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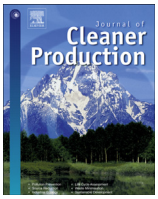

Life cycle assessment of sisal fibre – Exploring how local practices can influence environmental performance

Martijn L.M. Broeren*, Stijn N.C. Dellaert [1], Benjamin Cok [2], Martin K. Patel [3],
Ernst Worrell, Li Shen

Copernicus Institute of Sustainable Development, Energy & Resources Group, Utrecht University, Heidelberglaan 2, 3584CS, Utrecht, The Netherlands

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ABSTRACT

Sisal fibre can potentially replace glass fibre in natural fibre composites. This study focuses on the environmental performance of sisal fibre production by quantifying the greenhouse gas (GHG) emissions and energy use of producing sisal fibre in Tanzania and Brazil using life cycle assessment (LCA), based on region-specific inventory data. The results show that sisal fibre production has much lower GHG emissions (75–95%) and non-renewable energy use (85–95%) compared to glass fibre on a kg-basis, which is in line with published LCAs on natural fibres. Sisal fibre's GHG emissions are strongly influenced by potential methane emissions arising from the wet disposal of sisal leaf residues. Furthermore, because the direct energy and material requirements of sisal fibre production are low, its environmental performance is shown to vary strongly based on local practices such as residue disposal and fertiliser use, and is also sensitive to transportation distances. Several improvement options are explored to understand potential improvements in environmental sustainability. The most attractive option is limiting inadvertent methane emissions occurring at residue disposal sites, for instance by using them for the production of biogas.

1. Introduction

Sisal fibres are long natural fibres extracted from the leaves of the sisal plant, an agave species native to Mexico. Global sisal fibre production amounted to 640 (metric) kt/y in the 1960's (UNIDO/CFC, 2001), but has since declined due to the rise of synthetic fibres, recently stabilising around 230 kt/y (FAO, 2014). Sisal is mainly cultivated in Brazil, East Africa and China, typically without irrigation or fertilisation (Hartemink and van Kekem, 1994). The sisal sector was estimated to provide direct and indirect employment to around 850,000 people in Brazil, and approximately 2.1 million people in Tanzania (CFC, 2012). Large amounts of the produced fibre are exported. For example, Brazil and Tanzania exported 36 kt and 16 kt in 2012 respectively, corresponding to ~45–50% of their national production (FAO, 2014).

Traditionally, sisal fibre is used to produce twine, ropes, carpets and bags. However, natural fibres such as sisal are also increasingly used in composites in the automotive and construction sectors. In 2012, about 5% of the composites manufactured in Europe incorporated natural fibres, the remainder mainly consisting of glass fibre composites (Witten et al., 2014). In the same year, natural fibre-reinforced plastics were used to make 92 kt of components, mostly for the automotive sector (Witten et al., 2014). By 2020, the share of natural fibres in the total market for reinforcement materials could grow to 28% (Yan et al., 2014). Their low density and good mechanical properties result in favourable technical performance in composites (Pickering et al., 2015), although lower costs and environmental considerations are also important drivers (Hanninen and Hughes, 2010).

Sisal production is notable for generating substantial amount of organic residues. As 4% of sisal leaves consist of fibre, each tonne of fibre co-produces 24 t of organic residues. These residues are disposed of differently, depending on whether the fibre extraction process step ('decortication') is centralised. In Tanzania, sisal fibre is

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* Corresponding author.
E-mail addresses: m.l.m.broeren@uu.nl (M.L.M. Broeren), stijn.dellaert@tno.nl (S.N.C. Dellaert), bcok@snvworld.org (B. Cok), martin.patel@unige.ch (M.K. Patel), e.worrell@uu.nl (E. Worrell), l.shen@uu.nl (L. Shen).

[1] Present address: TNO, Netherlands Organization for Applied Scientific Research, Princetonlaan 6, 3584CB, Utrecht, The Netherlands.

[2] Present address: SNV Netherlands Development Organisation, Parkstraat 83, 2514JG, The Hague, The Netherlands.

[3] Present address: Institute for Environmental Sciences and Forel Institute, University of Geneva, Boulevard Carl-Vogt 66, 1205, Genève, Switzerland.

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primarily produced at a large scale at estates, using a centralised, stationary wet fibre extraction process. The large amounts of residues generated during decortication are washed away into open disposal ponds, a practice that can lead to methane emissions (CFC, 2012). In contrast, in Brazil sisal fibre is produced at smaller scale farms, using a decentralised, mobile dry decortication process, and organic residues are typically left on fields or used as animal feed. The differences in local practices could lead to different environmental impacts, which are not well understood for the production of sisal fibre.

The environmental impacts of many natural fibres such as hemp (Zampori et al., 2013), flax (Le Duigou et al., 2011), China reed (Corbiere-Nicollier et al., 2001), jute and kenaf (Althaus et al., 2007) have already been studied using life cycle assessment (LCA). However, no detailed quantitative environmental assessment of sisal fibre production exists in public literature. This paper therefore conducts attributional LCAs of sisal fibre production in both Tanzania and Brazil based on primary data, together covering approximately 45% of global production (FAO, 2014). Specific goals are to evaluate the effects of site-specific differences in agricultural and fibre processing practices, and to assess the influence of methane emissions from residue disposal on the overall environmental performance of sisal fibre production by using modelling and scenario analysis. The results are compared to glass fibre and other natural fibre LCAs. The target audience includes both producers and potential users of sisal fibre or other natural fibres (e.g. composite producers) who are interested in optimising the environmental sustainability of the sisal sector.

2. Methodology – life cycle assessment

This study uses the LCA methodology standardised in ISO 14040/14044 (ISO, 2006a, 2006b).

2.1. Goal, scope and functional unit

Given the potential demand for sisal in automotive or other high-end applications in developed countries, this paper aims to quantify the environmental impacts of high quality, ready-to-export sisal fibre from Tanzania (Tanga region) and Brazil (Bahia). The goal is to study the current average sisal fibre production systems, so an attributional/accounting approach is used, corresponding to situation C1 according to ILCD (EC-JRC, 2010).

