Comprehensively revised edition 2019

Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material

Study providing data for the automotive and insulation industry

Authors: Niels de Beus (nova-Institute), Michael Carus (nova-Institute), Martha Barth (nova-Institute)

April 2019, slightly revised version August 2019

Download this study and further nova sustainability studies at:

www.bio-based.eu/ecology

Table of contents

Imprint

Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material - Study providing data for the automotive and insulation industry. Comprehensively revised second edition, Hürth (Germany), April 2019.

Publisher: Michael Carus
(Responsible under press legislation)
nova-Institut GmbH
Industriestraße 300,
50354 Hürth, Germany
michael.carus@nova-institut.de

Authors: Niels de Beus (nova-Institute), Michael Carus (nova-Institute), Martha Barth (nova-Institute)

Cover picture (sources):
Wang Yu Fu, Institute of Bast Fibre Crops, Chinese Academy of Agricultural Sciences 2015; THERMO NATUR GmbH & Co.KG 2015; nova-Institut GmbH 2015

Layout: nova-Institut GmbH

nova-Institut GmbH
Chemiepark Knapsack
Industriestraße 300
50354 Hürth, Germany

T +49 (0) 22 33/48 14-40
F +49 (0) 22 33/48 14-50
contact@nova-Institut.de
www.nova-institut.eu

Foreword

The first edition of Study "Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material – Study providing data for the automotive and insulation industry" was published in 2015 and is considered the most comprehensive study of the carbon footprint of natural fibres in technical applications worldwide. The special feature of the study was its transparency: all inventory data are listed in the appendix in a comprehensible manner. The results showed that the carbon footprints of the various natural fibres processed into biocomposites or insulating materials in Europe differ only slightly. Emissions that Asian natural fibres save by using fewer machines are lost when they are transported to Europe. Compared to synthetic fibres, be they polymer, glass or carbon fibres, natural fibres have significantly lower GHG emissions.

Four years later, we decided on a comprehensive update. What has changed in recent years?

- The European FP7 project "Multipurpose hemp for industrial bioproducts and biomass" (project acronym: MultiHemp) delivered several new data on hemp and other natural fibres, which are not integrated in the update. The research has received funding from the European Union, Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 311849. In the project you will find a full life cycle assessment for hemp fibre with more impact categories than in the report, focusing in GHG emissions.
- We received updated data from the European Industrial Hemp Association (www.eiha.org) on industrial hemp cultivation and processing.
- We included coupled production of seeds and fibres for hemp.
- We received updated data from the German automotive supplier DRÄXLMAIER Group on the Kenaf cultivation and production in Bangladesh.
- We now performed two allocation methods: economy and mass allocation to discuss the impacts.

Join us in celebrating the update that further improves and refines the ecological evaluation of natural fibres compared to synthetic fibres, without compromising the transparency of inventory data.

Yours sincerely

Michael Carus and Niels de Beus
Hürth, April 2019


Michael Carus


Niels de Beus

1 Introduction

In the last twenty years more and more natural fibres have started being used in biocomposites, mainly for the automotive sector and also as insulation material. In several studies, natural fibres have been identified as potential environmentally friendly alternatives (for example Haufe & Carus 2011, La Rosa et al. 2013).

In the year 2012, 30,000 tonnes of natural fibres were used in the European automotive industry, mainly in so-called compression moulded parts, an increase from around 19,000 tonnes of natural fibres in 2005. As shown in Figure 1, in 2012 flax had a market share of 50% of the total volume of 30,000 tonnes of natural fibre composites. Kenaf fibres, with a 20% market share, are followed by hemp fibres, with a 12% market share, while other natural fibres, mainly jute, coir, sisal and abaca, account for 18% (Carus et al. 2015).

The total volume of the insulation market in Europe is about 3.3 Million tonnes – the share of flax and hemp insulation material is 10,000–15,000 tonnes (ca. 0.5%) (Carus et al. 2015).

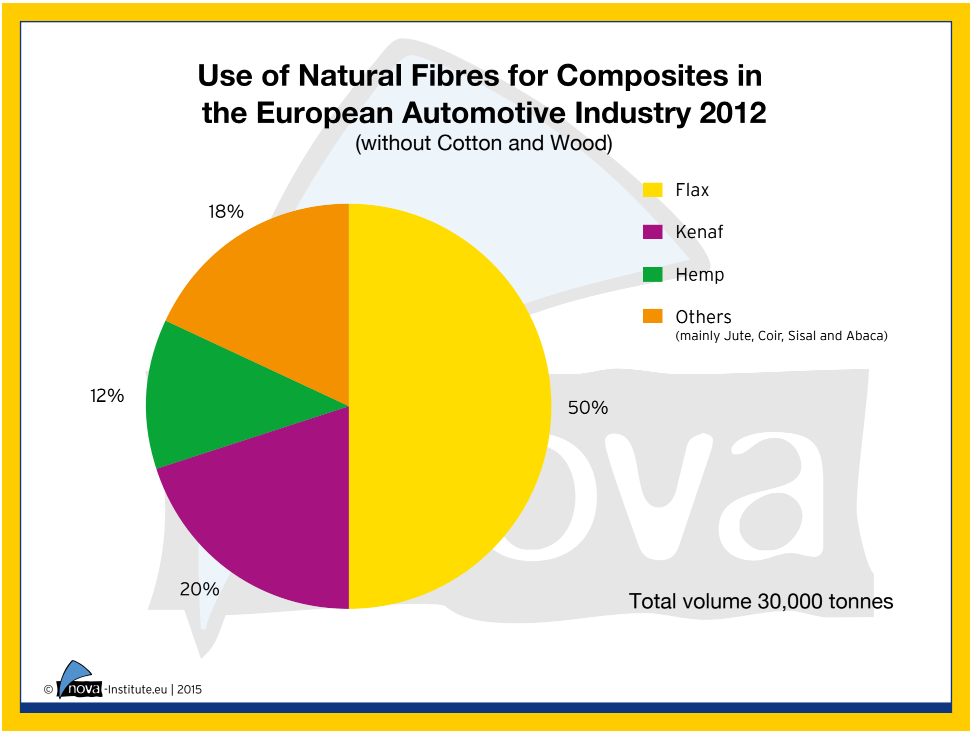


Figure 1: Use of natural fibres for composites in the European automotive industry 2012 (total volume 30,000 tonnes, without cotton and wood); "others" are mainly jute, coir, sisal and abaca (nova 2015, based on Carus et al. 2015)

Life Cycle Assessments (LCA) and carbon footprints cannot be compared easily, since the results depend on the definition of the system boundary, functional unit, data sets and allocation procedure used, among other things (Weisse, 2012). Moreover, the assumptions regarding agricultural yields and agricultural practice can also have a significant influence. In addition to these general issues, reviewing LCAs of natural fibres also shows that there are only limited data on some process steps within the fibre value chain of bast fibres. Furthermore, carbon uptake and storage in natural fibres is not always clearly shown and the impacts of the retting process is rarely discussed.

The most demanding step while conducting a LCA or calculating a carbon footprint is the collection of inventory data in order to create the life cycle inventory (LCI). Moreover, data availability is an issue as high-quality data are limited. This is particularly the case for jute and kenaf (partly improved in the second edition).

Based on the above described situation, the objective of this study is to provide industry with reliable data on the production processes and carbon footprint of the four most important bast fibres (flax, hemp, jute and kenaf). The study aims to provide insight in the entire production processes of the various fibres from cultivation to technical fibres for biocomposites and insulation material and the related carbon footprint. This study does not aim to compare the environmental impacts of the different end applications as the use of natural fibres requires further processing which could be different between applications. Nonetheless, the natural fibres resulting from the assessed processes are considered to be exchangeable among each other for the use in composite and insulation materials. The fibre quality grades are for technical non-woven applications and not for woven textile applications.

This is achieved by:

- conducting a comprehensive literature review (about 40 references including LCA studies and references from agricultural production);
- Using data collected during the European FP7 Multihemp project.

Moreover, since the carbon footprint addresses only the impact category climate change, further sustainability issues are described separately. To better understand the complete environmental impact of the different natural fibres, more environmental impact categories should be considered.

The European FP7 MultiHemp project has improved the inventory data of hemp as well as some specifics on kenaf (*www.multihemp.eu*). This study uses the data obtained within the MultiHemp project, and provides an update on the carbon footprint of natural fibres. In this update, the data obtained has been reviewed, checked with commercial producers of natural fibres and biocomposites, and updated where necessary to reflect the state of the art in natural fibre production.

2 Natural fibres in comparison

Natural fibres can be defined as fibres from plant, animal or mineral origin. Mineral fibres such as asbestos occur naturally as inorganic substances. Fibres from animals and plants are organic. Animal fibres include for example wool, cashmere, silk and alpaca. Plant fibres are extracted from plants. Depending on their function within the plant, fibres may be located in different regions of the plant. For example, fibres from dicotyledons can mainly be subdivided in seed fibres, stem fibres and fruit fibres. Figure 2 gives an overview of organic and inorganic natural fibres (Müssig & Slootmaker 2010).

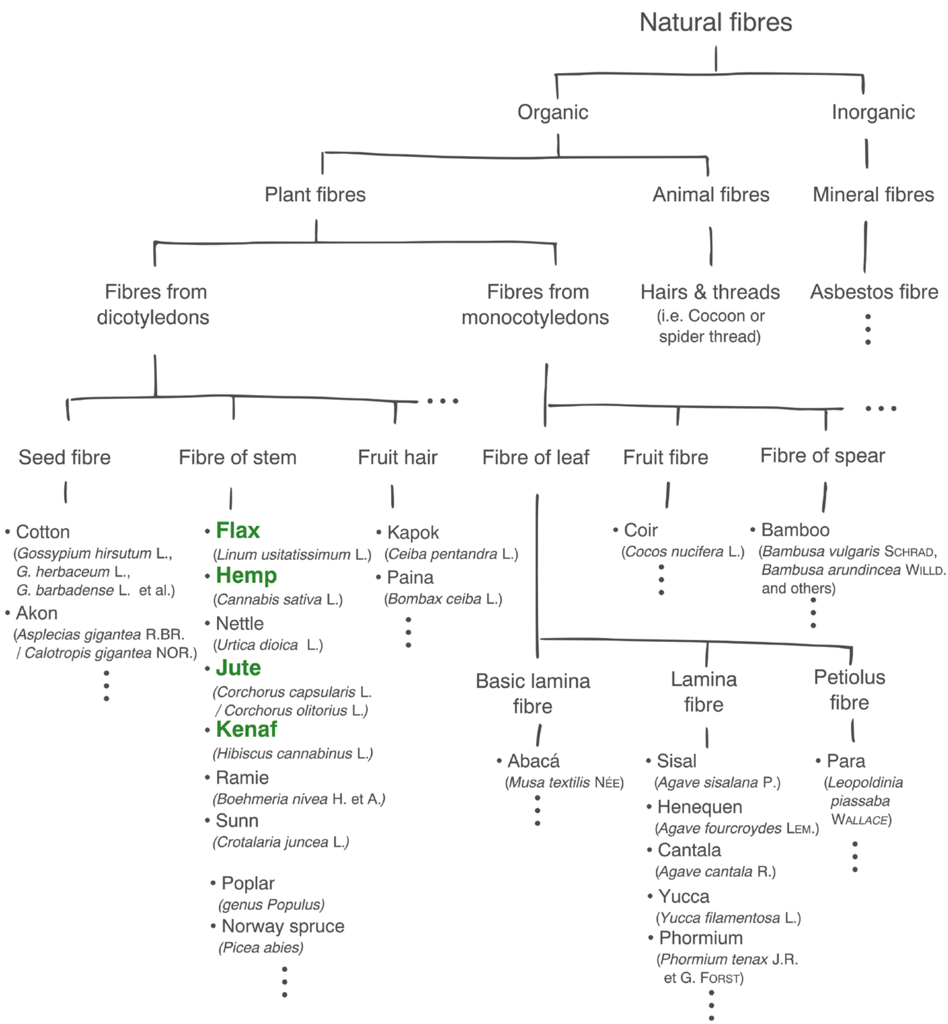


Figure 2: Overview of natural fibres (Müssig & Slootmaker 2010, adapted from Müssig 2015, by courtesy of Müssig)

Fibres found in the stems of dicotyledons (stem fibres) are also referred to as bast fibres (FAO 2008) (e.g. flax, hemp, nettle, jute, kenaf, ramie). They provide the plant with its strength and are very long as they usually run across the entire length of the stem.

Natural plant fibres are usually considered more environmentally friendly than synthetic fibres for several reasons, such as: the growth of plants results in sequestration of CO_2 from the atmosphere, natural plant cultivation consumes less energy than the production of synthetic polymers and fibres, natural fibres are produced from renewable resources, unlike the production of synthetic fibres which leads to depletion of natural resources. Furthermore, at the end of their lifecycle natural plant fibres are biodegradable. However, cultivation and processing of natural plant fibres consumes more water, may use synthetic fertilizers and pesticides, and results in emissions of greenhouse gases in some processing stages (Rana et al. 2014).

The properties of natural fibres are influenced by the conditions necessary for growth: temperature, humidity and precipitation, soil composition, and the air; all affect the height of the plant, strength of its fibres, density, etc. The way the plants are harvested and processed also results in a variation of properties. Processed to a compressing moulded part, the differences in properties are lower than differences of the natural fibres. Table 1 shows properties of selected natural fibres (flax, hemp, jute, ramie, sisal), which can all be used for biocomposites and insulation material; these properties are compared to the properties of glass fibre (E-Glass).

Table 1: Natural fibre properties compared to glass fibre (nova 2015)

	Density	Fineness	Young's Modulus / E-Modul	Elongation at break	Breaking strength
E-Glass	- -	adjustable	+ + +	- -	+ +
Flax	+	+/-	+ +	+	+
Hemp	+	-	+ +	+	+/-
Jute	+	+	+	+	+/-
Kenaf	+	+/-	+	+	+/-
Ramie	+	+ +	+ +	+	+
Sisal	+ +	-	+ / -	+ +	+/-

Compared with petrochemically based fibres, natural fibres can be processed into composites just as well with a polymer matrix in different production procedures. Besides their bio-based nature, natural fibres have good stiffness and strength and at the same time possess a low density compared with glass fibre. Young's specific modulus of natural-fibre- reinforced composites is comparable with that of glass-fibre composites. Good lightweight construction potential and positive break behaviour (i.e. they break without rough edges and the components do not splinter) are the advantages of natural fibre composites. However, their moisture expansion characteristics, their flammability and their variable quality are disadvantages (Graupner & Müssig 2010, p. 67).

Globally, cotton is the largest natural fibre produced, with an estimated average production of 25 million tonnes during recent years (2009–2016 est.) (FAOSTAT 2018). Jute accounts for around 3,3 million tonnes of production per year (based on data from 2009–2016, FAOSTAT 2018). Other natural fibres are produced in considerably smaller volumes. Globally, bast fibres play a rather small and specialized role in comparison to other fibres. The overview of worldwide production of "other" natural fibres for 1961–2013 based on FAO data (Figure 3) shows that jute has always been the most dominant of these materials. Apart from some fairly strong fluctuations, the overall volume of natural fibres produced globally has increased slightly over the last fifty years. The amount of jute has stayed more or less the same, coir has steadily increased its production volume, and production of flax and sisal has decreased.

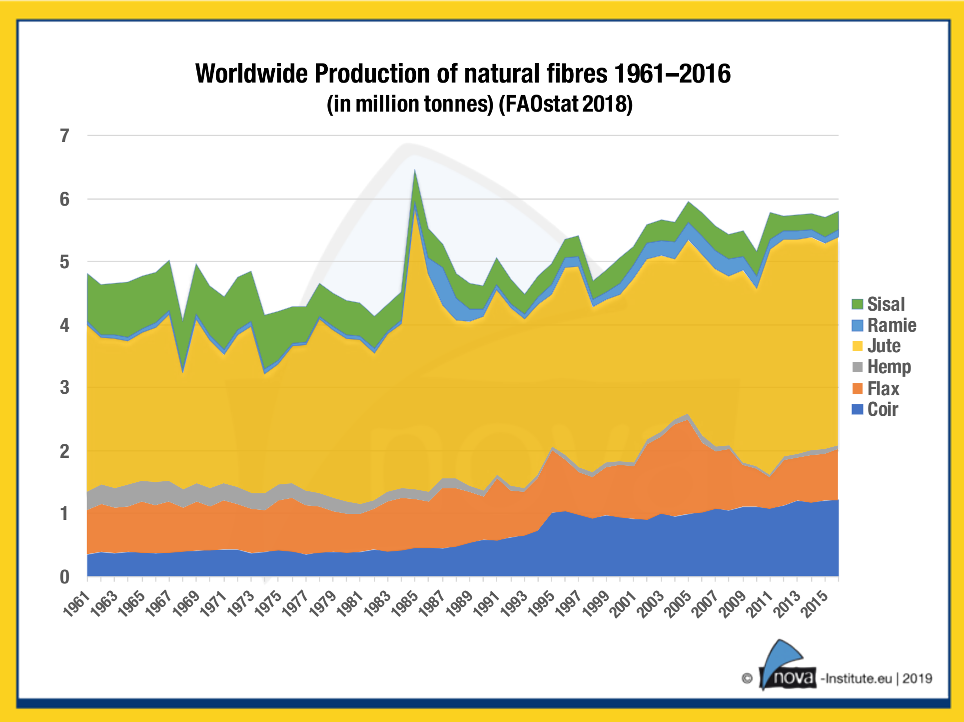


Figure 3: Development of worldwide natural fibre production 1961–2013 without cotton (nova 2019, based on FAOSTAT 2018)

Flax, hemp, jute and kenaf (in alphabetical order) are the bast fibres discussed in this study. The next section contains information on these four bast fibres. For further information on natural fibres visit *www.naturalfibres2009.org/en/fibres*. Information on flax (and hemp) fibres is available at *www.mastersoflinen.com/eng/lin/1-la- filiere-de-proximite*. For industrial use of hemp in Europe, visit the European Industrial Hemp Association online at www.*eiha.org*.

Facts about jute (and kenaf) are presented by the FAO as well as the Indian jute commissioner and are available at *www.fao.org/economic/futurefibres/fibres/jute/en* and *www.jutecomm.gov.in*, respectively.

