Natural Fibers and Fiber-based Materials in Biorefineries

Status Report 2018

This report was issued on behalf of IEA Bioenergy Task 42. It provides an overview of various fiber sources, their properties and their relevance in biorefineries. Their status in the scientific literature and market aspects are discussed. The report provides information for a broader audience about opportunities to sustainably add value to biorefineries by considering fiber applications as possible alternatives to other usage paths.

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Natural Fibers and Fiber-based Materials in Biorefineries

Status Report 2018

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EXECUTIVE SUMMARY

The biorefinery of the 21st century requires commercialization and policy support of current technologies to allow the industry to grow. Companies that attempt to enter the field of renewable raw materials and products must be aware of prices, performance values and volumes available. Such information can speed up new developments. Finding suitable matches for raw materials with the right industry and application may lead to improvements in the overall sustainability. While gaseous biofuels and liquid transportation fuels have a huge market volume (especially the latter), the product unit value created in these applications is limited. In contrast, biochemicals and biomaterials tend to represent smaller markets, although within a very wide range from commodities to specialties, including certain niche markets. However, as the performance of some commercial biorefineries suggests, a single biorefinery tends to develop product portfolios based on the high value-added products available, aggregating rather small markets, and the main product (in conjunction with the regional feedstock availability) defines the scale of the operation.

Therefore, those responsible for the individual biorefineries are confronted with a decision-making process whenever they consider the utilization of side streams and by-products, for example, fibrous residues. **This report identifies potential roles of biobased fibers and fiber-based materials in biorefinery development. It was written to provide information to a wider audience by describing the added value of fiber materials in combination with energy carriers and other products from biorefineries.**

Several fiber products that originate from dedicated feedstock, as well as from residues, can play roles for biorefineries. In addition to the conventional systems, other, so-called "advanced biorefinery types" are relevant with respect to fiber products, including:

1. Compared to some other biorefinery types, such as whole-crop biorefineries, the "lignocellulosic-feedstock biorefinery" benefits from high feedstock availability, moderate costs and no direct competition with food and feed production. The components (mainly cellulose, lignin and hemicellulose) are separated by using several available procedures before they are further processed into various products and bioenergy. For instance, lignin, has mainly been burned as black liquor (in pulp processes) up until now, and chemical recovery has been used to generate energy (heat, electricity). However, lignin also has a potential to be used to create products such as renewable polymers or materials in the future. Fibers and fibrous products account for the largest proportion of the product portfolio in this type of biorefinery; therefore, the lignocellulosic-feedstock biorefinery can be considered especially relevant for the fiber report. A large variety of products (high-value products and commodities) are traditionally produced from lignocellulosic sources, and many new applications will most probably be based on this feedstock class (e.g., nanomaterials).

2. A "whole-crop biorefinery," where a portfolio of products is produced from grain and straw fractions, the dried residue mash (combination of wet grains and syrup) is processed to "distiller's dried grains with solubles," which is used as cattle feed due to its high dietary fiber content and its nutritional characteristics. The residual straw (i.e., the fraction which is not needed on the ground for soil improvement) represents a lignocellulosic feedstock that is processed in a lignocellulosic-feedstock biorefinery. The economic feasibility could be enhanced substantially by creating high value by producing by-products. Therefore, although fibers will most probably account for a much smaller share of the typical product portfolio (compared to lignocellulosic biorefineries) in this case, the consideration of the

fiber compounds in this type of biorefinery is also relevant, particularly when it comes to adding value and moving towards a circular economy.

3. The "oleo chemical biorefinery" uses oil crops for biodiesel production, combined with high added-value, vegetable oil-based products; however, these face the global challenge of maintaining a balance between food, oleo chemical and energy uses when crude oil prices increase. Substantial amounts of additional biomass are generated as reusable residue, as seed oils only comprise approximately 5-10% of the total biomass. Therefore, the remaining parts of the plant (e.g., lignocellulose, press cake and hulls), which are not needed on the ground to maintain the humus content and soil fertility (amounts depending on site conditions), are available for valorization. As in the whole-crop biorefinery, fibers will most probably account for a rather small share of the typical product portfolio, and the advantages of their optimized use could be to increase value and contribute to the circular economy.

4. So-called "green biorefineries" use grassland for the production of fresh biomass (e.g., grass for animal feed) and, therefore, take advantage of the fact that traditional grassland utilization for cattle production is on the decline in some regions, such as in Europe. Using various processes, fresh biomass is converted into a liquid phase (nutrient-rich green juice containing lactic acids, amino acids, proteins and other components) and a solid phase that consists mainly of fibers (press cake), and whose economic return is said to determine the economic efficiency of this biorefinery type. Thus, in addition to components such as protein that are used as animal feed, the fibers can be used to make material for building, insulation, and packaging applications, biocomposites, biofuel feedstock and other products. Improvements in grass fractionation still need to be achieved; however, if green biorefineries manage to be economically competitive, they would offer new opportunities in rural areas and contribute to the preservation of cultural landscapes and biodiversity.

Several practical examples (companies, demo-scale facilities, research projects), which can be counted among these types of biorefineries, are described in more detail in the report, and some of the challenges that advanced biorefinery types are facing are illustrated.

In addition to these practical examples, fibers and fibrous materials are considered in state-of-the-art biorefinery research. Considering 657 abstracts from scientific articles published about biorefineries between 2010 and 2016, the importance of lignocellulosic feedstock in biorefinery development is dominant. In addition to wood as a major feedstock for fibers, grass plants (such as switch grass) are mentioned and used to a small extent as a source for fibers. The fiber press cake from green biorefineries, meanwhile, is often intended to serve as animal feed or insulation material. Biorefinery fibers tend to be mentioned in the context of residue utilization (especially from common agricultural crops like corn, wheat and sugarcane). Concerning residuals from starch and sugar crops, a strong focus has been placed on energy utilization (fuels) as compared to material exploitation in the underlying search. However, products such as composites, pulp and paper have also been partly considered. In scientific articles, residuals from oil crops are rather frequently used as fiber material (in 50% of the abstracts), for instance, due to their good self-bonding properties as insulation fiberboards. Composite reinforcements, nanomaterials, boards (mainly for insulation), pulp and paper products, carbon fibers from lignin, feed and dietary fibers are applications that were relatively frequently mentioned in these abstracts.

Many feedstock which provide a source for natural fibers (e.g., cotton, flax, hemp and jute) are suitable for biorefinery concepts but are not often considered in terms of biorefinery development. The supply of these traditional natural-fiber feedstock is rather limited; therefore, the resulting biorefinery concepts are difficult to develop.

In contrast, agricultural feedstock that are commonly available, like wheat or maize, are more often utilized in biorefinery concepts, but fiber products are rarely considered as an option in product portfolio development.

Compared to some other biorefinery products like fuels, the applications and markets associated with fiber products must be considered as relatively diverse and complex. Unlike the fuel-bio-fuel substitution, for example, the replacement of glass fibers (as well as petrochemical-based carbon fiber) does not depend entirely on the cost. Therefore, fiber products open opportunities to build biorefinery development pathways in the future.

A future economy that sustainably uses biobased resources instead of fossil fuels to meet people's needs will be dependent on the production of a variety of products such as food, feed, materials, chemicals and energy from limited resources, such as the amount of land available for cultivation. The possibility to produce "almost everything from almost everything," although resources are scarce (e.g., land, energy, water and nutrients), contributes to the necessity of using these resources as efficiently as possible.

In particular, it is expected that several issues and developing technologies will affect the topic of fibers and fiber-based materials in biorefineries in the future. The production of micro- and nano-fibrillated cellulosic materials, for example, could lead to many promising applications (e.g., films, nanocomposites, coatings, pharmaceuticals, separation membranes, rheological modifiers and biomedical applications). The use of lightweight, high-performance materials in vehicles is a prominent topic that touches on energy issues in the transportation sector, e.g., in the context of e-mobility; on this matter, the use of natural-fiber reinforced composites is a field in which increasing interest has been shown. Carbon fibers are already produced from natural resources to a small extent (e.g., from wood-based rayon), but lignin from wood biorefineries is also a potential precursor for biobased carbon fiber production. The strong growth of mail-order businesses adds to the necessity to pack products safely. Therefore, fibrous packaging materials such as paperboard will remain relevant, while the development of smart, biobased packaging materials can also be expected. The so-called fast fashion trend has supported the production of cheap synthetic and cotton fibers in recent years, while certain other segments of the textile industry (e.g., fair fashion, outdoor clothing) have recognized that sustainability is a relevant issue. Driven by increasing consumer awareness, the sustainable production of textiles (e.g., from natural fibers grown on a regional level) is increasing in relevance. This could be another opportunity for the use of sustainable fibers from biorefineries. In the context of resource efficiency and the circular economy, technologies for waste recycling and residue valorization will become of even greater importance. For instance, the biotechnological conversion of cellulose extracted from municipal solid waste into products such as sugars and ethanol can offer several advantages. These include creating added value by recycling of waste materials, saving GHG emissions and producing renewable energy without creating competition for food and land use.

CONTENTS

1. INTRODUCTION

The concept of sustainably processing biomass into a spectrum of marketable biobased products (food/feed ingredients, chemicals, materials) and bioenergy (fuels, power and/or heat) is not new. Thousands of years ago, for example, production techniques for vegetable oils or wine had already been developed, and in the 19th and 20th centuries, large-scale utilization of renewable resources (e.g., sugar – with an industrial biorefinery) already existed. Scientists placed a focus at that time also on topics related to fiber (Kamm et al., 2016) and, namely, on the "pulp and paper production from wood, saccharification of wood, nitration of cellulose for guncotton and viscose silk, production of soluble cellulose for fibers, fat curing, and the production of furfural for nylon" (Kamm et al., 2016; De Jong et al., 2015). However, the term "biorefinery" did not appear until the 1990's, when some industrial trends developed to utilize biomass. These trends included: increased policy- and consumer-driven awareness of the need to use biomass resources in an economically and environmentally (e.g., reduced CO_2 emissions), more rational way; a growing interest in biomass-upgrading to valuable products; a greater consideration for starch utilization for fuel production; and "a perceived need to develop more high-value products and diversify the product mix in order to meet global competition and, in some cases, utilize an excess of biomass (especially in the pulp and paper industry)" (Berntsson et al., 2014; Kamm et al., 2016).

Ragauskas and colleagues (2006) outlined their ideas of a research road map for the biorefinery of the 21st century and found that commercialization and policy support concerning current and near-term technologies are required to allow the industry grow. Keijsers et al. (2013) stated that it was important for industries to become aware of the price, performance value and volumes available while trying to utilize renewable raw materials. They concluded that such information can speed up new developments and that a suitable match of raw materials with the right industry and application could lead to improvements in the overall sustainability levels. Chambost and Stuart (2007) described the basis for a systematic product design methodology for Rapid Market Analysis, an approach that was suitable for evaluating the economic and commercial potential of a biorefinery project and used a set of business tools that included market and synergy identification. The selection of appropriate methods for decision support, which needs to be adapted to the individual case, is discussed in chapter 4.7.

This report identifies the potential roles of natural fibers and fiber-based materials in biorefinery development. It was written to provide information for a wider audience by describing the potential added value of fiber materials in combination with secondary energy carriers and other products from biorefineries and addressing the following questions: 1) How can natural fibers and fiber-based materials increase the value added by biorefineries? 2) How can natural fibers and fiber-based materials from biorefineries be classified and selected by applying clear criteria? 3) How can the relevance of natural fibers and fiber-based materials for biorefineries be determined?

Therefore, a general overview on natural fiber classification and natural fiber markets is first introduced in the study. Thereafter, certain natural fiber types that are potentially relevant for biorefineries are described in more detail. The most important technical natural-fiber applications are described based on their requirements. This information should enable the reader to roughly assess the usability and value of natural fibers or fiber-based materials that may be obtained from biorefining processes. A detailed case-to-case assessment is, however, a matter of considering individual framework conditions. Therefore, the report introduces some useful approaches that can be taken to perform such assessments. Finally, the report provides some best-practice examples that may be taken as references for future developments.

2. BIOREFINERIES – CONCEPT AND UTILIZATION OF NATURAL FIBERS

2.1 Definition, driving forces and motivation

Several definitions of the term *biorefining* exist, such as the definition provided by IEA Bioenergy Task 42, which defined it as the "sustainable processing of biomass into a spectrum of marketable biobased products (chemicals, materials) and bioenergy (fuels, power, and/or heat)" (De Jong et al., 2011), and that provided by the American National Renewable Energy Laboratory (NREL), which stated that "a biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power and chemicals from biomass" (Berntsson et al., 2014).

Therefore, biorefineries can be regarded as analogous to petrochemical refineries, where crude oil is fractionated into a large number of intermediates and further processed into a variety of final products by elaborate procedures, as shown in *Figure 1*. Biorefineries have different prerequisites, however, compared to petrochemical refineries, such as the variety of feedstock, the necessity for a larger range of processing technologies and the variability in quality and energy density (Clark et al., 2015; Türk, 2014; De Jong, 2015).

