a trade-off: the hydro scenario slightly increases water use (0.136 m^3) compared to the baseline (0.119 m^3), likely due to water use in hydropower generation. Conversely, wind (0.119 m^3) scenarios show marginal water efficiency improvements. For mineral resource scarcity, the solar scenario shows a higher impact (3.55E−03 kg Cu eq) than the baseline (3.05E−03 kg Cu eq), possibly due to the resource-intensive production of photovoltaic panels. These findings indicate that while renewables support SDG 9 by reducing air pollution, water and mineral resource use require careful context-specific planning.

3.4.3. SDG 12: Responsible consumption and production

SDG 12 promotes sustainable production patterns, with relevant impact categories including human non-carcinogenic toxicity (kg 1,4-DCB), freshwater eutrophication (kg P eq), and terrestrial ecotoxicity (kg 1,4-DCB). The baseline exhibits the maximum impacts. Renewable energy scenarios significantly reduce (Fig. 7c) human non-carcinogenic toxicity by 7%–14%, and freshwater eutrophication by 28%–32%. For terrestrial ecotoxicity, hydro (2.60E kg 1,4-DCB) and wind (2.64E kg 1,4-DCB) show reductions of 6%, and 4%, respectively, while solar (3.29E kg 1,4-DCB) exhibits a slight increase compared to the baseline, potentially due to the use of hazardous materials in solar panel manufacturing.

These results suggest that renewable energy sources enhance the sustainability of coir geotextile production by reducing toxicity and

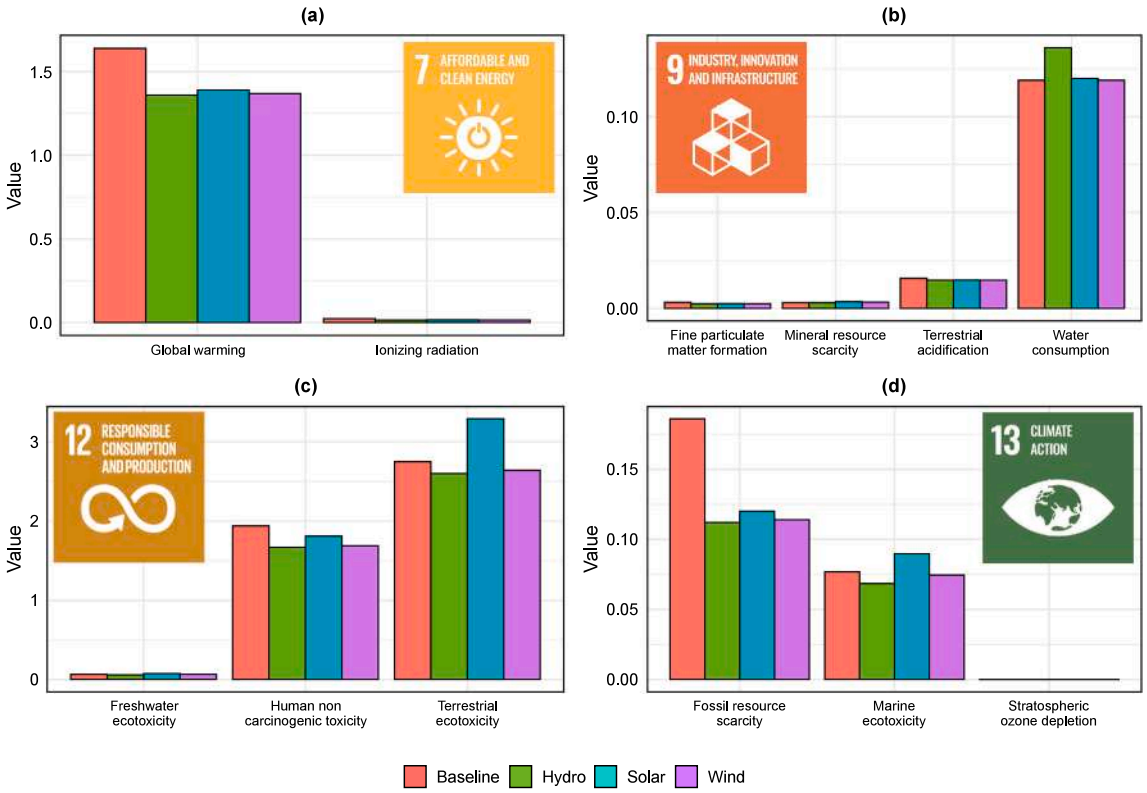


Fig. 7. The total environmental impact of each scenario under the SDGs.