Flax *(Linum usitatissimum L.)* (Source: nova 2015)

2.1 Flax

Latin name: *Linum usitatissimum L.*

Flax is an erect annual plant growing between 1.0 to 1.2 m tall, with slender stems. Flax fibres are amongst the oldest fibres in the world: the production of linen goes back at least to ancient times. Flax fibre is twice as strong as that of cotton and five times as strong as that of wool; its strength increases by 20% when wet (Tahir et al. 2011).
The yield stability of flax depends on the variety and its resistance to diseases. Because of the accumulation of harmful fungi, bacteria and root extractions, a six-year cultivation gap is recommended so as not to suffer a total loss of the harvest. Moreover, the nutrient supply to the plant, in particular nitrogen, should be controlled carefully and not exceed recommended amounts. After flax cultivation, the soil is left with few nutrients and is mostly weed-free (Heyland et al. 2006, p. 283).

Flax – cultivation area and production volume

The EU, Belarus, the Russian Federation and China are the largest producers of flax. France, the UK, the Netherlands and Belgium are the largest producers of flax within the EU. In 2016 France produced 587,000 tonnes, Belgium 87,162 tonnes, the UK 15,118 tonnes and the Netherlands 13,764 tonnes of straw (FAOSTAT 2018). The global flax cultivation area was around 220,000 hectares in 2016. Within Europe and globally, France has the highest cultivation area, with around 87,000 hectares in 2016 (FAOSTAT 2015).

Flax – main application

Flax is mainly produced in the traditional way of long-fibre processing with a preceding field-retted flax straw. This can be only done in areas with high humidity, for example near the coast. Up to 90% of the European flax long fibre is sold to China and processed into yarn, fabrics and cloths. The by-product tow (short fibre) is used in different technical applications, just like the fibres from the total fibre line (biocomposites in automotive applications and insulation). In periods of high demand from the linen fashion market, high amounts of the short fibres are also mechanically cottonized and used in combination with cotton or viscose/ lyocell (Carus et al. 2015, p. 54).

Flax – relevance for the automotive industry

As is shown in Figure 1, flax fibres had a market share of 50% in the use of natural fibres for composites in the European Automotive Industry in 2012. It is predicted that flax fibres will continue to play a dominant role within natural fibres, since a large amount of technical short fibres are created as side-products (tow) of the long-fibre textile production, which can be sold at an economic price at relatively good quality. The only disadvantage is: If the fashion year is successful, the textile industry also requires more short fibres, in order to cottonize them and process them together with cotton. In cycles, this leads to scarcity and a significant price increase. This problem will continue to exist and may lead to a slight decrease in use of flax fibres (Carus et al. 2015).


Hemp *(Cannabis sativa L.)* (Source: nova 2015)

2.2 Hemp

Latin name: *Cannabis sativa L.*

Hemp is a taproot annual herbaceous plant with erect stem reaching up to 4 meters in height (Amaducci & Gusovius 2010). Its benefits (suppressing weeds, free from diseases, improving soil structure and no consumption of pesticides) make hemp an attractive crop for sustainable fibre production. Hemp is a crop that has great adaptability to climatic conditions and it does not require pesticides[1] or irrigation water. Its consumption of fertilizers is modest and hemp crops suppress weeds and some soil-borne diseases, meaning that at the end of its cultivation, soil condition is improved and healthier (Gonzalez-Garcia et al. 2007).

Hemp – cultivation area and production volume

Hemp crop originates from the temperate regions of central Asia but is nowadays cultivated worldwide. China, Canada and Europe are the most important cultivation regions of hemp. In 2018 the global cultivation area of hemp was about 150,000 ha worldwide. Main cultivation regions are Canada with 56,000 ha (record), China with 47,000 ha and Europe with 43,000 ha (record). The main cultivation countries in Europe are France, Estonia, Romania and Italy. The European cultivation record is more due to the demand for hemp seeds and cannabinoids than for fibres. About 30,000 to 40,000 t of hemp fibres are produced in Europe. The fibre is used for speciality paper, insulation and biocomposites, mainly for automotive.

Hemp – main application

Hemp is used for different market applications. These are provided with fibres, shives and seeds/oil. In Europe, hemp is mainly produced in the total fibre line to gain technical short fibres. Long fibre processing for textiles does not exist in Europe anymore. In Europe the main hemp fibre products are pulp and paper, followed by insulation materials and compression moulding parts for the automotive industry. The most dominant product from hemp shives is animal bedding, especially for horses. The most important market for hemp seeds is animal feed and food (Carus et al. 2015).

Hemp – relevance for the automotive industry

In 2012 hemp fibres had a market share of 12% as natural fibres for composites used in the European Automotive Industry (as seen in Figure 1). In 2005 hemp fibres had a market share of 9.5% in the use for composites in the European Automotive Industry. Between 2005 and 2012 hemp fibre increased its market share. The development for hemp fibres in the coming years is expected to depend on the following factors (Carus et al. 2015):

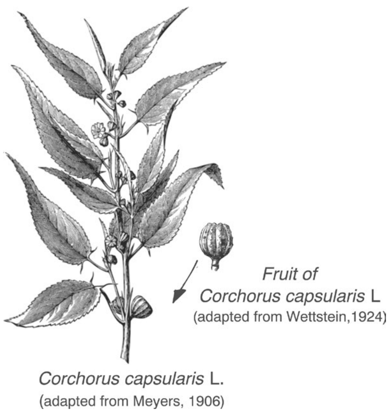
[1]Exception: Herbicides might be used during field pretreatment.

- Hemp fibres are almost exclusively produced in Europe, with some quantities coming from China. This dominance could change, depending on hemp industries being set up in Canada, the U.S. and Russia;
- In Europe (and in future probably also in the U.S. and Canada) hemp fibres are produced in a total fibre line, in a modern and techno-economic optimized processing line;
- With this technology, it is possible to produce a technical short fibre under high ecological and social standards at the same price level of Asian imports;
- However, this technology has its limitations when it comes to fibre fineness, regularity and residual shive content. This means that press-moulded parts can easily be produced at a high quality, but they can possess an irregular surface structure, which does not allow for very thin laminations;
- To solve problems of irregularity, additional treatments such as steam explosion, ultrasound or different chemical or enzymatic processing could be feasible approaches. These processes have not come into mainstream use so far, mostly due to cost reasons. Fibre quality could be even better than those obtained by water retting, but prices are much higher.

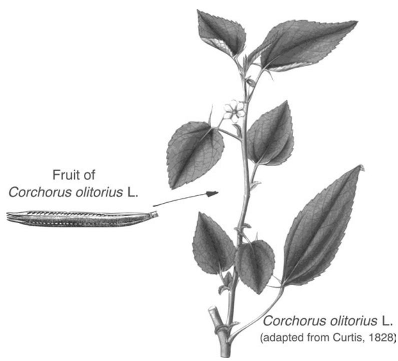
2.3 Jute

Latin name: *Corchorus capsularis L. / Corchorus olitorius L.*

Jute, tossa jute (Corchorus olitorius L.) and white jute (Corchorus capsularis L.) are extensively cultivated in India for their fibre. Jute is an annually grown natural fibre. Tossa jute and white jute are similar in general appearance. They have long straight stems about 3 cm in circumference and are branched at the top. The two species mainly differ in their fruits: whereas white jute has a rough, wrinkled, spherical seed box of about 0.75 cm in diameter, tossa jute has an elongated pod



White jute *(Corchorus capsularis L.)*
(Source: Müssig & Slootmaker 2010, adapted from Müssig 2015. - by courtesy of Müssig)



Tossa jute *(Corchorus olitorius L.)*
(Source: Müssig & Slootmaker 2010, adapted from Müssig 2015. - by courtesy of Müssig)

like a miniature cucumber about 5 cm long. Furthermore, white jute is usually shorter than tossa jute. White jute is grown on lower-lying ground, while tossa jute is grown on higher ground (Rahman 2010). Good conditions for jute cultivation are in the flood plains of the great rivers of the tropics and sub-tropics for example, where irrigation, often characterized by extensive flooding, and alluvial soils combined with long day lengths are available. Jute is grown in rain-fed, hot humid and sub-tropical conditions in the Bengal Basin in India and in Bangladesh (Sobhan et al. 2010).

Jute – cultivation area and production volume

Jute is the most important natural fibre of the bast fibres, and the second most dominant natural fibre on the world market after cotton. In 2016 worldwide production of jute was 3.3 million tonnes. With 1.9 million tonnes, India is the most important producing country, closely followed by Bangladesh at 1.3 million tonnes. China (mainland) is the third important country, with 40,000 tonnes in 2016.
The overall production area is about 1.5 million ha. The production area in India is 765,000 ha and in Bangladesh around 678,000 ha (FAOSTAT 2018).

Jute – main application

Jute has a wide range of usage. The dominant and traditional application of jute fibre worldwide is packaging materials such as hessian, sacking, ropes, twines, carpet backing cloth, etc. Moreover, jute is also used for so-called "diversified jute products" to overcome the declining market for the conventional products of jute. These are generally products for new, alternative and non-traditional uses of jute. For instance, jute is used for the following applications: floor coverings, home textiles, technical textiles, geotextiles, jute-reinforced composites (automotive interior parts), pulp and paper, particle boards, shopping bags, handicrafts, clothing, etc. (Rahman 2010).

Jute – relevance for the automotive industry

Jute could indeed become an important natural fibre for the automotive sector. Volumes and logistics are at a high level, but the fogging problem from batching oil has thoroughly damaged the reputation of jute (batching oil is used in the textile process chain to make the fibres easier to process). Today it should be easy to obtain large volumes of jute fibres free of batching oil, processing capacities often surpass demand from the mostly decreasing traditional applications. However, the ecologically and socially questionable activity of water retting and the lack of a modern processing technology remain problematic (Carus et al. 2015, p. 52-53).

Jute field (Source: Gupta 2015)

Kenaf *(Hibiscus cannabinus L.)* (Source: nova 2015)

2.4 Kenaf

Latin name: *Hibiscus cannabinus L.*

Kenaf is an annual plant originating from West Africa, growing to 1.5–3.5 m tall with a woody core. The stem's diameter is 1–2 cm and they are often, but not always, branched. The fruit is a capsule 2 cm in diameter, containing several seeds. The stem contains a bast fibre portion comprising 26–35% (by dry weight). The average length of the fibre is 2.5 mm, providing a desirable blend for many pulp and paper applications. Other uses of kenaf bast fibre include cordage, composite materials, and coarse cloth (Pari et al. 2014). Kenaf shows robust mechanical properties (Aji et al. 2009). In recent years, two main reasons have contributed to the very high interest in kenaf cultivation. One is kenaf's ability to absorb nitrogen and phosphorus within soil. The other is that kenaf is able to accumulate carbon dioxide at a significantly high rate (Aji et al. 2009).

Kenaf – cultivation area and production volume
The FAO groups kenaf statistics together in one category with so-called "allied fibres". India (110,000 tonnes) and China (60,000 tonnes) are the largest producers of kenaf, according to FAO data (2016), since three quarters of the world's kenaf production originated there in 2015/2016. Bangladesh is not included as a kenaf-producing country at all, even though fibre traders as well as manufacturers have repeatedly stated that kenaf fibres are imported from Bangladesh on a regular basis (Carus et al. 2015, p. 54-55). Kenaf is also grown in China and Indonesia.

Kenaf – main application
Kenaf can be grown for various applications. The crop has traditionally been used to produce fibre and food. The fibres can be used to make cordage, rope, burlap cloth, and fishnets because of its rot and mildew resistance. Besides these traditional applications there are a number of new uses, such as paper pulp, building materials, biocomposites, bedding material, oil absorbents, etc. Recently it has also come to be considered an important medicinal crop, as its seed oil has been shown to cure certain health disorders and manage blood pressure and cholesterol (Monti & Alexopoulou 2013).

Kenaf – relevance for the automotive industry
Kenaf fibres are used as reinforcement or filler in polymer composite materials, which are used increasingly in the automotive industries. Kenaf fibre composites are used in automotive applications primarily because

of its light weight and end-of-life properties (Monti & Alexopoulou 2013). Carus et al. (2015) state that the growing demand for kenaf in the automotive industry originates from Original Equipment Manufacturers (OEM). In this context the following considerations arise (Carus et al. 2015):

- Non-woven producers are reporting high fibre losses during the processing of kenaf fibres;
- Water retting is practiced to obtain the desired fibre qualities, as is practiced for jute. However, water retting implies negative ecological effects (biochemical oxygen demand of the retting water) and negative social impacts (mostly working conditions and wages) in the fibre producing countries, e.g. Bangladesh, India and Indonesia;
- Nevertheless, the quality of water-retted kenaf fibres make them especially interesting for the automotive industry, since they allow for very thin laminations on composites, which are desirable for design and weight reasons;
- In this second edition of this study, we also included a new kenaf fibre process from Bangladesh with mainly manual processing (DRÄXLMAIER Group, 2018);
- It is not easy to distinguish kenaf fibres from jute fibres, so customers cannot always be certain that their bale labelled "kenaf" does not contain any jute. In the textile process chain, jute is treated with batching oil to make the fibres easier to process. Due to fogging problems, fibres treated with batching oil are not acceptable for the automotive industry. However, if jute fibres that are free of batching oil are used, there is no fogging and they can be processed just as well as kenaf, sometimes even better.

Kenaf field (Source: Müssig 2013)

3 Carbon footprint

3.1 Introduction to the carbon footprint methodology

The Carbon Footprint is an abbreviation or synonym, because aside from a carbon balance being created, a greenhouse gas balance is also created, which, in addition to carbon dioxide (CO_2), also includes methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons. There are three main Product Carbon Footprint (PCF) standards that are applied worldwide: PAS 2050, GHG Protocol and ISO 14067. The main difference to LCA is that instead of many impact categories (e.g. global warming potential, acidification potential, eutrophication, ozone formation potential), only the impact category global warming potential is considered. The characterization factors are based on the default values given by the IPCC 2013 – timeframe 100 years. This carbon footprint is an assessment from "cradle to gate".

Goal and scope in a nutshell

The method of the carbon footprint assessment is based on ISO 14067.

Goal: provide data on the intermediate fibres to the biocomposite and insulation industry and to assess the carbon footprint of different bast fibres

Functional unit: 1 ton bast fibre in comparable technical quality for non-wovens and biocomposites

System boundaries: cradle-to-gate

Approach: Attributional carbon footprint based on both mass and economic allocation

Data sources: Primary production data was obtained from 2014-2018, literature and own calculations.

The comparison of the intermediate bast fibres has not been reviewed, but all inventory data are published in the appendix for a review.

Biogenic carbon storage is considered (see also chapter 4.2)

3.2 Goal and scope for flax, hemp, jute and kenaf

Subsequent, general specifications for the system used in this study are described:

Goal

The goal of this study is to provide industry with the carbon footprint of the production of technical bast fibres for biocomposites and insulation material. The study focusses on the production process of the fibres to provide inventory data for the further processing to different applications. The full inventory data for the production of the fibres can be found in the appendices to provide full transparency.

Functional unit

In this project the functional unit is defined as "one tonne of technical fibre for the production of non-wovens for biocomposites or insulation material". Data has been collected on the manufacturing processes for technical fibres which provide similar qualities in the final application, hence the fibres are interchangeable.

Time-related coverage

Inventory data related to current conditions (2014-2018) of the agricultural system, fibre processing and transportation were obtained from farmers and fibre producers and where necessary complemented with bibliographic sources.

Geographical coverage

The geographical areas covered in this study are Europe for hemp and flax, India for jute, and Bangladesh/India for kenaf. Moreover, Bangladesh/India transportation to non-woven-producers was assumed to take place in Europe.

Data uncertainty

Variability in the collected data has been accounted for by including error margins of the data. This is specially relevant for agricultural processes as agricultural practices vary depending on local conditions. Furthermore, yields can vary based on weather conditions. To take these aspects into account, error margins (minimum and maximum values) for the data have been determined based on literature. These are reported in the appendices and allow the assessment of a likely range for the impact of the technical fibre.

System boundaries

This study covers the cultivation, harvest, (retting,) processing and transportation of natural bast fibres from the northwest of Europe (flax and hemp), India and Bangladesh (jute and kenaf) to non-woven producers in Europe. Figure 4 below shows a schematic diagram of LCA processes from cradle to gate. Retting is discussed in a seperate chapter (see Chapter 3.3). The system studied includes the following general processes:

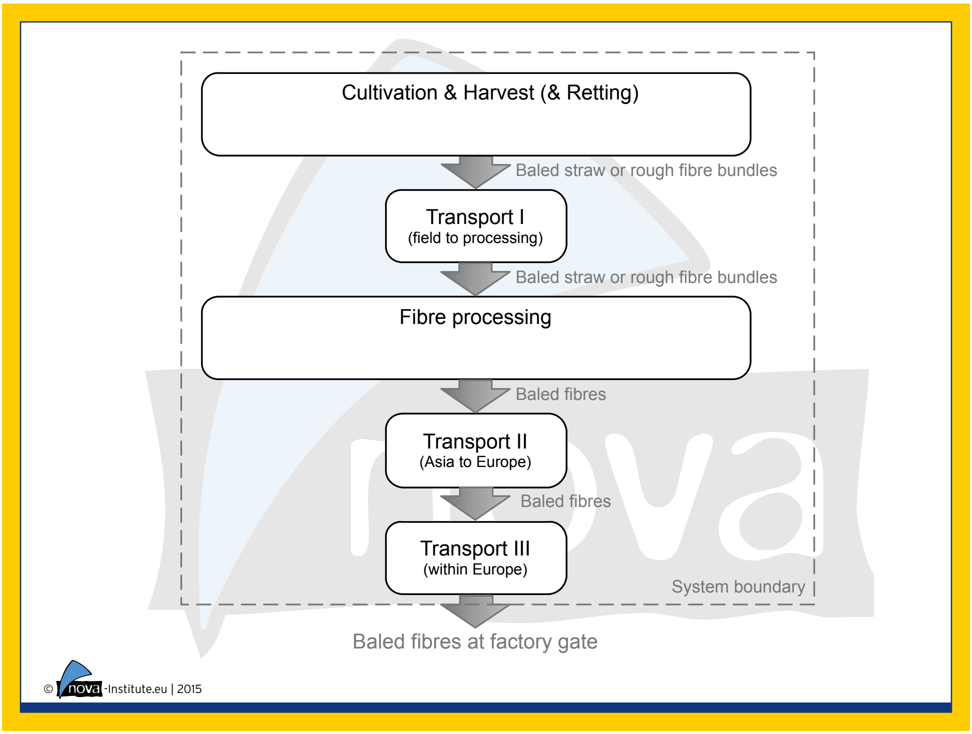


Figure 4: General system boundary and processes in this study (nova 2015)

- **Field operations**, including machinery for:
  - soil preparation
  - sowing
  - fertilizer-application
  - pesticide-application
  - cutting
  - turning (in case of hemp and flax)
  - swathing (in case of hemp and flax))
  - baler and bale-mover (in case of hemp and flax)

- **Seeds**
  Based on a study from Evans et al. (2006) the carbon, methane and NO_x requirement of seeds is estimated as followed: The emissions for cultivation were assumed to be as detailed as those for fibre-cultivation, with an allocation to seed of 70%. Road transportation to the cultivation area with a round trip of 100 km and low-density polyethylene (LDPE) packaging weighing 4 kg were also assumed.

