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A comprehensive life cycle assessment of sisal yarn production: Unveiling sustainability and resource optimization hotspots

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ABSTRACT

This study presents a comprehensive life cycle assessment (LCA) of sisal yarn production, covering key phases such as cultivation, transportation, decortication, brushing, baling, and yarn making to assess the environmental impacts associated with the production of 1 kg of sisal yarn. The results show that cultivation contributes the most to global warming potential (7.29 kg CO_2 eq, ≈51% of total emissions) and terrestrial ecotoxicity (112.02 kg 14-DCB eq, 97.7%), driven largely by the excessive use of pesticides, herbicides, and fertilizers. Decortication contributes significantly to marine eutrophication (83.7% of total impacts) and global warming (5.52 kg CO_2 eq, ≈40%). Although yarn making accounts for a smaller share of the global warming potential (0.97 kg CO_2 eq, 6.8%), it has a notable impact on human toxicity (contributing 21.7% to non-carcinogenic toxicity) and fossil fuel depletion (305.8 g oil eq, 10% of the total). A sensitivity analysis indicates that reducing chemical inputs, improving energy efficiency, and optimizing water use can reduce environmental impacts by up to 30%, lowering global warming potential to 11.59 kg CO_2 eq in the improvement scenario. These results align with Sustainable Development Goals (SDGs) on responsible production (SDG 12), climate action (SDG 13), and life on land (SDG 15), positioning sisal yarn as a sustainable alternative to synthetic fibers. Future research should focus on incorporating renewable energy, expanding region-specific LCA inventories, and exploring social and economic sustainability to further enhance the sisal value chain's sustainability.

1. Introduction

Natural fibers like sisal yarn, derived from the sisal plant (*Agave sisalana*), have gained prominence for their versatility and eco-friendly attributes (Thyavihalli Girijappa et al., 2019; Bhoj, 2022). Known for durability, strength, and biodegradability, sisal yarn is widely used in carpets, ropes, and textiles (Saxena et al., 2011; Dhaliwal, 2019).

Tanzania, a key global producer, accounted for 20% of global sisal production in 2022, with the Tanga region contributing 60% of the output at 3.2 tons per hectare (Kabissa et al., 2022; Nylander, 2024). The local industry's value addition is driven by spinning mills that transform raw sisal fibers into high-quality yarn for diverse applications (Mufuruki et al.; Song et al., 2019).

Previous Life Cycle Assessment (LCA) studies have been conducted to evaluate the environmental impacts associated with sisal fiber production (Broeren et al., 2017b; dos Santos et al., 2022; Ramesh et al., 2022). These studies typically focused on specific stages of the sisal fiber life cycle, such as cultivation and processing. While they provided valuable insights into the environmental performance of sisal fiber production, their scope did not extend to the entire value chain of sisal yarn production.

For instance, a study by Colley et al. (2021) examined the environmental impacts of sisal cultivation, highlighting the resource requirements and emissions associated with agricultural practices, and their circular economic opportunities. Similarly, Abdalla et al. (2023) reported that the energy consumption and waste generation associated with the processing stages of production are key drivers of environmental impact of natural fibers including sisal fibers. However, these studies lack focus on the ecological footprint of sisal yarn production, particularly the processing stage where fibers are spun into yarn.

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Comparative LCA studies have also been conducted on other natural fibers such as cotton, jute, and bamboo (Quintana et al., 2018; Peças et al., 2019; Ramesh et al., 2022). These studies revealed that while natural fibers generally have lower environmental impacts than their synthetic counterparts, they still pose challenges in terms of resource consumption, land use, and emissions.

Natural fibers including jute, flax, and hemp fibers have revealed varying environmental performance in terms of global warming and water consumption impacts across the production lifecycles. Singh et al. (2018), Seile et al. (2022), Kar and Singh (2023) report that Jute, flax, and hemp fiber production have been associated with a global warming potential (GWP) of 0.68, 0.53, and 0.78 kg CO_2-eq per kg of fiber, and water use of 0.255 m^3/kg, 3.3 m^3/kg, and 1.7 m^3/kg, respectively. Compared to sisal fiber, these natural fibers generally show lower environmental impacts, but the processing stages remain significant hotspots across the production cycles.

Furthermore, LCA studies on synthetic fibers including carbon fibers (Zhang et al., 2024) indicated that the spinning stage of carbon fiber production was on average associated with 52% of the total greenhouse gases, and contribute significantly to terrestrial ecotoxicity, photochemical ozone formation, and fossil fuels depletion. Likewise, the production of nylon fibers is associated with huge CO_2-eq compared to polyester and acrylic fibers (Ranabhat, 2019; Gustafsson Engström et al., 2019; Soares, 2023).

Despite the insights gained from previous studies involving the LCA of natural and synthetic fibers, there remains a gap in the literature regarding the comprehensive assessment of sisal yarn production (Colley et al., 2021; Haigh, 2023). Insufficient focus on the sisal yarn processing stage in prior LCA studies may have led to an underestimation of its overall environmental impact (Bachmann et al., 2017). To inform sustainable decision-making processes, it is imperative to conduct a thorough assessment of materials like sisal yarn, given the growing demand for sustainable fibers in advanced applications such as composite manufacturing, concrete reinforcement, and automotive components (Ahmad et al., 2022; Carvalho et al., 2024).

The Tanga region of Tanzania, a major center for sisal cultivation and processing, provides primary data for the present study's analysis of sisal yarn production. A cradle to gate life cycle assessment (LCA) is employed to examine the environmental effects of sisal yarn production, from cultivation to manufacturing, focusing on two primary objectives: (1) to determine the environmental impact of each phase of production, and (2) to highlight important environmental concern areas for future sustainability improvements. The results are intended to fill knowledge gaps in sustainable fiber production and assist producers, consumers, and legislators in improving the sustainability of the sisal yarn value chain.

2. Materials and methods

This study utilizes the life cycle assessment (LCA) methodology, standardized in ISO 14040/14044 (Technical Committee ISO/T.C. 207, Environmental Management, 2006).

2.1. Goal, scope definition, and functional unit

2.1.1. Goal

In light of the glowing demand for natural fibers in automotive and high-end industrial applications (Agarwal et al., 2020), the main objective of the present life cycle assessment (LCA) is to estimate the environmental impacts of producing one kilogram of sisal yarn, that is based on high quality sisal fibers produced in Tanga region, Tanzania (Fednand et al., 2022). The analysis determines which phases of the production process: cultivation, transportation, decortication, brushing and baling, and yarn making, have the greatest environmental impact. The findings are intended to improve approaches for mitigating negative environmental effects, optimizing resource utilization, and augmenting sustainability in the sisal yarn manufacturing process. Furthermore, the purpose of the present LCA is to help inform prospective consumers about the sustainability benefits of sisal yarn, with a focus on the building and automotive sectors. The goal is to position sisal yarn as a sustainable substitute for synthetic fibers. Producers, legislators, and sustainability experts will benefit from the findings as they optimize production process and encourage the usage of sisal yarn in environmentally conscious industries.