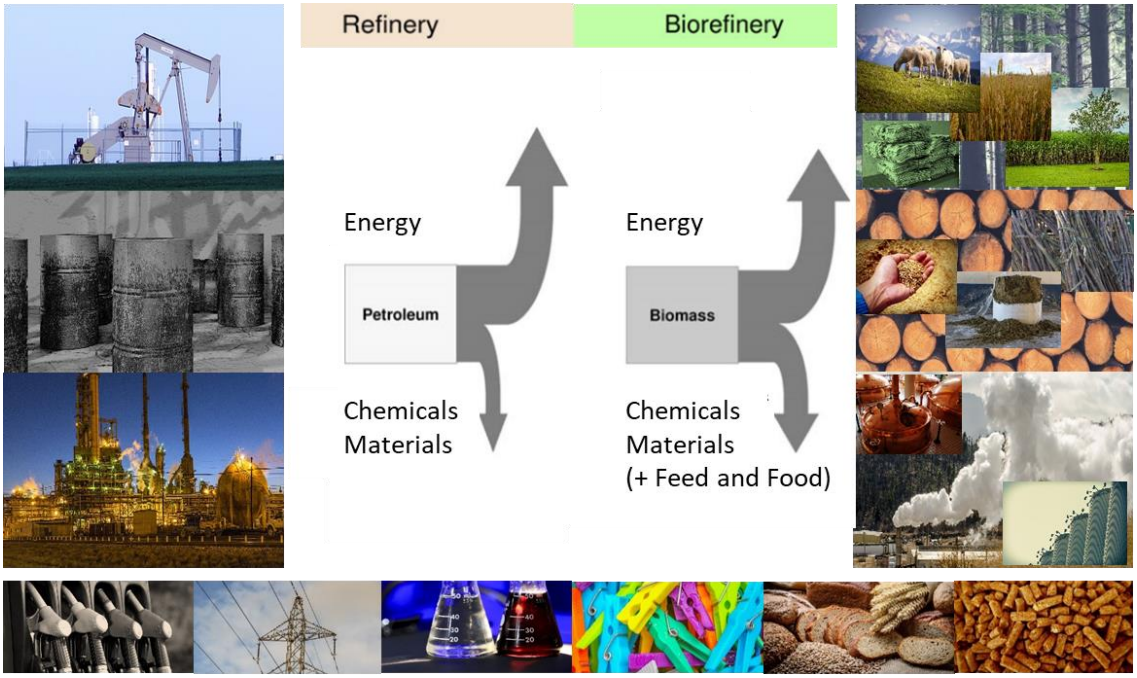

Figure 1: Comparison of the basic principles of petroleum refineries and biorefineries (modified from Clark et al., 2015 and from Kamm et al., 2016)

There are various driving forces behind the growing interest in moving from a fossil-resource-based economy towards a biobased economy. Major key motives include the expected peak production of non-renewable resources in the near future as well as price volatilities and increases; the desire to reduce the heavy dependence on imports of fossil fuel resources; the opportunities to promote regional and rural development; the chance to reduce GHG emissions to mitigate climate change; waste minimization; and the increased awareness of the importance of an economically, environmentally and socially sustainable global economy (De Jong et al., 2011; De Jong et al., 2015).

Several other parameters influence the success of biorefineries, such as the invitation of key stakeholders from separate backgrounds (e.g., agriculture/forestry, transportation fuels, chemicals, energy) to discuss various processing topics, encourage necessary R&D activities and deploy developed technologies in multi-disciplinary partnerships (De Jong et al., 2015).

In a sustainable biobased economy, a variety of products, such as food, feed, materials, chemicals and energy, must be produced from limited resources. The possibility to produce "almost everything from almost everything", although resources (e.g., amount of land available for cultivation, energy, water, and nutrients) are scarce, contributes to the necessity of using these resources as efficiently as possible to meet people's needs. "Using the Earth's limited resources in a sustainable manner while minimizing impacts on the environment" is the definition of resource efficiency used by the EC (European Commission, 2017), which strives to achieve sustainable growth using the means of a resource-efficient and low-carbon economy. To achieve this goal, well-developed technologies, tailored management and logistics, optimized product portfolios, but also sustainable consumption patterns, fair distribution and circular economy issues need to be considered. Some key terms and words that are used to describe the concept of the so-called circular economy include "maintaining the value of products and materials," "minimization of waste and resources" and "re-use" (European Commission, 2018). The concept of shifting from open-ended to more circular economic systems can be traced back to the 1960s (idea: Boulding, 1966) and late 1980s (theoretical framework: Pearce and Turner, 1989) and has been the subject of research and discussion since these times. The principles "Reduction, Reuse and Recycle" (the so-called 3Rs Principles) are the three actions with which circular economy is mainly associated (Ghisellini et al., 2016). Political actions towards a more circular economy have been taken, for example, by Japan, China and countries in the European Union (Mair et al., 2016).

The primary motivation to develop biorefinery concepts can either be the production of energy or biofuel ("energy-based biorefinery") or the production of a portfolio of biobased products ("product-based biorefinery"). Energy-based biorefineries focus on the production of liquid or gaseous road transportation biofuels, power or heat, however, also produce value-added products from residues to get additional economic and environmental benefits. Product-based biorefineries try to gain the highest economic benefit by fractionating and modifying biomass into a portfolio of biobased products (including natural fibers), also partly using process residues to gain energy.

2.2 Market aspects

A typical pattern that occurs in context of multi-product biorefineries is related to the ratio of the product value and associated market volume: The higher the product value, the smaller the associated market volume (specialties) and vice versa (commodities) (Stern et al., 2015). While gaseous biofuels and liquid transportation fuels have an enormous market volume (especially the latter), the product unit value created in these applications is limited (Lora, 2006; Berlin and Balakshin, 2014). In contrast, biochemicals, biomaterials and hybrids thereof tend to represent smaller markets, although within a very wide range from commodities to specialties, including certain niche markets. However, if single biorefineries (one site/factory/mill) are examined, the product portfolios based on several high value-added by-products seem to create a higher return than a combination of products with one dominating commodity. This rather theoretical perspective is, in practice, supported by the fact that fuel and chemical markets reflect the economies of scale of petrochemical industries. In contrast, biorefineries will never reach the average scale of operation that is available at petrochemical refineries. This fact is based on fundamental differences regarding feedstock supply. While oil fields and pipelines provide a centralized supply, biomass is produced decentrally. Hence, the scale of operation must reflect the availability of the required feedstock in an area that is defined by reasonable transportation costs (Jack, 2009).

The extension of this relation depends on the individual feedstock. Processing green, perishable feedstock (grasses), for example, will require the use of small-scale facilities that produce protein-rich juices and fiber materials. Imported lignocellulosic feedstock, on the other hand, probably will be processed in relatively large-scale facilities to produce chemicals/materials and secondary energy carriers in an efficient and synergistic way.
Still, whenever decision-makers of biorefinery operations consider the utilization of additional side streams and by-products, such as fibrous residues, the target products and markets including the target values and volumes need to be defined.

Lignocellulosic residues, such as agricultural residues (e.g., straws and stalks) are a source of fibers that can also have environmental and economic advantages (Puitel et al., 2015). These have been discussed for the production of fiber panels, particleboard plants, or composites based on several feedstock and, to a minor extent, for the production of insulation boards and other building materials, adding value to biorefineries (e.g., towards the concept of a whole-crop biorefinery) (Philippou, 2001).

2.3 Classifications

To cope with the rising number and complexity of biorefineries, several classification approaches have been introduced.

IEA Bioenergy Task 42 has developed a specific classification approach which is applicable to individual biorefinery systems and their possible combinations. In this approach, four main features are distinguished: 1) platforms (e.g., C5 and C6 sugars, oils, biogas); 2) products (energy products, such as electricity/heat or bioethanol; material products, biomaterials, or polymers); 3) feedstock (dedicated crops, such as oil crops, sugar crops, grasses; residues, such as lignocellulosic residues); and 4) processes (e.g., thermochemical, biochemical, chemical, mechanical) (Cherubini et al., 2009; De Jong et al., 2011).

Examples for the application of the classification system include:

- A C5/C6 sugars and lignin biorefinery for the biochemical processing of straw for the production of bioethanol, power and heat.
- A syngas biorefinery for the thermochemical processing of wood for the production of bioethylene, power and heat.

2.4 The role of natural fibers

From a technical point of view, almost all industrial materials based on fossil resources can be substituted by biobased equivalents (Raschka et al., 2012). However, these often cannot yet compete economically, based on the premises that they perform at least as well as the petrochemical counterpart and are more sustainable (De Jong et al., 2011).

Industrial utilization of natural fibers and fiber-based materials, in the context of what is currently called a "biorefinery," has played an important role for centuries. For instance, a mill using a sulfite wood-pulping process as well as processes to gain value-added products (ethyl alcohol and paper glue) from the spent liquor was already in operation in Germany in 1898 (Pötsch, 1988). In 1922, an American company produced furfural from oat husks.

As furfural was the cheapest aldehyde available, it was used as precursor for nylon up until the 1960s, before being substituted by intermediates based on fossil resources – a fate suffered by many biobased chemical products at that time (Ullmann, 1930; Ragauskas, 2006).

In the following section, some advanced biorefinery feedstock types which are relevant to specific natural fibers and which have received an increased amount of attention recently, are briefly described. An emphasis is placed on their relevance to fiber utilization. In addition to conventional biorefineries, the lignocellulosic-feedstock biorefinery is the most common type that is associated with fiber production; the whole-crop biorefinery, oleo-chemical biorefinery and green biorefinery are also mentioned as they produce lignocellulosic residues, which can add value to individual biorefining facilities.

The **lignocellulosic-feedstock biorefinery** uses lignocellulosic biomass as feedstock with the advantages of high availability, moderate cost, no direct competition with food and feed production, and a "good position of conversion products on the traditional petro-chemical and future biobased product market" (Kamm et al., 2016). The components (mainly cellulose, lignin and hemicellulose) are separated by several available procedures before being further processed into various products and bioenergy; however, certain technologies (e.g., separation, lignin utilization) still need to be further developed.

The pulp and paper industry serves as an example of this specific biorefinery type as it has placed an increasing focus on "value-added coproducts from underutilized streams and waste materials" since the 1980s (De Jong et al., 2015). With its fibrous main products and "value-added coproducts, including, e.g., tall oil, acetic acid, furfural, and lignosulfonates," the pulp and paper industry can also be considered as an early non-food-crop industrial biorefinery (De Jong et al., 2015).

For instance, lignin has mainly been burned as black liquor up until now, and the chemical recovery processes are used for energy (heat, electricity) production; however, lignin is also said to have great potential for use to create products in the future, such as renewable polymers or materials. An illustration of fiber-relevant aspects in lignocellulosic-feedstock biorefineries appears in *Figure 2*.

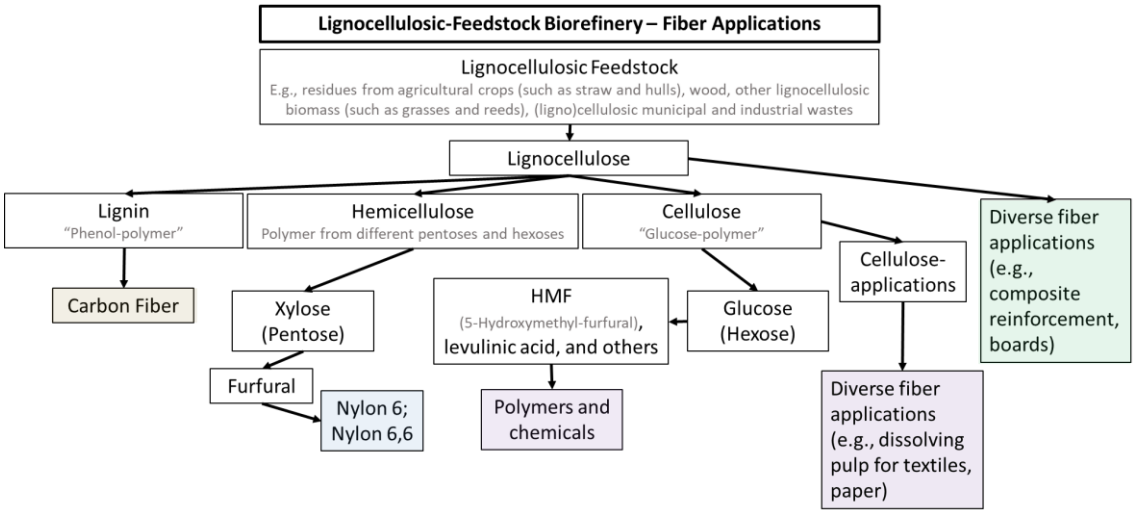

Figure 2: Potential natural fiber products from the lignocellulosic biorefinery (modified from Kamm et al., 2016*)*

In a **whole-crop biorefinery**, a portfolio of products is produced from different fractions such as grain, straw and seed. The dried residue mash (combination of wet grains and syrup) is processed to "distiller's dried grains with solubles," which can be used as animal feed due to its high dietary fiber content and nutritional characteristics. The residual straw represents a lignocellulosic feedstock that can be processed in a lignocellulosic-feedstock biorefinery (De Jong et al., 2015).

The **oleo chemical biorefinery**, which is based on oil crops (e.g., for biodiesel production in combination with high added value vegetable-oil-based products), generates substantial amounts of lignocellulosic residues for further use in a lignocellulosic-feedstock biorefinery (De Jong et al., 2015).

Green biorefineries use fresh biomass from grassland (e.g., grass for animal feed) and other types of green perishable biomass feedstock (such as sugar beet leaves). Therefore, these biorefineries take advantage of the fact that the traditional grassland utilization for cattle production is on the decline in some regions such as Europe.