The functional unit is *one metric tonne of sisal fibre, ready for export at sea-port*. Different grades of sisal fibre are distinguished based on fibre length and qualitative aspects such as colour and the presence of knots, impurities or defects (Anandjiwala and John, 2010). The sisal fibres produced in Brazil and Tanzania are not completely identical due to cultivation and decortication differences (dry decortication can reduce fibre quality; Mmari, 2012), and the grading systems used are different (Anandjiwala and John, 2010). These quality differences are partially reflected in the market price, as sisal fibre from Tanzania is more expensive than sisal fibre from Brazil (see also SM2: Supplementary Material, section 2). In this study, ‘sisal fibre’ refers to the Brazilian *Type 1*, *Type 2* and *Type 3* grades, and the Tanzanian *3S*, *3L* and *UG* grades. The remaining, co-produced grades are referred to as ‘off-grade fibre’ here, and include Brazilian *refugo* and Tanzanian *UF*, *SSUG*, and *tow* grades. These grades are deemed less suitable for the production of automotive composites due to their lower quality (e.g. increased defects and impurities).

The cradle-to-port scope includes all production stages from sisal plant cultivation up to and including the transportation of baled fibres to sea-port, and excludes the use phase and end-of-life. In line with the PAS2050 method, no impacts are assigned to the use of animal/human labour (BSI, 2011). For both countries, the currently used technologies are studied (primary data collected in 2013/2014). For Tanzania, estate-based production in the Tanga region is analysed, whereas for Brazil the average production in Bahia state is assessed.

2.2. Production systems

Sisal is an agave species grown in semi-arid regions. Sisal fibre production starts by clearing lands of vegetation and rubble and subsequent ploughing. Sisal bulbils or suckers are planted in rows (3000–5000 plants/ha). Sisal requires minimum precipitation levels of 400 mm/y and is not irrigated in Tanzania or Brazil (Anandjiwala and John, 2010). Harvesting of sisal leaves begins two to three years after planting. Cutters harvest and bundle the leaves, which are processed quickly to avoid deterioration. A decortication process employs mechanical scraping to remove leaf tissue and yield raw sisal fibre, accounting for 4% of the leaf by weight (Terrapon-Pfaff et al., 2012). In both Brazil and Tanzania, the raw fibres are sun-dried to reduce the moisture content to about 13%. Mechanical brushing removes impurities to make the fibres soft and shiny. The brushed fibres are graded and pressed into bales, ready for transportation.

Table 1 summarizes the main differences in sisal fibre production between Tanzania and Brazil. In Brazil, sisal production is concentrated in the state of Bahia, accounting for over 90% of national sisal production. Sisal is mainly cultivated by smallholders on family farms ranging from 5 to 100 ha, most being smaller than 10 ha. The agricultural techniques used are simple and traditional. Reports on average annual fibre yields range from below 1000 kg/ha (Sindifibras, 2012) to 1200 kg/ha (Andrade et al., 2011). The region has a semi-arid climate with average temperatures around 30 °C and 400–700 mm of annual rainfall. Sisal is one of the few crops that can be commercially cultivated in the region (Silva et al., 2008). In Tanzania, sisal is mainly produced at large scale at 57 estates, ranging from 400 to 9400 ha. The Tanga region accounted for 54% of the country's total sisal production of about 36 kt in 2012.

2.3. Life cycle impact assessment methods

Three environmental indicators are analysed in this study: renewable and non-renewable energy use (REU/NREU), both measured in GJ (Frischknecht et al., 2007), and GHG emissions, measured in kg carbon dioxide equivalents (CO_2 eq.). NREU measures primary energy depletion of fossil and nuclear resources and correlates well with energy-related environmental impacts (Huijbregts et al., 2006). REU consists of primary energy from biomass, hydropower, wind and solar energy.

GHG emissions are analysed according to IPCC's Fifth Assessment Report, using a 100 year time frame for comparability with other studies and a global warming potential of 28 kg CO_2 eq./kg for methane (IPCC, 2013). The accounting of biogenic carbon is conducted in line with PAS 2050 (BSI, 2011), ILCD handbook (EC-JRC, 2010), PEF (EC, 2013), and ISO 14067:2013 (ISO, 2013); GHG emissions to and removals from the atmosphere within the system boundaries are taken into account. Details on carbon uptake modelling are available in SM1. No GHG emissions related to land use change are taken into account, due to the decrease in land used for sisal production in past decades (see also Section 5.3).

In addition, agricultural land occupation (in ha y, i.e. area of land multiplied by time) and freshwater depletion (m^3) are quantified at inventory-level using ReCiPe Midpoint (H) v1.12 (Goedkoop et al., 2009), to assess sisal fibre's impact on the availability of these resources. In line with blue water footprints (Hoekstra et al., 2011), freshwater depletion measures the net groundwater and surface

Table 1
Characteristics of sisal fibre production in Brazil and Tanzania. Percentages refer to share of total fibre production.

	Brazil	Tanzania
Sisal variety	*Agave sisalana*	Hybrid 11648
Region	Bahia state (northeast)	Northeast - southeast
Sector structure	Smallholders	Estates
Farm size	5 - 100 ha	400–9400 ha
Planting material	Suckers	Bulbils
Yield	500–1200 kg fibre/ha	600–1600 kg fibre/ha
Mechanized land preparation	50%	100%
Use of commercial fertilisers	No	At some estates
Transportation of leaves	By animal	By trailer
Decorticator type	Small mobile decorticator	Large stationary decorticator
Decortication process	Dry	Wet
Fibre washing	Mostly (90%) not	Yes, during decortication
Sisal residue disposal	As fertiliser or animal feed	Frequently deposited in open ponds

water consumption, and does not credit releases of water polluted with organic material.

2.4. Data collection

Primary data on the sisal production process in Tanzania were collected onsite during interviews with managers of four estates and supplemented with statistical data from the Tanzania Sisal Board, literature, and modelling of inadvertent methane (CH_4) emissions from sisal residue disposal. The data from the four estates are averaged in the inventory, weighting values by the estates' 2012 sisal fibre production. Together, they account for about 45% of Tanzanian production and are deemed representative for estate-based production in the Tanga region.

For Brazil, primary data were collected by interviewing experts and organizations/research institutes related to the Brazilian sisal producers such as Embrapa, Sindifibras and CAMPOL. If primary data were not available, data from scientific literature, reports from relevant organizations and statistical databases were used after verification and cross-checking. The data are thus deemed representative for Bahia, which produces 95% of Brazil's sisal (Sindifibras, 2012).