2.1.2. Scope

This Life Cycle Assessment (LCA) encompasses the entire life cycle of sisal yarn production, from the growth of sisal plants to the end yarn making process. The phases that make up the boundaries of the system are the following: cultivation, in which sisal plants are grown and harvested; transport and logistics, which include sisal leaves being transported to processing factories and baled fibers being transported to the spinning factory; decortication, in which fibers are extracted from the leaves; brushing and baling, in which fibers are cleaned, bundled, and sun-dried for additional processing; and, lastly, yarn making, in which the fibers are spun into yarn or sisal bobbins. The system boundary used to generate data for the life cycle inventory (LCI) is shown in Fig. 1. The sisal fiber grade used for yarn manufacturing is 3 ft (3L) long, harvested from sisal plants with average plant age of 9 years. This fiber grade exhibits exceptional properties such as higher strength and modulus, high durability, recyclability with lower maintenance, wear, and tear (Abouzeid et al., 2018; Fednand et al., 2022).

2.1.3. Functional unit

One kilogram of sisal yarn packed at the gates of spinning factory is used as the functional unit in the present study. The evaluation of environmental consequences encompasses various categories, such as the global warming potential, ozone depletion, terrestrial ecotoxicity, eutrophication, resource consumption, and land usage. Primary data were collected on-site using a structured questionnaire covering all unit processes, while secondary data were sourced from Ecoinvent3 using the Allocation by Cut-off Unit method. Data processing was conducted using SimaPro v1.09 software, incorporating its built-in functions. To achieve a thorough assessment of the environmental effects related to the manufacturing of sisal yarn, life cycle inventories were modeled and impact estimates were performed using the World 2010 weighting technique and the midpoint indicators of the ReCiPe 2016 approach included into SimaPro software. In contrast to more general endpoint indicators, midpoint indicators reduce uncertainty by focusing on particular environmental impacts and provide comprehensive, dependable, and actionable insights. They are also perfect for focused environmental assessments since they are less arbitrary, support scientific consensus, and aid in pinpointing areas that require improvement.

2.2. Data collection

Primary data for the production of sisal yarn was collected on-site through interviews with sisal estate and factory managers, as well as field observations. This process involved gathering data on the different stages of sisal yarn production, which encompass sisal plant cultivation, harvesting, decortication, cleaning, drying, fiber baling, and yarn spinning. The collected data comprises material resources such as land size, fertilizers, herbicides, and water; energy materials such as diesel, gasoline, and electricity; and transport distances traveled throughout the sisal yarn production lifecycle (see Table 1 and Fig. 1). Furthermore, the study inquired about the wastes generated and their disposal, especially at processing facilities, and supplemented this information with secondary data from ecoinvent libraries.

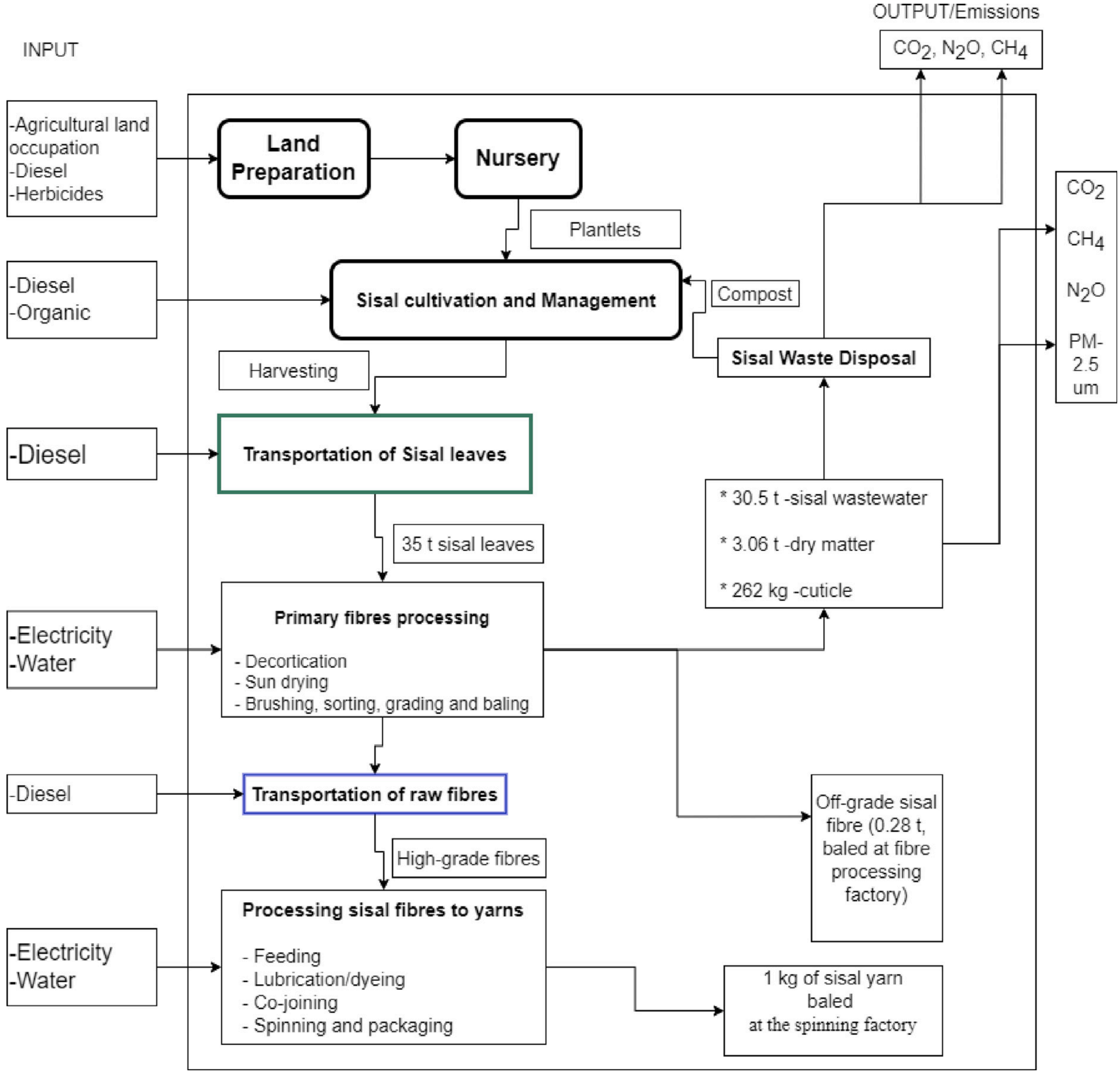

Fig. 1. Cradle-to-gate system boundary of 1 kg of sisal yarn production.
Source: Modified from: Broeren et al. (2017b).

2.2.1. Sisal yarn production process

The production of sisal yarn begins with the cultivation of sisal plants. This process involves clearing the land using a bulldozer, loosening the soil with a tractor-mounted disc harrow, and manually transplanting sisal bulbils to the main field. The studied sisal estate reported an average of 3500 plants per hectare. The sisal farm obtains additional nutrients from sisal compost, which is applied especially during the transplanting stage. Weeding is carried out three times a year during the early growth stage, using both manual labor and chemicals. Subsequent plant management relies solely on manual labor. For this study, the sisal leaves were harvested from plants aged between 8 to 10 years.

Approximately 35 tonnes of sisal leaves were reported to be harvested per hectare and transported by tractor over a road distance of around 15 km to the sisal fiber-processing factory, where the desired fiber grade was obtained for pre-processing involving sun-drying, brushing, sorting and baling. The baled sisal fibers were subsequently transported from the fiber-processing factory located in Korogwe district to the spinning factory in the Tanga City center, covering a distance of approximately 170 kilometres, using a lorry with a capacity of less than 10 tonnes at a 50% loading factor.