- **Fertilization**
  This group classifies emissions from mineral fertilizers and emissions from organic fertilizer (pig slurry) for hemp (scenario 2). Inventory data on the production of fertilizers used in the system were taken from the Ecoinvent database (“ecoinvent data v3.4”). Please note that only a second and third scenario is conducted for hemp fibres using organic fertilizer (pig slurry) and cultivation for both seeds and fibres. This is due to the fact that flax does not tolerate organic fertilizers. Jute and kenaf are not fertilized with organic fertilizer (manure), because the amount of animal production is too low to leave a manure surplus for fertilization. On the other hand, the Netherlands and the north of Germany do have pig slurry and poultry and cattle manure surpluses. Furthermore, the north of Germany boasts high quantities of fermentation residues. Therefore, the application of organic fertilizer (here: pig slurry) is only taken into consideration in the hemp fibre system (scenario 2).

- **Fertilizers induced N_2O-emissions**
  N_2O-N emissions are 1% of applied N (also from the nitrogen-yield of the pig slurry). N_2O emissions are then obtained by dividing by 28 and multiplying by 44.

- **Pesticides**
  According to the definition of EPA[2], herbicides, insecticides and fungicides and their emissions are included in this system stage. Inventory data were taken from the Ecoinvent database (“ecoinvent data v3.4”).

- **Transportation I**
  from the field to the fibre processing facility, or from the water-retting facility to the “fibre-fine-opening-process”.

- **Fibre Processing**
  The processing of the stems into the fibres is different for flax and hemp compared to jute and kenaf. Flax and Hemp are processed using the “Total fibre line”, and takes place within Europe. Literature was used to assess the electricity and diesel consumption of this process. For jute and kenaf, the fibre fine opening process takes place in South Asia. This is the first step in the production of textiles from jute and kenaf. Hence assumptions on electricity and diesel use could be based on that part of the textile production process. To summarise:
  - Total fibre line (flax and hemp);
  - Fibre fine opening process (jute and kenaf).

[2] EPA (*www.epa.gov/pesticides/about/* - last accessed 2015-02-24) uses the following definition of pesticide: A pesticide is any substance or mixture of substances intended for: preventing, destroying, repelling, or mitigating any pest. Though often misunderstood to refer only to insecticides, the term pesticide also applies to herbicides, fungicides, and various other substances used to control pests.

- **Transportation II**
  from the fibre processing site in Asia to the harbour in Hamburg.
- **Transportation III**
  from the fibre processing site in Europe or the harbour in Hamburg to the non-woven-producer in Europe.

Allocation

Within LCA, allocation occurs whenever a process produces more than one product (multi-output process), in which case the environmental burden caused by the process needs to be distributed over the different products. The ISO 14040 provides a list of how to approach allocation, with the following preference:

- Avoid allocation by system expansion or increased detail;
- Partitioning based on physical relationships;
- Partitioning based on other relationships such as income (Baumann & Tillmann 2004).

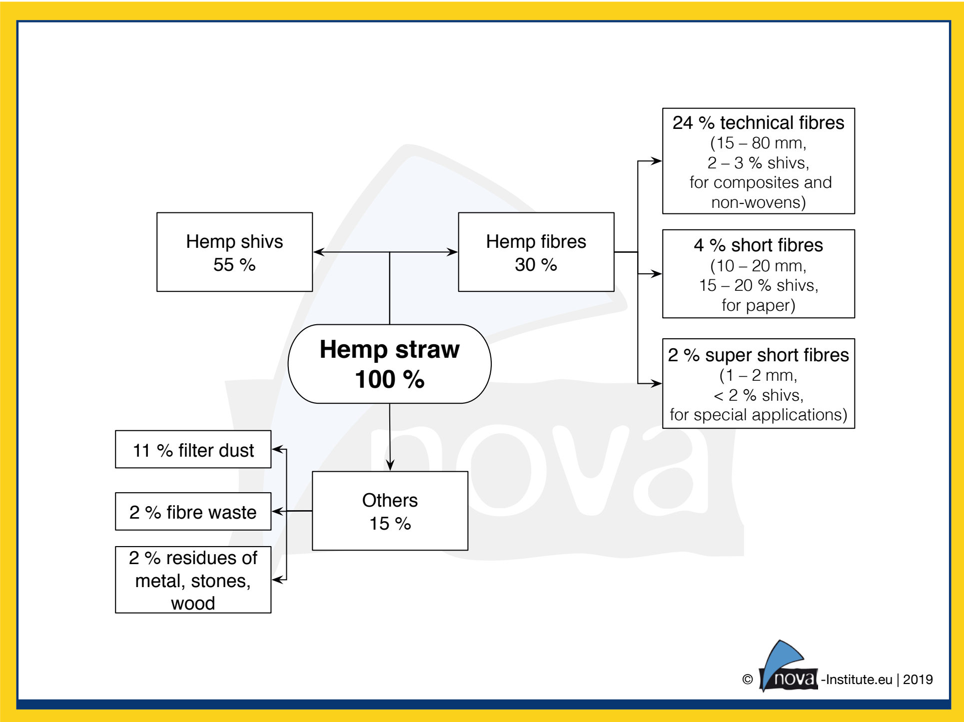


Figure 5: Typical product fractions of a total fibre line for hemp fibre production (nova 2019)

Allocation was necessary within the study as all four fibre systems provide more than one product: e. g. the fibre process also produces shives and dust (see Figure 5). In this publication mass-based and economic-based allocation were used for all four investigated systems. It should be noted that mass-based allocation is more stable than economic allocation, as prices of products tend to fluctuate. The prices of natural fibres fluctuate according to supply and demand, which is affected by many factors, ranging from agricultural yield to fashion trends.

Additionally, prices for the by-products (hemp and flax shives, jute and kenaf cores) can vary widely, depending on time reference, region and fibre type. On the other hand, mass-based allocation underestimates the role of the fibre, the main target and high value product of the whole process. All the different fibre types produced out of the total fibre line (as seen in Figure 5) have been summarized to one output of fibre for simplification reasons. Similarly, this procedure was adapted for other natural fibres, as can be seen in the Appendix. Allocation is performed per actor in the value chain. The allocation factors are presented in Appendix E. For the economic allocation within the processing of jute and kenaf assumptions have been made for the price of the side streams.

Limitation

The study is a cradle-to-gate study for an intermediate product. The processes to convert the fibres into final products is not included in this study. Different applications require different further processing into the final product. As the goal of the study is to provide industry with data on the carbon footprint of the fibres as intermediates, further processing is not considered in this study. Furthermore, it should be noted that the different applications of the natural fibres result in variability in the use and end-of-life phase. Due to limited and unreliable data regarding the retting and the uncertainty within the retting process, this is not included in this study. The impact of different retting processes can have a significant impact on the outcome of the carbon footprint. for more information on retting, see chapter 3.3. The study only assesses the carbon footprint of the different natural fibres. To better understand the complete environmental impact of the different natural fibres, more environmental impact categories need to be considered. This study has not been reviewed, nonetheless the life cycle inventory and allocation factors are provided in the appendix.

3.3 Retting

Retting is a (micro)biological fibre separation process, which can be conducted in several ways, including dew and water retting and some new processes such as chemical, enzymatic or steam explosion. After harvesting, the stems are usually kept either in the field (dew retting) or under water (water retting) for two to three weeks, during which the pectic substances that bind the fibre to other plant tissues are softened and degraded by microorganism based enzymatic activity. The traditional methods for separating the long bast fibres are mostly based on water retting, and also based on dew. Both methods require 14 to 28 days to degrade the pectic materials, hemicellulose, and partial lignin. Even though the fibres produced from water retting can be high quality, this method has its weaknesses, in that it takes a long time and causes water pollution (Tahir et al. 2011). Furthermore, the procedure utilizes great quantities of water, which in turn leads to large quantities of waste water. Waste water requires considerable treatment, as it has a high biological and chemical oxygen demand. For example, Zawani et al. (2013) have shown that during jute retting in ponds there is sharp increase in the water's biochemical oxygen and chemical oxygen uptake. Moreover, Mondal & Kaviraj (2007) found that retting water leads to a sharp decrease in dissolved oxygen. Lastly, it has been known for centuries that the depletion of oxygen due to retting water in rivers causes fish mortality.

In general, water retting can be used with flax, hemp, kenaf and jute. Nowadays it is mostly used with kenaf and jute. Looking at greenhouse gas emissions, literature only states methane emissions for jute water retting. In comparison, literature does not provide data for GHG emission from dew retting, though they might exist.

The following references on jute water retting were found:

- Banik et al. (1993) state that: "… in vitro experiments carried out in our laboratory indicate that about 3.1 mg of methane are evolved per gram of jute stem retted". The experiments were conducted over four years in jute-retting tanks in West-Bengal, India.
- Islam & Ahmed (2012), based on data from the International Jute Study Group 2011, say that "Methane emitted during retting has been estimated to be 1–2 m^3 kg^{-1} of solid material, which on computation gives an average of 1.428 kg methane per kg of jute fibre. … It can be used for household purpose" (p. 27). These numbers are also mentioned in Üllenberg et al. (2011, p. 138) for stem retting. Moreover this article also mentions that CO_2 and methane, which are the main contributors to global warming, are emitted during retting. There are no numbers listed for CO_2-emissions during retting. The retting of jute-ribbons causes less emissions (Üllenberg et al. 2011, p. 138).
- Mudge & Adger (1994, p. 23–24) calculate with the following approach: "…, for anaerobic decomposition of coarse fibres in this study it is assumed that at least 12 percent of the anaerobically decomposing stem tissue in retting ponds is converted to methane, since the decomposing mixture in the flooded rice fields does not differ greatly from the decomposing tissue in the retting ponds". And estimated 15% of stems are said to have decomposing stem tissue. Based on this estimate we calculated methane conversion for one tonne of stem; this accounts for 0.018 tonnes methane per tonne of stem.

Apart from CO_2, methane and H_2S may sometimes be produced during the anaerobic phase. Accumulating volatile fatty acids, especially butyric acid, are responsible for the characteristic, unpleasant smell arising from water retting (Ayuso 1996). However, direct air emissions from retting were not considered in this study due to a lack of emission data.

Table 2: Methane emissions during water retting of jute

Methane emitted during water retting of jute				
	Unit	Banik et al. (1993)	Islam & Ahmed (2012) and Data from the International Jute Study Group 2011	Mudge & Adger (1994)
Geographic coverage		India	Bangladesh	Global
Methane per kg solid material	m^3 CH_4/kg solid material		estimation: 1-2	
Methane per t stem	kg CH_4/t stem	3.1		18(*)
Methane per t fibre	kg CH_4/t fibre	15.5(**)	1,428	90(**)
CO_2-eq per t fibre	kg CO_2-eq/t fibre	434	39,984 (not scientifically comprehensible)	2,520

(*) own calculation based on the estimations in Mudge et al. (1994).
(**) values calculated on the methane-emission per tonne of stems and the assumption that 1 t stem is processed to 0.2 t fibres (plus shives).

Since the data above (see Table 2) is not consistent and its sources cannot be verified, the carbon dioxide equivalent of the methane emissions varies greatly: between 400 to 40,000 tonnes CO_2-eq per tonne of jute fibre. The process of retting has not been covered so far in of the literature consulted on LCAs. We suggest that experiments should measure values for greenhouse gas emissions of the retting process (dew and water retting).
Experts have hitherto estimated that greenhouse gas emissions from water retting may be higher compared to those of field retting, because of the assumed methane emissions during water retting. On the other hand, experts state that N_2O emissions from field retting cannot yet be excluded. Since N_2O emissions have a global warming potential of 265 kg CO_2-eq per kg (GWP 100) of nitrous oxide emission, these emissions could also have a negative effect on the carbon footprint. Retting was not included in this study due to the already mentioned uncertainty of the given data; nevertheless, its influence may be significant.

The next chapters present life cycle inventory data as well as the separately calculated carbon footprints for each natural fibre.

Scene of jute water retting (Source: Gupta 2015)

3.4 Carbon footprint of flax

Data for flax fibre production were gathered from flax fibre producers in Middle Europe and complemented with data from the literature. The inventory data used are shown in Table A in the Appendix. Figure 6 shows stages in the life cycle of flax fibre production included in this study.

Cultivation and harvest consist of the following stages: pre-sowing application of pesticides, ploughing and harrowing, fertilizer application, sowing, pesticide application, cutting the plants, turning, swathing, baling and bale moving. Lorries transport baled flax straw. Fibre is processed in a total fibre line, followed by lorry transport of the fibres to the gate of the non-woven producer.

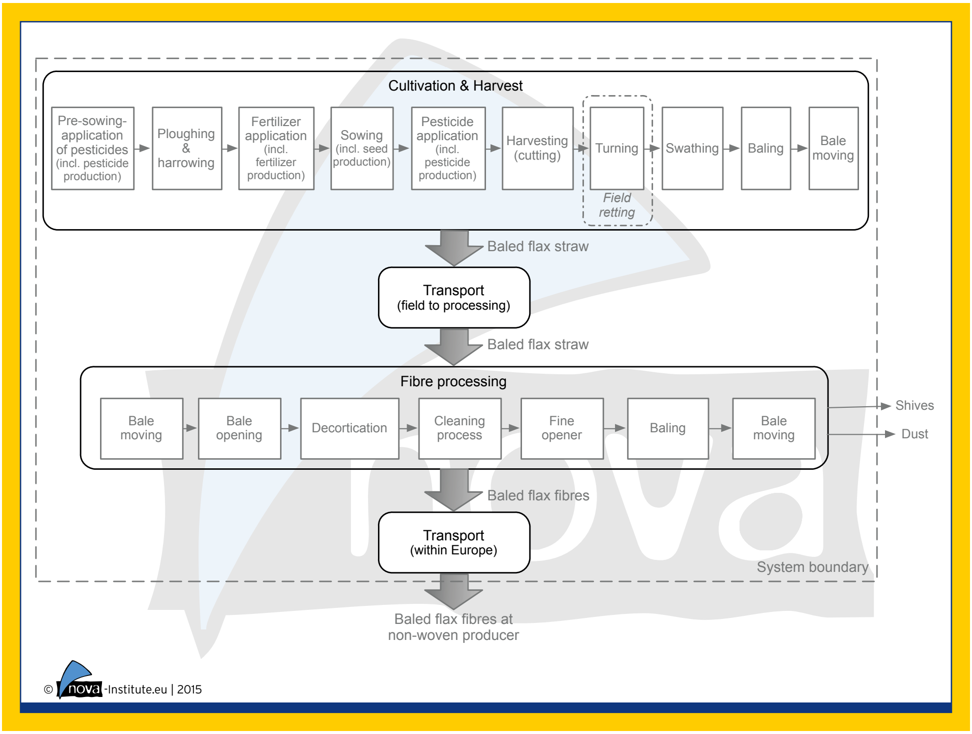


Figure 6: System boundary and process chain of the flax fibre production (total fibre line) (nova 2015)

The (cradle to gate) carbon footprint of flax fibre production in the case described above is 349 kg CO_2-eq/tonne of flax fibre when mass allocation is used and 902 kg CO_2-eq/tonne of flax fibre when economic allocation is used. The result is presented in Figure 7, which shows the greenhouse gas emissions for the production and transportation of one tonne of flax fibre arriving from Europe at the factory gate of a non-woven producer in Germany.

Cultivation and harvest is subdivided into five stages and is shown in Figure 7: field operations, seed production, fertilizer production, release of fertilizer-induced N_2O-emissions and pesticides production (mainly herbicides). The impact from transporting the straw to the fibre processing facility, fibre processing and transportation of the fibre to the factory gate of a non-woven producer are shown separately. As can be seen, the impact of fertilizer production is the highest, followed by the field operations. Emissions from the fibre processing step have the third largest release of GHG emissions.