Background processes are taken from Ecoinvent v2.2 (Frischknecht et al., 2005). Tanzania's electricity mix is modelled with IEA statistics for 2011(IEA, 2015) (see SM2).

3. Life cycle inventory analysis

Fig. 1 displays the production systems in Tanzania and Brazil. The inventories for Brazil and Tanzania are discussed in Sections 3.1 and 3.2, respectively, and summarised in Table 2. Section 3.3 discusses co-product allocation.

3.1. Brazil

3.1.1. Fibre production

At Brazilian sisal farms, sisal is planted once every 10 years. Land clearing is done manually and the vegetative waste is left in or around the fields to reduce soil erosion (Alvarenga Júnior, 2012). For ploughing, tractors (50%) or animals (50%) are used. After ploughing, pits are dug out and the sisal suckers are planted on the field, without use of a nursery (Vale et al., 1998). Weeds are removed manually. Sisal leaf residues can be distributed on the field by hand to restore nutrients to the soil and limit evapotranspiration (Sindifibras, 2012). In Brazil, sisal plants are not fertilised.

After two years, leaves are manually harvested annually and transported by animal to a mobile decorticator close to the field running on diesel (Embrapa, 2014). The leaves are decorticated in a dry process which does not consume water. About 10% of farms wash the raw fibres in large tanks of water to remove leaf tissue and juice (Personal communication Embrapa and Sindifibras), which improves fibre quality (Anandjiwala and John, 2010). The decorticated sisal fibres are sun-dried over several days. The raw sisal is transported with small trucks to a large facility for brushing, grading and baling (Peerboom, 2012). The sisal bales are transported with trucks over about 340 km to Salvador da Bahia (Dellaert, 2014).

3.1.2. Sisal residue disposal

Due to the dry decortication process and comparatively small production volumes per farm in Brazil, the sisal residues dry quickly (Sindifibras, 2012). Because the residues are not submerged in water for long periods, we assume that no anaerobic digestion takes place. After drying, the residues are applied to the sisal field to act as organic fertiliser and reduce moisture evaporation, or used as animal feed after removing short fibres and juice (Sindifibras, 2012). These practises are representative for approximately 95% of sisal farms (Personal communication Embrapa). As the organic fertiliser stays within the sisal fibre production system and the sisal residues are unlikely to have any economic value, no environmental impact/credit is assigned to this activity.

3.2. Tanzania

3.2.1. Fibre production

At Tanzanian estates, the fields are cleared using a ‘brush cutter’, a bulldozer connected to multiple heavy rollers. Residual plant material is incorporated into the soil when the land is ploughed. Afterwards, the soil is loosened by disk harrowing and weeds are cleared manually. In Tanzania, sisal bulbils are raised in a nursery field for about 2 years before they are transplanted to the main field. A productive lifetime of 10 years is assumed. Fertiliser and herbicide use is not common in sisal cultivation (Hartemink and van Kekem, 1994), but some high-yield estates in Tanzania apply synthetic fertilisers such as trisodium phosphate and muriate of potash. This study accounts for the production, transportation and application of fertilisers.

After manual harvesting, the sisal leaves are transported to a central building for decortication, brushing and baling. Small tractors collect and transport bundles of harvested leaves to processing facilities. Tanzanian estates use large stationary decorticators processing up to 25,000 leaves per hour, running on grid electricity (Anandjiwala and John, 2010). However, due to regular power outages a diesel generator provides the necessary back-up power for roughly 20–25% of the operational time. Therefore, additional diesel is required to generate electricity (assuming 40%

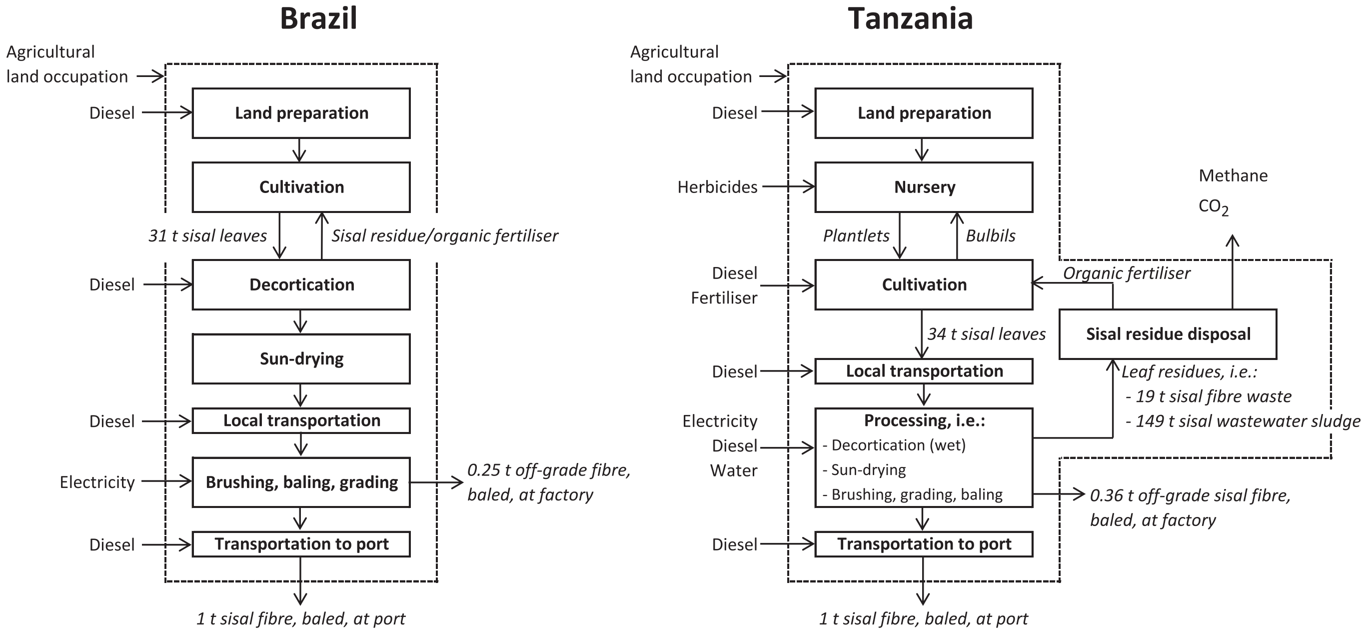

Fig. 1. Overview of sisal fibre production systems in Tanzania and Brazil.

efficiency) during power outages. Decortication generates 24 t sisal leaf residues/t fibre (Terrapon-Pfaff et al., 2012). About 100 t water is used to wash away the leaf residues through concrete channels to disposal sites (90%) and to clean the extracted fibres of mucilage (10%) (UNIDO/CFC, 2010). Decorticated fibres are sun-dried in yards close to the decorticator (UNIDO/CFC, 2001). The dried fibres are mechanically brushed, then manually sorted on quality and length, and pressed into bales of 250 kg for storage. The bales are transported by lorry to Tanga port over 60 km on average.