On average, the extraction of 35 tonnes of sisal leaves produces approximately 1.4 tonnes (4%) of wet fibers (Terrapon-Pfaff et al., 2012; Nerini et al., 2016). These fibers undergo drying, brushing, grading, and baling processes, generating 1.12 tonnes (80%) of marketable long fiber grades, while the remaining portion is sorted as off-grades (20%) (Essien et al., 2021). The decorticating process, which uses 30 m^3 of freshwater, produces approximately 30.5 tonnes of sisal wastewater (87.25%), 3.06 tonnes of dry matter (8.75%), and 262 kilograms of cuticle (0.75%) (Yhdego and Mng’agi, 2017).

The processing activities in this study utilize electricity from the national grid, both at the raw sisal fiber-processing factory and the yarn-spinning factory. At the spinning factory, raw sisal fibers undergo a series of processing steps, including feeding, lubrication/softening, co-joining, spinning, and spooling, using machinery systems to obtain yarns packed according to buyer specifications.

This study’s environmental impact analysis focuses on 1 kilogram of packed sisal yarn ready for purchase at the gates of a sisal yarn spinning factory. Table 1 reports the primary process-level data used to model the life cycle inventories, with background data extracted from the *ecoinvent3* database and related literature. The life cycle impacts associated with the production of one kilogram of sisal yarn were modeled and analyzed using *Simapro 9.6.0.1*.

Table 1
Sample data used for generating life cycle inventory.
Source: Field data (2024).

Unit Process	Sub-activity	Material/Resource	Input amount	Unit
Cultivation	Land preparation	Diesel – Clearing	100 litres	1 ha
		- Ploughing	100 litres	1 ha
	Nursery preparation	Diesel - Clearing	10 litres	0.1 ha
		- Ploughing	10 litres	0.1 ha
	Transplanting at the main field	Petrol - transport sisal plantlets	7 litres/petrol	1 ha
		Diesel - transport compost/ fertilizer	15 litres/diesel	1 ha
	Weeding: 3 times/ year/ for first 3 years after transplanting	Diesel - hallowing @7 litres/ hallow/ 1st 3 years Herbicides - 4 kg/ha for at least 4 years Water - for herbicide application	21 litres×3 = 63 litres 4 kg×4 = 16 kg 100 litres×4 = 400 litres	1 ha
Harvesting	Harvesting sisal leaves and transporting to primary processing	Diesel - 2 trips @15 litres Distance - 15 kilometres from farm to processing factory. Sisal leaves	15 litres×2 = 30 litres/diesel Distance = 60 kilometres 35 tons	t or km
Sisal fiber Extraction	Decortication Washing	Electricity Water	448 kWh 25,000 litres of water	n/a
Primary Sisal fiber processing	Drying Brushing/ Sorting/ Grading/Baling and labeling	-Sun drying -Electricity -Packaging (Polypropylene water/moisture proof)	24 h daylight 504 kWh/all unit processes 5 kg for bales of 250 kg	n/a
Secondary Sisal fiber processing	Transportation of baled fibers to the Spinning factory	-Diesel; -Distance from primary fiber processing to the Spinning factory	42.5 litres 170 km (to and from)	n/a
	Spinning to obtain yarn	-Electricity -Water for softening dry fibers -Lubricating oil	1539.104 kWh 100 litres/water 10 litres/base oil	

2.3. Life cycle impact assessment methods

The ReCiPe 2016 Midpoint (H) method in SimaPro 9.6.0.1 was utilized in this study to evaluate the environmental effects of sisal yarn production. This offers a thorough assessment of environmental burdens across different production phases when combined with the Ecoinvent3 database and the Allocation by Cut-off method.

2.3.1. Rationale for choosing ReCiPe 2016 midpoint indicators

ReCiPe 2016 Midpoint indicators were chosen for their accuracy in measuring particular environmental consequences, including eutrophication, terrestrial acidification, and global warming potential (GWP). These indicators enable a thorough examination of the environmental hotspots associated with the production of sisal yarn, such as the extensive use of pesticides and fertilizers during cultivation and the high energy requirements associated with yarn creation and decortication. According to studies by Zampori et al. (2019), midpoint indicators are chosen in life cycle assessments (LCAs) involving agricultural goods because they reduce uncertainty.

Studies on natural fibers, such those by Broeren et al. (2017a) and Pereira et al. (2019), which looked at the effects of sisal fiber production on the environment in Tanzania and Brazil, have used ReCiPe 2016 Midpoint. These studies validate the usefulness of midpoint indicators in identifying substantial impacts such as eutrophication and GWP. ReCiPe's midpoint categories assist in concentrating on certain improvements for sisal yarn, such lowering chemical inputs in agriculture or maximizing energy use during processing.

2.3.2. Use of Ecoinvent3 database and allocation by cut-off

Because of its vast and legitimate data on industrial and agricultural activities, the Ecoinvent3 database was used for modeling life cycle inventories (LCI). According to studies on sisal by Broeren et al. (2017a) and Colley et al. (2021), ecoinvent3 is a resource that is frequently utilized in LCAs for fiber production. For precise input modeling across the production phases, including water, energy, and chemicals, these studies recommend the use of such database.

To ensure a just allocation of environmental burden between sisal yarn and its byproducts, like waste fibers, the Allocation by Cut-off, Unit approach was employed. In natural fiber LCAs, this method is frequently used to prevent overestimating the primary product's environmental impact. The efficacy of this approach in sisal production is demonstrated by studies conducted by Broeren et al. (2017a) and Pereira et al. (2019). Co-products such as fiber waste have the potential to be highly reused in bioenergy or other uses.

3. Results and discussion

This section presents the findings from the life cycle impact assessment (LCIA) of sisal yarn production, highlighting both quantitative and qualitative environmental impacts across various production phases. The results focus on key impact categories such as global warming potential, ozone depletion, terrestrial and marine ecotoxicity, resource consumption, and water usage. Each phase of the sisal yarn production process from cultivation through transport, decortication, brushing, baling, and yarn making, was assessed to determine its contribution to the overall environmental burden. These findings provide insights into the most environmentally significant phases and suggest targeted interventions for improving sustainability. The results are analyzed in the context of sensitivity scenarios aimed at reducing environmental impacts by improving energy efficiency, minimizing chemical inputs, and reducing water consumption. The discussion links these findings to global sustainability objectives, particularly the Sustainable Development Goals (SDGs), highlighting the importance of optimizing sisal yarn production for enhanced environmental performance.

3.1. Environmental impacts across production phases

The production of sisal yarn in this study involved several phases including sisal cultivation and harvesting, leaf decortication, sisal fiber brushing and baling, transport logistics, and yarn-making. Each of these phases contributed differently to the key environmental categories, such as global warming, ecotoxicity (both terrestrial and marine), land use, and water consumption. Table 2 displays quantitative environmental impact values of several categories across production phases of 1 kg of sisal yarn produced, followed by comparative analysis and discussion on their implications for sustainability of sisal yarn production.

Furthermore, Fig. 2 is provided to enhance the analysis and visualization of the proportionate contribution of each impact category across phases of production as discussed below.

Table 2
Total environmental impact of sisal yarn production across production stages.
Source: Compiled by Author from simaPro software and Ms. Excel.