eutrophication impacts, aligning with SDG 12's focus on responsible production. However, the higher terrestrial ecotoxicity in the solar scenario highlights the need for improved material selection and end-of-life management in photovoltaic systems to fully align with sustainable production goals. Coir's natural biodegradability (Mahmud et al., 2023) further supports this goal, offering an eco-friendly alternative to synthetic geotextiles that often contribute to plastic waste globally.

3.4.4. SDG 13: Climate action

SDG 13 addresses the climate change mitigation, with fossil resource scarcity (kg oil eq), stratospheric ozone depletion (kg CFC11 eq), and marine ecotoxicity (kg 1,4-DCB) as key impact categories. The baseline scenario shows the highest fossil resource scarcity (1.86E−01 kg oil eq), while hydro (1.12E−01 kg oil eq), solar (1.20E−01 kg oil eq), and wind (1.14E−01 kg oil eq) reduce this impact by approximately 35%–40%. This substantial reduction underscores the role of renewable energy in decreasing reliance on fossil fuels, a critical aspect of climate action (Fig. 7d).

Stratospheric ozone depletion impacts are relatively similar across all scenarios, with the baseline at 8.62E−06 kg CFC11 eq and renewable scenarios ranging from 6.80E−06 to 8.57E−06 kg CFC11 eq, indicating minimal differences. This suggests that energy source transitions have a limited influence on ozone depletion in this context. For marine ecotoxicity, hydro (6.85E−02 kg 1,4-DCB) and wind (7.47E−02 kg 1,4-DCB) reduce impacts by 11% and 3%, respectively, compared to the baseline (7.69E−02 kg 1,4-DCB), while solar (8.98E−02 kg 1,4-DCB) shows a slight increase, possibly due to chemical releases during solar panel production. These findings highlight that hydro and wind energy contribute significantly to SDG 13 by reducing fossil fuel dependency and marine ecotoxicity, while solar energy requires further optimization to minimize ecotoxicological impacts.

The scenario analysis reveals that renewable energy sources, hydro, solar, and wind, consistently outperform the fossil-based baseline across most impact categories, supporting the transition to sustainable energy systems in coir geotextile production. Hydro and wind generally exhibit the lowest environmental impacts, especially in global warming, toxicity, and fossil resource scarcity, making them strong choices for SDGs 7, 12, and 13. Solar energy, though effective for GHG reduction, shows higher impacts in mineral resource scarcity and terrestrial ecotoxicity, suggesting a need for advancements in photovoltaic manufacturing and recycling.

The hydro scenario's higher water consumption highlights a trade-off that must be considered in water-scarce regions, aligning with the need for context-specific energy planning as noted in recent LCA studies. The minimal variation in stratospheric ozone depletion across scenarios indicates that this impact category is less sensitive to energy source changes, consistent with findings from broader renewable energy LCAs.

3.5. Comparison of coir geotextile with geosynthetics

The comparison between coir geotextile and geosynthetics is illustrated in Fig. 8. The analysis clearly demonstrates the superior environmental performance of coir-based alternatives across the majority of life cycle stages and impact categories. The results show that coir geotextiles, being derived from renewable and biodegradable natural fibers, exert substantially lower environmental pressures compared to geosynthetics, which are primarily composed of petroleum-derived polymers such as polypropylene, PET, and PP. The production of geosynthetics involves high energy consumption, fossil fuel dependency, and significant greenhouse gas emissions during polymer synthesis and extrusion processes. In contrast, coir geotextiles utilize coconut husk, an agricultural by-product, making their raw material acquisition far less resource-intensive and more circular in nature. The utilization of agricultural waste material not only reduces environmental burden but also supports rural economies and waste valorization in coconut-producing regions, as emphasized by studies (Ali and Russell, 2025; Schipfer et al., 2024) which highlight the role of natural fibers in promoting low-carbon, circular bioeconomies.