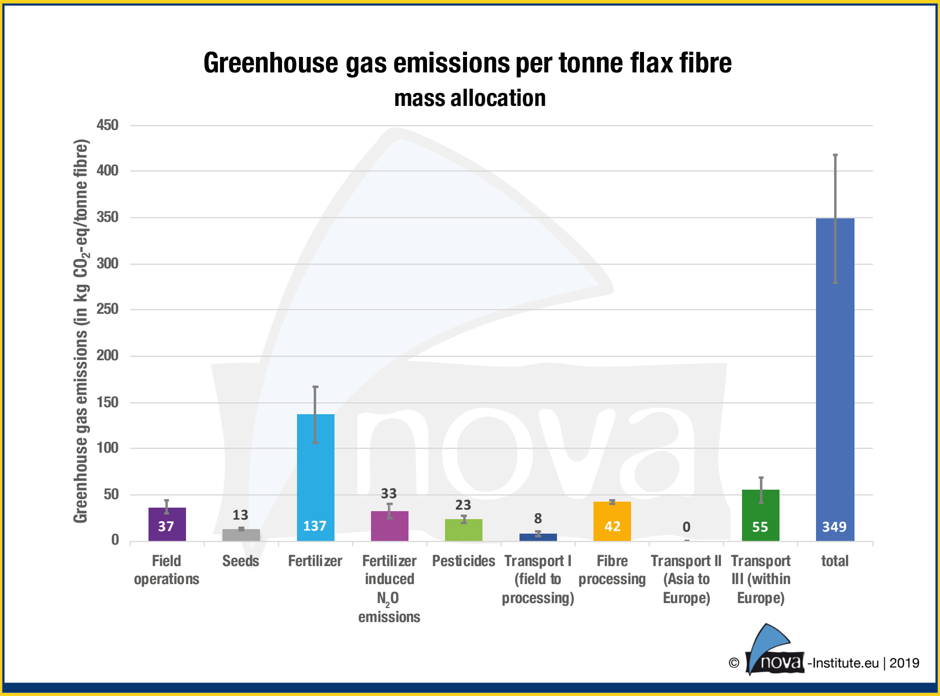


Figure 7a: Greenhouse gas emissions of 1 tonne flax fibre from the cultivation in Europe to the factory gate of the non-woven producer in Germany (nova 2019)

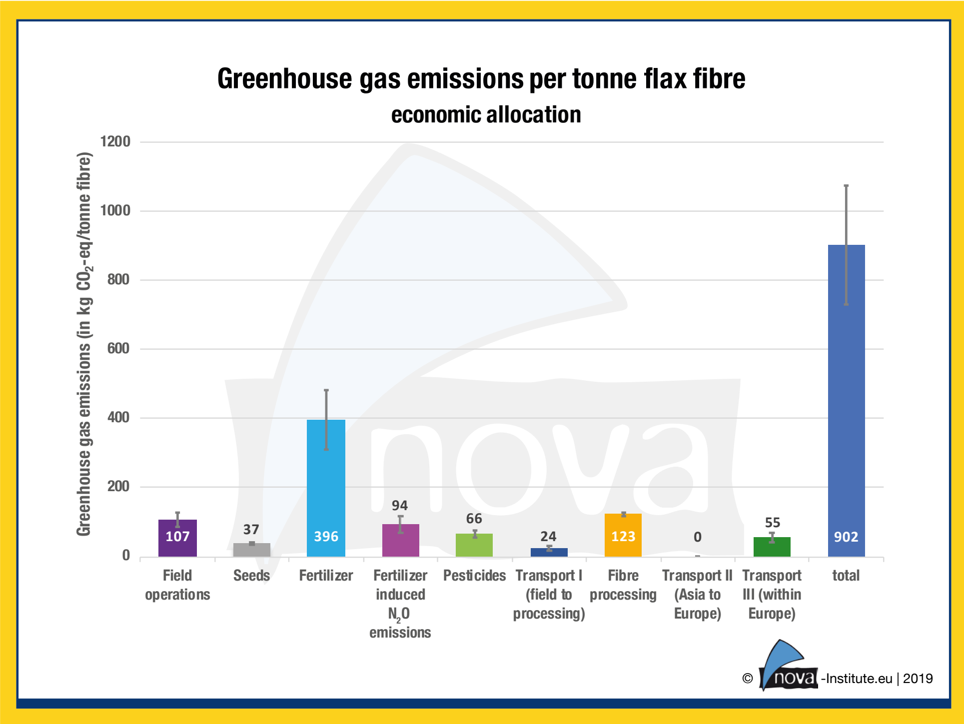


Figure 7b: Greenhouse gas emissions of 1 tonne flax fibre from the cultivation in Europe to the factory gate of the non-woven producer in Germany (nova 2019)

3.5 Carbon footprint of hemp

The cultivation system for hemp is similar to the flax system, with the following differences: higher application of mineral fertilizer, harrowing and sowing are done in one step and no application of pesticides after sowing. However pesticide application can take place before sowing as pre-treatment of the field with herbicides. Further steps are shown in Figure 8. Inventory data of the hemp fibre process is shown in Table B in the Appendix. Three different scenarios are described for hemp fibre cultivation in the Netherlands: scenario one involves fertilizing hemp with mineral fertilizer, while scenario two uses organic fertilizer, in particular pig slurry. Scenario three involves fertilizing with mineral fertilizer and harvest of straw and seeds (for food/feed applications). The second scenario was based on two reasons: (1) Pig slurry is available in large amounts in the north of the Netherlands. (2) Hemp tolerates organic fertilizer. For the other fibres the use of organic fertilizers is not assessed, as flax does not tolerate organic fertilizer. Moreover, India and Bangladesh, the cultivation regions for jute and kenaf, have no manure surpluses. The third scenario is included as hemp is often grown as a dual-purpose crop, where both straw and seeds are produced from one field.

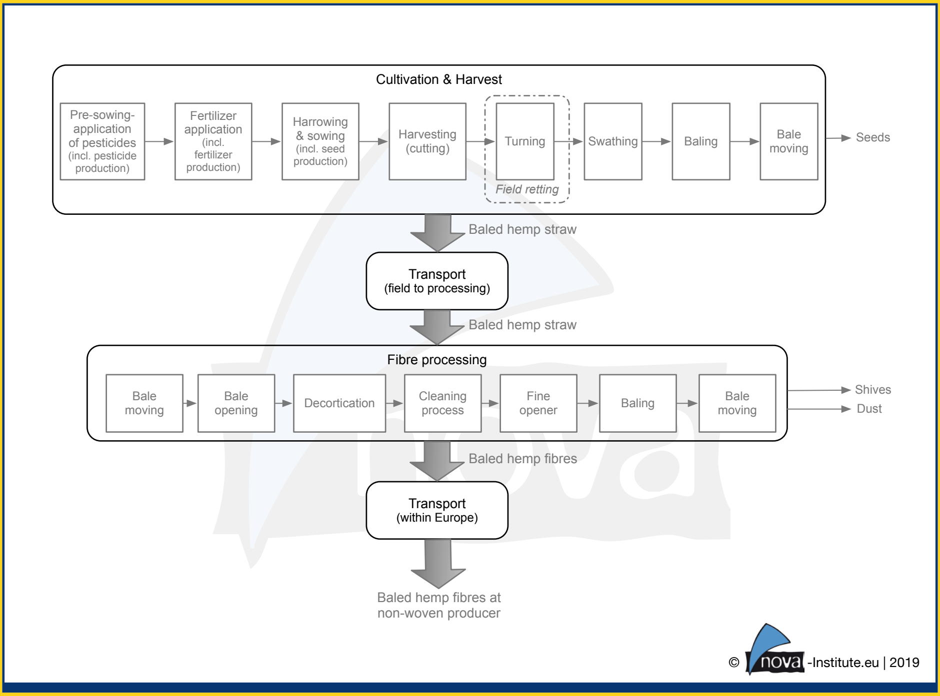
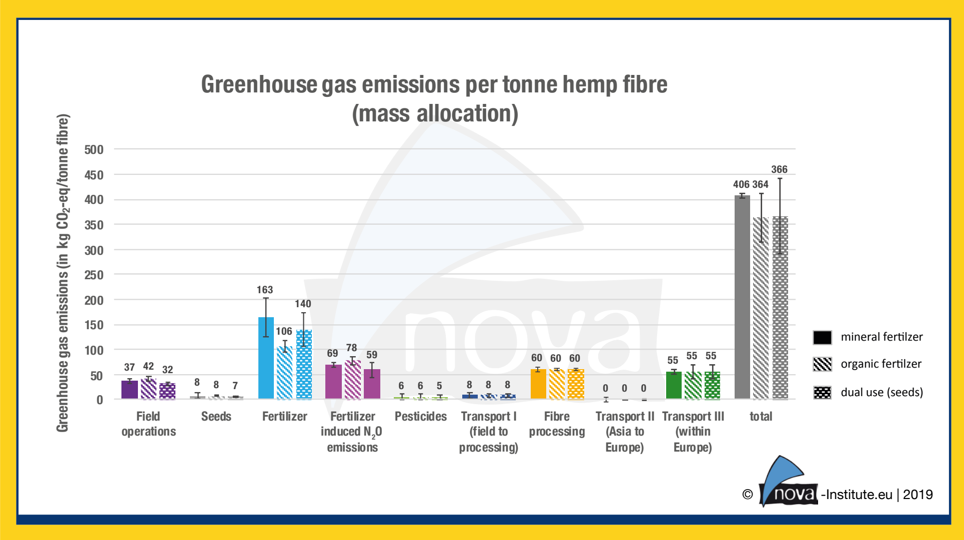


Figure 8: System boundary and process chain of the hemp fibre production (total fibre line) (nova 2019)

The (cradle to gate) carbon footprint of hemp fibre scenarios using mass allocation are 406 kg CO_2-eq/tonne of hemp fibre for scenario one, whereas the carbon footprint of hemp fibre scenario two is 364 kg CO_2-eq/tonne of hemp fibre, scenario three has a carbon footprint of 366 kg CO_2-eq/tonne of hemp fibre. Economic allocation results in a carbon footprint of 846 kg CO_2-eq/tonne of hemp fibre for scenario one, 759 kg CO_2-eq/tonne of hemp fibre for scenario two and 530 kg CO_2-eq/tonne of hemp fibre for scenario three. As is shown in Figure 9, the use of fertilization, both mineral and organic, was identified as most responsible for emissions contributing to greenhouse gas emissions.

Therefore, using organic fertilizer can reduce the carbon footprint of hemp fibre at the factory gate. Field operations, release of fertilizer induced N_2O-emissions and emissions from the fibre processing facility are the second most important contributors to the carbon footprint in both scenarios. Transportation processes are proportionally small, however, as cultivation and non-woven production is located in Europe. Furthermore, it can be seen that harvesting multiple products, in this case the hemp seeds, results in a reduction of the carbon footprint, especially when economic allocation is used as the seeds have a relative high value per tonne compared to the straw.



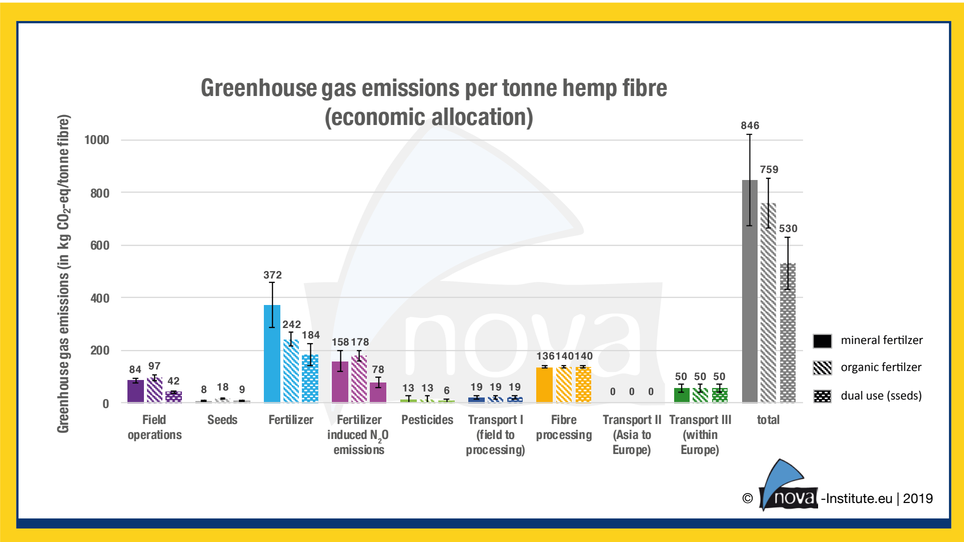


Figure 9: Greenhouse gas emissions of 1 tonne hemp fibre from the cultivation in Europe to the factory gate of the non-woven producer in Germany (nova 2019)

3.6 Carbon footprint of jute

Figure 10 indicates the system studied for cradle to gate jute fibre production. Cultivation to fibre processing steps are assumed to take place in India and Bangladesh; transportation from India to a harbour in Hamburg, Germany, is done by ships and continues on land with lorries headed to the factory gate of German non-woven producers. Inventory data and assumptions are summarized in Table C in the Appendix. The jute life cycle starts with agricultural cultivation; the jute is then cut and submerged in a pond or in a river for water retting. After retting the fibres are manually extracted from the stems, then washed and dried. Farmers do this manually. Sobhan et al. (2010) state that not all agricultural and decortication work is done manually, but for example bullock- or tractor driven ploughs are used to produce fine tilth. Lastly, the sun-dried fibres are delivered in rough fibre bundles to the so-called “fine-opening-processing” site, where the fibres are refined and cut into the desired length for selling to the non-woven producer (this is only the first part of the whole textile process, which leads to sliver for yarn production).

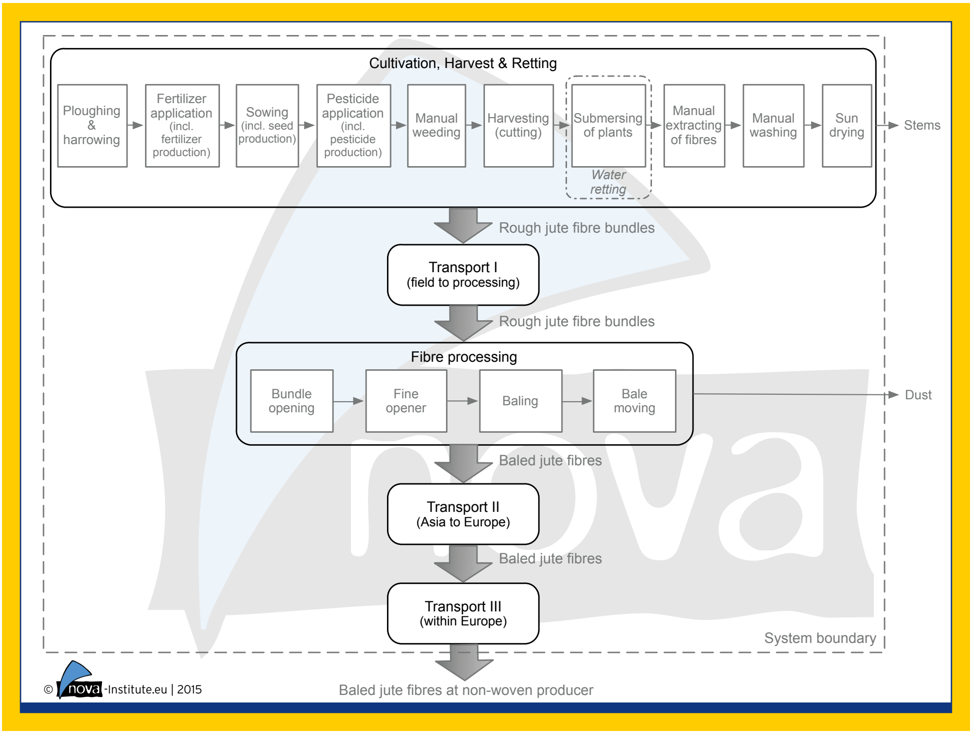
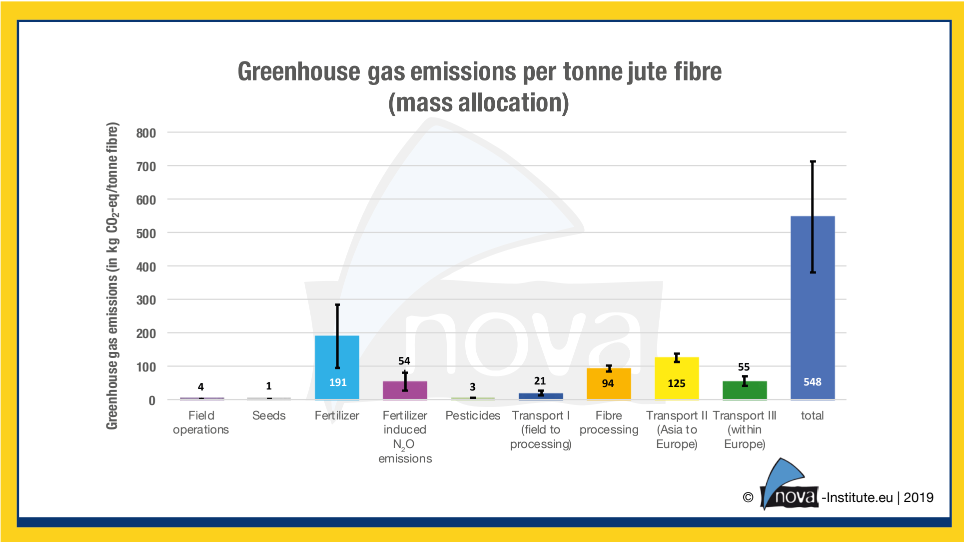


Figure 10: System boundary and process chain of the jute fibre production (nova 2015)

The (cradle to gate) carbon footprint of the jute fibre scenario is 479 kg CO_2-eq/tonne of jute fibre when mass allocation is used. When economic allocation is used the carbon footprint is 976 kg CO_2-eq/tonne of jute fibre. Figure 11 shows that fertilization contributes most to GHG emissions. In contrast to hemp and flax, jute plant cultivation is done mainly manually, but small tractors are also used for this kind of work. Because of manual field operations emissions resulting from this process are quite small. On the other hand, emissions from transporting the jute from Asia to Europe have to be considered as well. These GHG emissions are significant.



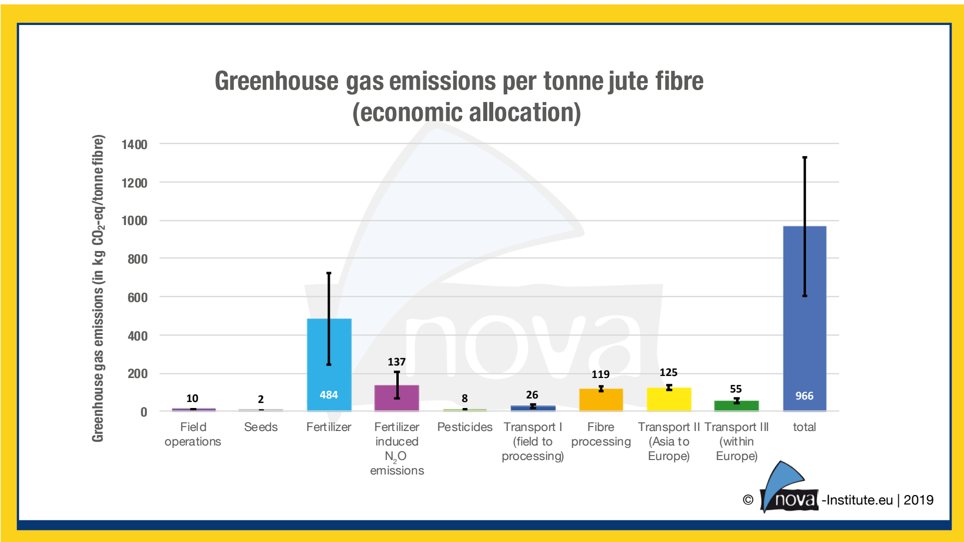


Figure 11: Greenhouse gas emissions of 1 tonne jute fibre from the cultivation in India to the factory gate of the non-woven producer in Germany (nova 2019)

3.7 Carbon footprint of kenaf

Two scenarios have been developed for the production of kenaf fibre; one process is based on a traditional mechanical fibre production from the straw to fibre, whereas the second scenario is based on the supply chain of DRÄXLMAIER Group, mainly with manual processing. Figure 12 below presents the system of scenario 1 studied for cradle to gate kenaf fibre production, for which cultivation and fibre processing are assumed to take place in India and Bangladesh. Transportation to the harbour in Hamburg, Germany, happens via ship and continues with lorries go to the factory gate of the non-woven producer in Germany. Inventory data and assumptions are summarized in Table D in the Appendix. Kenaf – like jute – is cut and water retted. After retting, the fibres are manually extracted from the stems, then washed and sun-dried. These activities are done manually by farmers, but not all agricultural and decortication steps are done manually: some field applications involve tractors (Sobhan et al. 2010). Lastly, the dried fibres are delivered in rough fibre bundles to the so-called "fine-opening-processing" site, where they are refined and cut into the desired length for selling to the non-woven producer. These finishing steps are done with machines.