Impact category	Unit	Cultivation	Transport logistics	Decortication	Brushing-baling	Yarn making	Total - Impact
Global warming	kg CO_2 eq	7.2911	0.0507	5.5198	0.4463	0.9656	14.2735
Stratospheric ozone depletion	kg CFC11 eq	0.000002	0.00000	0.00000	0.00000	0.00000	0.000003
Ionizing radiation	kBq Co-60 eq	0.00654	0.000037	0.00005	0.000508	0.000128	0.00726
Ozone formation, Human health	kg NOx eq	0.0391	0.00013	0.000791	0.00088	0.00189	0.04278
Fine particulate matter formation	kg PM2.5 eq	0.008717	0.000053	0.000338	0.000438	0.00087	0.010415
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.040435	0.000168	0.000834	0.000960	0.0020204	0.044418
Terrestrial acidification	kg SO_2 eq	0.019919	0.000147	0.000993	0.0012321	0.002678	0.024969
Freshwater eutrophication	kg P eq	0.000599	0.0000002	0.000115	0.000026	0.000002	0.000742
Marine eutrophication	kg N eq	0.000139	0.000001	0.001676	0.000042	0.000028	0.001887
Terrestrial ecotoxicity	kg 1,4-DCB	112.0246	0.100514	0.4827856	0.738352	1.48	114.8262
Freshwater ecotoxicity	kg 1,4-DCB	0.033874	0.000022	0.00272	0.00117	0.000155	0.03795
Marine ecotoxicity	kg 1,4-DCB	0.086476	0.000111	0.00414	0.00118	0.00127	0.0932
Human carcinogenic	kg 1,4-DCB	0.01093	0.00006	0.01306	0.00048	0.000878	0.02542
Human non-carcinogenic toxicity	kg 1,4-DCB	1.6715	0.00194	0.2693	−0.000492	0.02171	1.964
Land use	m^2a crop eq	0.04258	0.00009	0.01195	0.02762	0.01488	0.0971
Mineral resource scarcity	kg Cu eq	0.00818	0.000016	0.00005	0.00005	0.00002	0.00831
Fossil resource scarcity	kg oil eq	2.431445	0.07263	0.0959	0.1551	0.30578	3.0608
Water consumption	m^3	0.01434	0.000041	0.03125	0.0086	0.02135	0.0756

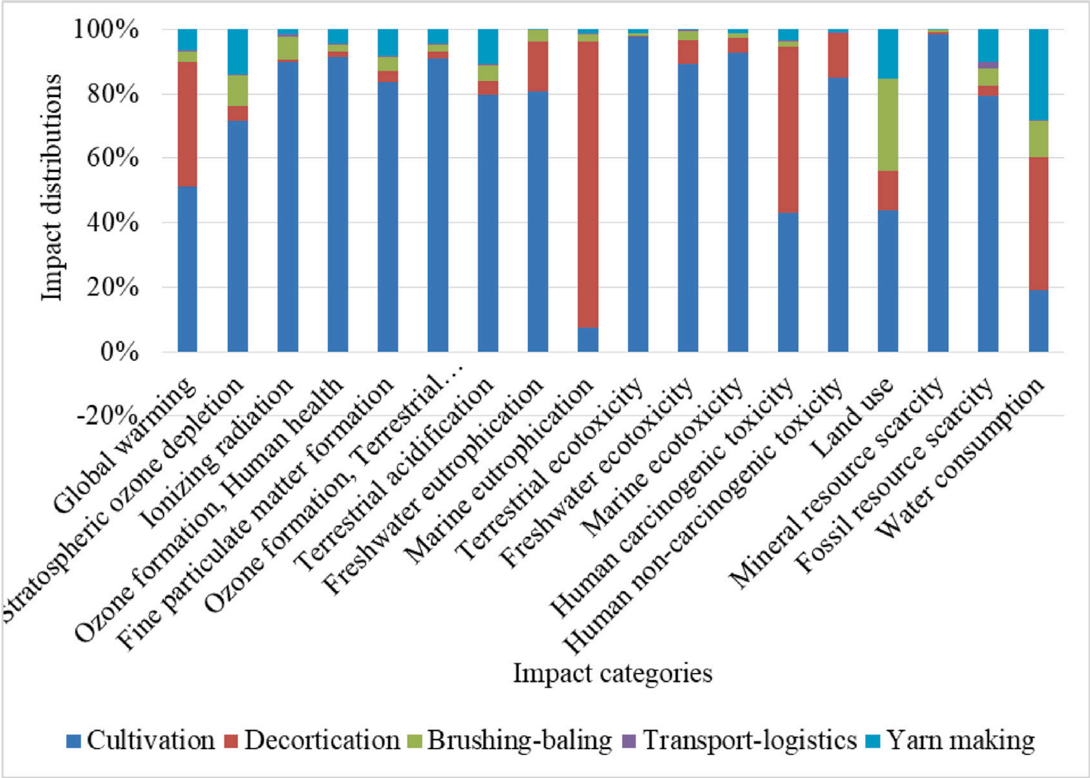

Fig. 2. Proportionate contribution of environmental impacts of 1 kg of sisal yarn production across production stages.
Source: Compiled by author from SimaPro software & Excel.

3.1.1. Global warming potential (kg CO_2 eq)

The cultivation phase is the primary contributor to greenhouse gas emissions, with 7.29 kg CO_2 eq/kg, representing 50.9% of the total 14.27 kg CO_2 eq emissions. Energy-intensive farming practices, including machinery use and fertilizer application, are significant drivers. The decortication phase adds 5.52 kg CO_2 eq (38.9%), mainly due to electricity consumption. Other phases, including transportation (0.05 kg CO_2 eq, 0.4%), brushing and baling (0.45 kg CO_2 eq, 3.1%), and yarn production (0.97 kg CO_2 eq, 6.8%), have comparatively minor contributions.

3.1.2. Ozone depletion (kg CFC11 eq)

The analysis of ozone depletion potential (ODP) measured in kg CFCC11 eq indicates that cultivation phase contributes 0.00000355 kg CFC11 eq, or 81.6% of the total ozone depletion potential of 0.00000435 kg CFC11 eq per kg of sisal yarn. Transport contributes 0.00000001 kg CFC11 eq (0.2%), decortication (0.00000012 kg CFC11 eq, 2.8%), brushing and baling (0.00000027 kg CFC11 eq, 6.2%), and yarn production (0.00000040 kg CFC11 eq, 9.2%), with the remaining phases contributing negligible effects.

3.1.3. Ionizing radiation (kBq Co-60 eq)

For every kilogram of sisal yarn produced, the estimated overall ionizing radiation impact is 0.00547 kBq Co-60 eq, with cultivation accounting for the majority of this impact at 0.00475 kBq (86.8%). The remaining contributions are as follows: yarn manufacturing (0.000129 kBq, 2.3%); brushing and baling (0.000509 kBq, 9.3%); decortication (0.000049 kBq, 0.9%); and transportation (0.000038 kBq, 0.7%).

3.1.4. Ozone formation, human health (kg NOx eq)

Each kilogram of sisal yarn produced, there is a total of 0.0429 kg NOx equivalent that could impact human health due to ozone production. 0.0392 kg NOx eq (91.3%) is attributed to the cultivation phase, indicating a high level of NOx emissions from agricultural practices. For every kilogram of sisal yarn, the following modest contributions are made: transport (0.000131 kg, 0.3%), decortication (0.000790 kg, 1.8%), brushing and baling (0.000884 kg, 2.1%), and yarn manufacturing (0.001889 kg, 4.4%).