3.2.2. *Sisal residue disposal*

Two types of sisal residue are distinguished in this study. The liquid *sisal wastewater sludge* (SWS) fraction amounts to 110 t/t sisal fibre, and consists of juice present in the leaves (accounting for 41% of the residues; UNIDO/CFC, 2010) and the water added during decortication. The solid *sisal fibre waste* (SFW) fraction amounts to 14 t/t sisal fibre, consists of the shredded skin and flesh of the leaves and short fibres, and has a moisture content of 60–75% (Muthangya et al., 2013). Most Tanzanian estates dispose of the fibre waste and wastewater sludge in heaps and sedimentation ponds or lagoons in the direct surroundings without prior treatment or waste management control mechanisms (UNIDO/CFC, 2001). After depleting dissolved oxygen, the volatile solids in the wastewater can decompose to form methane (Mshandete et al., 2006). Over several years, this decomposition process turns the solid residues into organic fertiliser. At the moment, only high-yield sisal estates apply this organic fertiliser to their mature fields. Other literature sources indicate that sisal residues are occasionally sun-dried and burned (THESA, 2008), but it is unclear how common these practices are in Tanzania and they are not considered in this study.

To our knowledge, no in-situ measurements of the inadvertent methane emissions from sisal residue ponds are available. Therefore, the UNFCCC methodology to estimate the methane emissions occurring at solid waste disposal sites is applied here (UNFCCC, 2012). This method is based on a first-order decay model (i.e. the decomposition rate depends only on the waste material's concentration), since the decomposition process of degradable organic carbon (DOC) can be approximated by first-order reaction kinetics (IPCC, 2006). The method differentiates between different types of waste (e.g. wood, food waste, textiles), each associated with different decay rates, and disposal practices (managed or unmanaged). Four climate types are distinguished, based on average temperature (temperate/tropical) and precipitation (humid/dry) (UNFCCC, 2012).

The model parameters used in this study are based on empirical methane potential measurements from sisal residues and the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). In the default scenario we assume that the sisal residues are deposited for a period of 5 years, as was the case at one of the visited estates. Further modelling details are provided in SM4. Based on our model, emissions amount to 11 kg methane/t fibre produced (default scenario). The effects of varying modelling parameters are discussed in Section 5.1, whereas the potential for biogas production is explored in Section 5.2.

3.3. *Co-product allocation*

The environmental impacts of sisal fibre production are partitioned among the co-products sisal fibre and off-grade fibre. Subdivision or system expansion cannot be applied here. In line with the ILCD's situation C1 (EC-JRC, 2010), economic allocation is applied, yielding allocation factors of 78% for Tanzania and 83% for Brazil for sisal fibre based on 2011 prices (see SM3).

4. Results

4.1. *Energy and GHG emissions*

Fig. 2 shows the cradle-to-port NREU, REU and GHG emissions of sisal fibre production (after allocation). The Tanzanian production system's NREU (5.7 GJ/t) exceeds that of Brazil's (4.0 GJ/t). In Brazil, 53% of total NREU is due to fibre processing (i.e. decortication, brushing and baling). Transportation of the baled fibres to port makes up a further 38% of the energy use. The breakdown for Tanzania shows substantial contributions of cultivation (33%), local transportation (16%) and processing (37%). REU is dominated in both countries by the cultivation stage due to the (biomass) energy content of the sisal fibre (97–99%). Brazil's and Tanzania's cradle-

Table 2
Activity-level data used to derive life cycle inventory for the production of 1 t sisal fibre in Brazil and Tanzania, before allocation. Unit processes are taken from Ecoinvent v2.2 unless indicated otherwise. New abbreviations: TZ - Tanzania; BR - Brazil; RER - Europe; CH - Switzerland; OCE - Oceanic; GLO – Global.

Process and dataset name	Unit	Brazil	Tanzania	Comment
Nursery[a]				
Brush cutting/TZ	ha	–	0.01	Modified Ecoinvent process[b]
Tillage, ploughing/CH	ha	–	0.01	
Tillage, harrowing, by rotary harrow/CH	ha	–	0.01	
Tillage, harrowing, by spring tine harrow/CH	ha	–	0.01	
Herbicides, at regional storehouse/RER	kg	–	0.03	
Land preparation[a]				
Brush cutting/TZ	ha	–	0.11	Modified Ecoinvent process[b]
Tillage, ploughing/CH	ha	–	0.11	
Tillage, harrowing, by rotary harrow/CH	ha	–	0.11	
Tillage, land preparation/BR	ha	0.06	–	Modified Ecoinvent process[c]
Cultivation[a]				
Carbon dioxide, in air	kg	1539	1539	Based on fibre carbon content of 42% (Salazar and Leão, 2006)
Energy, gross calorific value, in biomass	GJ	18	18	Energy content of sisal fibres, assumed equal to jute and kenaf fibre in Ecoinvent v2.2
Fertilising, by broadcaster/CH[d]	ha	–	0.4	Distribution of commercial fertilisers
Solid manure loading and spreading, by hydraulic loader and spreader/CH	kg	–	11.8	Distribution of sisal residues
Transport, transoceanic freight ship/OCE	tkm	–	86.7	Transport of fertiliser from South Africa; 3100 km
Transport, lorry >16t, fleet average/RER	tkm	–	9.8	Transport of fertiliser from Dar es Salaam; 350 km
Mowing, by rotary mower/CH	ha	–	2.1	Mowing before leaf harvesting to improve mobility
Triple superphosphate, as P_2O_5, at regional storehouse/RER	kg	–	17.7	
Potassium sulphate, as K_2O, at regional storehouse/RER	kg	–	10.3	Used as a proxy for muriate of potash, for which no impact assessment data is available
Fibre processing (decortication, brushing, baling)				
Water, unspecified natural origin, BR	t	0.03		
Water, unspecified natural origin, TZ	t		100.1	
Transport, tractor and trailer/CH	tkm	–	178.9	Transport of sisal leaves over 7 km
Diesel, burned in mobile decorticator/BR	MJ	1440	–	Modified Ecoinvent process[e]
Electricity, medium voltage, production TZ, at grid/TZ	kWh	–	215.0	Electricity for fibre processing; new process, see SM2.
Diesel, burned in diesel-electric generating set/GLO	MJ	–	561.9	Diesel use for fibre processing in case of grid outages
Transport, lorry 3.5–7.5t, EURO3/RER	tkm	26	–	Transport of raw fibre for brushing
Transport, tractor and trailer/CH	tkm	2	–	Transport of mobile decorticator
Electricity, medium voltage, production BR, at grid/BR	kWh	20	–	Electricity use brushing machine
Electricity, medium voltage, production BR, at grid/BR	kWh	8	–	Electricity use baling machine
Sisal leaf residue disposal				
Methane, from sisal fibre waste	kg	–	2.6	Default scenario, see SM4
Methane, from sisal wastewater sludge	kg	–	8.4	
Transportation to port				
Transport, lorry 3.5–16t, fleet average/RER	km	340	59.8	Transport, baled sisal fibre to port