Fresh biomass is converted into a liquid phase (nutrient-rich green juice containing lactic acids, amino acids, proteins and others) and into a solid phase by various processes. The solid phase consists mainly of fibers (press cake) and the economic return of this fraction is said to determine the economic efficiency of this biorefinery type. While protein can be used, e.g., as feed for pigs and poultry, the fibers can be used to produce green feed pellets, "building materials, insulation material, plant pots, biocomposites, packaging material and biofuel feedstock" (De Jong et al., 2015), although improvements in grass fractionation still need to be achieved (De Jong et al., 2015; Kamm et al., 2016).

In practice, these concepts are under development, and some tasks are still difficult to complete. Therefore, we illustrate some companies which can be counted as examples of the four types of biorefineries and/or some of the challenges that decision-makers of these biorefineries commonly face:

- Concerning the lignocellulosic biorefineries, a number of lignin-producing biorefineries have been financed and developed to date. However, the economic viability is challenging in the current environment, even if price support is available, and technical optimization is still underway. Projects like DuPont's Hugoton facility is now up for sale, and the Crescentino facility is on care and maintenance. Both these facilities utilized the lignin portion of biomass as a source of power, but were unable to take advantage of the potential higher value that could be achieved from lignin if the appropriate technology had been available. In all likelihood, higher-value products could have helped; however, the technology required was not necessarily available.
- Work has already commenced in the area of whole-crop biorefineries, with various companies looking to convert more of the fiber contained in corn into more valuable ethanol. As time progresses, it is expected that more fiber will be harvested from the fields rather than from the corn and integrated into these "whole-crop biorefineries." It should be noted that there are still few successful projects that have taken the corn stover and incorporated it directly into the current process route. It could be argued that POET's Project Liberty is the first project that integrates this technology in such a way, but the fiber from the corn plants is processed in a separate way and, thus, it not really fully integrated in the classic sense.
- The particular case of oleo chemical biorefineries presents a rather big challenge to developers from an economic standpoint. Oil crops are relatively expensive on a unit basis and, although the by-product can be sold as a feed, current economic conditions

tend to require subsidies in order to generate returns. One of the advantages of these refineries is that their products can be used as a drop-in-fuel for heavy transport and as aircraft fuel. The economics would suggest that the medium-term potential of this type of biorefinery is perhaps more limited than that of the first two biorefinery options described.

- Several "green biorefinery" demonstration plants have been installed in different countries. Their economic viability depends strongly on the utilization of the solid fraction, as the protein product alone would not create sufficient revenue; therefore, research on further development of alternative products is recommended for better economic efficiency. A practical example of this is the Biowert facility, which produces electricity, composites, insulation materials and fertilizers with an annual production capacity of 2,500 tons of cell fibers from locally grown meadow grass.

3. FIBERS WITH RELEVANCE FOR BIOREFINERIES

Fibers are polymers, and, more specifically, they represent a "class of materials that are continuous filaments or are in discrete elongated pieces." This means the aspect ratio is a relevant criterion for the definition of the material as a fiber (Thakur et al., 2016).

According to the International Union of Pure and Applied Chemistry (IUPAC), a polymer is "a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetitions of units derived, actually or conceptually, from molecules of low relative molecular mass" (Jenkins et al., 1996).

Natural polymers are produced without fully disassembling or changing their original natural structure, which distinguishes them from synthetic, man-made polymers. Natural, organic polymers come from living organisms; prominent representatives of this group are cellulose, lignin, hemicellulose, chitin and collagen. In contrast, synthetic polymers are formed by the polymerization of petrochemical-based or biobased monomers. The process of shaping a product is one of the most important steps and determines whether a polymer will either be made into a fiber or not. Examples of some technologies include extrusion, fiber spinning and injection molding.

Despite the fact that these highly general definitions give rise to a large number of possibilities, fibers are commonly divided into two main categories in the literature: **natural fibers** and **man-made fibers** (both described in more detail later in the report). Within these categories, there are several classes that differ slightly depending on the reference cited (Kozlowski et al., 2008; Jawaid et al., 2011; Mohanty et al., 2000; Türk, 2014).

In *Figure 3*, the classification of **natural fibers** is exemplified: these are either plant-based (ligno)cellulosics, animal-based protein fibers, or inorganic polymers.

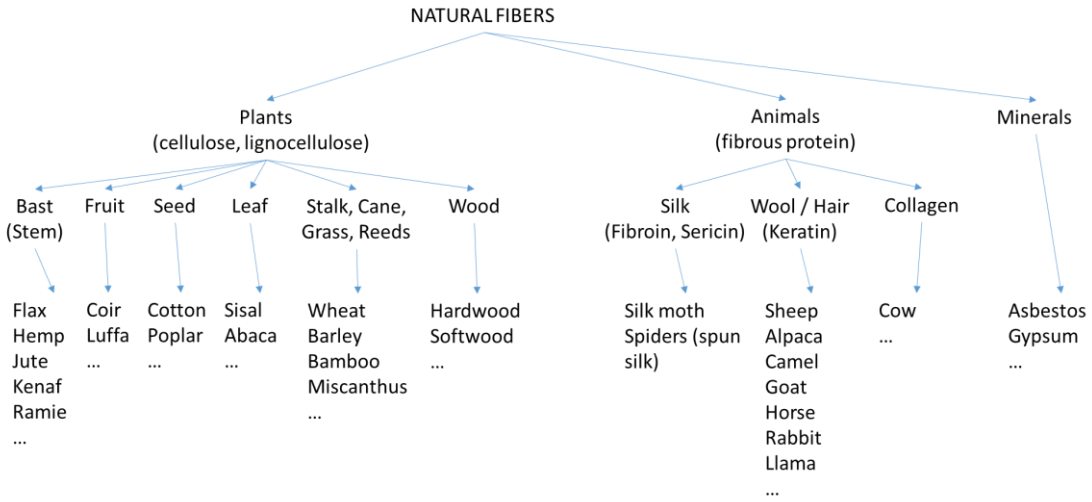

Figure 3: Classification of natural fibers (modified from Kozlowski et al., 2008; Jawaid et al., 2011; Mohanty et al., 2000; Türk, 2014)

Man-made fibers can be either organic or inorganic (see *Figure 4*), whereas organic polymers are commonly divided into modified natural polymers and synthetic polymers. Some synthetic polymers are derived from natural monomers (e.g., polylactic acid), and inorganic carbon fibers (although based on organic precursors) might as well result from (carbonized) biomass. It is, therefore, important to make sure that the categories "natural fibers" and "man-made fibers" are not simply equated with "biobased" and "non-biobased."

When evaluating different fiber types according to their potential future relevance for biorefineries, it is necessary to consider the potentially substituted product (either biomass-derived or not). A new fiber material that is produced to provide a substitute for a product that already exists on the market must be competitive, for instance, regarding its material properties, sustainability, or costs. Therefore, not only the new fibrous material, but also the reference material (e.g., properties, sustainability, price) must be considered when evaluating potential market applications.

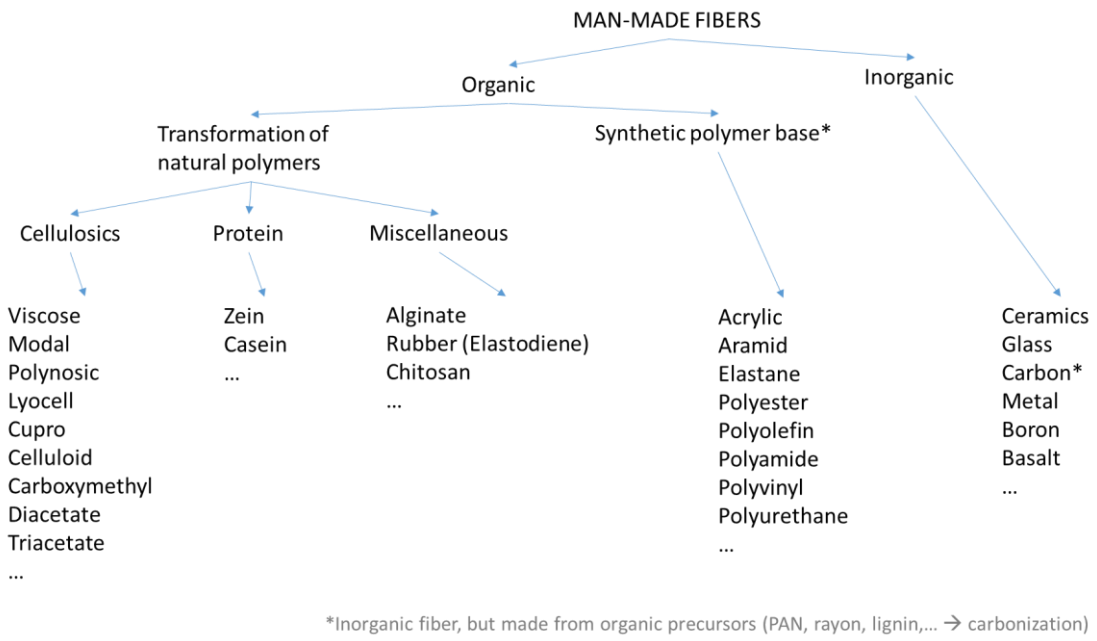

Figure 4: Classification of man-made fibers (modified from Jawaid et al., 2011)

A review of 657 abstracts from scientific articles published between 2010 and 2016 reveals the importance of lignocellulosic feedstock in biorefinery development (*Figure 5*). Of all the feedstock mentioned in the abstracts, the majority referred to lignocellulose, which was mainly derived from dedicated lignocellulosic crops and residues. The results of this review exemplify the high abundance of lignocellulosic and, therefore, the importance of fiber-containing feedstock in scientific research on biorefineries in general. Although it does not specifically refer to fiber applications, *Figure 5* illustrates the fact that the most commonly used basis material for natural fiber production is a topic of continuous discussion in the context of biorefineries.

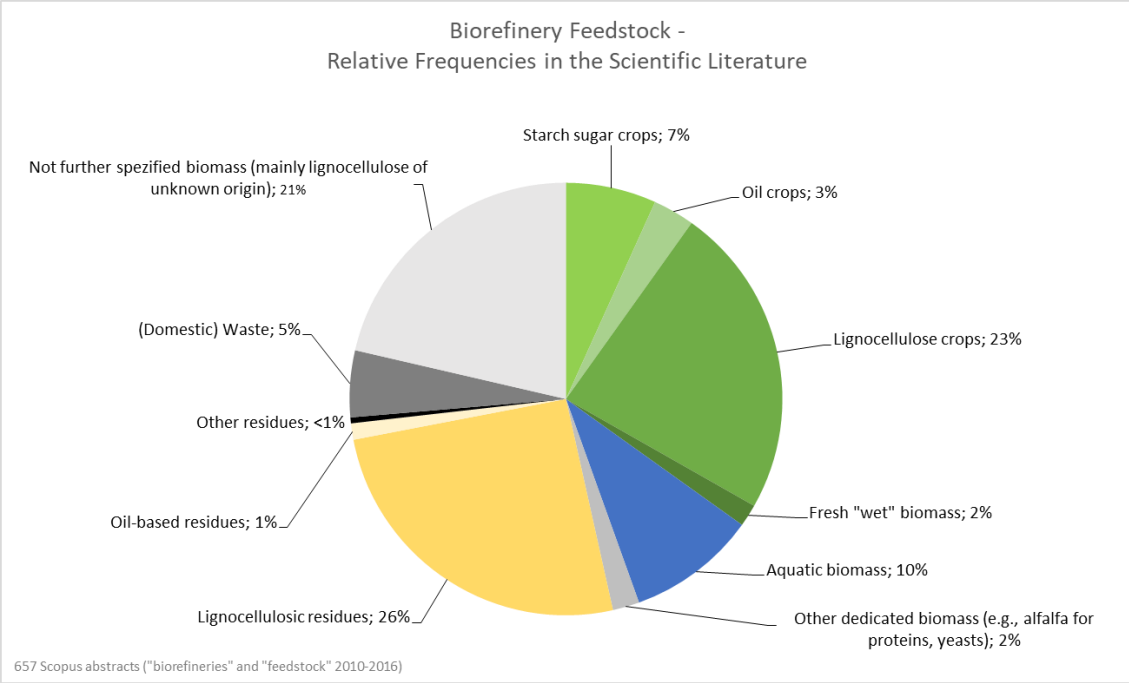

Figure 5: Feedstock mentioned in abstracts (657 articles published from 2010 to 2016)

In the literature surveyed, frequently discussed biorefinery feedstock were lignocellulosic crops and especially wood (hardwood and to a minor extent softwood). Also lignocellulosic biomass derived from grasses, such as switch grass or energy crops, seem to play an important role. Lignocellulosic residues from agriculture, and especially corn stover, sugarcane bagasse, wheat straw and rice straw were mentioned frequently in this scientific literature on biorefineries. The abundance of these feedstock can probably be explained by the fact that they represent the residual biomass of some of the most common crops in the world. Algae (mainly microalgae) are strongly represented in the abstracts of these scientific articles, and fresh grass (green biorefineries) is also mentioned.

Figure 5 and *Figure 6* exemplify the potential importance of lignocellulosic sources as dedicated crops, but also as residual material from various processes (e.g., in whole-crop biorefineries or conventional, food-production-related biorefineries).