3.1.5. Fine particulate matter formation (kg PM2.5 eq)

The sisal cultivation phase contributes 0.00925 kg (84.5%) of the total impact in this category, which is 0.01095 kg PM2.5 equivalent per kg of sisal yarn produced. This suggests that a major contributor to particulate matter emissions is the use of machinery, particularly during land clearance, tillage, and weeding operations during cultivation. Transport (0.000053 kg, 0.5%), decortication (0.000338 kg, 3.1%), brushing and baling (0.000438 kg, 4.0%), and yarn manufacturing (0.000870 kg, 7.9%) are the other phases that contribute less.

3.1.6. Terrestrial ecotoxicity (kg 14-DCB eq)

Terrestrial ecotoxicity potential emerges as an exceptional contribution to the ecological toxicity impact of cultivation phase, with 117.46 kg 14-DCB eq, or 97.7% of the total 120.26 kg 14-DCB eq. This highlights a crucial area for possible improvement, which is mostly caused by the use of pesticides and herbicides during the sisal growing period, especially during nursery and early years of plant growth. Other processes including transport (0.10 kg, 0.1%), decortication (0.48 kg, 0.4%), brushing and baling (0.74 kg, 0.6%), and yarn manufacturing (1.48 kg, 1.2%), contribute relatively little impact on land based ecological damage.

3.1.7. Marine eutrophication (kg n eq)

The decortication phase has been found to contribute nearly 0.00168 kg (83.7%) to the total impact of 0.002 kg N eq per kg of sisal yarn produced. This implies that sisal wastewater and other chemical discharges during the fiber extraction process is a significant pollutant for marine habitats, due to untreated waste disposal. The contributions from other processes contribute much less with brushing and baling (0.000043 kg, 2.1%), transport (0.000001 kg, 0.1%), yarn manufacturing (0.000028 kg, 1.4%), and cultivation (0.000254 kg, 12.7%).

3.1.8. Resource scarcity and water consumption

In terms of fossil resource scarcity (kg oil eq), the total impact is 3.04 kg oil eq per kilogram of sisal yarn produced, with cultivation contributing 2.41 kg (79.3%), showing substantial energy demand during this phase. The spinning fibers to yarns adds 0.31 kg oil equivalent (10.1%), whereas brushing and baling add 0.16 kg oil equivalent (5.1%). At 0.031 m^3 (47.2%) of the total 0.0662 m^3, the decortication phase has the largest water consumption per kg of sisal yarn produced, suggesting that water use, especially for retting sisal leaves and cleaning fibers during this phase is a major contributor to water depletion impact.

3.1.9. Land use

The most significant land use impact associated with sisal yarn production is associated with the brushing and baling processes, accounting for 30.8% and 39.3% of the total land use equivalent per kilogram of sisal yarn produced, respectively. While sisal plants need a large amount of land to be grown for cultivation, handling and processing of the fiber during the brushing and baling stage also requires a large amount of available space. In addition, decortication and yarn processing contribute 13.3% and 16.6%, respectively. This is mostly because of space requirements for operations and facilities. With a sheer value of 0.1%, transportation and logistics have very little effect on land use.

3.2. Comparative life cycle assessments of natural and synthetic fibers

Comparative Life Cycle Assessment (LCA) studies conducted recently have revealed the sustainability potential and environmental concerns associated with the manufacturing of sisal fiber in different nations. According to Tracey et al. (2017), extensive sisal farming practices in Tanzania can deplete up to 25% of soil nutrients, endangering regional ecosystems. Agro-ecological methods and the recycling of sisal waste, with digestate being utilized to replace soil nutrients, were suggested by the researchers as ways to lessen this. Similarly, Broeren et al. (2017a) discovered that energy processing accounted for 35% of greenhouse gas emissions in Tanzania's sisal production, with fertilizer application accounting for almost 60% of the emissions. To lessen their impact on the environment, they stressed the importance of energy efficiency and precision farming.

Making comparisons, Pereira et al. (2019) found that Brazil's usage of precision agriculture resulted in emissions savings of approximately 30% when compared to Tanzania, with fewer greenhouse gas emissions of 1200 kg CO_2e per ton of sisal fiber. The study by Kavita et al. (2020) found that fertilizer application in sisal growing accounts for half of the environmental load, with energy use adding 250 MJ per ton of sisal fibers. The researchers suggested switching to organic methods and using renewable energy sources. Additionally, findings by Santos et al. (2021) in Portugal found transportation as a key contributor to the carbon footprint, accounting for 40% of emissions (400 kg CO_2e per ton), calling for localized processing to reduce overall carbon footprint of sisal value chain.

Furthermore, energy consumption was found to be a major contributing factor in the environmental effect by Owen et al. (2022) and Hernández et al. (2023) from Madagascar and Mexico, respectively. They suggested using cleaner technology and increasing processing energy efficiency.

Taken together, these studies highlight prevalent sustainability issues in the sisal industry, namely related to energy consumption, fertilizer handling, and transportation. However, they also provide solutions such as precision farming, waste management, and the incorporation of renewable energy sources to mitigate environmental effects.

In contrast, LCA studies of jute, flax, and hemp fibers have revealed varying environmental performance. Jute, flax, and hemp fiber production have respectively been reported to have a global warming potential (GWP) of 0.68, 0.53, and 0.78 kg CO_2-eq per kg of fiber, and water use of 0.255 m3/kg, 3.3 m^3/kg, and 1.7 m^3/kg, respectively (Korol et al., 2020; Jha, 2021; Shuvo, 2020). Compared to sisal, these natural fibers generally show lower environmental impacts, but the processing stages remain significant hotspots across the production cycles.

On the other hand, the findings reported by Zhang et al. (2024) indicated that the spinning stage of carbon fiber production was on average associated with 52% of the total greenhouse gases, 20.24 kg oil equivalent of fossil fuels depletion, 67.79 kg CO_2equivalent of carbon dioxide emissions, 165.63 kg 1.4-DCB equivalent of terrestrial ecotoxicity potential, and 0.14 kg NOx equivalent of photochemical ozone formation. Moreover, synthetic fibers such as polyester, nylon, and acrylic have been found to generate high environmental impact compared to natural fibers consistently. On average, polyester fiber production has a global warming potential (GWP) of 6.8 kg CO_2-eq/kg, while the nylon and acrylic fibers are reported at 11.8 kg CO_2-eq/kg and 5.8 kg CO_2-eq/kg, respectively (Nixon-Pearson et al., 2022; Bocquet et al., 2022).

In comparing the present LCA with other natural and synthetic fibers, a number of significant distinctions and similarities emerges. In terms of quantitative comparison, sisal yarn has a larger global warming potential (GWP) of 14.27 kg CO_2 eq/kg than other natural fibers like jute, flax, and hemp (0.53–0.78 kg CO_2 eq/kg). However, sisal yarn performs better than synthetic fibers such as polyester, nylon, and acrylic, whose GWP ranges from 5.8 to 11.8 kg CO_2 eq/kg. In contrast,

Table 3
Adjusted Input Amounts for 10% and 30% Improvement Scenarios.
Source: Author's assumptions and calculations.