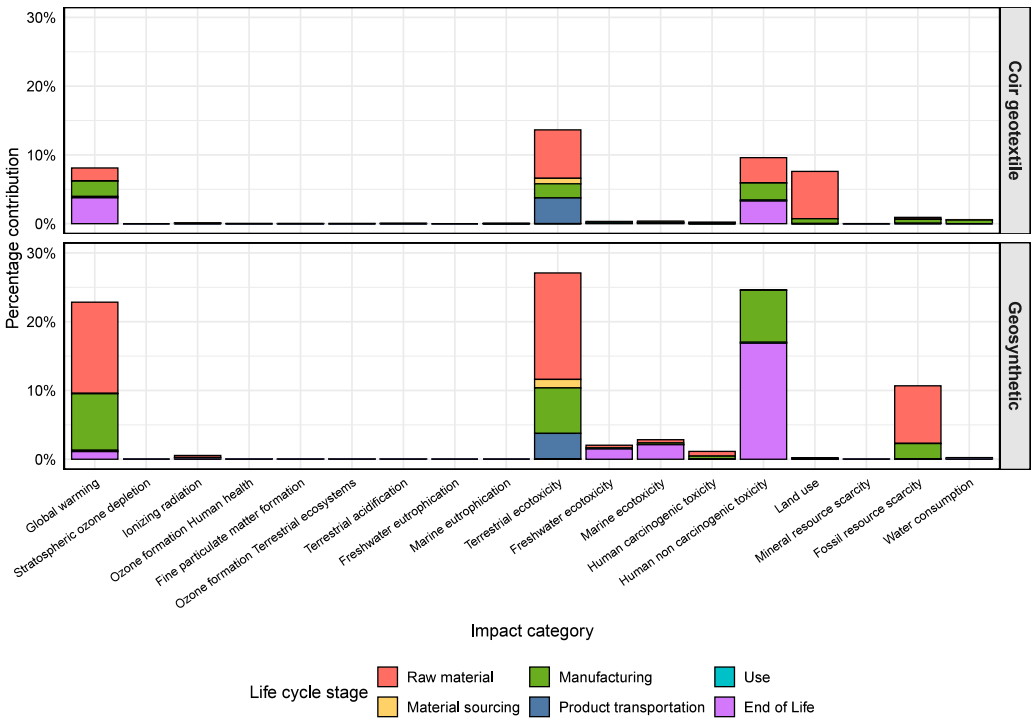


Fig. 8. Comparison of coir geotextile with geosynthetics.

In terms of life cycle phases, the majority of impacts for coir geotextiles arise during raw material processing and manufacturing, primarily due to energy use for fiber extraction, retting, and weaving. However, these energy inputs are significantly lower than those of their synthetic counterparts. The use of manual or semi-mechanized operations in coir matting often relies on electricity from renewable or grid-based low-emission sources, further minimizing the carbon footprint. In geosynthetic production, the extraction and refinement of fossil fuels into polymers contribute heavily to climate change impacts and non-renewable resource depletion. Furthermore, the polymerization and thermal bonding stages are energy-intensive, amplifying emissions of CO_2 and other pollutants. Polymer-based geotextiles exhibit high life cycle burdens, particularly in categories linked to global warming potential, fossil resource scarcity, and human toxicity, all of which stem from upstream petrochemical processes.

Another critical difference lies in the end-of-life (EoL) phase. Coir geotextiles, being biodegradable, can naturally decompose under aerobic conditions, contributing minimal residues to the environment. Their decomposition enriches soil organic matter and aligns with the principles of the circular economy and waste minimization. Conversely, geosynthetics are highly persistent in the environment, exhibiting limited recyclability due to contamination and heterogeneous polymer composition. The majority of geosynthetic wastes are landfilled or incinerated, releasing additional greenhouse gases and potentially toxic by-products. This persistence raises concerns about microplastic generation and long-term ecological effects, issues widely discussed in recent works (Zhu et al., 2025; Tao et al., 2025). Hence, from both environmental and ecological standpoints, coir geotextiles offer a more sustainable and circular alternative, minimizing post-use burdens.

Transportation and material sourcing contribute marginally to the overall impacts in both systems, though the relative burden is somewhat higher for geosynthetics due to the globalized petrochemical supply chain. In contrast, coir fibers are often sourced and processed locally in tropical regions, reducing transportation emissions and supporting local employment. Additionally, because coir geotextiles are less energy-intensive, the associated emissions per functional unit remain considerably lower even when considering extended durability treatments such as bitumen or natural resin coatings.