Figure 6: Examples for biorefinery fibers in the abstracts of scientific articles (2010-2016)

Findings of the systematic literature review (abstracts of scientific articles) on the topics of fibers and biorefineries are illustrated in *Figure 6*: Using the search term mentioned in *Figure 6*, 177 abstracts were found and read. It was not possible to obtain complete results, because researchers that work on diverse fibers for biorefineries use different terms and keywords; however, using the search-string described and the number of articles considered, a rough overview of some utilized fibers and their applications can be given. The fibers (including "fibers") were sorted according to the feedstock mentioned (only abstracts with clearly indicated feedstock were taken into account), the share of abstracts with a fiber product (others mostly addressed energy-driven biorefineries, but also the production of chemicals and others) was determined and is visualized in the red/grey pie chart and, finally, the fiber products mentioned in the abstracts were briefly summarized.

Wood biorefineries, and especially biorefineries belonging to the pulp and paper industry, are conventional biorefineries, and tend to see themselves as such. Fiber products, such as pulp, play major roles although other fractions of the wood are also used, e.g., for energy purposes. Fractionation of lignocellulose, modifications and valorization of co-products and use of side streams

are strategies undertaken to stay economically competitive. For instance, lignin usually serves as energy source, but other utilization pathways, such as carbon fibers, resins, adhesives, or foams, were also covered in the underlying abstracts. Conventional fibers were rarely found using the search terms described, probably because people who deal with traditional fiber types tend not to refer to the relatively new term "biorefinery." However, the few examples found all referred to final fiber products, and, to a minor extent, also biofuels and chemicals. Grass plants as dedicated lignocellulosic feedstock (such as switch grass) were mainly used as energy crops and only to a small extent as a source for fibers, whereas fibers from green biorefineries commonly served as animal feed or insulation material. Few abstracts referred to aquatic biomass as a basis for fibers, and if so, they mentioned niche applications.

Fibers were often mentioned in the context of biorefineries regarding residue utilization (especially from corn, wheat and sugarcane, as these crops are among the most common food crops in the world). A reason for this might be the fact that biorefineries are often discussed in the context of using all biomass fractions optimally and generating value-added products by valorizing residues and wastes. Concerning residuals from starch and sugar crops, a stronger focus was placed on energy production compared to material exploitation. However, products such as composites, pulp and paper were also mentioned to a minor extent. Residuals from oil crops were more often used as fiber material (in 50% of the abstracts), for instance, due to their effective self-bonding properties when used in insulation fiberboards. Composite reinforcements, nanomaterial, boards (mainly for insulation), pulp and paper products, carbon fibers from lignin, feed and dietary fibers are fiber applications that were commonly mentioned. Non-fiber applications noted were usually energy production (mainly cellulosic bioethanol as biofuel but also biogas) and products from fractionated lignocellulose (e.g., various chemicals, plastics).

Figure 7 combines the identified biorefinery fiber feedstock with a commonly used classification of fibers, including traditional high volume and/or high value fibers and fibers occurring in the context of biorefineries. Frequently occurring feedstock with a potential use in the context of biorefineries were taken into account, with the exception of dedicated starch and sugar crops due to their competition with food production. In the case of dedicated starch and sugar crops, only their residues were considered. Cotton and glass fibers were indicated as a potentially substituted material, and so was carbon fiber. The latter, however, can also be partly produced from biogenic raw material, such as lignin, in theory. Animal protein fibers (such as wool) were not taken into account, as in the common literature they – justifiably or unjustifiably - rarely occur in the context of biorefineries.

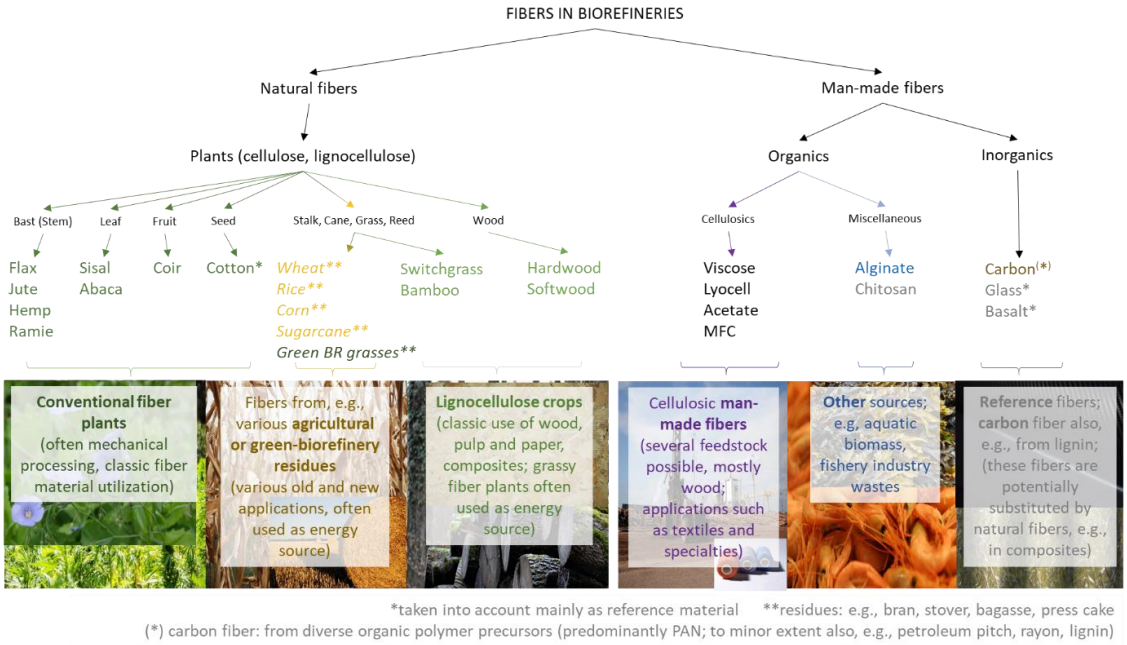

Figure 7: Selected fibers with relevance to biorefineries based on common feedstock mentioned in the abstracts of scientific papers

3.1 Natural Fibers

As shown in *Figure 3*, natural fibers are produced by plants, animals, or have a mineral origin: No chemical modification or man-made polymerization process is used to create them, which differentiates them from man-made or synthetic fibers. There are many processing possibilities, e.g., they can be spun into a filaments, threads, or ropes, and then they can be woven, knitted, matted, or bound. Plant fibers are mainly composed of cellulose, hemicellulose and lignin, but also to a minor extent, fats, waxes, pectin, water-soluble substances and color-carrying substances are included. The shares of these substances vary from fiber to fiber. Also, the indicated properties of natural fibers can have considerable variations (depending on the growing conditions and the harvesting time, extraction methods, treatment as well as storage procedures) and will, therefore, serve only as a rough guideline (Pickering et al., 2016).

Utilization of natural fibers has a long tradition in cultures around the world (e.g., for the production of clothing, buildings materials and fishing nets); therefore, people who deal with traditional fiber types do not necessarily tend to refer to the relatively new term "biorefinery." However, the possibilities of sustainably using several plant parts (seeds, lignocellulose parts of lower value) for various purposes, replacing less sustainable products (such as fossil-resource-based materials) and increasing regional added-value bring natural fibers into the limelight again in the context of the discussion of building a biobased economy. Regarding technical applications, the largest share of natural fibers is still used for traditional applications such as yarns, twines and clothes; other applications are pulp and paper (especially specialty papers), composites (e.g., for the automotive industry), geo- and agro textiles, insulation products and by-product utilization (e.g., animal bedding, construction material, gardening and boards), and for the purpose of energy (Müssig, 2010).

Disclaimer

In the following section, some particular fibers are described in greater detail. They were selected because of their volume and/or value, their (future) relevance to important, more advanced biorefinery types (such as those described above), or because they will potentially be substituted by biorefinery material. This selection of both the fibers and the information contained in the sub-paragraphs is controversial despite a careful and conscientious approach (with the help of common literature, scientific literature, market data and inputs from biorefinery experts) and therefore no claim is made to completeness. To present a broad perspective of biorefinery fibers, this overview is intended as a guide and was written to increase the awareness of the potential of fibers to valorize biorefineries in general (as main products or co-products in energy- and material-based biorefineries of different implementation status). Further investigations will be required (e.g., based on the cited literature) to examine single fibers or application types in more detail. For decision-making, individual biorefinery assessments will have to be conducted (a short example in the form of a table is given in chapter 4).

As visualized in *Figure 8*, cotton accounts for the largest share of natural plant fibers produced worldwide by far.

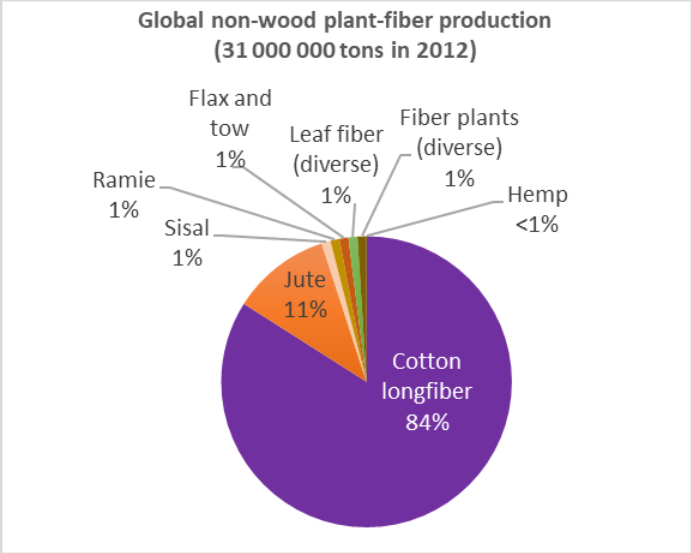

Figure 8: Worldwide natural fiber production, omitting wood fibers (data source: FAOSTAT)

Some characteristics, such as the density and some mechanical properties of selected, traditional, natural fibers, are listed in *Table 1*. Müssig (2010) gathered data on fiber properties from different sources and pointed out that there are large variations in the mechanical properties of plant fibers within and between fiber types. Because of these variations (partly explained by natural variations and technical factors and also by the influence of the testing procedure), the reader of this report should bear in mind that all numbers given are approximate guidelines rather than exact values. If more information about a specific fiber is required, it is recommended to check the associated references and clarify how the authors of these reference assessed the underlying values.

Such conclusive tables were not available for the other fibers in this report, which are not considered in *Table 1* (e.g., fibers from residues or grasses); therefore, values found in the literature are mentioned in the respective sub-chapter. We recommend, however, that these be interpreted particularly carefully.

Wood (soft- and hardwood) originates from various species of plants, and species-dependent properties influence other factors (e.g., anatomical, environmental and processing-related factors); therefore, if more information about a specific kind of wood is needed, we recommend the reader to look up the property values in cited literature (for instance: in Winandy J.E., 1994).

Table 1: Properties of selected natural fibers based on Müssig (2010)

Property	Seed fiber	Bast fibers				Leaf fibers		Fruit Fiber
Plant name	Cotton	Jute	Flax	Hemp	Ramie	Sisal	Abaca	Coir
(Single) fiber diameter [µm]	12-38	5-30	1.7-76	3-51	4.6-126	4-47	6-46	12-24
(Single) fiber length [mm]	10-64	1-6	4-140	8.3-55	40-260	0.5-8	2-12	0.3-1.2
Tensile strength [MPa]; (value in brackets: most frequently published)	220-840 (450)	187-800 (500)	343-1500 (700)	310-1110 (800)	290-1060 (800)	80-855 (600)	12-980 (600)	95-270 (200)
Youngs's modulus [GPa]; (value in brackets: most frequently published)	4.5-12.6 (8)	3-64 (30)	8-100 (70)	3-90 (65)	5-128 (55)	9-38 (12)	12-72 (50)	2.8-6 (5)
Elongation at break [%]; (value in brackets: most frequently published)	2-10 (8)	0.2-3.1 (1.8)	1.2-4 (3)	1.3-6 (3)	1.2-4.6 (3)	1.9-14 (3)	1-12 (4)	15-51.4 (30)
Density [g/cm^3]	1.5-1.6	1.3-1.5	1.4-1.52	1.4-1.6	1.5-1.56	1.0-1.5	1.4-1.5	1.15-1.5
Fibril angle (main cell wall) [deg]	20-30	7-10	5-10	2-6.2	7.5-12	10-25	10-12	30-49
Shares: Cellulose Hemicellulose Lignin Pectin Fat and Wax Ash Water-soluble substances [%]; (value in brackets: most frequently published)	82-96 (90) 2-6 (4) 0-1.6 (0.7) 0-7 (4) 0.6 (0.6) 0.8-2 (1.4) 0.4-1 (0.7)	51-84 (65) 12-24 (15) 5-14 (10) 0.2-4.5 (1.5) 0.4-0.8 (0.5) 0.17-0.7 (0.4) 0.5-2 (1)	60-81 (70) 14-21 (17) 2-5 (2.5) 0.9-3.8 (2) 1.3-1.7 (1.5) 1.5 (1.5) 3.9-10.5 (6)	57-92 (70) 6-22 (16) 2.8-13 (6) 0.8-2.5 (1) 0.7-0.8 (0.7) 0.7-3 (1.5) 0.8-2.1 (1)	68-85 (72) 3-17 (14) 0.5-1 (0.7) 1.9-2.1 (2) 0.3 (0.3) 0.3 (0.3) 5.5-6.4 (6)	43-88 (66) 10-15 (12) 4-14 (10) 0.5-10 (2) 0.2-2 (1) 0.14-0.55 (0.3) 1.2-6 (3.5)	56-68 (60) 19-25 (21) 5-13 (10) 0.5-1 (0.8) 0.2-3 (1.4) 1.4 (1.4)	32-53 (40) 0.2-0.3 (0.2) 40-45 (43) 3-4 (3) 4.5 (4.5)
Absorption regain [%] at 65 % relative humidity, 20°C	7-25	8.5-17	7-12	6-12	7.5-17	10-22	5-14	2-13
Transverse swelling [%]		20-22	20-25		12-15	18-20		6-15
Water retention [%]	45-50	25-35	50-55	50-55		30-45		

3.1.1 Seed fibers

Cotton is the dominant natural fiber with an estimated volume of 23.27 million tons produced in 2016/17 according to the United States Department of Agriculture (USDA, 2017), and 26.16 million tons produced in 2014 according to FAOSTAT (FAO, 2017). It is the purest form of cellulose available in nature, and its strength and good absorbency makes it a fiber that is very often used for textile applications.