Production Phase	Inputs	Amount (Adjusted for 1 kg of sisal yarn)	Adjusted Input Amounts	
			With 10% Improvement	With 30% Improvement
Cultivation	Diesel	0.24108 kg	0.21697 kg	0.16876 kg
	Petrol	0.0237 kg	0.02133 kg	0.01659 kg
	Herbicides	0.0498 kg	0.04482 kg	0.03486 kg
	Water	0.001245 m^3	0.0011205 m^3	0.0008715 m^3
	Organic compost	27.5 kg	24.75 kg	19.25 kg
	Lubricant oil	0.00044 kg	0.00039 kg	0.00031 kg
Decortication	Water	0.025 m^3	0.0225 m^3	0.0175 m^3
	Lubricant oil	0.000022 kg	0.000019 kg	0.000015 kg
	Electricity	0.448 kWh	0.4032 kWh	0.3136 kWh
Brushing-baling	Electricity	0.504 kWh	0.4536 kWh	0.3538 kWh
	Packaging film	0.02 kg	0.018 kg	0.014 kg
Yarn Making	Lubricant oil	0.000077 kg	0.000069 kg	0.000054 kg
	Electricity	1.5391 kWh	1.3852 kWh	1.0774 kWh
	Lubricant oil	0.000082 kg	0.000074 kg	0.000057 kg
Transport-logistics	Diesel	0.0609 kg	0.05481 kg	0.0426 kg
	Lubricant oil	0.000114 kg	0.000103 kg	0.00008 kg

the spinning phase of sisal yarn contributes significantly less to the total environmental impact than carbon fiber production's spinning phase, with about 67.79 kg CO_2 equivalent (≈52%) of total carbon dioxide emissions, 20.24 kg oil equivalent of fossil fuel depletion, 165.63 kg 1.4-DCB equivalent of terrestrial ecotoxicity potential, and 0.14 kg NOx equivalent of photochemical ozone formation.

Nonetheless, sisal yarn production uses less water (0.0756 m^3/kg) than hemp and flax, making it a better option for areas with limited water resources. The high terrestrial ecotoxicity of sisal yarn (112.02 kg 14-DCB eq/kg) is a noteworthy environmental burden that is primarily caused by the application of pesticides and herbicides during early stages of sisal cultivation, which is higher than that of other natural fibers.

Sisal yarn, on the other hand, has a far lower fossil fuel depletion (305.8 g oil equivalent/kg) than synthetic fibers, which mostly rely on petroleum-based inputs. Although the eutrophication method is different, sisal yarn qualitatively shares issues about marine eutrophication with other natural fibers. Furthermore, compared to synthetic fibers, the effects of sisal yarn on human toxicity are moderate, with potential reductions possible through advancements in the yarn-making process.

Generally, sisal yarn has a more environmentally friendly profile than synthetic fibers, but to bring its effects more in line with other natural fibers, focused optimization in cultivation and energy use is required.

3.3. Sensitivity and uncertainty analysis

Major impact categories that represent environmental hotspots were identified through the analysis of Life Cycle Assessment (LCA) findings. These include the potential for global warming, the impact of ozone formation on human health, terrestrial acidification, terrestrial and marine ecotoxicity, human non-carcinogenic toxicity, scarcity of fossil resources, and water consumption. A sensitivity and uncertainty analysis were carried out to investigate these environmental hotspots in more detail using three scenarios intended to lessen these harms. In the first scenario, less chemical herbicides are assumed while better agronomic techniques are adopted during sisal cultivation. The second scenario aimed to increase energy efficiency in every stage of the industrial process. Finally, the third scenario targeted to minimize the amount of water used during both the decortication and cultivation stages.

A range of 10%–30% improvements in input materials was envisaged for each of these scenarios throughout the entire production phases as shown in Table 3.

The recalculation of environmental impacts using the ReCiPe 2016 Midpoint calculation method, the World 2010 weighting method, and the Ecoinvent3-Allocation-Unit database was made possible by the incorporation of these revisions into the inventory reconstruction process. The Fig. 3 compares the total environmental impacts of producing 1 kg of sisal yarn across different scenarios: Baseline, 10% Improvement, and 30% Improvement. The results reveal that the baseline scenario has the highest environmental impacts across all categories, with terrestrial ecotoxicity dominating due to resource-intensive practices in cultivation and decortication. Improvements of 10% and 30% significantly reduce these impacts, particularly in categories like global warming and terrestrial ecotoxicity, showcasing the potential benefits of optimization strategies. However, categories such as water consumption and marine ecotoxicity show only marginal reductions, indicating areas where further interventions are necessary. The findings emphasize the importance of targeting resource efficiency and waste management for sustainable sisal yarn production.

3.3.1. Quantitative impact reduction (10% and 30% scenarios)

1. *Global Warming Potential:*
   In the baseline scenario, global warming potential was approximately 14.27 kg CO_2 equivalent per kg of sisal yarn. With a 10% improvement scenario, this decreased by 6.3% to 13.38 kg CO_2 equivalent, while in the 30% scenario, it dropped by 18.8% to 11.59 kg CO_2 eq. The greatest reductions occurred during the cultivation phase, indicating that this phase has the most significant potential for reducing emissions.
2. *Ozone Formation Impact on Human Health:*
   A significant decrease in the environmental impacts was also observed in the ozone formation impact on human health, where the baseline value was 0.0428 kg NOx eq. The 10% improvement scenario resulted in a reduction to 0.0386 kg NOx equivalent, a decrease of approximately 9.7%, while the 30% scenario showed a more substantial drop of 29.8% to 0.0301 kg NOx equivalent.
3. *Terrestrial Acidification:*
   The baseline value of 0.0243 kg SO_2 equivalent was reduced to 0.0225 kg SO_2 eq. (by 7.4%) in the 10% scenario, and to 0.0176 kg SO_2 eq. (by 27.6%) in the 30% scenario. These reductions highlight significant potential improvements in reducing acidification damages, especially with greater input reductions.
4. *Terrestrial Ecotoxicity:*
   Terrestrial ecotoxicity was the impact category with the highest absolute values. The impact was 114.83 kg 14-DCB eq in the baseline scenario. With the 10% improvement scenario, this

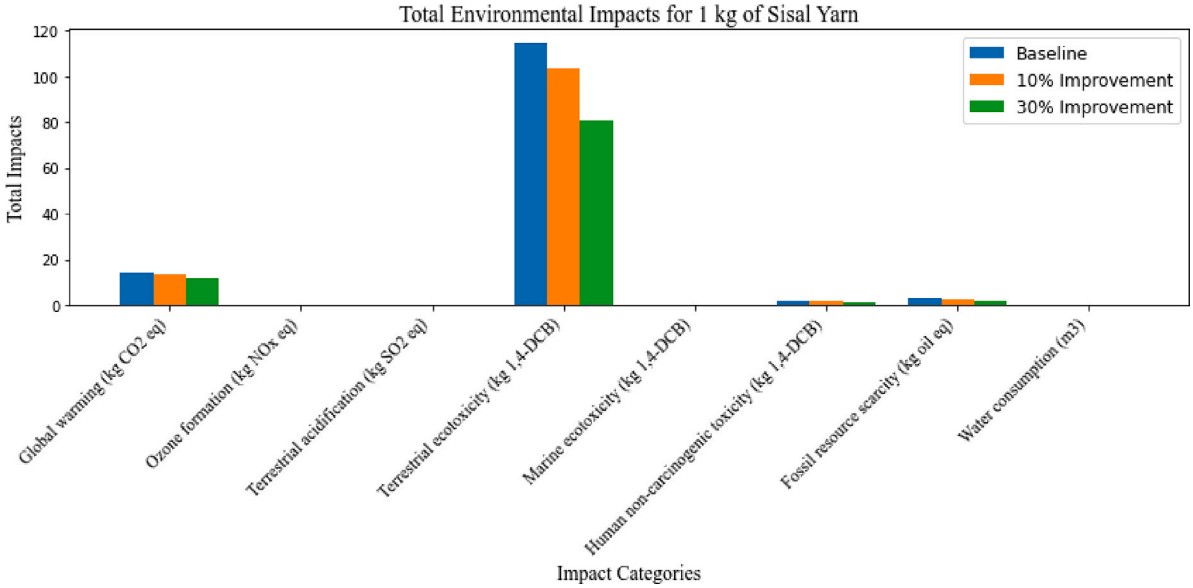

Fig. 3. Illustration of sensitivity analysis results on the environmental impact of 1 kg of sisal yarn based on 10% and 30% improvement scenarios. *Source:* Compiled by author from Python software.

impact decreased to 103.37 kg 14-DCB eq., and in the 30% improvement scenario, it decreased to 80.46 kg 14-DCB eq. Even though this impact was the highest, it also experienced the greatest improvements, especially in the cultivation stage.