In the second scenario (real life scenario for the DRÄXLMAIER Group value chain), fertilizer use and yields are based on data made available by DRÄXLMAIER Group from a previous project. Fibres are sorted manually based on different qualities. These fibres are cut at a further processing site, however they do not require fine opening. Further fine opening is achieved at the non-woven producer in Europe in the unmodified non-woven process.

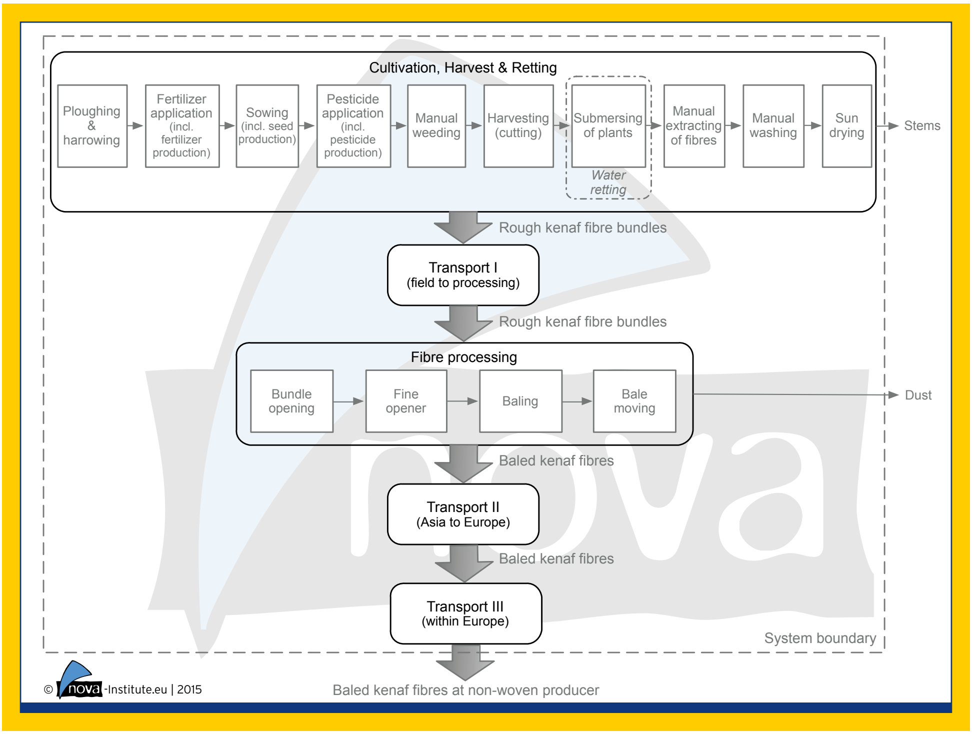


Figure 12: System boundary and process chain of the kenaf fibre production (nova 2015)

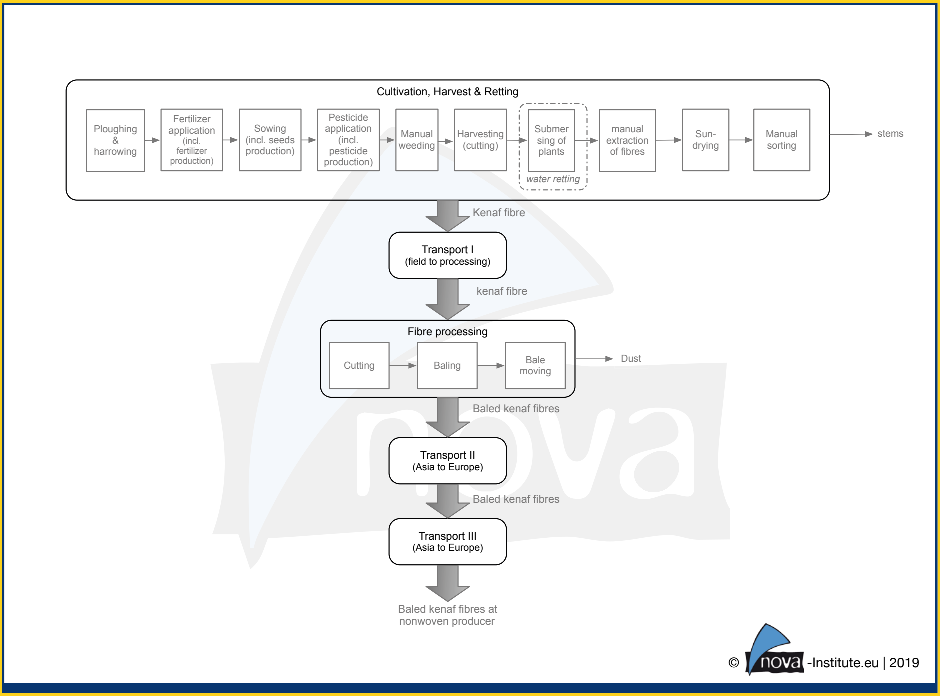
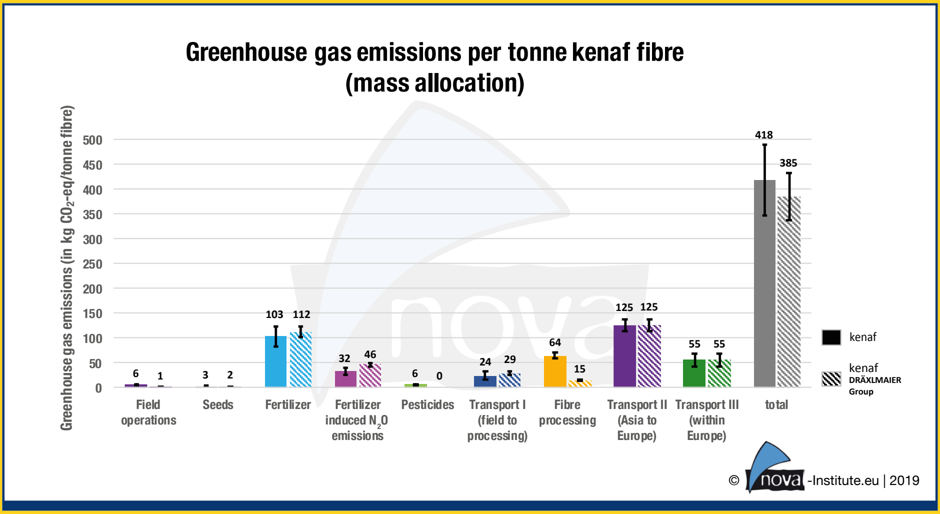


Figure 13: System boundary and process chain of the kenaf fibre production by DRÄXLMAIER Group (nova 2019)

Regarding the kenaf scenarios, Figure 14 shows that fertilization is the main contributor to kenaf's carbon footprint. The (cradle to gate) carbon footprint of the first kenaf fibre scenario using mass allocation is 418 kg CO_2-eq/tonne of kenaf fibre, for the second scenario this is 385 kg CO_2-eq/tonne of kenaf fibre. Using economic allocation (based on assumptions made by nova-Institute), the carbon footprint of the first scenario is 975 kg CO_2-eq/tonne of kenaf fibre, for the second scenario this is 770 kg CO_2-eq/tonne of kenaf fibre.

In contrast to hemp and flax, kenaf plants are generally cultivated manually, though sometimes small tractors are also used for this kind of work. Because of manual field operations, emissions stemming from this process are quite small. On the other hand, emissions from transporting the kenaf from Asia to Europe have to be considered as well. These GHG emissions are significant. It can also be seen that the high-quality fibres have an advantage as less machine processing is required for their production. The fibre qualities are different and also the further processing and the applications.



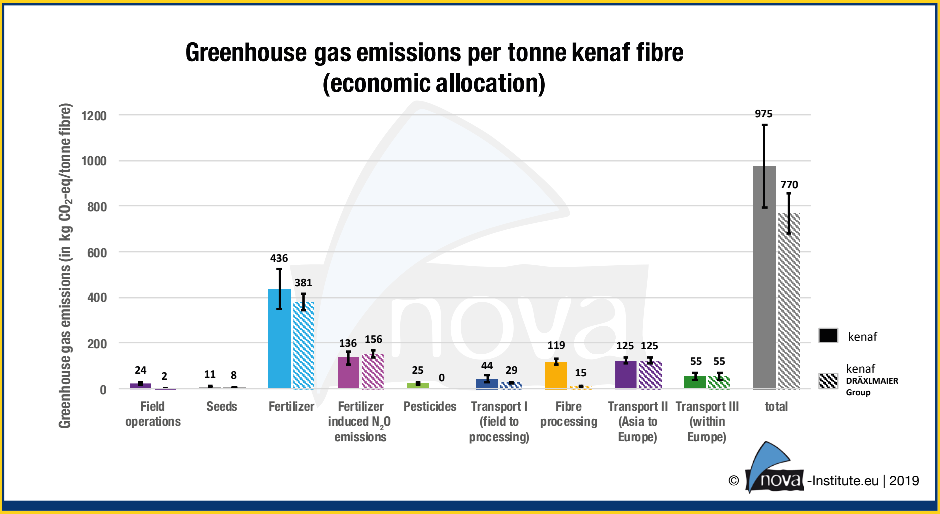


Figure 14: Greenhouse gas emissions of 1 tonne kenaf fibre from the cultivation in India/Bangladesh to the factory gate of the non-woven producer in Germany, traditional and DRÄXLMAIER Group value chain (nova 2019)

4 Discussion of results

4.1 Overview of the carbon footprint of flax, hemp, jute and kenaf

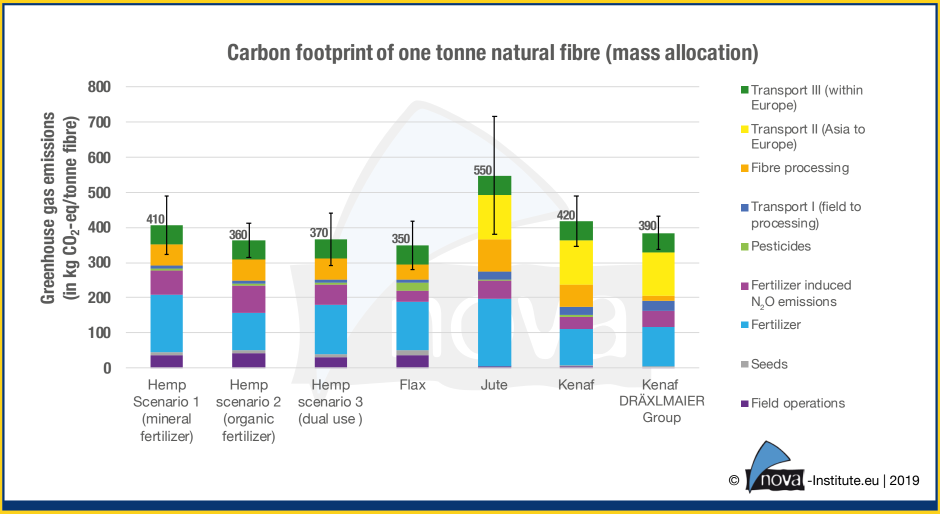


Figure 15: Overview of the greenhouse gas emissions per tonne natural fibre, using mass allocation (flax, hemp, jute and flax) (nova 2019)

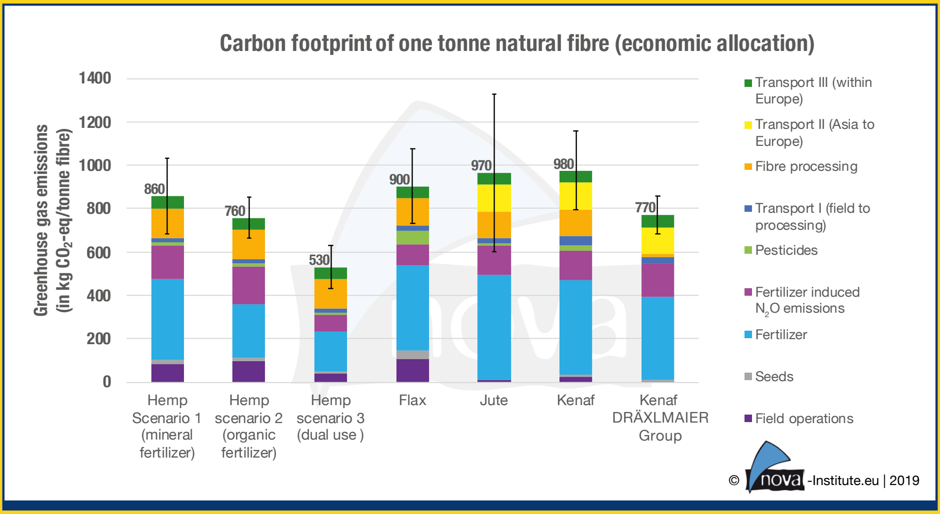


Figure 16: Overview of the greenhouse gas emissions per tonne natural fibre, using economic allocation (flax, hemp, jute and flax) (nova 2019)

Figure 15 and 16 gives an overview of the results of our GHG emission calculation for flax, hemp, jute and kenaf, using mass and economic allocation. The result indicates that GHG emissions per tonne show no significant differences, especially when taking the uncertainty of the data into account (see the error bars). However, there are some differences in results, which are described in more detail below:

- Jute has a slightly higher carbon footprint as the fibre yield per hectare is lower compared to the other fibres.
- The emissions related to the fertilizer sub-system are the most important contributors to greenhouse gas emissions of each considered bast fibre.
- However, the use of organic fertilizer for hemp cultivation (scenario 2) minimizes these emissions. Organic based fertilization is, however, not an option for all fibres, for the following reasons: some plants, such as flax, do not tolerate organic fertilizer; in the case of kenaf and jute, there is insufficient organic fertilizer, as these plants are grown in areas with low animal production (with therefore no manure surpluses to turn into organic fertilizer).
- Pesticides contribute relatively little to the carbon footprint of each fibre, except for the emissions stemming from pesticides used during flax cultivation. Due to its low shading capacity, flax is prone to weed infestation (Heyland et al. 2006, pp. 285). Therefore, herbicides usually need to be applied for flax in higher doses. In the two hemp scenarios, the share of pesticides is very low: herbicides are only used to prepare the field, but no pesticides are applied during the growing period. Due to its vigorous growth, shading capacity and resistance to diseases, hemp can be grown without the use of herbicides or fungicides (Heyland et al. 2006, pp. 304).
- Field operations, decortication and transportation differ for jute and kenaf and hemp and flax. For kenaf and jute, field operations and decortication are mainly done manually which causes relatively low emissions, this effect is even stronger in the DRÄXLMAIER Group value chain. Since jute and kenaf are grown and processed outside of Europe, however, transportation must be considered, both overland transport from the farm to the processing site as well as marine transportation to the factory gate in Europe. This means that for kenaf and jute, emissions caused by transport constitute a large portion of total emissions, only being surpassed by emissions caused by fertilizer production. In other words, low emissions from manual field operations are offset by the emissions caused by transport from Asia to Europe, when the fibres are used in Europe.
- For flax cultivation, the emissions from field operations are quite high in comparison with hemp field operations. This is due to the lower straw and coherent fibre yield per area unit of flax. Additionally, emissions for flax seed production are comparably higher, due to a higher sowing rate. Jute has a very low sowing rate in comparison to kenaf, so emissions from jute seed production are lower compared with the other bast fibres.
- Life cycle stage transport III contributes the same amount of emissions in each fibre scenario, because this stage involves transportation of the baled fibres within Europe, either from the harbour in Hamburg or from the fibre processing facility in Europe to the non-woven producer. These emissions are based on the same assumptions for all scenarios.

In economic allocation the environmental impact is distributed differently over the products. Economic allocation shows the advantage of multi-product crop cultivation, as the burden of the cultivation process in the dual use hemp scenario is divided between the straw and seeds, resulting in a significant lower impact for the fibres.

- Furthermore, using economic allocation increases the environmental burden towards the fibres, as the value of the fibres are higher compared to the value of the shives, stems and dust.

However, the difference in carbon footprint between the different natural fibres is still not significant when using economic allocation.

4.2 Biogenic carbon storage

This chapter details the biogenic carbon storage of the intermediate flax, hemp, jute and kenaf fibres. The carbon storage is based on the biochemical composition of the fibre. From this information the quantity of carbon present in the fibre, and the quantity of CO_2 removed from the air through photosynthesis, was calculated - see Table 3. As this study focusses on an intermediate product, this chapter aims to shows the significance of the biogenic carbon storage to industry. Carbon storage is considered differently by various standards and modelling choices, for more information see for example Tellnes et al. (2017) or Matthews et al. (2014).