[a] The Ecoinvent flows *"Occupation, arable, non-irrigated"*, *"Transformation, from arable, non-irrigated"* and *"Transformation, to arable, non-irrigated"* are included in the modelled Nursery, Land preparation and Cultivation processes, but not shown in Table 2 since they do not contribute to NREU and GHG emissions.

[b] One ha of brush cutting requires 35–45 l diesel (density: 0.84 kg/l) and 10 ha of brush cutting is done in an 8 h shift, resulting in an average consumption of 26.9 kg diesel/ha brush cutting.

[c] Process based on *"Tillage, ploughing/CH"* process. Diesel use (and associated emissions) was increased to 69.7 kg/ha, which follows from 7 l diesel/hour, 12 h/ha and 0.84 kg/l.

[d] Assumed annual application of trisodium phosphate (total of 10 times over productive lifetime), while muriate of potash is applied after planting (50 kg/ha) and after first (50 kg/ha), second (100 kg/ha) and third cut (500 kg/ha). Combined fertilisation is assumed for both fertilisers after first and third cut, resulting in 12 times fertilisation over a productive lifetime of 10 years.

[e] This process is based on Ecoinvent's *"Diesel, burned in building machine/GLO"* process. In this process, the ratio of diesel to lubricating oil use was changed to 40:1 to model the mobile decortication process (Embrapa, 2014).

to-port GHG emissions are −1285 and −870 kg CO_2 eq./t sisal fibre respectively, since the sequestered biogenic carbon (−1539 kg CO_2 eq./t) exceeds the total emissions of other production stages (250 and 670 kg, respectively). The NREU results for the four Tanzanian estates diverge by up to ±20% from the averages reported here, whereas GHG emissions vary by up to ±10% (see SM5).

Overall, the breakdowns for GHG emissions and NREU are similar in both countries, apart from the methane emissions from residue disposal in Tanzania (discussed further in Section 5.1). In Brazil, the nursery, land preparation and cultivation processes contribute very little (0–7%) to its NREU and GHG emissions due to the large share of manual labour. In Tanzania, land preparation has higher impacts due to higher mechanisation. Furthermore, the diesel use of mowing and fertiliser use result in a larger contribution of cultivation (33% of NREU). Local transportation is also far more significant in Tanzania, since entire fresh sisal leaves are transported, compared to Brazil where only fibres are transported (decentralised decortication). However, the transportation distance to sea-port is larger in Brazil, resulting in proportionally higher impacts.

Fibre processing has similar GHG emissions and NREU (2.1 GJ/t) in both countries. In Brazil nearly all NREU comes from diesel consumed in the mobile decorticators. In Tanzania 35% of the NREU required in decortication comes from the diesel use during grid outages. If the Tanzanian electricity grid were always on line, the NREU of fibre processing would be reduced by 20%, and overall NREU by 10%. The poor grid reliability in Tanzania thus strongly influences sisal's environmental performance.