5. *Marine Ecotoxicity:*
   The baseline value for marine ecotoxicity was comparatively low at 0.0932 kg 14-DCB eq., the 10% scenario reduced it by 9.5% to 0.0843 kg 14-DCB equivalent, and the 30% scenario reduced it even more, by 28.6%, to 0.0666 kg 14-DCB equivalent.
6. *Human Non-Carcinogenic Toxicity:*
   The impact was first 1.96 kg 14-DCB eq in the baseline; in the 10% and 30% scenarios, it decreased to 1.79 kg 14-DCB eq (an 8.7% reduction) and 1.45 kg 14-DCB eq (a 26% reduction). This shows that the improvement scenarios have notable savings mostly to the energy usage throughout the yarn-making operations.
7. *Fossil Resource Scarcity:*
   A baseline value of 3.06 kg oil eq was observed. In the 10% scenario, the impact decreased by 9.9% to 2.76 kg oil eq, and by 29.8% in the 30% scenario, reaching 2.15 kg oil eq. This showcases the potential benefits of improving energy efficiency in the production process.
8. *Water Consumption:*
   Water consumption impact in the baseline scenario was at 0.0755 m^3. The 10% reduction scenario reduced it by 9.8% to 0.0681 m^3, and the 30% scenario showed a further 29.7% reduction to 0.0531 m^3. Improvements water consumption are especially beneficial to the decortication phase, which requires a lot of water in fiber extraction.

3.3.2. *Qualitative analysis of impact changes*

1. *Energy Efficiency and Water Reduction:*
   Impact areas like water usage, land ecotoxicity, and global warming potential showed the highest reductions. These findings suggest that improving energy use efficiency in all stages of production, particularly during decortication and cultivation, might have a significant positive impact on the sustainability of the sisal yarn production. The efficiency improvements from lower energy use are reflected in the lower numbers of scarcity for fossil resources, while lower energy consumption in the yarn-making process is linked to lower levels of human toxicity.
2. *Agricultural Practices:*
   The scenarios for improvement emphasize how crucial it is to optimize farming methods. Lowering chemical inputs throughout the cultivation stage can greatly lessen environmental damages in acidification, global warming, and terrestrial ecotoxicity impact categories. This implies that enhancing the total environmental performance of sisal yarn production requires a focus on sustainable farming practices.
3. *Production Phase Focus:*
   The notable finding is that, in every scenario, the cultivation phase produced the greatest percentage of impacts. Therefore, while enhancements in every production phase are advantageous, focusing on the cultivation process yields the greatest results, particularly through improvement in agronomic practices.
   In conclusion, the sensitivity analysis reveals that strategic interventions aimed at reducing chemical use, increasing energy efficiency, and optimizing water use can mitigate the environmental effects of sisal yarn production by up to 30%, especially in high-impact categories like terrestrial ecotoxicity, global warming, and the depletion of fossil fuel resources. To produce sisal yarn in a more sustainable manner, resource-efficient production stages and sustainable farming practices must be given top priority.

3.4. *Interpretation and implications*

The analysis of the findings of sisal yarn production life cycle assessment (LCA) reveals that the cultivation and decortication processes have the greatest overall influence on the environment, especially to the global warming potential, terrestrial ecotoxicity, and scarcity of fossil fuels impacts. Due to energy-intensive agricultural practices, cultivation accounts for more than 50% of the entire impact of global warming, highlighting the need for more sustainable farming methods. Similarly, the necessity for energy and water efficiency improvements in fiber extraction operations is demonstrated by decortication, which contributes significantly to water consumption and roughly 40% of CO_2 emissions.

Improved organic fertilizer application, reduced use of pesticides and herbicides during sisal growing can have a major positive influence on reducing acidification and terrestrial ecotoxicity. Given the significant contribution of synthetic chemical use in farming operations, switching to organic or low-impact alternatives might significantly lessen environmental damage, particularly while sisal plants are still in their early stages of growth.

Energy use is a major contributor to the potential for global warming and the depletion of fossil fuels during the decortication phase. The environmental impact of this stage could be lessened by putting energy-efficient technologies into place, such as water recycling systems and renewable energy sources. The production process's carbon footprint may be further reduced by innovations like the use of solar energy in processing facilities or the production of biogas from sisal waste.

Even if the brushing-baling and yarn-making stages have a smaller total environmental impact, there is still room for improvement. Reducing the amount of land space used for brushing and baling, and water usage as well as improving energy efficiency in the spinning phase of yarn manufacturing, could further minimize the negative environmental impacts.

The results highlight how crucial energy-efficient technologies and sustainable farming methods are to lowering the environmental impact of sisal yarn manufacturing. Producers may greatly reduce the detrimental effects on climate, ecosystems, and resource consumption by addressing the most important stages: cultivation and decortication. These interventions, together with optimizing land usage and reducing water use, are essential to connecting the production of sisal yarn with global sustainability goals and promoting it as an environmentally friendly replacement for synthetic fibers in the textile and automotive industries.

3.5. Relationship to the sustainable development goals (SDGs)

This study evaluates the environmental effects of sisal yarn manufacturing and finds potential for more sustainable practices throughout the life cycle, which is closely aligned with several of the Sustainable Development Goals (SDGs) of the United Nations. The following SDGs are mostly pertinent:

3.5.1. SDG 12: Responsible consumption and production

Sisal yarn's life cycle assessment (LCA) sheds light on environmental sustainability and resource efficiency, notably with regard to material inputs, energy use, and waste production. The study directly supports SDG 12, which aims to ensure sustainable industrial processes, by identifying the environmental hotspots and suggesting mitigation techniques including lowering chemical inputs and increasing energy efficiency. This promotes circular economy principles by reducing waste and resource depletion.

3.5.2. SDG 13: Climate action

The study's emphasis on global warming potential draws attention to the substantial carbon emissions connected to the production and processing of sisal fiber. Through recommendations for enhanced agricultural practices and energy efficiency, the study supports SDG 13 by lowering greenhouse gas emissions. These results support efforts to mitigate climate change, particularly by promoting the development of environmentally friendly and sustainable agricultural systems.

3.5.3. SDG 6: Clean water and sanitation

SDG 6 is especially related to water use, one of the present study's major environmental concerns. Water efficiency in agricultural and industrial operations is promoted by the sensitivity analysis, which finds chances to cut back on water use throughout both the cultivation and decortication stages. This lowers the hazards associated with water scarcity and advances sustainable water management.