Table 3: Typical values of compositions and stored carbon dioxide of flax, hemp, jute and kenaf fibre

	Unit	Flax	Hemp	Jute	Kenaf
Cellulose	kg/kg fibre	0.72	0.65	0.57	0.55
Hemicellulose	kg/kg fibre	0.18	0.15	0.13	0.14
Lignin	kg/kg fibre	0.03	0.10	0.14	0.12
Stored carbon dioxide	**kg CO_2-eg/kg fibre**	**1.39**	**1.39**	**1.33**	**1.27**

The CO_2 uptake and carbon storage in the considered fibres (see Table 3) is calculated on the basis of typical cellulose, hemicellulose and lignin content of the fibres (data based on *www.phyllis.nl*) and their embedded carbon content. The calculations show that flax, hemp, jute and kenaf fibre take up around 1.3 to 1.4 kg of CO_2 per kg fibre. There are no significant differences between the above-mentioned fibres. This CO_2 is removed from the air during the growth of the plant. It should be noted that the embedded carbon will be released back into the atmosphere at the end-of-life. If the embedded carbon is completely released as CO_2 at the end-of-life, the 1.3–1.4 kg CO_2 will be released again. However, if the embedded carbon is partially released as methane (which is a stronger greenhouse gas) CO_2-equivalents can increase.

In figure 17 and 18, the carbon storage is presented separately to give an indication on the relevance of this flow to the industry. As mentioned above, standards regarding carbon storage and credits related to them depend on final product application, product lifetime, end-of-life and timing of the uptake and release. As the fibres are an intermediate product, several of these factors are unknown. A complete LCA, including use and end-of-life, can model the biogenic carbon content accordingly.

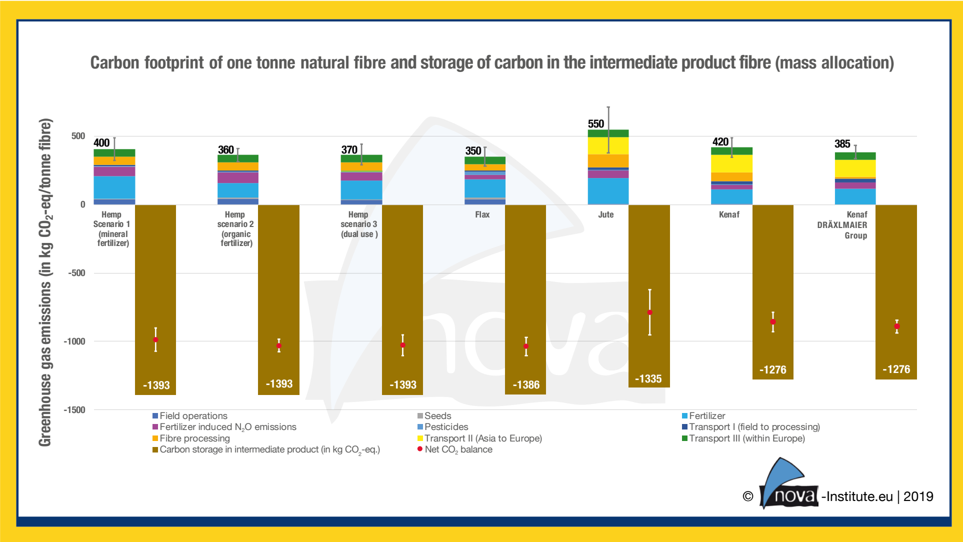


Figure 17: Overview of the greenhouse gas emissions per tonne natural fibre and carbon storage (in CO_2-eq.) in the intermediate product fibre (flax, hemp, jute and flax) (nova 2019)

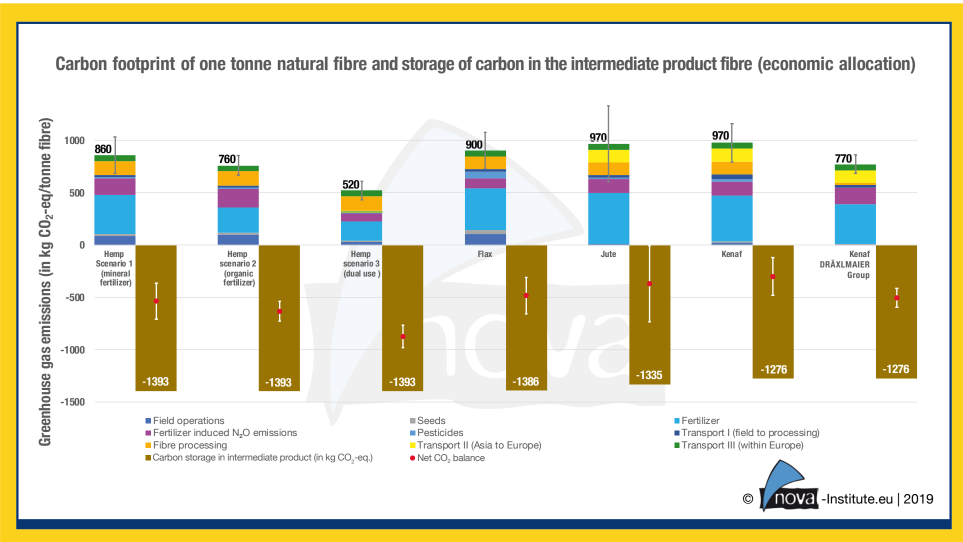


Figure 18: Overview of the greenhouse gas emissions per tonne natural fibre and carbon storage (in CO_2-eq.) in the intermediate product fibre (flax, hemp, jute and flax) (nova 2019)

4.3 Biocomposites

Natural fibres are used in biocomposites, among other things. Biocomposites are composed of a polymer and natural fibres, the latter of which gives biocomposites their strength. Biocomposites with natural fibres can have similar functionality as other composites, enabling comparison of the final product. Haufe and Carus (2011) indicate that hemp fibre composites show greenhouse gas emission savings of 10 to 50% compared to their functionally equal fossil-based counterparts (see figure 19); when carbon storage is included, greenhouse gas savings are consistently higher, at 30–70% as can be seen in the yellow bars in figure 19 (Haufe & Carus 2011). However, the great advantage of natural fibres compared to glass fibres, in terms of greenhouse gas emissions, only partially remains for their final products, because further processing steps mitigate their benefits.

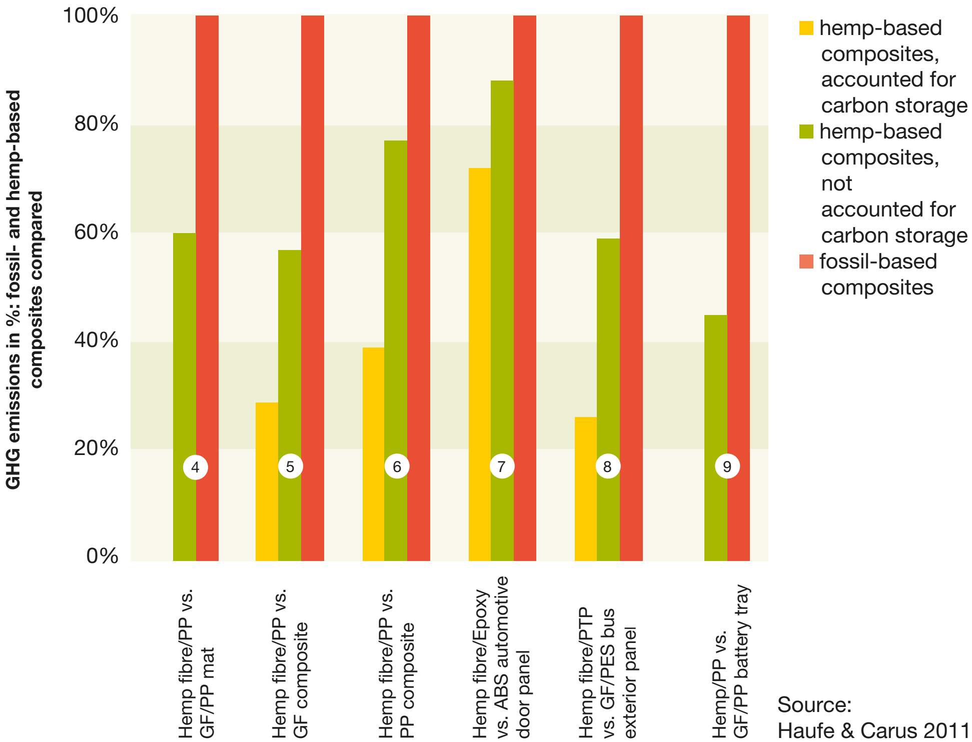


Figure 19: GHG emissions expressed in percent for the production of fossil based and hemp-based composites for a number of studies – showing the effects of biogenic carbon storage where available (Haufe & Carus 2011)

5 Discussion on further sustainability aspects of natural bast fibres

Although carbon footprints are a very useful tool to assess the climate impact of products, a comprehensive ecological evaluation must consider further environmental categories. Only considering greenhouse gas emissions can lead to inadequate product reviews and recommendations for action, in particular when other environmental impacts have not been considered at all. Therefore, one task of further studies is to take other impact categories into consideration. Furthermore, sustainability also includes social and economic aspects.

Since natural fibres are used in many industry sectors, certification is a suitable instrument to prove sustainability. At the moment there are certification systems available which insure the production of biomass in a social and environmentally sustainable way. For natural technical fibres there are three favourable systems in place which are recognized worldwide. These are (in alphabetical order):

1. Better Biomass certification scheme is managed by the NEN, the Netherlands Standardization Institute, based on NTA 8080-1:2015 and NTA 8080-2:2015. It is used to demonstrate the sustainability of the biomass used for energy, fuels or bio-based products. The underlying sustainability criteria have been established in a multi-stakeholder consensus process between private companies, government and civil society organizations.

2. International Sustainability & Carbon Certification (ISCC PLUS) for food and feed products as well as for technical/chemical applications (e.g. bioplastics) and applications in the bioenergy sector (e.g. solid biomass). For further information see: *www.iscc-system.org/process/certification-scopes*.

3. Roundtable on Sustainable Biomaterials (RSB) is an international multi-stakeholder initiative for the global standard and certification scheme for sustainable production of biomaterials and biofuels. For further information see: *www.rsb.org*.

According to ISCC PLUS the sustainable production of natural fibres is characterized by the six principles mentioned below (ISCC certifies according to these principles) (ISCC 2014). In addition, ISCC states a seventh principle, which deals with the designation of greenhouse gas emissions and which needs to be applied for the production of biomass (ISCC 2013). These principles are:

1. Biomass shall not be produced on land with high biodiversity value or high carbon stock. High conservation areas shall be protected.

2. Biomass shall be produced in an environmentally responsible way. This includes the protection of soil, water and air and the application of Good Agricultural Practices.

3. Safe working conditions through training and education, use of protective clothing and proper and timely assistance in the event of accidents.

4. Biomass production shall not violate human rights, labour rights or land rights. It shall promote responsible labour conditions and workers' health, safety and welfare and shall be based on responsible community relations.

5. Biomass production shall take place in compliance with all applicable regional and national laws and shall follow relevant international treaties.

6. Good management practices shall be implemented.

7. Calculation and verification of greenhouse gas emissions must be provided by the biomass producer.

The entire land area of a farm/plantation, including agricultural land, pasture, forest and any other land must comply with ISCC Standard 202 (ISCC 2014) (Principle 1–6).

EU Member Countries that have implemented cross compliance only need to control principle 1, as principles 2 to 6 are already covered by cross compliance and other control systems. Moreover, the designation of GHG emissions is mandatory for biomass production and must be available at the first gathering point (see point 7 above) (ISCC 2013). As shown above, EU member countries cultivating fibres only need to fulfil principle 1 and carry out the calculation of greenhouse gas emissions within ISCC PLUS (see point 7). For natural fibres from Asia the procedure is more complex, due to for instance working conditions and the impact of water retting on the environment.

Benefits of sustainability certificates for technical fibres

Certification expresses and allocates the added value of sustainability within the market. It also yields further positive economic effects and has far-reaching positive effects.

First of all, it strengthens sustainable ways of using resources. For companies producing fibres, it strengthens their marketing effects, as the certification label raises attention and helps to establish brands. More important, however, is the fact that companies are given the opportunity to add an additional margin to their products based on the emotional performance ("GreenPremium") that is part of overall product performance and valued by end consumers. Moreover, certification strengthens companies' supply chains as it ensures transparency and process reliability.

Especially the automotive industry and the bio-building sector are interested in showing that the materials they use are "green".

Hemp fibres are so far the only natural fibres on the world market available with an ISCC PLUS sustainability certification. Hemp straw and fibre producers in the Netherlands, Germany and Romania are meanwhile certified. This has hopefully opened the door for more natural fibres to be certified under the ISCC PLUS certification scheme in the future.

6 Executive summary

Natural fibres such as flax, hemp, jute or kenaf are being used more and more in technical applications. The main new applications that have been developed and implemented over the last 20 years are biocomposites in automotive interiors and insulation material in construction. This study provides an overview of the production processes, data on the production processes and carbon footprint of these natural fibres. The study does not include the processing into the final application and end-of-life, due to the various end applications of natural fibres. This study assesses the GHG emissions, further impact categories need to be assessed to determine the full environmental impact of the natural fibres.

The carbon footprints of the different natural fibres (flax, hemp, jute and kenaf) are not significantly different. In the range of uncertainty, the carbon footprint to the factory gate of the European non-woven producer in the automotive or insulation sector is about 400 kg of CO_2-eq per tonne of natural fibre for all four natural fibres, when applying mass allocation. Jute and kenaf show less emissions during cultivation, harvesting and decortication because of manual processing, but long transport to Europe levels this advantage.

When economic allocation is used, more of the greenhouse gas emissions stemming from plant cultivation and processing are placed on the fibres, as their value is higher than the by-products' value. The carbon footprint of natural fibres using economic allocation is around 900 kg of CO_2-eq per tonne of natural fibre.

Because fertilizers have a high share in the total calculation of emissions, substituting mineral fertilizers by organic fertilizers leads to a lower carbon footprint of 360 kg of CO_2-eq per tonne of hemp fibre instead of 400 kg of CO_2-eq/t (mass allocation). Using organic fertilizer is only possible if the crop and the region are suitable. Currently pig slurry and fermentation residues are only used for hemp grown in the north of the Netherlands and Germany. Furthermore, it is shown that cultivating hemp for both seeds and straw reduces the carbon footprint of the hemp fibre. This effect is significant when using economic allocation due to the high value of the seeds.

This study has calculated the CO_2 uptake based on the embedded carbon in the natural fibres at around 1,3 to 1,4 t CO_2/t fibre. This is important technical information for conducting an LCA on products containing natural fibres. The embedded carbon in the natural fibre will be released at the end of the products life. The form in which this carbon is released can have significant impact on the carbon footprint. Further processing increases the GHG emissions.

But in total, natural fibres composites have a significant lower carbon footprint than conventional composites (Haufe and Carus 2011). For example hemp fibre composites show greenhouse gas emission savings of 10 to 50% compared to their functionally equal fossil-based counterparts; when carbon storage is included, greenhouse gas savings are consistently higher, at 30–70%.

The data on GHG emissions in the production of natural fibres still show some gaps, especially for water and field retting, where no solid data are available. Experiments are recommended to fill these data gaps.

European hemp fibres that have an ISCC PLUS sustainability certificate, which demands much more than a carbon footprint, have become available on the world market. Hopefully other fibres will follow.

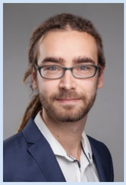
7 Acknowledgement

The authors wish to acknowledge funding from EU MultiHemp project (Grant agreement 311849) (*www.multihemp.eu*).

nova-Institute thanks the following experts for their contribution to this paper (in alphabetical order):

- **Dr. Stefano Amaducci**
  (Università cattolica del Sacro Cuore, Italy) - project coordinator in MultiHemp project
- **Heinz Amolsch**
  (Thermo Natur GmbH & Co. KG)
- **Prof. Dr. Georg Stephan Barfuß**
  (DRÄXLMAIER Group)
- **Albert Dun**
  (Hennepverwerkingsbedrijf Dun Agro B.V., The Netherlands) – partner in MultiHemp project
- **Bernd Frank**
  (Bafa GmbH, Germany) – partner in MultiHemp project
- **Subrata Gupta**
  (Jute Commissioner, India)
- **Dr. Hans-Jörg Gusovius**
  (Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V., Germany) - partner in MultiHemp project
- **John Hobson**
  (Plant Fibre Technology Ltd, Great Britain)
- **Prof. Dr. Jörg Müssig**
  (Hochschule Bremen, Germany) - partner in MultiHemp project
- **Melanie Niestatek**
  (DRÄXLMAIER Group)
- **Mark Reinders**
  (HempFlax, The Netherlands)
- **Farid Uddin**
  (Services and Solutions International Ltd., Bangladesh)
- **Alfons Üllenberg**
  (Consultant for Rural Development)
- **Wang Yu Fu**
  (Chinese Academy of Agricultural Sciences (CAAS), Institute of Bast Fibre Crops, China)

The authors of the study



M.Sc. Niels de Beus (nova-Institute, Germany) studied at Wageningen university and Research and graduated in biotechnology. He works at the sustainability department of nova-Institute since June 2015. There he uses his expertise on process engineering and system analysis to perform sustainability assessments and life cycle assessments of innovative products. Niels de Beus works in several EU projects and has broad expertise on bio-based products, from natural fibres, to bio-based chemicals.

Dipl.-Phys. Michael Carus (nova-Institute, Germany) physicist, founder and managing director of the nova-Institute, is working for over 20 years in the field of Bio-based Economy. The focus of his work is market analysis, techno-economic and ecological evaluation as well as the political and economic framework for bio-based processes and applications. Since 2005, Michael Carus is managing director of the European Industrial Hemp Association (EIHA). Michael Carus is main author of different fundamental reports and policy papers on Bio- based Economy in the EU. Most of them can be downloaded for free: www.bio-based.eu/policy

Dipl.-Ing. Martha Barth studied at the Technical University of Vienna and at the Montanuniversität Leoben (Austria) and graduated in „Industrial Environmental Protection, Waste Disposal Technology and Recycling“. Martha Barth is the author of the first version of the study contributing with her comprehensive knowledge of waste, supply and disposal management. Martha Barth has left nova-Institut in the summer of 2016.

8 References

Aji, I.S., Sapuan, S.M., Zainudin E.S., and Abdan, K. 2009: Kenaf fibres as reinforcement for polymeric composites: a review. In: International Journal of Mechanical and Materials Engineering (IJMME), Vol. 4, No. 3, 239–248.

Amaducci, S. & Gusovius, H.-J. 2010:Hemp – Cultivation, Extraction and Processing. In: Müssig, J. (Ed.): Industrial Applications of Natural Fibres - Structure, Properties and Technical Applications. Chichester (UK): John Wiley & Sons. Pp. 109–134.