To a great extent, ecological and social problems are associated with cotton farming and processing, such as the high consumption of chemical pesticides, fertilizers and water. This leads to a change in whole ecosystems and severe socio-ecological difficulties for the people who produce and process the cotton (Faget, 1993).

Prices and policies are overall linked to the further development of earlier cultivars or pure lines which possess white and/or colored lint and appropriate pest and disease resistance characters (de Carvalho et al., 2014).

Cotton plays a role in biorefineries (e.g., additional utilization of the hulls, stalks and oil seeds); however, it is mainly regarded as a reference material within this study.

3.1.2 Bast fibers

Bast fibers, such as jute, flax, hemp and ramie, as shown in *Figure 8*, are the second largest group of natural plant fibers produced. Their traditional use (e.g., sacks and bags, ropes, twines and yarns) as well as their "new" applications are quite similar. Roy et al. (2012), Kozlowski et al. (2012), Shahzad (2013) and FNR (2008) mentioned manifold applications: for instance, fiber-reinforced composites (e.g., replacing glass fibers in aerospace and automotive industries due to their comparable stiffness), construction and building materials, insulation materials, several kinds of textiles (woven and nonwoven, home, technical, geo), particle boards, paper pulp (e.g., for specialty papers), cellulose derivatives and coatings.

The typical processing procedure of bast fibers begins by retting of the stalks (different process types), during which microbes or chemicals loosen the bast fiber bundles by breaking down the gluing pectin and woody tissues surrounding them. After that, woody parts are removed from the fibers by breaking (a crushing process for separation of fiber from the inner woody core), scutching (mechanical removal of the broken straw) and heckling (splitting and straightening of fibers by "combing" them, which also removes impurities).

After that, the long fibers are ready for spinning and further processing. The woody residuals from the procedure (shives) and the residual short coarse fibers (tow) can also be considered for manifold biorefinery applications (such as animal bedding, soil erosion control and filler material).

Jute

According to Roy et al. (2012), jute ranks second to cotton in terms of production. As an example for the utilization of jute within a biorefinery, Jahan et al. (2011) described jute as a raw material for the preparation of microcrystalline cellulose. Value-added products should help slow the recent decline in the use of jute in some Asian countries like Bangladesh (e.g., as sack, bag, yarn and carpet backing), where this raw material traditionally is of major socio-economic importance. Examples for future high-value applications could be, for instance, micro- and nano-cellulose crystal (MCC/ NCC) for the production of light-weight and high-strength hybrid composites (Jahan et al., 2011) or dissolving the pulp from jute stick for rayon production (Matin, 2015). However, these options have not yet been commercialized on a large scale.

Flax

Until the eighteenth century, flax was the dominant fiber in Europe, but it was later replaced by cotton. It has a potential as a source of valuable textile fibers and for technical applications. Additionally, the oily seeds can be used for the production of linseed oil and linseed cake (food, pharmaceutical, technical, paints), broken capsules for feed (especially race horses, sheep), short broken straws for particleboards and composites and seed capsule powder for poultry feeding.

The German Agency for Renewable Resources (Fachagentur Nachwachsende Rohstoffe e.V. - FNR) also points out the importance of a further development of traditional material process chains in a report on natural fibers (emphasis on flax and hemp). These traditional material process chains account for more than 95% of the material use and often play a major role concerning regional added value (FNR, 2008). A practical example for biorefining flax was given by Wilke (2010), who

mentioned a pilot plant producing fiber-pulp from flax (feedstock pretreatment, fiber pulping process) installed by the Hamburg University of Technology.

Hemp

Before the expansion in the cultivation of cotton and jute, hemp was another major fiber crop in Europe, North America and Russia along with flax. Today, the leading global producers include South Korea, China, Chile, Russia and Europe (FAO data from 2015 and 2016). Besides the applications mentioned above (fibers and shives), the seeds have applications in high-value food (oil, proteins) and cosmetic products and are also used for bird feed. The aim of the project "MultiHemp - Multipurpose hemp for industrial bioproducts and biomass," funded by the European Union's Seventh Framework Program, was to develop an integrated hemp-based biorefinery producing fiber, oil, construction materials, fine chemicals and biofuels. An improved feedstock was subject to efficient and modular processing steps, and all components of the harvested biomass were expected to be used (Multihemp, 2017).

Ramie

Ramie is said to be one of the strongest and longest natural fine textile fibers in the world. However, due to the lack of suitable large-scale processing equipment and the high cost of production methods, it is currently of minor importance in world trade. Usually, ramie is blended with other textile fibers, e.g., to increase the strength of cotton blends and reduce shrinkage in wool. Ramie, like some other natural fibers, is used by the automotive industry (e.g., Dunne et al., 2016); for instance, it finds application in the Toyota Prius 2010, which reduces the use of petrochemical products.

3.1.3 Leaf fibers

Sisal

Sisal, mainly produced in Brazil (it can survive the semi-arid climate), has the advantages of strength, durability, ability to stretch, affinity for certain dyestuffs and resistance to deterioration in saltwater (Corona Comercio Industria Ltda., 2017). In the context of a biorefinery, e.g., research on composites combining sisal fibers with lignosulfonate-phenolic type matrices (sodium lignosulfonate as a phenol substitute) was carried out; values reached in this study indicated a possible applicability of the material in the automotive industry (Da Silva et al., 2012).

Abaca

Abaca (Manila hemp) is a leaf fiber which is mainly cultivated in the Philippines. It has a great mechanical strength, resistance to saltwater damage and long fiber lengths (up to 3 m). Paper making (specialty paper) is the main use of the fiber, for instance, for tea and coffee bags, sausage-casing material and currency notes (e.g., there is up to 30% abaca in Japan's yen banknotes) (FAO, 2017). In the exterior of the Mercedes-Benz A-class, abaca fibers partly substitute glass fibers (FAO, 2017). Thus, 60% of the primary energy can be saved according to the manufacturer (Daimler AG, 2017).

3.1.4 Fruit fibers

Coir

According to the Food and Agriculture Organization of the United Nations, coir is the "thickest and most resistant of all commercial natural fibers." The coarse fiber extracted from the outer shell of coconuts has a low decomposition rate, which makes it suitable for durable geo-textiles, for example, that are used to control erosion. Some typical characteristics of coir are its strong concentration of lignin (stronger but less flexible material compared to cotton and unsuitable for dyeing), low tensile strength compared to some other natural fibers and good resistance to microbial action and salt water damage (FAO, 2017).

To give an example for biorefinery applications of coir, manifold coir eco-products are offered, especially for gardeners (e.g., plant pots, protection mats). As the plant is mainly grown for the production of coconuts and coconut oil, the lignocellulosic residues are often burnt in the open as they are not ideal for composting (long decomposition time due to high lignin content). Therefore, the material use of the residues is said to be an environmentally friendlier and more valuable alternative (FAO, 2017; Proflora GmbH, 2017).

3.1.5 Stalk fibers from agricultural residues

Wheat and rice

Wheat and rice are among the most popular crops in the world, generating considerable amounts of residual straw. Animal fodder, bedding, thatching, artistic works and burning to prevent soilborne disease are some traditional applications. Studies have been conducted to investigate on the potential of wheat and rice straw for pulp and paper applications, however, specific properties (e.g., waxy covering of surface, morphological issues and silica content) require additional pretreatment steps. Rice straw fibers can, for instance, be blended with cotton and further processed on short staple cotton machinery into yarns for fabrics (Reddy et al., 2015). Some properties are given in *Table 2*.

Table 2: Tensile properties and moisture regain of wheat and rice straw fibers compared to cotton, linen and kenaf (taken from Reddy et al., 2015, and Müssig et al., 2015)

	Wheat straw	**Rice straw**	Cotton	Linen	Kenaf
Denier	**35 – 100**	**27 ± 14**	3 – 8	1.7 – 17.8	50
Length [cm]	**4 – 8**	**2.5 – 8.0**	1.5 – 5.6	20 – 140	150 – 180
Strength [g/den]	**2.1 ± 0.2**	**3.4 ± 0.6**	2.7 – 3.5	4.6 – 6.1	1.0 – 2.3
Elongation [%]	**2.7 ± 0.1**	**2.2 ± 0.3**	6.0 – 9.0	1.6 – 3.3	1.3 – 5.5
Modulus [g/den]	**10 ± 1.2**	**20 ± 2.6**	54.6 – 90.0	20	9.2 – 23.1
Moisture regain [%]	**9.5**	**9.8**	7.5	12.0	9.5 – 10.5
Shares [%]: (value in brackets: most frequently published)					
Cellulose	**29-51 (40)**	**28-70 (49)**	82-96 (90)	60-81 (70)	36-72 (44)
Hemicellulose	**15-31 (25)**		2-6 (4)	14-21 (17)	20-21 (21)
Lignin	**12-25 (20)**	**12-16 (14)**	0-1.6 (0.7)	2-5 (2.5)	9-19 (18)
Pectin			0-7 (4)	0.9-3.8 (2)	2 (2)
Fat and Wax			0.6 (0.6)	1.3-1.7 (1.5)	
Ash	**4.5-9 (6.7)**	**15-20 (18)**	0.8-2 (1.4)	1.5 (1.5)	
Water-soluble substances		**9-14 (12)**	0.4-1 (0.7	3.9-10.5 (6)	

Corn

After sugarcane, corn (maize) is the second-most frequently grown agricultural crop in the world. Stover (stalks, leaves, cobs, husks) is used for fuel ethanol, and due to its low costs and its properties, corn stover also has good potential for material use. The length of corn husk fibers can be up to 20 cm, and, due to their lengths, they are suitable for processing on short- and long-staple spinning systems and can be blended with other fibers such as cotton, linen, or wool. In order to use the fibers for textile and composite applications, they are usually pretreated in high-temperature alkali solutions, sometimes also followed by other treatment steps; bleaching and dyeing is also possible (Reddy et al., 2015).

Table 3: Properties of fibers obtained from cornhusks and cornstalks (from Reddy et al., 2015)

		Corn husk	Corn husk	Corn stalk
Length [cm]		**2 - 8**	**10 - 20**	**3**
Tensile properties	Strength [g/den]*	**2.0 ± 0.3**	**1.4 - 1.6**	**2.2 ± 1.0**
	Elongation [%]	**11.9 ± 1.1**	**13 - 16**	**2.2 ± 0.7**
	Modulus [g/den]*	**49 ± 3.7**	**36**	**127 ± 56**

* 1 g/den is approximately equal to 130 MPa

3.1.6 Soft and hardwoods

Due to its cellular composition, wood has varying structural characteristics depending on the level of hierarchy: trunks (i.e., for masts and beams), larger parts of grown structures (e.g., planks and veneers), particles (e.g., for engineered wood products such as chipboards and oriented strand boards), defibrillated wood and cell wall components (e.g., pulp and wood fiber board) as well as compounds at the molecular level (e.g., resins and phenols) are examples for wood components that are being used for a large variety of applications.
The variety of soft- and hardwood species that is available for biorefinery applications results in a wide range of properties; therefore, if more information about a specific kind of wood is needed, we recommend readers to check the property values cited in the literature (for instance: in Winandy J.E., 1994). Wood fibers find several applications, e.g., as main components of paper (mostly chemical or mechanical pulp as basis) and wood-reinforced plastic composites (WPC).

Wood pulp is also the common basis material for man-made fibers, which are discussed in chapter 3.2, and are mainly used for textiles.

3.1.7 Cane, grasses and reed

Switch grass

Switch grass is a native bunch grass that has the ability to produce moderate- to high-biomass yield on marginal lands (Alexopoulou et al., 2008). It is also considered suitable for the production of cellulosic fuel ethanol, including biogas, and for thermal energy uses by direct combustion of the yielded biomass. This plant may become weedy or more invasive in some regions or habitats and may displace other vegetation if not properly managed.

The potential use of switch grass as fibers in the textile industry has been addressed recently (Reddy et al., 2015). Switch grass can be a source for fibers in that it requires fewer inputs to grow and could be economically more viable than traditional fiber crops, such as cotton, jute and flax. In addition, the long fibers can be used for high-value applications, and the remaining short fibers and hemicellulose could still be used for fuel ethanol production. Its low growing costs, high fiber yield and distinct fiber properties make switch grass a crop with a high potential for fiber production in biorefinery settings.