3.5.4. SDG 15: Life on land

This work supports SDG 15, which focuses on safeguarding ecosystems, promoting sustainable land use, and minimizing environmental deterioration, by addressing issues like terrestrial acidification and ecotoxicity. Reducing the use of dangerous agricultural pesticides and implementing the study's recommended modifications to land management techniques will help to protect biodiversity and enhance soil health.

3.6. Contribution to sustainable development

This study contributes significantly to advancing sustainable practices in sisal yarn production by aligning its findings with key Sustainable Development Goals (SDGs). The insights gained are essential for improving the environmental performance of the sisal value chain while laying a foundation for integrating broader sustainability dimensions in future work.

1. **Environmental Sustainability (SDGs 12, 13, and 15)**: The study highlights critical environmental hotspots, particularly in the cultivation and decortication phases, which are linked to high global warming potential, terrestrial ecotoxicity, and resource scarcity. Recommendations for reducing chemical inputs, improving energy efficiency, and optimizing water use directly address SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). Additionally, the focus on sustainable land management practices and reduced pesticide use supports SDG 15 (Life on Land) by protecting ecosystems and biodiversity.
2. **Future Integration of Social and Economic Dimensions (SDGs 8 and 10)**: While this study's scope was limited to environmental metrics, social and economic sustainability are vital for realizing holistic sustainability outcomes. Imminent research are ought to integrate evaluations of fair labor practices, just economic benefits for smallholder farmers, and the potential of sisal production to contribute to poverty alleviation (SDG 1) and decent work (SDG 8). Assessing the socio-economic impacts of sustainable interventions can ensure inclusive and equitable development (SDG 10).
3. **Sustainability Innovation and Policy Implications**: This study identifies environmental hotspots in sisal yarn production and proposes waste recycling and the incorporation of renewable energy in production process as measures to improve future sustainability of the production chain. Its findings provide stakeholders with useful information and guide policy to establish sisal yarn as a competitive, environmentally responsible substitute for synthetic fibers while lowering lifetime impacts and encouraging innovation.

4. Limitations of the study

While this study provides valuable insights into the environmental impacts of sisal yarn production, several limitations should be noted.

1. **Reliance on Secondary Data**: While primary data was gathered from Tanzania's Tanga region, a major sisal production hub, several life cycle inventory components depended on secondary data from the Ecoinvent3 database. Despite providing reliable, validated data, Ecoinvent3's generalization can miss out essential environmental factors, energy profiles, and agricultural methods unique to a given region that are relevant to sisal production. For example, differences in agriculture practices, water management, and energy sources between locations may result in disparate environmental effect outcomes. To improve generalizability and dependability, future studies should focus on broadening primary data collection across various production environments and geographical areas.

2. **Limited Scope of Sustainability Assessment**: The primary focus of this study was the analysis of environmental sustainability parameters associated with the manufacture of sisal yarn. However, when elements like labor practices, community well-being, and the financial feasibility of sustainable initiatives are not investigated, results in a gap in broad coverage. For a more comprehensive understanding of the sustainability of the sisal yarn value chain, future studies are ought to incorporate these factors.
3. **Use of Midpoint Indicators**: Although midpoint metrics like eutrophication, ecotoxicity, and global warming potential were chosen for in-depth analyses, they do not take into account more extensive endpoint environmental effects like ecosystem health or human well-being. Future studies should include endpoint indicators to enhance understanding of the long-term impacts of sisal production, including ecosystem resilience and societal benefits.
4. **Sensitivity Analysis Constraints**: The sensitivity analysis conducted in this study was limited to three improvement scenarios: reducing chemical inputs, increasing energy efficiency, and optimizing water use. While these scenarios provide actionable insights, additional strategies such as renewable energy integration, enhanced waste management, and circular economy approaches (e.g., utilizing sisal waste for bioenergy) could further enhance the environmental performance of sisal yarn production. These potential strategies should be explored in future work. The incorporation of such innovative strategies could yield more actionable insights, aligning production processes with global sustainability goals.

Addressing these limitations, future research can build on this study's findings to provide a more robust and comprehensive sustainability assessment of sisal yarn production.

5. Conclusion and recommendations

5.1. Key contributions and novelty of the study

This study presents a number of significant innovations that deepen our understanding of the environmental effects of sisal yarn production. It first offers a thorough life cycle assessment (LCA) of sisal yarn from cultivation to yarn-making, including all phases of the process. This holistic method delivers a complete environmental profile, identifying consequences across the whole production process, in contrast to previous studies that have mainly concentrated on individual production stages. Secondly, the research identifies particular areas in the environment, where the potential for global warming and terrestrial ecotoxicity are disproportionately increased by cultivation and decortication. These results show previously unrecognized focused potential for sustainability improvements.

The quantification of the environmental effects of the yarn-making phase, which accounts for 10.1% of fossil fuel depletion and 21.7% of human toxicity, is another noteworthy contribution. This aspect has not received much attention in prior evaluations of natural fibers including sisal, despite contributing less to global warming. The study also uses a sensitivity analysis, which shows how optimizing chemical inputs, energy use, and water consumption can result in impact reductions of up to 30%. This study extends the analysis that looks forward and provides practical suggestions for lowering the environmental impact of sisal yarn production, a missing feature in the previous studies.

Lastly, sisal yarn is positioned as a feasible, sustainable substitute for synthetic fibers due to the study's clear compatibility with the Sustainable Development Goals (SDGs) of the United Nations, namely SDG 12 (responsible production), SDG 13 (climate action), and SDG 15 (life on land). These contributions close gaps in the literature and offer doable solutions for improving the sisal industry's environmental sustainability.

5.2. Recommendations for future work

Policymakers should establish incentives and regulations to advance sustainability in the sisal value chain. Key actions include subsidies for renewable energy adoption, efficient water use, and sustainable farming practices like precision agriculture and organic fertilizers. Clear guidelines for waste management, particularly in decortication, are essential. Investments in region-specific life cycle assessments (LCAs) and innovations such as wastewater recycling and renewable energy systems should be prioritized. Capacity-building programs and awareness campaigns can further promote sisal as a sustainable alternative to synthetic fibers.

Manufacturers should adopt renewable energy and advanced machinery to optimize energy and water use in fiber extraction and yarn production. Waste valorization, such as converting sisal waste into bioenergy or organic fertilizers, and closed-loop water systems can further enhance sustainability. Pursuing certifications like ISO 14001 will strengthen market positioning and align with global environmental standards.

Researchers should broaden LCAs to include social and economic dimensions, such as labor practices and market viability, and integrate endpoint indicators for ecosystem health and human well-being. Innovative materials and processes, including biodegradable additives and efficient agronomic practices, should be explored to reduce reliance on synthetic inputs. Collaboration with stakeholders to gather region-specific data and disseminate findings will ensure actionable insights for sustainable practices.

These focused recommendations provide clear strategies for improving the environmental, social, and economic sustainability of the sisal value chain.

CRediT authorship contribution statement

Nickson Severian Kahigi: Writing – original draft, Visualization, Methodology, Data curation. **Josephine Joseph Mkunda:** Supervision, Editing, and Reviewing. **Mwema Felix Mwema:** Supervision, Editing, and Revising- methodology. **Revocatus Machunda:** Fund acquisition, Supervision, and Reviewing.

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Declaration of competing interest

The authors declare that, they have no financial or interpersonal conflicts that might affect the quality, and credibility of this study's findings.

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Data availability

This work includes the primary data collected on-site, while the secondary data obtained from online library sources has been modeled directly using functions built into *SimaPro* software.

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