Banik, A., Sen, M., and Sen, S.P. 1993: Methane emission from jute-retting tanks. In: Ecological Engineering, Vol. 2, No. 1, pp. 73–79.

Baumann, H. & Tillmann, A.-M. 2004: The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Lund, Sweden: Studentlitteratur.

Behmel, U. 2014: personal communication with M. Carus, Germany.

Bocsa, I., Karus, M., and Lohmeyer, D. 2000: Der Hanfanbau - Botanik, Sorten, Anbau und Ernte, Märkte und Produktlinien. Münster-Hiltrup: Landwirtschaftsverlag.

Carus, M., Eder, A., Dammer, L., Korte, H., Scholz, L., Essel, R. and Breitmayer, E., Barth, M. 2015: Wood-Plastic Composites (WPC) and Natural Fibre Composites (NFC): European and Global Markets 2012 and Future Trends. Hürth (DE): Carus, M., nova- Institut GmbH. (www.bio-based.eu/reports)

Carus, M., Sarmento, L. 2016: The European Hemp Industry: Cultivation, processing and applications for fibres, shivs, seeds and flowers. Hürth, May 2016 (www.eiha.org)

Carus, M., Vogt, D., and Breuer, T. 2008: Studie zur Markt- und Konkurrenzsituation bei Naturfasern und Naturfaserwerkstoffen (Deutschland und EU). In: Gülzower Fachgespräche, Band 26. Gülzow (DE): Fachagentur Nachwachsende Rohstoffe e.V. (FNR).

Cherrett, N., Barrett, J., Clemett, A., Chadwick, M., and Chadwick, M.J. 2005: Ecological Footprint and Water Analysis of Cotton, Hemp and Polyester. Stockholm: Stockholm Environmental Institute (SEI).

Dissanayake, N.P.J. 2011: Life Cycle Assessment of Flax Fibres for the reinforcement of polymer matrix composites. PhD thesis at the University of Plymouth.

ELG Carbon Fibre, 2017: LCA benefits of rCF, Conference: Composite Recycling & LCA Stuttgart 9th March 2017 Available at: *www.elgcf.com/assets/documents/ELGCF-Presentation-Composite-Recycling-LCA-March2017.pdf* (Last accessed 2018-12-05).

Essel, R. 2013: Results from a field trip to Hemp Technology Ltd. Halesworth, UK.

Evans, A., Ruff, E., and Mortimer, N. 2006: Selective Life Cycle Assessments for Agricultural Fleece Production from Hemp and Polypropylene Produced from Crude Oil. North Energy Associates Ltd. Prepared for DEFRA project Environmental Assessment Tools for Biomaterials (NF0614), Stocksfield, England.

FAO 2008: Technical Paper No. 56: Discover natural fibres 2009- Proceedings of the Symposium on Natural Fibres. Available at *www.fao.org/docrep/011/i0709e/ i0709e00.htm* (last accessed 2015-02-24).

FAOSTAT 2018: Statistical database of the FAO. Available at: http://faostat3.fao.org/home/E (last accessed 2018- 10-31).

González-García, S., Hospido, A., Moreira, M.T., and Feijoo, G. 2007: Life Cycle Environmental Analysis of Hemp Production for Non-wood Pulp. In Manuscript of: LCM 2007 in Zurich. Available at *www.lcm2007.org/paper/109.pdf* (last accessed 2015-02-10).

González-García, S., Hospido, A., Feijoo, G., and Moreira, M.T.2010a: Life cycle assessment of raw materials for non- wood pulp mills: Hemp and Flax. In: Resources, Conservation and Recycling, Vol. 54, No. 11, pp. 923–930.

González-García, S., Moreira, M.T., Artal, G., Malanodo, L., and Feijoo, G. 2010b: Environmental impact assessment of non-wood based pulp production by soda-anthraquinone pulping process. In: Journal of Cleaner Production, Vol. 18, No. 2, pp. 137–145.

Gosh, T. 1983: Handbook of Jute. FAO Publication.

Graupner, N. & Müssig, J. 2010: Technical Applications of Natural Fibres: An Overview. In: Müssig, J. (Ed.): Industrial Applications of Natural Fibres - Structure, Properties and Technical Applications. Chichester (UK): John Wiley & Sons. Pp. 63–71.

Grießhammer, R. & Hochfeld, C. 2009: Product Carbon Footprint Memorandum - Position statement on measurement and communication of the product carbon footprint for international standardization and harmonization purposes. Freiburg (DE): Öko-Institut e.V.

Haufe, J. & Carus, M. 2011: Hemp Fibres for Green Products – An assessment of life cycle studies on hemp fire applications. The European Hemp Association (EIHA). Available at *www.bio-based.eu/download/?did=1086&file=0* (last accessed 2015-02-05).

Heyland, K.-U., Hanus, H., and Keller, E.R. 2006: Ölfrüchte, Faserpflanzen, Arzneipflanzen und Sonderkulturen. Handbuch des Pflanzenbaus, Volume 4. Stuttgart (DE): Eugen Ulmer KG.

ISCC 2014: ISCC PLUS 202 Standard on Sustainability Requirements for the Production of Biomass. International Sustainability & Carbon Certification (ISCC). Available at *www.iscc-system.org/uploads/media/ISCC_EU_202_Sustainability_Requirements-Requirements_for_theProduction_of_Biomasse_2.3.pdf* (last accessed 2015-03-27).

ISCC 2013: ISCC PLUS 201 System Basics ISCC PLUS Standard for the certification of sustainable biomass and its processing steps. International Sustainability & Carbon Certification (ISCC). Available at *www.iscc-system.org/uploads/ media/ISCC201SystemBasics.pdf* (last accessed 2015-03-27).

Islam, K. & de Silva, H. 2011: Jute value chai in Bangladesh: Information and knowledge gaps of smallholders. Report of LIRNEasia. Available at *www.lirneasia.net/ wp-content/uploads/2010/07/jute.vc_1.pdf* (last accessed 2015-02-27).

Islam, M.S. & Ahmed, S.K. 2012: The Impacts of Jute on Environment: An Analytical Review of Bangladesh. In: Journal of Environment and Earth Science, Vol. 2, No. 5., pp. 24-31.

Islam, M. 2014: Research Advances of Jute Field Weeds in Bangladesh: A Review. In: ARPN Journal of Science and Technology, Vol. 4, No. 4, pp. 254–268.

La Rosa, A.D., Cozzo, G., Latteri, A., Recca, A., Björklund, A.,Parrinello, E., and Cicala, G. 2013: Life cycle assessment of a novel hybrid glass- hemp/thermoset composite. In: Journal of Cleaner Production Vol. 44, pp. 69–76.

Mahapatra, B.S., Mitra S., Sinha, M.K., and Ghorai, A.K. 2009: Research and development in jute (Corchorus sp.) and allied fibres in India - A review. In: Indian Journal of Agronomy, Vol. 54, No. 4, pp. 361–373.

Matthews, R.,, Sokka L., Soimakallio S., N Mortimer N., Rix J., Schelhaas, M-J., Jenkins, T., Hogan, G., Mackie, E., Morris, A., Randle, T. 2014: Review of literature on biogenic carbon and life cycle assessment of forest bioenergy. Final Task 1 report, EU DG ENER project ENER/C1/427, 'Carbon impacts of biomass consumed in the EU'. Forest Research: Farnham.

Mondal, D.K. & Kaviraj, A. 2007: Ecotoxicological effects of jute retting on the survival of two freshwater fish and two invertebrates. In: Ecotoxicology, Vol. 17, No. 3, pp. 207–211.

Monti, A. & Alexopoulou, E. 2013: Kenaf: A Multi-Purpose Crop for Several Industrial Applications – New Insights from the Biokenaf Project. London: Springer-Verlag.

Mudge, F. & Adger, N. 1994: Methane emissions from rice and coarse fibre production. CSERGE GEC Working Paper 94-08.

Müller-Sämann, K.M., Reinhardt, G., Vetter, R., and Gärtner, S. 2003: Nachwachsende Rohstoffe in Baden-Württemberg: Identifizierung vorteilhafter Produktlinien zur stofflichen Nutzung unter besonderer Berücksichtigung umweltgerechter Anbauverfahren. Mülheim (DE): Institut für umweltgerechte Landbewirtschaftung, Mülheim and Heidelberg (DE): Institut für Energie- und Umweltforschung.

Müssig, J. & Slootmaker, T. 2010: Types of Fibre. In: Müssig, J. (Ed.): Industrial Applications of Natural Fibres - Structure, Properties and Technical Applications. Chichester (UK): John Wiley & Sons. Pp. 41–48.

Pari, L., Hepin, X., and Reinders, M. 2014: Harvesting, Processing and Logistics of the Fibre Crops – D1.3 FIBRA project interim report.

PAS 2050, 2011: Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. London (UK): British Standards Institution (BSI).

Pless, P.S. 2001: Technical and environmental assessment of thermal insulation materials from bast fiber crops. Dissertation at the University of California.

PwC 2016: Life cycle assessment of CFGF – Continuous Filament Glass Fibre Products. Report prepared for GlassFibreEurope. Available at: *www.glassfibreeurope.eu/wp-content/uploads/2016/11/LCA-report-CFGF-products_20161031_PwC.pdf* (last accessed 2018-12-05).

Rahman, S. Md. 2010: Jute - A Versatile Natural Fibre - Cultivation, Extraction and Processing. In: Müssig, J. (Ed.): Industrial Applications of Natural Fibres - Structure, Properties and Technical Applications. Chichester: John Wiley & Sons. Pp. 135–161.

Rana, S., Pichandi, S., Parveen, S., and Fangueiro R. 2014: Natural Plant Fibers: Production, Processing, Properties and Their Sustainability Parameters. In: Roadmap to Sustainable Textiles and Clothing. Textile Science and Clothing Technology. Singapore: Springer Verlag. Pp. 1-35.

Salmon-Minotte, J. & Franck, R. R. 2005: Flax. In: R. R. Franck (Ed.): Bast and other plant fibres. Cambridge: Woodhead Publishing.

Schmidt, A.C., Jensen, A.A., Clausen, A.U., Kamstrup, U., and Postlethwaite, D. 2004: A comparative Life Cycle Assessment of Building Insulation Products made of stone wool, paper wool and flax. In: International Journal of Life Cycle Assessment, Vol. 9, No. 1, pp. 53–66.

Singh, D.P.: Mesta (Hibiscus Cannabinus & Hibiscus Sabdariffa). Report of Central Research Institute for Jute & Allied Fibres, West Bengal, India. Available at: www.assamagribusiness.nic.in/mesta.pdf (last accessed 2015-02-03).

Sobhan, M.A., Sur, D., Amin, M.N., Ray, P., Mukherjee, A.,Samanta, A.K., Guha Roy, T.K. Abdullah, A.B.M., Bhuyan, F.H., Roul, C., and Roy, S. 2010: Jute basics. IJSG Publication.

Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, B., and Midgley, P.M. (Eds.) 2013: IPCC - Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge & New York: Cambridge University Press.

Tahir, P., Ameld B.A., Syeed O.A.S., and Zakiah A. 2011: Retting process of some bast plant fibres and its effect on fibre quality: a review. In: BioResources, Vol. 6, No. 4, pp. , 5260–5281.

Tellnes, L., G., F., Ganne-Chedeville, C., Dias, A., Dolezal, F., Hill, C., Zea Escamilla, E. (2017): Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: a review study for construction materials based on forest products. iForest : Biogeosciences and Forestry, 10:815-823.

Thüringer Landesanstalt für Landwirtschaft (Ed.) 2009: Anbautelegramm Faserlein (Linum usitatissimum L.). Dornburg, Germany.

Üllenberg, A., Simons, J., Hoffmann, J., Siemers, W., Baoy,N., Abdullah, A.B.M., Murthy, P.V.G.K., and Geisen J. 2011: Nachwachsende Rohstoffe für die stoffliche Nutzung - Auswirkungen für Entwicklungs- und Schwellenländer: Am Beispiel von Palmkernöl, Kokosöl, Rizinusöl, Naturkautschuk und Jute. Eschborn (DE): Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

van der Werf, H.M.G. 2004: Life Cycle Analysis of field production of fibre hemp, the effect of production practices on environmental impacts. In: Euphytica, Vol. 140, No. 1-2, pp. 13–23.

van der Werf, H.M.G. & Turunen, L. 2008: The environmental impacts of the production of hemp and flax textile yarn. In: Industrial Crops and Products, Vol. 27, No. 1, pp. 1–10.

Vetter, A., Graf, T., Heydrich, R., Reidel, H., Wurf, G., and Biertümpfel, A. 2002: Anbau und Verwertung von Faserpflanzen in Thüringen - Teilbericht: Einfluss agrotechnsicher Maßnahmen und Sortenwahl auf Ertrag und Qualität. Thüringer Landesanstalt für Landwirtschaft- Themenblatt-Nr. 42 03 430 / 2002.

Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S.,Hermann, B. and Patel, M.K. 2012: A review of the Environmental Impacts of Biobased Materials. In: Journal of Industrial Ecology, Vol. 16, No. S1, pp. 169–181.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B. 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: *www.link.springer.com/10.1007/s11367-016-1087-8*

Zawani, Z., Chuah-Abdullah, L., Ahmadun, F.-R., and Abdan, K. 2013: Acclimatization Process of Microorganisms from Activated Sludge in Kenaf-Retting Wastewater. In: Ravindra, P., Bono, A., and Chu, C. (Eds.). Developments in Sustainable Chemical and Bioprocess Technology. New York: Springer. Pp. 59–64.

Zöphel, B. & Kreuter T. 2001: Nachwachsende Rohstoffe (Hanf, Flachs, Salbei und Kamille) - Anbau und Bedeutung für den Lebensraum Acker. Leipzig (DE): Sächsische Landesanstalt für Umwelt und Geologie.

9 Appendix

The inventory of all in- and outputs of the considered natural fibre processes are listed in the following tables.

Table A: LCI data on flax

FLAX					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	110	10		in Vetter et al. (2002): 120–140 kg/ha in Schmidt et al. (2004): 80 kg/ha in Müller–Sämann et al. (2003): 110–140 kg/ha in Pless (2001): 100–130 kg/ha in van der Werf & Turunen (2008): 115 kg/ha
Fertilizers					
Nitrogen	kg N/ha*a	40	10		in Zöphel & Kreuter (2001): N-P-K: (60–120)-(80–160)-(70–120) in Schmidt et al. (2004): N-P-K: 40-17-70 in Dissanayake (2011): N-P-K: 40-50-50 in Carus et al. (2008): N-P-K: 40-40-40 in Pless (2001): N-P-K: 50-80-80 in van der Werf & Turunen (2008): N-P-K: 40-30-60
Phosphorus	kg P_2O_5/ha*a	40	10		
Potassium	kg K_2O/ha*a	80	10		
Lime	kg $CaCO_3$/ha*a	60	15		in Salmon-Minotte & Franck (2005): 60–75 kg/ha in Dissanayake (2011): 666 kg/ha in van der Werf & Turunen (2008): 333 kg/ha
Pesticides					in van der Werf & Turunen (2008): 2.6 kg/ha - active ingredient of pesticide in Pless (2001): 0.5 kg/ha unspecified pesticides
Insectizide-Trafo WG (active substance: Lambda-Cyhalothin)	kg Trafo WG/ha*a	0.15		Thüringer Lan-desanstlat für Landwirtschaft (2009)	
Herbicide - Callisto	litre Callis-to/ha*a	2	0.5		Thüringer Landesanstlat für Landwirt-schaft (2009): 1.5 litre/ha Vetter et al. (2002): 1.5 litre/ha
Herbicide - Roundup (active substance: Glyphosate)	litre Round-up/ha*a	4	0.5	Thüringer Landes-anstlat für Land-wirt-schaft (2009)-ripening-ac-celertation	
Fuel use for field operations					
Soil prepartion: pri-mary and secondary tillage (mouldbord ploughing)	litre/ha*a	20.1	2		based on Dissanayake (2011): mould-board plough: 15.1 litre/ha
Sowing: grain drill	litre/ha*a	6.6	2.3		in Pless (2001) there's a range from 1.3–5.9 litre/ha

FLAX					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Pesticide-application (sprayer)	litre/ha*a	7.5	1.5		based on Pless (2001) 3 times sprayer: pre-sowing - Callisto, at pest infestation - Insecticide, for ripening-acceleration - Roundup
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	4.5	0-5		adapted from hemp scenario: value-area based on an interview with M. Reinders (2014)
Cutting	litre/ha*a	5.4	2.9	Pless (2001)	
Turning (2-times)	litre/ha*a	6	1		Pless (2001): 4–12.4 litre/ha per 2-times windrowing turning of hemp based on an interview with M. Reinders (2014): 2 litre/ha per one-time-turning
Swathing	litre/ha*a	2	0.25		adapted from hemp scenario: value-area based on an interview with M. Reinders (2014) in Pless (2001): 2–6.2 litre/ha (windrow)
Baling (round bales)	litre/ha*a	6.6	0.5	Pless (2001): 6.6 litre/ha	
Bale moving	litre/ha*a	3	1		adapted from hemp scenario: value based on an interwiev with M. Reinders (2014) in Pless (2001): 5.6 litre/ha (tractor with front-end loader)
Transport					
Transport I: Transport of flax straw from the field to the processing-site	km (roundtrip)	60	20		assumption from nova based on hemp-scenario Type of transportation: lorry 16–32 t, EURO 5
Transport II: Transport of flax fibre to the harbour in Hamburg	km (one-way)	-			does not apply for this process, because flax is produced in Europe Type of transportation: transoceanic freight ship
Transport III: Transport of flax fibre on the road in Europe	km (roundtrip)	400	100		assumption from nova for all transportation within Europe on the road to the non-woven-producer Type of transportation: lorry 16–32 t, EURO 5
Fibre processing					
Electricity use	kWh/t fibre	279		Essel (2013)	
Diesel fuel use	litre/t fibre	1.67		Essel (2013)	
Yields					
Straw yield (only stems)	t retted straw/ha*a	6		Dissanayake (2011): 6 t/ha Carus et al. (2008): 5–6 t straw/ha	Yields can vary largely depending on producers, climatic conditions, region, soil characteristics, sowing and harvesting date, and the type of seed sown.