4.2. Land and water use

Agricultural land occupation is 0.76 ha y/t sisal fibre for Tanzania

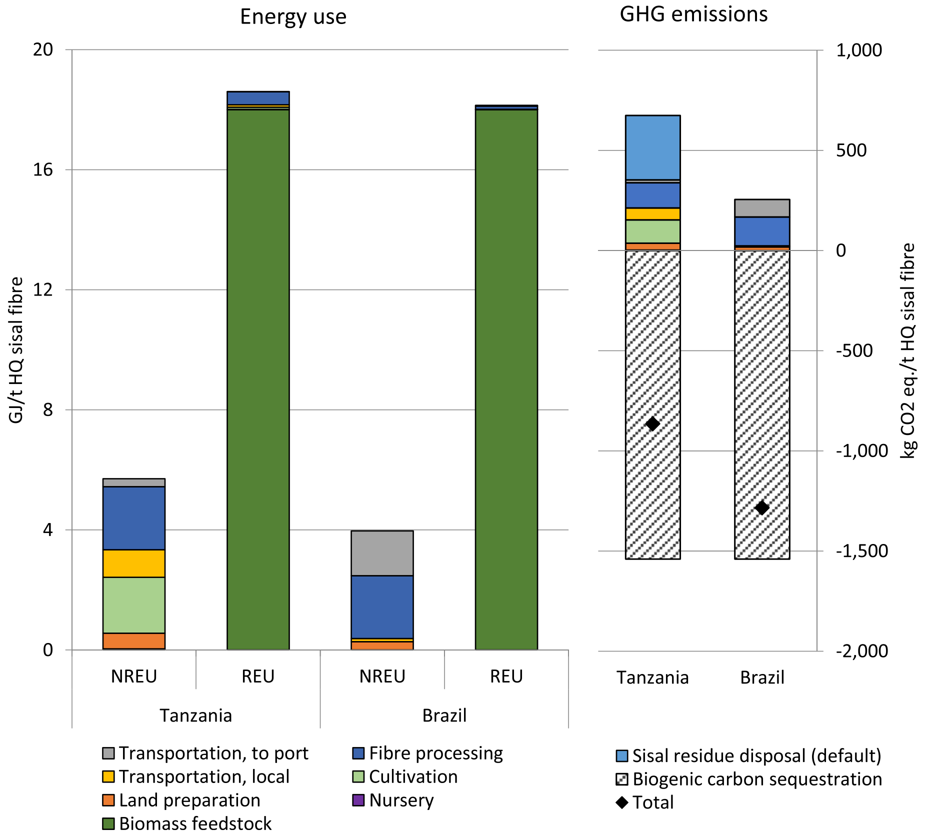

Fig. 2. Cradle-to-port NREU, REU and GHG emissions of 1 t sisal fibre production in Tanzania and Brazil by production stage.

and 1.03 ha y/t sisal fibre for Brazil, mostly due to lower yields in the latter country (Table 1). Freshwater depletion amounts to 1 m^3/t sisal fibre for Brazil and 111 m^3/t sisal fibre for Tanzania due to the wet decortication process. Note that these figures do not credit releases of water containing organic material that could occur after residue disposal.

5. Discussion

5.1. Uncertainty analysis of sisal residue disposal in Tanzania

An uncertainty analysis is carried out for sisal residue disposal modelling by changing specific parameters (one at a time), as described in Table 3. The analysis focuses on Tanzania, as residues most likely degrade aerobically in Brazil (Section 3.1). This analysis quantifies the potential differences in emissions arising from different residue management practices (cases 1–5, in which the amount of waste deposited is kept constant), and can be used to derive best practices. Furthermore, given that the fibre content in sisal leaves varies between about 2.7% and 7.3% (Muthangya et al., 2013), cases 6 and 7 explore how the associated increase/decrease in the amount of leaf residue deposited per tonne of fibre produced affects the GHG emission results.

The total GHG emissions of sisal fibre production vary between -1.0 and 0.3 t CO$_2$ eq./t fibre in the uncertainty analysis cases (Fig. 3). In the remainder of this section, we focus on the gross GHG emissions, i.e. cradle-to-port GHG emissions excluding sequestered CO$_2$, to highlight the changes in each case (carbon sequestration is constant). Most critical are the disposal period (case 1) and the depth of disposal ponds (case 3). Using a 100 year disposal period (case 1) allows much more of the organic material to degrade anaerobically; gross GHG emissions increase by 145% as methane emissions rise from 11 kg/t fibre output (i.e. sisal fibre and off-grade fibre) in the default scenario to 44 kg. The slowly degrading SFW is most strongly affected by this change. Assuming a deeper disposal site (case 3) increases gross GHG emissions by 120%, as the increased pond depth limits aerobic digestion in the disposal site's top layers. These two parameters can be influenced by the sisal estates. To minimize methane emissions, the degradation period should be kept short (e.g. by spreading out the residues over fields to act as fertiliser) and ponds should be shallow to maximize aerobic degradation.

The other cases study factors outside the estates' control: sisal residue volumes (cases 6/7), decay speeds (case 2) and methane generation (cases 4/5). The most critical change is seen for faster decay rates (case 2), which increases gross GHG emissions by 59% because more SWS degrades. Assuming lower methane potentials (case 4) leads to the largest (22%) decrease in GHG emissions, as methane emissions drop to 6 kg/t fibre output. Finally, assuming higher or lower fibre content in the sisal leaves (case 6 and 7) leads to minor differences (±7%) in GHG emissions.

5.2. Biogas production

The previous section illustrated that methane emissions from residue disposal can strongly influence sisal fibre's GHG emissions. However, sisal residues can also be used for biogas production to reduce water pollution, limit methane emissions and alleviate electricity shortages in Tanzania (Kivaisi and Rubindamayugi, 1996). A pilot plant for anaerobic digestion of sisal leaf residues was installed at Katani Hale Estate in 2008 (UNIDO/CFC, 2010).

Here we explore the potential of biogas co-production to reduce

Table 3
Uncertainty analysis cases. The parameters and the model's default values[a] are discussed in SM4.

Case	Scenario	Modelling parameter changes	Assumption/reasoning
1	Longer disposal period: 100 years	Disposal period (y): 100 y	Fully unmanaged residue disposal
2	Faster decay	Decay rates (k_j): SFW: 0.035 y^{-1} SWS: 0.400 y^{-1}	Switch to wet climate (annual precipitation >1000 mm); appropriate for some estates in Tanzania
3	Deeper ponds	Methane correction factor (MCF_y): SFW: 0.8 SWS: 0.8	Deep instead of shallow ponds. SFW: "Unmanaged deep SWDS"; SWS: "Anaerobic deep lagoon" (IPCC, 2006).
4	Low methane generation	Biochemical methane potential (BMP_j): SFW: 0.005 t CH_4/t waste SWS: 0.001 t CH_4/t waste	Switch to extreme values found in literature. See Tables SM4.2 and SM4.3 in Supplementary Material.
5	High methane generation	Biochemical methane potential (BMP_j): SFW: 0.016 t CH_4/t waste SWS: 0.004 t CH_4/t waste	
6	Low fibre content	Amount of waste deposited (W_j): SFW: 22.5 t SFW/t sisal fibre SWS: 121.8 t SWS/t sisal fibre	Low-/high-end estimate of 2.7% and 7.3% fibre content in sisal leaves implies that more/less residues are deposited for each t sisal fibre produced (Muthangya et al., 2013).
7	High fibre content	Amount of waste deposited (W_j): SFW: 7.9 t SFW/t sisal fibre SWS: 111.6 t SWS/t sisal fibre	

[a] Default model values: $y = 5$, $k_{SFW} = 0.025$, $k_{SWS} = 0.085$, $MCF_{y,\ SFW} = 0.4$, $MCF_{y,\ SWS} = 0.2$, $BMP_{SFW} = 0.01$, $BMP_{SWS} = 0.003$, $W_{SFW} = 15.0$, $W_{SWS} = 116.5$ (see SM4).

sisal fibre's associated NREU and GHG emissions. We assume a best practice case in which the biogas is used for electricity production and the digestate is used as organic fertiliser to replace synthetic fertiliser. We only consider Estate 1, since it is the only estate currently using fertilisers.