Beyond carbon and resource considerations, coir geotextiles also perform favorably in terms of toxicity-related and ecosystem impact categories. The absence of synthetic additives, stabilizers, and plasticizers reduces emissions of carcinogenic and non-carcinogenic substances during both production and degradation. Furthermore, their biodegradability ensures that no long-lasting residues or microplastic particles are introduced into the environment. In contrast, geosynthetics, due to their polymeric nature and processing chemicals, contribute substantially to toxicity and particulate emissions throughout their life cycle. These findings align with previous research highlighting the environmental advantages of natural fibers over synthetic polymers (Ribeiro et al., 2025; Satchanska et al., 2024), which confirms that natural fiber-based composites are less harmful to ecosystems and human health.

When the overall life cycle is viewed holistically, coir geotextiles clearly emerge as the more sustainable option for applications in erosion control, soil stabilization, and slope protection. They embody the core principles of sustainable material selection—renewability, biodegradability, low embodied energy, and end-of-life compatibility with natural systems. Moreover, they contribute to several Sustainable Development Goals (SDGs). This multi-dimensional sustainability benefit positions coir geotextiles as a strong candidate for replacing synthetic counterparts in a range of civil and environmental engineering applications.

And, the comparative assessment demonstrates that coir geotextiles significantly outperform geosynthetics in terms of life cycle sustainability. Their production leverages renewable agricultural residues, requires lower energy inputs, and generates fewer emissions, making them a superior alternative in most environmental impact categories. The findings corroborate the growing body of literature advocating for the transition from fossil-based materials to bio-based alternatives to achieve circularity and carbon neutrality in the construction and geotechnical sectors. By integrating local resource utilization, sustainable processing, and biodegradable material design, coir geotextiles not only minimize environmental burdens but also promote socioeconomic resilience and alignment with global sustainability agendas. As global industries seek to decarbonize and adopt greener materials, coir-based geotextiles exemplify how traditional, nature-based solutions can

effectively replace synthetic materials while maintaining functional performance and advancing multiple SDGs simultaneously.

4. Implications

The findings of this study present important implications for practitioners and policymakers working at the intersection of sustainable materials, rural development, and climate-resilient infrastructure. Coir geotextiles, derived from coconut husk, a renewable and biodegradable resource, are increasingly promoted as eco-friendly alternatives to synthetic geotextiles. However, this study demonstrates that their actual environmental sustainability is strongly dependent on regional factors, particularly the source of electricity used in processing and the agricultural practices associated with coconut cultivation.

LCIA reveals that the manufacturing stage is the principal hotspot across all three countries analyzed, with energy consumption, especially from fossil fuels, being the major contributor to environmental impacts. Among the countries studied, India records the highest impact during the manufacturing phase due to its coal-dominated electricity grid. Indonesia shows the highest overall life cycle impact, largely because of resource-intensive coconut farming practices. In contrast, the Philippines demonstrates a more balanced profile due to the higher share of renewables in its national electricity mix. Additionally, scenario analysis confirms that replacing conventional grid electricity with renewable sources such as hydro, solar, or wind could lead to a significant reduction in climate-related impacts, especially in the manufacturing phase.

For policymakers, these results emphasize the importance of aligning regional energy and agricultural strategies with material sustainability goals. Incentivizing the use of renewable energy in decentralized coir processing units, through financial subsidies, tax exemptions, or rural electrification programs, can drastically reduce the product's carbon footprint. Introducing green public procurement policies that prioritize low-impact, certified coir geotextiles for public infrastructure works such as road stabilization, erosion control, and slope reinforcement could further enhance demand for environmentally responsible products.

Practitioners, including coir product manufacturers and infrastructure developers, can play a direct role in improving environmental performance by adopting energy-efficient equipment, reducing process energy intensity, and sourcing electricity from cleaner alternatives wherever possible. In agricultural regions, promoting sustainable coconut cultivation practices, such as intercropping, efficient water use, and agroforestry, can reduce upstream impacts and contribute to more circular, low-emission value chains. These interventions are particularly important in regions where coir production is linked to the livelihoods of smallholder farmers and micro-enterprises, providing an opportunity to couple environmental gains with socio-economic benefits.