Table 4: Properties of fibers from switch grass leaves and stems (from Reddy et al., 2015)

	Switch grass		Linen	Cotton
	Leaf	**Stem**		
Fineness [denier]	**30 ± 12**	**60 ± 20**	1.7 - 17.8	1 - 3.3
Length [cm]	**6.5 ± 4.3**	**5.8 ± 3.3**	20 – 140	1.5 - 5.6
Strength [g/den]	**5.5 ± 1.2**	**2.7 ± 0.8**	4.6 - 6.1	2.7 - 3.5
Elongation [%]	**2.2 ± 0.7**	**6.8 ± 2.1**	1.6 - 3.3	6.0 - 9.0
Modulus [g/den]	**240 ± 74**	**70 ± 23**	203	55

Sugarcane (agricultural residues)

Sugarcane is one of the most common crops in the world, and bagasse is the material that remains after the cane has been pressed for sugar. The pith and the outer rind of the plant have been investigated as fiber sources (pith density: 220 kg/m^3; rind density: 550 kg/m^3). Compared to fibers obtained from the oil plants, bagasse fibers have low elongation (1.1%), moderate strength (222 MPa; 1.7 g/den), a modulus of 27 GPa (208 g/den), fineness of 6.5–14 Tex and lengths from 2.5 to 20 cm. A wide range of particle sizes and a high moisture content have also been reported (Reddy et al., 2015). Müssig (2010) has gathered some properties of bagasse from several literature sources, which are illustrated in *Table 5* (Müssig, 2010).

To a great extent, sugarcane bagasse is used for energy purposes (e.g., fuel source in sugar mills, cogeneration and ethanol production), although a license agreement has been signed to build the first Brazilian facility to produce PHAs bioplastic from sugarcane co-products (BIO-ON, 2015). Pulp, paper and board are options for material production from bagasse (mainly in subtropical countries), whereby bagasse primarily replaces wood.

The value of bagasse is increased by using it for building materials or biodegradable, compostable packaging materials and disposable tableware. Several companies like Vegware and Bionatic produce, for instance, plates and bowls that are pressed into shape in a high-heat, high-pressure process. They can sustain contact with hot, wet, or oily food and are more rigid than paper products (Bionatic GmbH & Co. KG, 2017; Vegware Ltd., 2017).

Table 5: Properties of bagasse (from Müssig, 2010)

		Bagasse
(Single) fiber diameter [µm]		**18-20**
(Single) fiber length [mm]		**0.8-2.8**
Tensile strength [MPa]; *		**20-290 (170)**
Youngs's modulus [GPa]; *		**2.7-17.0 (15)**
Elongation at break [%]; *		**0.9-1.1 (1)**
Density [g/cm^3]		**0.45-1.25**
Shares [%]; *	Cellulose	**32-55 (44)**
	Hemicellulose	**16-30 (23)**
	Lignin	**19-34 (23)**
	Pectin	**10 (10)**
** Values in brackets: most frequently published*	Ash	**1.1-5.0 (3)**
	Water-soluble substances	**0.7-3.5 (2.1)**

Bamboo

Bamboo is a fast-growing, renewable species that needs minimal input and has fibers with exceptional tensile properties. For instance, mechanical, chemical and enzymatic methods are used to extract fibers from bamboo. The properties of raw and NaOH-threated bamboo fibers are given in *Table 6*. For instance, the fibers are used for viscose production (textiles) and paper (especially in China) and, in some countries, also for food additives (high-fiber, texture improving), boards, composites and construction material.

Table 6: Properties of raw and chemically / mechanically treated bamboo fibers (taken from Reddy et al., 2015, and Müssig, 2010)

		Bamboo	Chemical + compression	Chemical + roller mill
Diameter [µm]		–	**0.15 ± 0.07**	**0.09 ± 0.04**
Strength [g/den]		**1.1 - 6.2**	**5.0 ± 1.1**	**2.8 ± 0.5**
Elongation [%]		**1.3**	**5 - 12**	**4.5 – 12**
Modulus [g/den]		**131**	–	–
(Single) fiber diameter [µm]		**25-40**		
(Single) fiber length [mm]		**1.5-4**		
Tensile strength [MPa]; *		**140-1000 (500)**		
Youngs's modulus [GPa]; *		**11-89 (30)**		
Density [g/cm^3]		**0.6-1.5**		
Fibril angle (main cell wall) [deg]		**85-90**		
Shares [%]; *	Cellulose	**26-43 (35)**		
	Hemicellulose	**15-30 (22)**		
	Lignin	**21-31 (26)**		
** Values in brackets: most frequently published*				

Fresh grass (green biorefinery)

Green biorefineries mainly use grassland (e.g., forage grass; various species) for the production of a solid and a liquid fraction from fresh biomass. The solid fiber-rich cake, which is produced in green biorefineries in addition to the amino-acid-rich juice, might be processed into biobased products (along with feed, energy and chemicals) that include insulation material, composites (e.g., for the building sector), paper and board.

3.2 Man-made fibers

Man-made fibers are either significantly modified natural fibers (so-called regenerates, mostly cellulose), mineral (inorganic) man-made fibers, or synthetic fibers (man-made monomers are polymerized and processed into fibers).

3.2.1 Modified natural polymers – man-made cellulose fibers

In contrast to natural fibers, man-made cellulosic fibers are not defined by single feedstock (e.g., viscose can be produced from wood as well as from cotton linter). The characterization of these fibers depends on the production processes used and the final fiber properties. Important man-made cellulose-based fibers include Viscose, Modal, Lyocell and acetate fibers, which can be produced as staple or as filament fibers (Röder et al., 2013). The main source of man-made cellulosic fibers is wood. A variety of processes is available to separate the cellulosic wood fibers, which are often followed by different bleaching procedures.

Man-made cellulose fibers were estimated to have a share of about 7% (around 7 million tons) in the global fiber market in 2016, which was said to be around 100 million tons in 2016 (Lenzing AG, 2017; The Fiber Year Consulting, 2016). Compared to natural cellulose fibers, the market share of man-made fibers was assumed to account for 62% in 2015.

In 2015, market analysts estimated the value of the global man-made cellulose fiber market at around USD 17.5 - 20.5 billion (Grand View Research, 2016). The global production of man-made cellulose fibers has grown by 5.8% per year between 2011 and 2014. Continuous growth is

anticipated at a compound annual growth rate (CARG) of 9.0% (Grand View Research, 2016) that will be driven by a further increase in production in China and Southeastern Asia (Qin, 2014).

Market analysis provides several additional drivers for the expected growth of the global market for man-made cellulose fibers. One main driver is seen in the strong adoption of this fiber type in the textile industry as a substitute for cotton, and its use in new applications, such as in the area of nonwoven materials (Strategyr, 2016; Qin, 2014). Another driver could be the growing demand for fibers that are produced from renewable sources and that exhibit low environmental impacts (Transparency Market Research, 2016). In the Asian-Pacific market, the increasing population and improving standard of living are driving the demand for textiles (Grand View Research, 2016). The growth in the Asian-Pacific market is expected to be led by China, given the large domestic production, growing apparel demand, a growing number of new production centers and increasing foreign direct investments in each of the countries (Strategyr, 2016). The second-largest market will be Europe, where regulations are already promoting biodegradable fabrics. Man-made cellulosic fibers are mainly used in the textile industry with applications in clothing textiles, spun yarn and fabrics (Transparency Market Research, 2011). Other applications include their use as nonwoven materials (such as tissues, wipes and medical products), in the paper industry or for carpet production. Clothing accounted for around 60% of the global cellulose fiber market share in 2015, with a revenue of about USD 10.5 billion (Global Market Insights, 2017).

It is also expected to be the most rapidly growing segment with a CAGR of more than 9.5% by 2024 on the account of the growing clothing and apparel demand (Global Market Insights, 2017). Spun yarn, manufactured by twisting loose cellulose fiber strands (staple fibers), accounted for over 13% of the global cellulose fiber market. The global demand for cellulose fibers is expected to reach USD 36.9 billion by 2020 (Markets and Markets, 2017).

Viscose

A special kind of wood pulp (dissolving pulp) is used as the basis for viscose rayon fiber. The purified cellulose is chemically and mechanically treated in several steps (steeping, pressing, shredding, ageing, xanthation, dissolving, ripening, filtering, degassing), leading to a dissolved compound which is forced through a spinneret to produce viscose filaments (spinning). Further processing steps (drawing, washing, cutting) lead to the production of a highly absorbent, soft and easy-to-dye fiber (with properties similar to those of cotton and silk) suitable for manifold applications, such as in yarns, fabrics, apparel, home furnishing, industrial use and hygiene products.

The global production of viscose staple fibers was estimated at 5.3 million tons in 2016 (Lenzing AG, 2017) with an increase of 6.6%, while viscose filament yarns increased by 0.2% to 365,000 tons (Yarnsandfibers, 2013). There has been strong growth in the viscose/rayon market as clothing manufacturers continue to use it as a substitute for more expensive natural fibers, such as cotton (UNECE, 2016). The company Lenzing AG produces viscose using a biorefinery concept (e.g., acetic acid, furfural, xylose / xylitol), as described in more detail in chapter 4 (best practice).

Lyocell

Lyocell is a man-made fiber made from cellulose (a well-known brand name is TENCEL™). The Lyocell process is a cellulosic-fiber-producing technology: Cellulose is directly dissolved in *N*-methylmorpholine-*N*-oxide monohydrate (NMMO) at about 100°C, making chemical derivatization redundant (physical process). After filtration, the spinning dope is spun and the fiber is washed and dried. It is said to be a very strong and is known for its durable properties as well as its high absorption efficiency and tenacity. Applications of Lyocell fibers can be found in apparels, home textiles, surgical products, baby diapers, automotive filters and other applications such as vehicle carpeting and cigarette filters (Woodward, 2017).

Market analysis estimated the Lyocell fiber market size at around USD 850 million in 2016, and it is anticipated to grow at a CAGR of around 8% over the forecast timespan owing to its extensive usage in various end-use industries including home textiles, apparels and medical equipment (Technavio, 2017; GMInsights, 2017). An example for a Lyocell-producing biorefinery (Lenzing tradename: TENCEL™) is described in chapter 4 (best practice).

Cellulose acetate

Cellulose acetate is a thermoplastic cellulose ester typically produced by acetylation of pretreated cellulose with glacial acetic acid and acetic anhydride in the presence of sulfuric acid, followed by hydrolysis, precipitation, dissolution in acetone, filtration, extrusion and further processing of the filaments. It is available in various forms and usually obtained from wood pulp. Cellulose acetate fibers are, for instance, used to make fabrics, apparels, filters, diapers or other products (Zion Market Research, 2016).

Market analysts valued the global cellulose acetate market at around USD 4.82 billion in 2015 and expect it to reach USD 7.01 billion in 2021, growing at a CAGR of around 3.6% between 2016 and 2021 (Zion Market Research, 2016). The market volume in 2015 was estimated at around 0.6 million tons (Borregaard, 2016). Asia-Pacific was the largest cellulose acetate market with a market share of 50% in 2015 (Zion Market Research, 2016). The abovementioned growth in textiles, but also in the cigarette filter market, is anticipated to drive the growth in this region. Europe and North America are mature markets for cellulose acetate and are estimated to witness sluggish growth rates over the forecast period. Latin America is expected to witness a significant increase in the cellulose acetate market due to a large demand from the textile industry (MRFR, 2018).

Micro-fibrillated cellulose (MFC) and nano-cellulose

In addition to conventional fibers, micro- and nanoscale cellulose are promising materials. They can be grouped into three main types: micro-fibrillated cellulose (MFC), nano-crystalline cellulose (NCC) and bacterial nano-cellulose (BNC), which can be distinguished according to their dimensions, functions and preparation methods. *Table 7*, taken from Klemm et al. (2011), gives a brief summary of MFC, NCC and BNC (sources, formation and average size).

Table 7: Nano-cellulose materials: sources, formation and average size (from Klemm et al., 2011)

Type of nano-cellulose	Selected references and synonyms	Typical sources	Formation and average size
Micro-fibrillated cellulose (MFC)	Micro-fibrillated cellulose, nano-fibrils and micro-fibrils, nano-fibrillated cellulose	Wood, sugar beet, potato tuber, hemp, flax	Delamination of wood pulp by mechanical pressure before and/or after chemical or enzymatic treatment; diameter: 5–60 nm; length: several micrometers
Nano-crystalline cellulose (NCC)	Cellulose nanocrystals, crystallites, whiskers, rod-like cellulose microcrystals	Wood, cotton, hemp, flax, wheat straw, mulberry bark, ramie, Avicel, tunicin, cellulose from algae and bacteria	Acid hydrolysis of cellulose from many sources; diameter: 5–70 nm; length: 100–250 nm (from plant celluloses); 100 nm to several micrometers (from celluloses of tunicates, algae, bacteria)
Bacterial nano-cellulose (BNC)	Bacterial cellulose, microbial cellulose, biocellulose	Low-molecular-weight sugars and alcohols	Bacterial synthesis; diameter: 20–100 nm; different types of nanofiber networks

Nano-cellulose has a large range of potential applications, with the highest demand for composites (35% of the total nano-cellulose demand), pulp and paper (15%), paints, films and coatings (15%). Nano-cellulose applications are still facing the challenge of production scale-up, with an estimated 1000–1500 tons of nano-cellulose currently produced in a small number of commercial, demonstration and pilot plants. However, significant growth in the market has already been projected for the upcoming years, with even larger mid- to long-term prospects (Marketsandmarkets, 2015).

The nano-cellulose market will have a projected market size of USD 250 million by 2019, with a compound annual growth rate (CAGR) of 19% between 2014 and 2019 (Marketsandmarkets, 2015). The rapid growth of markets for nanotechnologies was also estimated by Roco (2011), who assumed a total market volume of USD 3 trillion for all kinds of nanotechnologies by 2020.