Three cases are considered, reflecting low, average and high methane production from the sisal residues, based on methane potential values for SFW (13–60 m^3 CH_4/t; fresh matter basis) and SWS (2–6 m^3 CH_4/t) (Fischer et al., 2010). These potentials are multiplied with Estate 1's SFW and SWS production to yield three methane production levels. We assume an electricity conversion efficiency of 30%. The electricity is used internally for sisal fibre processing, and any excess production is assumed to be fed into the grid (in which renewables currently account for about 50% of electricity production; SM2). This yields an NREU/GHG emissions credit by replacing average grid electricity (avoiding allocation by system expansion). The inputs of the biogas plant (e.g. auxiliary materials, electricity use of conveyor belts, stirrers) as well as any biogas leakage are not accounted for due to lack of information. As the biogas plant can supply all required electricity, no backup diesel generator power is required. Furthermore, the digestate offers sufficient nutrients to replace all synthetic fertilisers (SM6). We assume that all available digestate is spread out over the sisal fields.

Fig. 4 shows that the low biogas production case reduces cradle-to-port GHG emissions to −1570 kg CO_2 eq./t sisal fibre, whereas high biogas production results in −2580 kg CO_2 eq./t. Similarly, Estate 1's default NREU of 6.4 GJ/t sisal fibre is reduced to −1.1 to −19.4 GJ/t in the low and high biogas production cases, respectively. The electricity surplus provides between 270 and 1270 kg CO_2 eq. of credits per tonne fibre. Further savings are achieved by avoiding mineral fertiliser use (120 kg CO_2 eq.) and uncontrolled methane emissions (310 kg CO_2 eq. in default analysis). However, emissions associated with distributing the digestate on the fields increase fivefold (110 kg CO_2 eq.), because more material is spread out (increasing diesel consumption).

5.3. Other data and methodological uncertainties

The study's background data (e.g. for transportation, ploughing, and fertiliser production) from Ecoinvent are based on average

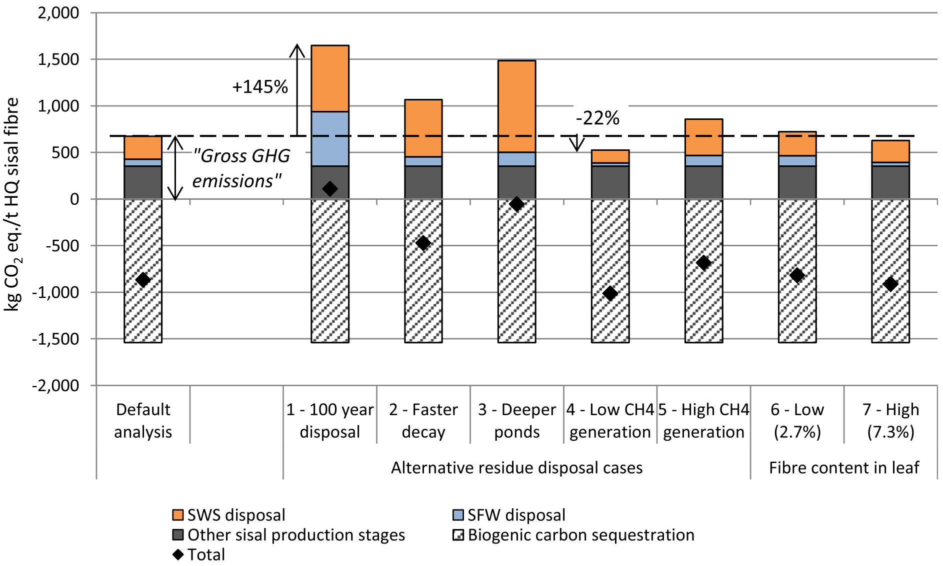

Fig. 3. Cradle-to-port GHG emissions of 1 t sisal fibre in Tanzania under different residue disposal assumptions.

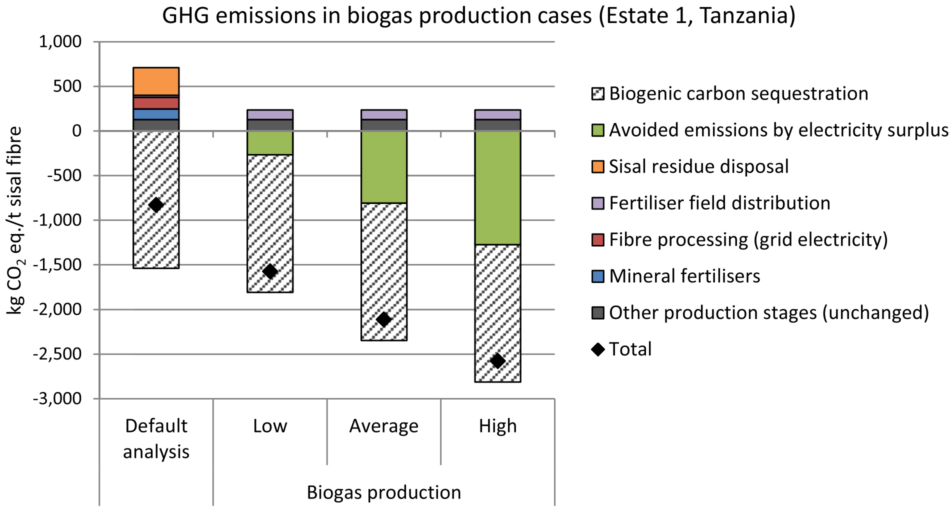

Fig. 4. Cradle-to-port GHG emissions of 1 t sisal fibre at Estate 1 in Tanzania for three biogas production cases.

European, global, or Swiss data. Because sisal production has low direct energy and material requirements, the choice of background datasets is important. Transportation processes are most critical, accounting for 41% of the NREU of sisal fibre in Brazil and 21% in Tanzania. The representativeness of the Ecoinvent transportation datasets for Brazil and Tanzania is uncertain, as they represent typical European load factors of trucks and vans (e.g. considering volume-constrained transport and empty return trips). Further data collection and analysis would be required in order to account for the concrete circumstances (e.g. transportation distances, modes and load factors).