FLAX					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Water content of straw	%	15		Carus et al. (2008)	
Land requirement					
Cultivated area	ha*a/t fibre	0.8			Calculation based on straw yield, water content and fibre yield
Outputs					
Flax-fibre	% of retted and transported straw	24.5		based on Essel (2013): 25-50-25	
Flax-shives		51			
Flax-dust		24.5			

Table B: LCI data on hemp

HEMP					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	42.5	2.5	based on data obtained in MultiHemp (2017) inter-views (Frank, B 2018)	35 kg/ha in NL (interview with M. Reinders-2014) 32–33 kg/ha in NL (interwiew tih A. Dun-2014) 30–40 kg/ha are mentioned in Carus et al. (2008)
Fertilizers					
Nitrogen	kg N/ha*a	100	25		interview with M. Reinders (2014): N-P-K: 120-80-120 in Carus et al. (2008): N-P-K: 100-75-80 in González-García et al. (2010a) and (2010b): N-P-K: 85-65-125 in Heyland et al. (2006): suggestion of: N-P-K: (60–150)-(40–140)-(75–200) in van der Werf (2004): N-P-K: 75-38-113
Phosphorus	kg P_2O5/ha*a	75	5		
Potassium	kg K_2O/ha*a	100	20		
Lime	kg $CaCO_3$/ha*a	-	-		5–6 years with a rate of 200 kg/ha depending on the pH of the soil (interview with A. Dun-2014)
Pig slurry	m^3 slurry/ha*a	22.5	2.5	based on an interview (Frank, B 2018)	23 m3/ha (interview with A. Dun-2014, B. Frank 2018) in van der Werf (2004): 20,000 kg/ha
Transport of pig slurry from pig-farm to the field	km	200			

HEMP					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Pesticides					Hemp crops are rarely threatened by dangerous pests. Only in some cases is glyphosate used prior to sowing.
Herbicide - Glypho-sate	kg Glyphosate/ha*a	2.57	2.57	based on inter- views (Dun, A. 2014, Reinders, M 2014 & Frank, B 2018) & MultiHemp (2017)	2 litre/ha in Rumania (interview with M. Reinders-2014) 3 litre/ha in NL (interview with A. Dun-2014) 0 possible in Germany (interview B. Frank 2018) in Cherrett et al. (2005): 2 litre/ha
Fuel use for field operations					
Soil-preparation with a "spar-machine" (harrow-ing, drill and sowing in one machine)	litre/ha*a	32	2		value-area based on an interview with M. Reinders (2014)
Pesticide-application (boom sprayer)	litre/ha*a				is not yet included in the calcu-lation; in Pless (2001) a range of literature values from 0.4–1.6 litre/ha is mentioned
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	4.5	0.5		value-area based on an interview with M. Reinders (2014)
Slurry tank with trac-tor (organic fertilizer application)	litre/ha*a	11	1.5		value-area based on an interview with M. Reinders (2014) 25,000 litre-slurry-tank; including loading
Cutting	litre/ha*a	15	1		value-area based on an interview with B. Frank (2018)
Turning (2-times)	litre/ha*a	3	0.5		value-area based on an interview with B. Frank (2018)
Swathing	litre/ha*a	3	0.25		value-area based on an interview with B. Frank (2014) in Pless (2001): 2–6.2 litre/ha (windrow)
Baling (square bales)	litre/ha*a	7.5	0.5		in Pless (2001): 6.6 litre/ha interview with M. Reinders (2014): 8.3 litre/ha
Bale moving	litre/ha*a	3	1		value based on an interwiev with M. Reinders (2014) in Pless (2001): 5.6 litre/ha (tractor with front-end loader)
Transport					
Transport I: Transport of hemp straw from the field to the processing-site	km (roundtrip)	60	20		value-area based on an interview with M. Reinders (2014) Type of transportation: lorry 16–32 t, EURO 5

HEMP					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Transport II: Transport of hemp fibre to the harbour in Hamburg	km (one-way)	-			does not apply for this process, because hemp is produced in Europe Type of transportation: transoceanic freight ship
Transport III: Transport of hemp fibre on the road in Europe	km (roundtrip)	400	100		assumption from nova for all transportation within Europe on the road to the non-woven-producer Type of transportation: lorry 16–32 t, EURO 5
Fibre processing					
Electricity use	kWh/t fibre	310	10	Essel (2013)	
Diesel fuel use	litre/t fibre	1.67	0.06	Essel (2013)	
Yields					
Straw yield (only stems)	t retted straw/ha*a	7.5		Bocsa et al. (2000): 7–9 t retted stem/ha Carus et al. (2008): 6–8 t straw/ha in Germany	Yields can vary greatly depending on producers, climatic conditions, region, soil characteristics, sowing and harvesting date, and the type of seed sown. value based on an interview with B. Frank (2018)
Hemp-seeds	t seeds/ha*a	1		Interview B. Frank (2018)	
Water content of straw	%	15		Carus et al. (2008)	
Land requirement					
Cultivated area	ha*a/t fibre	0.555			Calculation based on straw yield, water content and fibre yield
Outputs					
Hemp-fibre	% of retted and transported straw	30		Carus et al. (2008) & MultiHemp (2017)	
Hemp-shives		55			
Hemp-dust		15			

Table C: LCI data on jute

JUTE					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	6	2	Mahapatra et al. (2009): olitorius and capsularis jute: 4 to 6 and 6 to 8 kg/ha	Rahman (2010): 5–5.5 kg/ha (broadcast methode) (general information) Islam & de Silva (2011): 10–12 kg/ha (Bangladesh)
Fertilizers					
Nitrogen	kg N/ha*a	40	20	Mahapatra et al. (2009): 60–20	
Phosphorus	kg P_2O_5/ha*a	10	10	Mahapatra et al. (2009): 0–13	
Potassium	kg K_2O/ha*a	45	20	Mahapatra et al. (2009): 25–63.3	
Lime	kg $CaCO_3$/ha*a	62	2		Sobhan et al. (2010): for tossa jute requirement: 128 kg CaO and white juste 120 kg CaO; Mahapatra et al. (2009): 0.5 LR (Lime Requirement)
Magnesium Oxide	kg MgO/ha*a	16	6		Sobhan et al. (2010): for tossa jute: 22 kg/ha Mahapatra et al. (2009): 10 kg/ha
Pesticides					
Pesticide Metolachlor	kg Metolachlor/ha*a	1	1	Mahapatra et al. (2010): for olitorius jute + hand-weeding	Gosh (1983): Fluchloralin: 1 kg/ha for weed control; Üllenberg et al. (2011): unspecified pesticides: 0.5 kg/ha Islam (2014): weeds are generally cont-rolled by raking and niri (hand weeding)
Fuel use for field operations					
Soil prepartion	litre/ha*a	10	2		assumption based on Sobhan et al. (2010): where bullock- or tractor driven ploughs (3–5 times) used for the fine tilth), assumption small tractor and 3–5 times plough
Sowing: grain drill	litre/ha*a	0	0		manpower based on Rahman (2010) and Islam & de Silva (2011): broadcast methode - sower is walking
Pesticide-application (sprayer)	litre/ha*a	1	0		assumption: manpower, but using production machinery as a tool
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	1	0		assumption: manpower, but using production machinery as a tool

JUTE					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Cutting	litre/ha*a	0	0		manpower based on Islam & de Silva (2011) and Sobhan et al. (2010): plants usually cut by hand.
Transport					
Transport I: Transport of jute straw from the field to the processing-site	km (roundtrip)	60	20		assumption from nova based on hemp-scenario Type of transportation: lorry 16–32 t, EURO 5
Transport II: Transport of jute fibre to the harbour in Hamburg	km (one-way)	13,996	1,822		based on www.hafen-hamburg.de and www.searates.com: Port Chittagong (Bangladesh) - Port Hamburg: 14,986 km Port Mumbai (India) - Port Hamburg: 12,193 km (last accessed: 2014-11-01) Type of transportation: transoceanic freight ship (assumption from nova)
Transport III: Transport of jute fibre on the road in Europe	km (roundtrip)	400	100		assumption from nova Type of transportation: lorry 16–32 t, EURO 5
Fine fibre processing					
Electricity use	kWh/t fibre	200	20		assumption from nova
Diesel fuel use	litre/t fibre	1.5	0.05		assumption from nova
Yields					
Straw yield (only stems)	t retted straw/ha*a	3.9		based on Sobhan et al. (2010)	
Water content of straw	%	20		based on Sobhan et al. (2010)	
Land requirement					
Cultivated area	ha*a/t fibre	1.08			Calculation based on straw yield, water content and fibre yield
Outputs					
Jute-fibre	% of retted and transported straw	30		own assump-tions based on Gosh (1983)	
Jute-shives (stems)		60			
Jute-dust		10			

Table D: LCI data on kenaf

KENAF					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	25	5	Behmel (2014): 25–30 kg/ha	www.andhrabank.in/download/mesta.pdf (last accessed: 2015-02-27) and Singh: 13–17 kg/ha
Fertilizers					
Nitrogen	kg N/ha*a	50	10	www. andhrabank. in/download/ mesta.pdf: 40-60 kg N/ha	Behmel (2014): no fertilizer data for India or Bangladesh
Phosphorus	kg P_2O_5/ha*a	25	5	www.andhra-bank.in/down-load/mesta. pdf: 20–40 kg P_2O_5/ha	
Potassium	kg K_2O/ha*a	25	5	www.andhra-bank.in/down-load/mesta. pdf: 20–40 kg K_2O/ha	
Lime	kg $CaCO_3$/ha*a	0	0		no lime according to literature
Magnesium Oxide	kg MgO/ha*a	0	0		no lime according to literature
Pesticides					Behmel (2014): herbicide extration via handweeding
Herbicide	litre Glyphosate/ ha*a	2	0. 5		www.andhrabank.in/download/mesta. pdf: 2.2 litre/ha Fluchloralin; calculated with Glyphosate because in SimaPro no Fluchloralin found
Fuel use for field operations					
Soil prepartion	litre/ha*a	10	2		in assumption to jute -Sobhan et al. (2010): where bullock- or tractor driven ploughs (3–5 times) used for the fine tilth
Sowing: grain drill	litre/ha*a	0	0		manpower
Pesticide-application (sprayer)	litre/ha*a	1	0.5		assumption: manpower, but using production machinery as a tool
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	1	0.5		assumption: manpower, but using production machinery as a tool
Cutting	litre/ha*a	0	0		manpower
Transport					
Transport I: Transport of kenaf straw from the field to the processing-site	km (roundtrip)	60	20		assumption from nova based on hemp-scenario Type of transportation: lorry 16–32 t, EURO 5

KENAF					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Transport II: Transport of kenaf fibre to the harbour in Hamburg	km (one-way)	13,996	1,822		based on www.hafen-hamburg.de and www.searates.com: Port Chittagong (Bangladesh) - Port Hamburg: 14,986 km Port Mumbai (India) - Port Hamburg: 12,193 km (last accessed: 2014-11-01) Type of transportation: transoceanic freight ship (assumption from nova)
Transport III: Transport of hemp fibre on the road in Europe	km (roundtrip)	400	100		assumption from nova Type of transportation: lorry 16–32 t, EURO 5
Fine fibre processing					
Electricity use	kWh/t fibre	200	20		assumption from nova
Diesel fuel use	litre/t fibre	1.5	0.05		assumption from nova
Yields					
Straw yield (only stems)	t retted straw/ha*a	7.6		based on Singh: 7.6 t dry raw ribbons and dry wood stem	
Water content of straw	%	15		based on Singh	
Land requirement					
Cultivated area	ha*a/t fibre	0.86			Calculation based on straw yield, water content and fibre yield
Outputs					
Kenaf-fibre	% of retted and transported straw	18			based on Singh: 18 % of dry raw ribbons and dry wood stems are processed to retted and dried fibre
Kenaf-shives (stems)		64			
Kenaf-dust		17			

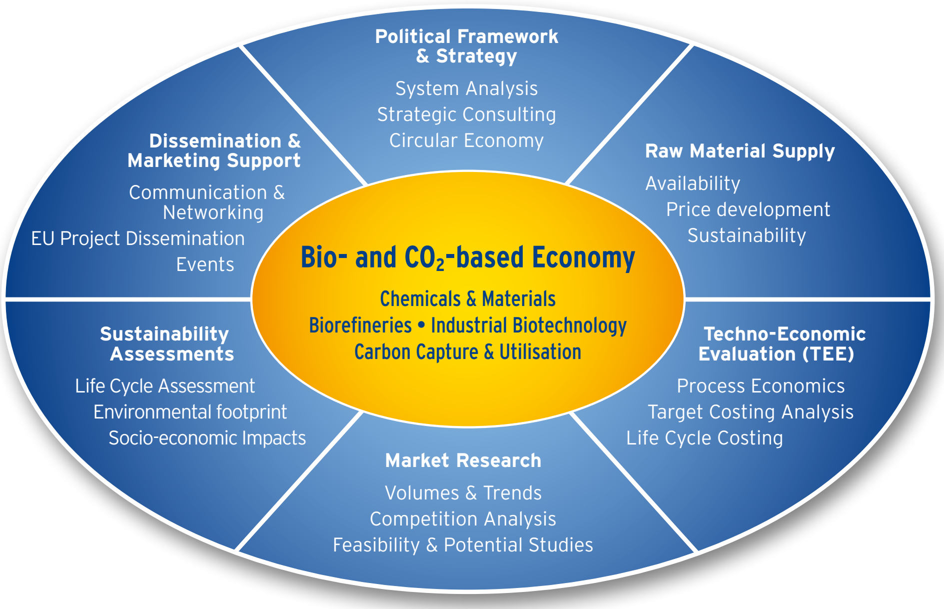
KENAF DRÄXLMAIER GRUOP					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	25	2.5	DRÄXLMAIER Group	Range assumption made by nova
Fertilizers					
Nitrogen	kg N/ha*a	75	7.5	DRÄXLMAIER Group	Range assumption made by nova
Phosphorus	kg P_2O_5/ha*a	35	3.5	DRÄXLMAIER Group	
Potassium	kg K_2O/ha*a	35	3.5	DRÄXLMAIER Group	
Lime	kg $CaCO_3$/ha*a	0			
Magnesium Oxide	kg MgO/ha*a	0			
Pesticides					
Herbicide	litre Glyphosate/ ha*a	0			
Fuel use for field operations					
Soil prepartion	litre/ha*a	1.5	0.15	DRÄXLMAIER Group	Range assumption made by nova
Sowing: grain drill	litre/ha*a	0		DRÄXLMAIER Group	manpower
Pesticide-application (sprayer)	litre/ha*a	0		DRÄXLMAIER Group	manpower
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	0		DRÄXLMAIER Group	manpower
Cutting	litre/ha*a	0		DRÄXLMAIER Group	manpower

KENAF DRÄXLMAIER GRUOP					
Materials / Energy	Units	Value	Range (+/-)	Data source / Reference	Comments
Transport					
Transport I: Transport of kenaf straw from the field to the processing-site	km (roundtrip)	60	20		assumption from nova based on hemp-scenario Type of transportation: lorry 16–32 t, EURO 5
Transport II: Transport of kenaf fibre to the harbour in Hamburg	km (one-way)	13,996	1,822		based on www.hafen-hamburg.de and www.searates.com: Port Chittagong (Bangladesh) - Port Hamburg: 14,986 km Port Mumbai (India) - Port Hamburg: 12,193 km (last accessed: 2014-11-01) Type of transportation: transoceanic freight ship (assumption from nova)
Transport III: Transport of hemp fibre on the road in Europe	km (roundtrip)	400	100		assumption from nova Type of transportation: lorry 16–32 t, EURO 5
fibre processing					
Electricity use	kWh/t fibre	21.4	0.2	DRÄXLMAIER Group	Range assumption made by nova
Loss during processing	%	4		DRÄXLMAIER Group	
Yields					
ribbon yield (only stems)	t retted rib-bons/ ha*a	1.67		DRÄXLMAIER Group	
Kenaf Stems	t stems/ha*a	5.42		DRÄXLMAIER Group	
Land requirement					
Cultivated area	ha*a/t fibre	0.62			Calculation based on ribbon yield and fibre yield

Table E: Allocation factors

Allocation		
Flax	Mass allocation	Economic allocation
Fibres (at fibre processing)	0.245	0.71
Shives (at fibre processing)	0.51	0.26
Dust (at fibre processing)	0.245	0.03
Hemp	Mass allocation	Economic allocation
Straw (Only for scenario with seeds)	0.86	0.49
Seeds (Only for scenario with seeds)	0.14	0.51
Fibre (at fibre processing)	0.3	0.68
Shives (at fibre processing)	0.55	0.3
Dust (at fibre processing)	0.15	0.02
Jute	Mass allocation	Economic allocation
Ribbons (after ribbon extraction)	0.4	0.8
Stems (after ribbon extraction)	0.6	0.2
Fibres (at fibre processing)	0.75	0.95*
Dust (at fibre processing)	0.25	0.05*
Kenaf	Mass allocation	Economic allocation
Ribbons (after ribbon extraction)	0.35	0.8
Stems (after ribbon extraction)	0.65	0.2
Fibres (at fibre processing)	0.51	0.95*
Dust (at fibre processing)	0.49	0.05*
Kenaf (DRÄXLMAIER Group)**	Mass allocation	Economic allocation
Ribbons (after ribbon extraction	0.24	0.8
Stems (after ribbon extraction)	0.76	0.2

(*) Assumption made by nova
(**) Dust is not assumed to be valorised due to the low percentage of losses during the process



nova-Institute

The nova-Institut GmbH was founded as a private and independent institute in 1994. It is located in the Chemical Park Knapsack in Huerth, which lies at the heart of the chemical industry around Cologne (Germany).

For the last two decades, nova-Institute has been globally active in feedstock supply, techno-economic and environmental evaluation, market research, dissemination, project management and policy for a sustainable bio-based economy.

Key questions regarding nova activities

What are the most promising concepts and applications for Industrial biotechnology, biorefineries and bio-based products? What are the challenges for a post petroleum age – the Third Industrial Revolution?

nova-Institut GmbH

Chemiepark Knapsack
Industriestraße 300
50354 Hürth, Germany

T +49 (0) 22 33/48 14-40
F +49 (0) 22 33/48 14-50

contact@nova-Institut.de
www.nova-institut.eu