The attention paid to nano-cellulose is also reflected in the scientific literature in that a steady increase in the number of respective publications has occurred since 2007. An innovative application is the preparation of efficient polymer solar cells fabricated on optically transparent cellulose nanocrystal (CNC) substrates. The solar cells fabricated on the CNC reach a power conversion efficiency of 2.7%. They offer the advantage that they can be easily separated and recycled into their major components (Zhou et al., 2013).

3.2.2 Modified natural polymers – non-cellulosic man-made fibers

Chitosan

Chitin is, after cellulose, one of the most abundant natural polymers, and occurs as a waste product from shrimp fisheries. It is mainly derived from two marine crustaceans, shrimp and crab, and can be used as fiber films, sponges, or powders (Rinaudo, 2006). Chitosan is the most important derivative of chitin (Rinaudo, 2006). It finds applications in the food, cosmetics, biomedical and pharmaceutical sectors because of its variety of beneficial principal characteristics, such as biocompatibility, biodegradability and nontoxicity (Rinaudo, 2006).

The global market for chitin and chitosan derivatives is forecasted to reach 0.156 million tons by 2022, driven by growing investments in new drug developments, attractive biomedical applications and emerging non-medical uses, such as in the detoxification of water and wastewater (Strategyr, 2017). A practical example for the utilization of chitosan is the product Crabyon, which is manufactured by blending chitosan and cellulose viscose and extruding the blended viscose into a spin-bath. The advantages of this material are its antibacterial and antimicrobial performance, comfort, anallergenicity and high humidity absorption. It is, therefore, used for textiles (e.g., sports, underwear, nonwoven materials), and also in the medical, health and pharmacological fields (Swicofil AG, 2017).

Alginate

Alginate is a linear and unbranched polysaccharide comprising of (1-4)-linked β-D-mannuronic acid and (1-4)-linked α-L-guluronic acid residues. It is mainly extracted from the cellular walls of brown seaweeds and can be employed for third-generation biofuel production (mainly ethanol) in synergy or in place of microalgae (Milledge et al., 2014). It can also be produced from bacterial biofilms. By binding it with water, it forms a viscous gum by absorbing the water and quickly solidifying. Alginates from different seaweeds often have variations in their chemical structures and physical properties. Some of these may be yielded as an alginate that forms a strong gel, while another forms a weaker gel; some may readily form a cream/white alginate and other only form gels with difficulty (Donati and Paoletti, 2009).

Alginate is used overall in the pharmaceutical and biomedical fields (Augst et al., 2006; Gombotz and Wee, 2012) for drug delivery (Tønnesen and Karlsen, 2002) and in tissue engineering (Kuo and Ma, 2001; Machida-Sano et al., 2010; De Corato et al., 2018a) due to its high bio-compatibility, low toxicity, low cost and simple and rapid gelation (Lee and Mooney, 2001). The wound healing industry uses "moist-healing" alginate products (gels, foams, fibrous nonwoven materials), which either absorb wound fluids or release water onto a dry wound (hydrated gel).

The non-toxicity, renewability and, in the case of calcium alginate fiber, haemostatic effect of alginate, as well as its ability to provide a moist interface for the wound surface are some appealing properties in this area. In the form of a fiber, it is possible to "process the alginate fibers into woven, nonwoven, knitted and various composites to address specific wound management problems" (Quin, 2008, p. 171): They can be used as carriers (for zinc, silver and other bioactive metal ions), and bioactive materials (e.g., drugs, and enzymes) can be combined into the alginate fibers (Quin, 2008).

For example, the use of a 3% sodium-alginate solution with 0.1 M calcium chloride has been found to be a better mix for producing encapsulated nodal segments for plant regeneration via non-embryogenic synthetic seeds (Verma et al., 2015). In addition, 3% sodium-alginate has been used to include, immobilize and preserve antagonistic yeasts for more than one year shelf life, suppressing green mould diseases caused by the phytopathogenic fungus *Penicillium digitatum* on citrus fruit under postharvest conditions (De Corato et al., 2017; De Corato et al., 2018b). Owing to its gelling, thickening, stabilizing and viscose properties, alginate is traditionally a prominent component in functional food products (Holdt and Kraan, 2011).

Particularly in textile and paper industries, alginate allows the reduction of color and adsorbable organic halides (AOX) from the Kraft bleach plant effluents. It has been investigated in the past using a laboratory-scale fungal bioreactor containing calcium alginate entrapped with the lignin-lytic, white-rot fungus *Trametes versicolor* (Pallerla and Chambers, 1997).

3.2.3 Inorganic man-made fibers

Three fiber types (glass, carbon and basalt fibers) are described in this paragraph on inorganic man-made fibers, because they could potentially be substituted by lignocellulosic fibers, mainly as reinforcement materials in the application field of composites. Furthermore, carbon fiber can be manufactured from various organic precursors, such as lignin. As in the case of biofuels used as substitutes for petrochemical fuels, the replacement of these inorganic man-made fibers by various biobased fibers could contribute to an overall reduction in GHG emissions.

Glass fiber

Glass fiber is formed by a melting and fiberizing process from quarry products at high temperatures. There are various fiber glass types (distinguished by the chemical makeup), e.g., E-glass fiber (electrical) that has good electrical properties and a relatively low cost and R-, S-, or T-glass fibers that are more expensive and have higher tensile strength and moduli than E-glass as well as better wet strength retention (e.g., used in the aerospace and defense industries). Glass-fiber products are mainly used as fiber-optic light guides for several applications (such as data transmission and lasers), as fiberglass-reinforced plastics (fiberglass) and as insulation materials.

Joshi et al. (2004) indicated that natural-fiber-reinforced composites (substituting glass-fiber-reinforced ones) might gain relevance in the future as they are cheaper, lighter and environmentally superior to glass-fiber composites. Also, glass fibers are suspected of potentially causing respiratory and skin health problems (Sripaiboonkij et al., 2009).

Carbon fiber

Carbon fibers are composed mainly of carbon atoms and are produced from precursors such as polyacrylonitrile (PAN), but also from other organic polymers like rayon, petroleum pitch, or even lignin. There are variations within the precursor, which are often trade secrets.

Some advantageous properties of carbon fiber are its high degree of stiffness and tensile strength as well as its low weight, high chemical resistance, high temperature tolerance and low thermal expansion.

Carbon fibers are used primarily in applications with a demand for high mechanical performance, such as sports equipment, aircraft, satellites, Formula 1 racing cars, pressure vessels, specialized tools, wind turbine components and to reinforce concrete in areas that are at high risk of earthquakes (Axegard, 2014). The global demand for carbon fibers was estimated at 0.1 million tons in 2016, and the current production capacity does not meet the demand (Kühnel et al., 2015). Carbon fiber production has exhibited a growth of about 9–12% on average over the last 23 years, and further increases are expected.

There is a high potential for lignin-based carbon fiber with high environmental benefits. For instance, *"(...) diverting 10 percent of the lignin potentially available in the US could produce enough carbon fiber to replace half of the steel in domestic passenger vehicles*" (Holladay et al., 2007, p.22f).

The main barrier for the widespread use of carbon fibers is their high price compared to those of other composites and materials. The current price of carbon fiber is around USD 18,000 per ton, which is determined largely by the production costs of polyacrylonitrile (PAN), the precursor to almost 80% of the commercial carbon fibers (Smolarski, 2012). These cost barriers provide opportunities for the use of lignin as an alternative to PAN (Smolarski, 2012). Lignin accumulates in large quantities during the pulp production process, it is relatively inexpensive and structurally rich in the phenyl propane group with high carbon content (Smolarski, 2012). However, it still possesses several disadvantages: The most notable is the difficulty of recovering lignin in a clean and pure form.

Basalt fiber

Basalt is the common term used to describe some volcanic rocks, formed from the molten lava after solidification. Basalt fiber is a material made from extremely fine fibers of basalt, which is composed of the minerals plagioclase, pyroxene and olivine (Singha, 2012). It has good hardness and thermal properties and can have various applications mainly as construction materials. Basalt has applications in the fiber reinforcement of composites. Basalt fibers can withstand very high temperatures and can be used in high-performance applications (Jamshaid et al., 2016).

3.2.4 Synthetic fibers

Synthetic polymers are formed either by addition-polymerization or condensation-polymerization reactions. These polymers belong to the classes of thermoplastics, elastomers, or duroplasts. The shaping process of a polymer is one of the most important steps and determines whether the polymer will become a fiber or not. Extrusion, fiber spinning, filament winding, mixing and compounding, injection molding and spin coating are some general processing technologies used to form polymers.

A broad variety of synthetic polymers can be processed into fibers and, although they are mostly based on petrochemicals, biobased building blocks and polymers are available for fiber production. These so-called biobased polymers are generally used as counterpart to fossil-resource-based polymers. Some of these are biodegradable and some are not, and not all of these are

environmentally friendlier as their fossil-resource-based equivalents. The raw material basis of these materials is, for instance, starch-based glucose (e.g., maize) and fatty acids from plant oils (e.g., palm, castor), although other sources, such as lignocelluloses, are also used.

There are some certifications for biobased polymers (e.g., "OK biobased" by AIB-Vinçotte), which are usually made on the basis of the radiocarbon-method. This method is used to determine the percentage of renewable raw materials (% biobased material). As an example for a synthetic biobased fiber, PLA can be spun to fibers for medical, agricultural and other applications (Bhat et al., 2008).

However, although the demand is rising, the production volumes are still too small. The producers cannot yet profit from economies of scale. A study conducted by the European Bioplastics Trade Association reported that biopolymers made up about 1% of the total volume of the 320 million tons of plastics manufactured in 2017 (European Bioplastics e.V., 2017).

Bioplastic materials are a broad field on their own, and the fact that diverse biobased materials are transformed to monomers and later polymerized (often in combination with other biobased or petrochemical-based compounds) into a variety of different polymers generates an enormous degree of complexity. The utilization of new materials versus drop-in polymers, the necessity for a case-to-case evaluation of environmental effects and the broad spectrum of applications inside and outside the fiber-production area increase the breadth of this topic in general. Therefore, this topic was not further investigated as a part of this report. Instead, the topic is mentioned to raise awareness that this area of fiber production also exists, and that several compounds produced in a biorefinery might find useful applications in this field. The consideration of biorefinery platforms especially makes sense with reference to bioplastics.

3.3 Market value and volume of selected fiber types and reference products

The values illustrated in *Table 8* and *Figure 9* are based on average global trade values and market volumes from sources such as the UN Comtrade, FAOSTAT and industry reports. Cautious interpretation of the values is required, because the volumes and prices fluctuate strongly depending on the data source (calculation approach is usually not transparent) and also over time. In addition, different sources (probably using different approaches) were required for data collection, and values were taken from the years 2011 to 2017. Therefore, the intention of presenting the table is to give a rough idea of the market volumes and prices rather than to cite exact values (which was not possible). This table exemplifies which fibers are produced in large volumes, usually at a low price and vice versa. In this context, *Figure 9* illustrates where the respective fibers are roughly ranked on the market compared to the others. The synthetic fibers accounted for more than 60% of worldwide fiber production during this time period (~ 67 million tons out of 105 million tons altogether in 2017), with approximately 75% accounting for polyesters (price of polyester staple fibers: approximately USD 1,400 /ton) (Lenzing AG, 2017). Therefore, generally speaking, they have a rather high volume and a rather low price compared to those of many natural fibers.

Table 8: Indicative volumes (t) and market values (USD/t) of fibers (various sources)

Fiber	Volume (tons)	Price (USD/t)
Polyester fibers	50,100,000	1,400
Cotton	23,270,000	1,700
Viscose staple fibers	5,300,000	1,500
Glass fiber (E type)	3,840,000	2,000
Jute	2,700,000	600
Wool	2,000,000	10,000
Coir	1,024,000	300
Glass fiber (S, T, R type)	875,000	10,250
Lyocell (and other artificial fibers)	500,000	2,260
Viscose yarn	365,000	2,200
Coir yarn	340,000	1,300
Sisal	247,000	2,400
Kenaf	230,000	400
Flax	190,000	2,750
Carbon fiber	172,000	15,040
Chitosan	100,000	20,000
Abaca	78,000	1,000
Cellulose acetate	60,000	4,000
Henequen	10,900	1,000
MFC	1,000	10,000
Hemp	1,000	1,500
Modal	NA	2,350
Wheat fiber	NA	1,650
Alginate	NA	NA