For Brazil the default transportation distance to Salvador port (340 km) is not representative for all fibre processing facilities in Bahia. Varying this distance between 180 and 590 km (roughly corresponding to nearby and faraway facilities) changes cradle-to-port NREU by −15% to +30%, and gross GHG emissions by −20% to +25%. In addition, transportation modes can affect GHG emissions.

Furthermore, GHG emissions related to direct or indirect land use change (LUC) are not taken into account in this study. This is primarily because the methodology and databases to assess iLUC are still in development (BSI, 2011). However, LUC emissions are expected to be minor in this case. Due to the decreasing demand for natural fibres in the past decades, 72% of the agricultural land of sisal estates in Tanzania lay fallow in 2012, whereas sisal acreage in Brazil has also declined (Cunha et al., 2011). The original conversion of this land to sisal farms happened over 20 years ago, and thus associated direct LUC emissions do not need to be considered according to PAS2050 (BSI, 2011). In addition, sisal can be grown on marginal lands, and is for instance one of a few crop options for northeastern Brazil (Campbell, 2007). Along with the available fallow land, this makes it unlikely that increasing demand for sisal will displace other crops and cause indirect LUC.

Regardless of sisal fibre's low GHG emissions and NREU, other

Table 4
Cradle-to-factory gate environmental indicators for sisal fibre, other natural fibres and glass fibre (from peer-reviewed literature; see footnotes).

Fibre type	Agricultural land occupation, ha y/t	Freshwater depletion, m^3/t	NREU, GJ/t	REU, GJ/t	GHG emissions, excluding sequestered carbon, kg CO_2 eq./t	
					IPCC (2013) method	IPCC (2007) method
Sisal fibre, Tanzania	0.8	111	5.4	18.6	660	590
Sisal fibre, Brazil	1.0	1	2.5	18.1	170	170
Jute, India[a,b]	0.2	53	3.0	18.1	555	560
Kenaf, India[b]	0.2	506	3.1	18.1	560	570
Cotton, China[b]	0.8	6997	30.7	19.7	3290	3470
Cotton, United States[b]	1.1	1517	36.0	18.9	2960	3060
Hemp, Spain[c]	n.a.	n.a.	13.2	n.a.	n.a.	1600
Hemp, Italy[d,e]	0.3	n.a.	8.0	18.0	n.a.	200
Flax, France[f]	0.1	n.a.	11.7	n.a.	n.a.	250
Flax, Spain[c]	n.a.	n.a.	12.4	n.a.	n.a.	437
China reed, Switzerland[g]	n.a.	n.a.	3.6	n.a.	660[h]	
Glass fibre, Europe[i]	0.0	70	44.4	1.4	2630	2630

[a] Rainfed system.
[b] Althaus et al. (2007).
[c] González-García et al. (2010).
[d] Zampori et al. (2013).
[e] Values reflect economic allocation. NREU and REU values are derived from a graph.
[f] Le Duigou et al. (2011).
[g] Results reported by Joshi et al. (2004), based on original work by Corbiere-Nicollier et al. (2001).
[h] This value is based on CO_2 emissions only.
[i] Kellenberger et al. (2007).

environmental impact categories may show important trade-offs. For example, the disposal of sisal leaf residues and wastewater in Tanzania can pollute groundwater and rivers (Terrapon-Pfaff et al., 2012). Like eutrophication, this process can lead to oxygen depletion which in turn affects ecosystem diversity (THESA, 2008). This issue and its magnitude are highly location-dependent, e.g. based on whether there are streams or rivers nearby, whether dedicated sedimentation ponds are used, and how the residues are treated. For the present analysis, insufficient information on these emissions was available to quantify the damage potential.

5.4. Comparison to other LCAs for commodity fibres

The results obtained here cannot be directly compared to earlier work, as no LCAs on sisal fibre exist in scientific literature. Table 4 therefore compares the results for cradle-to-factory gate sisal fibre production to other peer-reviewed LCA studies on natural fibres and glass fibre. It should be noted that there may be methodological differences between the studies which are not corrected here. The table therefore cannot be used for comparative assertions; it serves only to indicate whether the results obtained here are in the same range compared to earlier studies.

Sisal fibre has relatively high land requirements, but water depletion is limited compared to fibres requiring irrigation. Cotton, with its intensive and industrialised production systems, has relatively high NREU and GHG emissions, whereas the impacts for jute and kenaf are most similar to sisal fibre's, likely due to the low level of mechanisation in India. While the studies in Table 4 found low environmental impacts for natural fibres, there are large variations. Given that this study identified various reasons for such variations which could also apply to other natural fibre production systems, such as site-specific differences between countries and individual estates (SM5) and modelling uncertainties related to transportation and residue disposal, we consider our results in line with other non-energy intensive natural fibres.

6. Conclusions

This study shows that sisal fibre produced in Tanzania or Brazil has low cradle-to-port NREU and GHG emissions. It illustrates that sisal fibre's environmental performance can vary substantially based on site-specific practices, location and assumptions. In particular, it is shown that sisal residue disposal in open ponds can generate relatively large amounts of GHG emissions, depending on the disposal practice. In the worst case, sisal fibre's associated gross GHG emissions increase by 145% (Section 5.1). However, these emissions can also be mitigated by keeping disposal periods short and ponds shallow, or by using the residues to generate biogas (Section 5.2). Regardless of the residue disposal practice however, sisal fibre's associated NREU and GHG emissions are lower than glass fibre's on a same weight-basis, by 75%–95% in the default scenarios (Table 4).

Future research could focus on quantifying other impact categories, such as the eutrophication potential associated with sisal residue disposal in ponds. Such research would ideally be combined with in-situ measurements of methane emissions from residue ponds in Tanzania. Reduction of water use in water-stressed areas also merits further analysis.

The potential variations in environmental performance indicate that for sisal fibre, as well as for other non-energy intensive agricultural products, single values claiming to represent large regions should be used with caution. End-user companies are recommended to analyse specific supply chains and work with suppliers to implement best practices regarding the environmental and social sustainability of sisal fibre production.

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Appendix A. Supplementary material

Supplementary material related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.02.073.

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