At a global level, the study supports the inclusion of natural fiber-based geotextiles like coir in international efforts toward low-carbon and circular infrastructure materials. In countries where synthetic alternatives contribute to long-term plastic pollution and landfill burden, coir geotextiles present an attractive, locally sourced solution. Development agencies and climate finance institutions can support their adoption through pilot programs, inclusion in climate-resilient infrastructure portfolios, and integration into sustainable public works policies. Furthermore, the creation of product-level environmental declarations and lifecycle transparency tools can enable better market access and informed material selection in both domestic and export markets.

5. Conclusion

The LCA study demonstrates that coir geotextiles provide a sustainable alternative to synthetic geotextiles, achieving a 34%–40% reduction in GW and lower toxicity impacts across their cradle-to-grave life cycle. The manufacturing phase, particularly weaving, emerges as the dominant environmental hotspot, contributing approximately 75% of the total GW due to reliance on fossil fuel-based electricity. However, scenario analysis reveals that integrating renewable energy sources, such as hydropower, can reduce overall life cycle impacts by up to 50%, with manufacturing burdens decreasing significantly. In contrast, the end-of-life phase favors coir geotextiles, as their biodegradability eliminates disposal-related energy demands and emissions, unlike synthetic alternatives that incur higher GW from landfilling (methane emissions under anaerobic conditions).

Comparatively, coir geotextiles outperform synthetic geotextiles in raw material and EoL stages, leveraging renewable biomass from coconut husks and avoiding energy-intensive disposal processes. While synthetic geotextiles benefit from optimized manufacturing, coir's environmental advantages in GW and waste reduction highlight its potential. The study also shows that transportation impacts remain negligible, even with domestic sourcing, reinforcing coir's low-impact profile. The use phase, assumed neutral for both materials, does not alter this comparison.

These findings position coir geotextiles as a key material for sustainable infrastructure, aligning with SDGs #7 (affordable and clean energy), #9 (industry, innovation, and infrastructure), #12 (responsible consumption and production), and #13 (climate action). For instance, adopting coir geotextiles in erosion control and slope stabilization projects could reduce environmental burdens equivalent to avoiding significant synthetic waste streams. By integrating renewable energy and capitalizing on coir's natural properties, infrastructure applications can achieve both technical efficacy and substantial sustainability gains, supporting global efforts toward low-impact development.

Additionally, geographical variation scenario analysis reveals significant regional variations in environmental impacts. Indonesia exhibits the highest life cycle impacts, driven by resource-intensive coconut cultivation practices with large land and water demands, contributing to elevated greenhouse gas emissions. India's impacts are dominated by the manufacturing phase, where reliance on coal-heavy electricity grids increases the carbon footprint, particularly during energy-intensive processes like weaving. In contrast, the Philippines demonstrates a more balanced profile, benefiting from a higher share of renewable energy sources, such as geothermal and hydro, which reduce manufacturing-related emissions. These regional differences illustrate the need for context-specific interventions, such as promoting sustainable farming practices in Indonesia and increasing renewable energy adoption in India, to enhance the overall sustainability of coir geotextile production across diverse geographical contexts.

6. Limitations and future research

The data pertaining to each life cycle stage were collected specifically from Asian countries. As a result, the outcomes may not be directly transferable to other regions with differing environmental conditions, energy sources, and raw material availability. Additionally, geotextile manufacturing processes in advanced economies may differ significantly due to the use of more sophisticated machinery and technologies. Therefore, similar studies conducted across diverse geographical contexts are essential to develop a comprehensive understanding and identify opportunities for process optimization.

Future research should also investigate the integration of hybrid energy systems and improved material recovery methods to enhance the sustainability of coir geotextile production in line with global sustainability targets. Moreover, expanding the scope to include social and economic dimensions would offer a more holistic assessment of coir geotextile sustainability, thereby supporting stakeholders in making informed decisions and boosting public acceptance and market potential of these eco-friendly materials.

CRediT authorship contribution statement

Krishnashree Achuthan: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Vysakh Kani Kolil:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **S.U. Parvathy:** Writing – original draft, Investigation. **Narayanan R. Nambiar:** Visualization, Methodology, Investigation. **Vivek Prasad Shaw:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147879.

Data availability

Data will be made available on request.

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