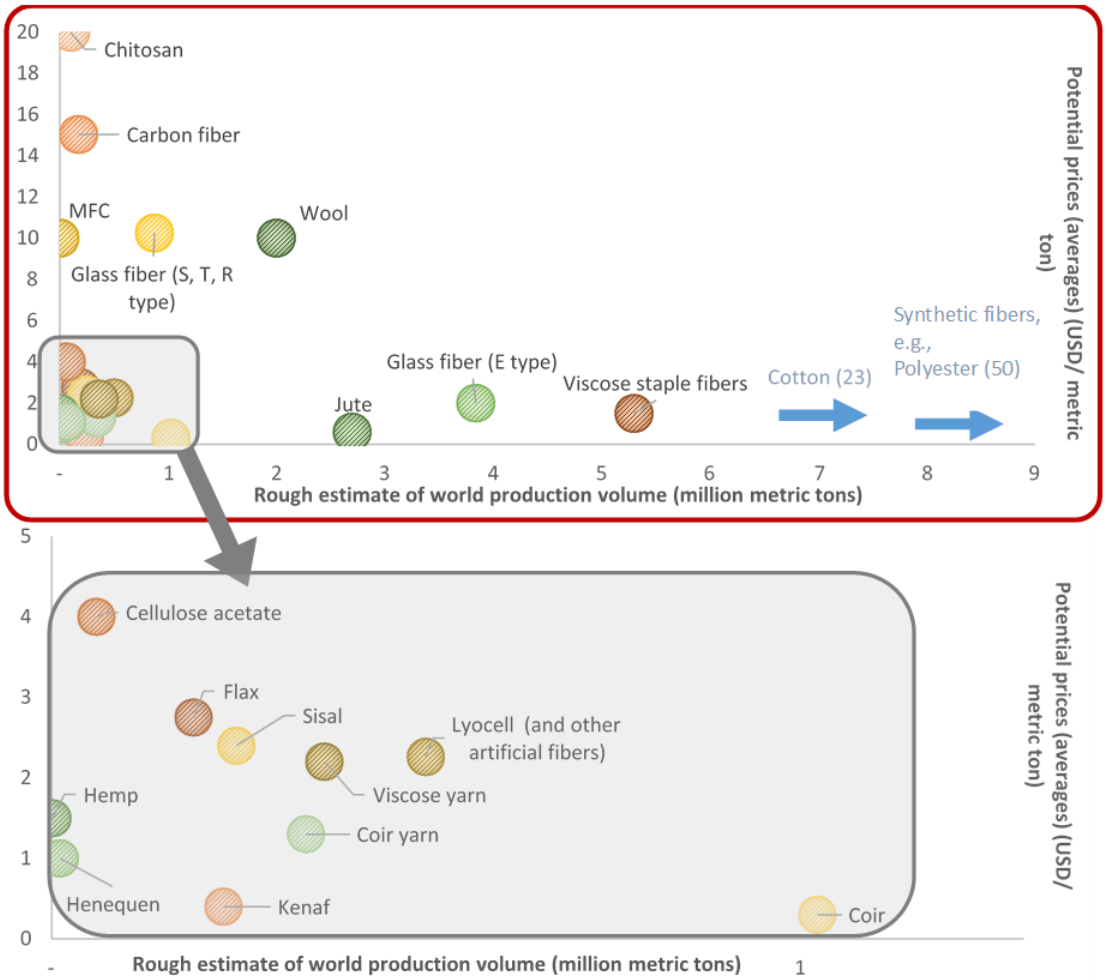

Figure 9: Relation of volume and value of different fiber types

In *Figure 10*, a conclusive combination of the results described in chapters 2 and 3 is presented, illustrating relevant fiber types and their applications within the context of biorefineries.

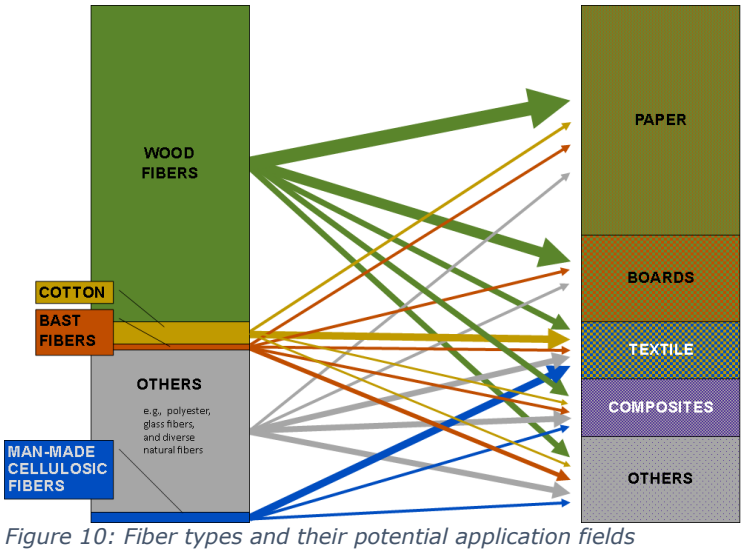

Figure 10: Fiber types and their potential application fields

4. APPLICATIONS

Chapter 4 describes the most important application fields for relevant natural fibers and fiber-based materials. In this chapter, we explain the basic relationships between properties, market volumes and product values. The applications described below begin with the largest market volume application and move towards more and more specialized applications. Within each application, certain niches are mentioned, as they may be the most interesting market entrance options for new biorefinery-related fibers.

Figure 11 (modified from nova-Institut, 2015) illustrates the industrial material use of several biobased fibers in Europe in 2015. The thickness of the arrow indicates their market volumes; products with a yellow background are considered growth markets. In this figure, protein fibers such as wool are also mentioned, which were not further considered in this report, as they were not prominently mentioned in the biorefinery literature.

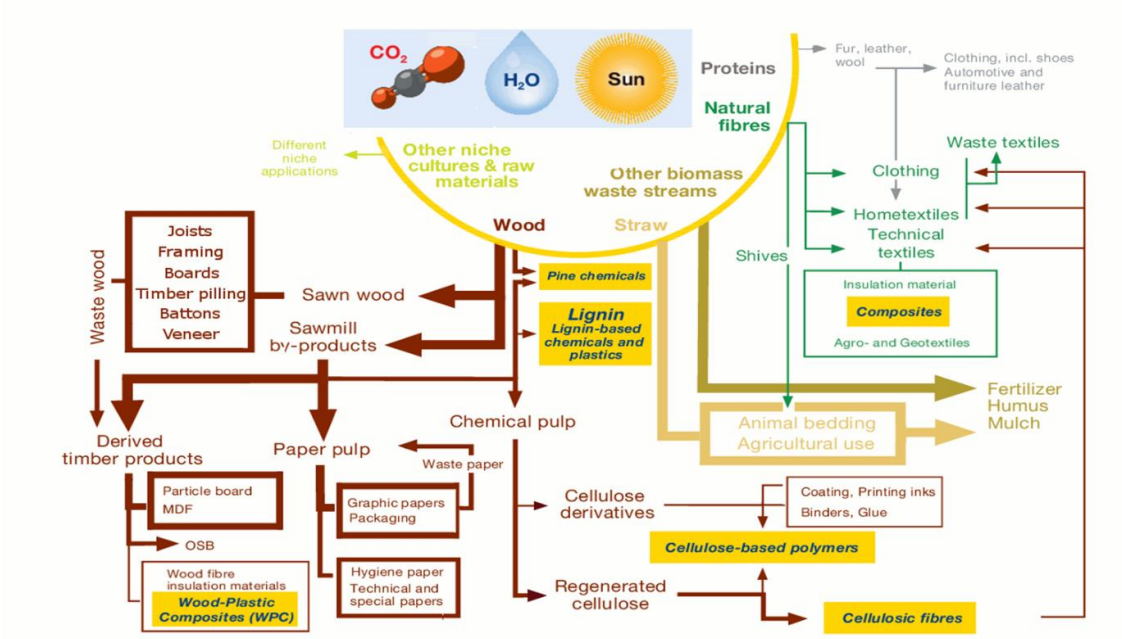

Figure 11: Industrial material use of biomass with focus on fibers in Europe (© nova-Institut, 2015; modified): yellow-highlighted boxes represent growth markets, the thickness of the arrows implies the market volumes from "up to 500,000 tons" (thinnest) to "more than 5 million tons" (thickest)

4.1 Paper

In terms of mass, paper and paper board are the biggest of the fiber applications relevant to this study. World paper and paper board production is over 400 million tons a year, of which about 57% is allocated to packaging and 31%, to graphic paper (FAO, 2017). While the demand for printing paper (in particular newsprint) is expected to stagnate or even decline as a consequence of digitalization, other application fields like packaging and tissue production are expected to grow on a global scale.

Paper is mainly, but not solely, produced from wood pulp. Other lignocellulosic feedstock, such as cotton are used to produce paper for specific purposes, like banknotes. While the total world production of paper and paper board is dominated by mass products yielding about USD 800 to 850 per ton, niche and specialty paper products, like cotton paper for banknotes, cost several thousand USD per ton. For the purpose of this study, these specialty applications may be the most interesting, since it is unlikely that a new biorefinery would target average paper products, given its often limited capacity compared with that of existing pulp mills (wood biorefineries). Such interesting specialty applications might be those for the production of décor paper, cigarette paper, or tissue paper. For each of these applications, niches with distinct requirements regarding paper properties can be defined. Hence, to apply fibers from biorefineries to these applications, a detailed match of fiber properties with the application requirements is required.

4.2 Fiber-based boards

The application of fibers in boards includes a large range of different products (e.g., HDF, MDF, particle board) and applications (e.g., construction, insulation, packaging, furniture). The global particle board production is over 115 million cubic meters (equivalent to 76 million tons), and the global MDF/HDF production is over 95 million cubic meters (equivalent to 57 million tons) (FAO, 2017). The production of other (wood-based) fiber boards has been reported by the FAO as just over 9 million cubic meters. In addition, similar boards for specific purposes are produced from other feedstock (e.g., hemp fiber and straw-based boards) or from solid wood (e.g., plywood). Comparable to the application of fibers in paper and paper-board making, the largest application is setting the benchmark in terms of prices. Therefore, the world particle board trade refers to import/export values of about USD 240 per cubic meter which is equivalent to USD 150 and 160 per ton. In contrast, the MDF/HDF board trade, due to the higher feedstock quality requirements, refers to about twice the value of particle boards in terms of mass. The demand for these products is typically driven by the construction sector and private consumption. However, except for the particle board production in 2009/2010, the world production of fiber boards has grown constantly over the last ten years.

New fibers from biorefineries might be considered in board production either as (partial) substitutes for the existing, mainly wood-based fibers in mass production or could serve in specialty applications due to their special properties. In order to replace fibers in mass applications, a lower price must be considered as the main argument; hence, such a strategy would yield a low value but have the advantage of having almost no market capacity constraints. In contrast, a specialty application may allow for more value to be received for the fibers produced. The identification of such application fields based on fiber properties is a complex and demanding task. Furthermore, specialty applications require only limited volumes, which may be lower than the inelastic supply created by a multi-product biorefining process. Even if the supplied volumes are clearly below the global demand in such an application, an additional supply could have severe impacts on such niche markets and be reflected by falling prices.

4.3 Textiles

Textiles account for the consumption of almost 100 million tons of different fibers (mainly cotton, synthetic and man-made cellulosic fibers). The world consumption of textile fibers has been increasing rapidly over the last ten to twenty years and has mainly been covered by the production of synthetic fibers. Still, the textile industry makes extensive use of natural fibers, such as wool, cotton and silk, although cotton is the only significant player in terms of volume. Cotton accounts for 25 to 30% of the textile fiber processed worldwide. Even though the absolute cotton production is stable or shows a slightly increasing trend, its relative share is clearly decreasing.

Compared to the previous applications, fibers yield much more value in textile applications. Even polyester and cotton as the most common textile fiber commodities are clearly over USD 1000 per ton. While polyester fiber prices are assumed to interact with crude oil prices, cotton prices are associated accordingly with the polyester fiber prices. However, textile fiber is also increasingly being produced from (wood) pulp. So called man-made or regenerated cellulose fibers accounted for approximately 3.5 Mt in 2005 and were expected to account for 6.5 Mt in 2016. Hence, the textile application is first discussed in this report where the dominant product is fossil-resource-based. Still, biobased fibers entering this market would most likely tend to be used in specialty applications to substitute mainly other natural or man-made cellulosic fibers to avoid cost competition on the polyester-dominated mass market.

When comparing different fiber types, the environmental impact caused during their product life cycle, ranging from the raw-material to the end-of-life treatment (i.e., disposal, recycling, reuse), is an essential factor along with the costs and technical properties. Although biobased materials are generally considered to be more sustainable than conventional petrochemical materials, because they are made from renewable instead of non-renewable raw materials (Shen et al., 2008), detailed environmental assessments are needed to test these assumptions in each specific context.

In a fiber context, such life cycle assessments (LCAs) can, for instance, illustrate how biobased fibers compete against synthetic fibers. When it is the intention to conduct such a comparison of different products (i.e., different types of fibers), an adequate functional unit needs to be defined that specifies the "…quantified performance of a product system for use as a reference unit (International Organization for Standardization, 2006)." This implies that comparisons can only be conducted for specific applications and on the basis of the same function that is fulfilled by a certain fiber type. In the following, relevant LCA results from literature are briefly summarized.

In the application field of textiles, biobased fibers tend to have environmental benefits over their petrochemical counterparts. For instance, Laursen et al. (1997) compared different fiber types using the indicator "non-renewable energy use" (NREU) for the functional unit "1 ton of staple fiber." They showed that wool consumes 8 MJ/kg; cotton, 49 MJ/kg; viscose, 35 MJ/kg; polyester, 109 MJ/kg; and acrylic fibers, 158 MJ/kg during fiber production. These values indicated that natural fibers had significantly lower environmental impacts compared to synthetic fibers during production in terms of the indicator NREU. Similar results were found by Shen et al. (2010), who compared three man-made cellulose fibers (Viscose, Modal and TENCEL™) with cotton, PET and PP fibers. They concluded that all man-made cellulose fibers, except for Viscose produced in Asia, had lower environmental impacts than cotton, PET and PP (Shen et al., 2010). During the textile manufacturing, the type of processing is the main determining factor of the environmental impact, and the fiber type only has a limited influence (Shen et al., 2008). More specifically, in the manufacturing phase of textiles *"…the energy consumption per kilogram yarn is inversely proportional to the yarn size in decitex"* (i.e., the energy consumption per kilograms proportional to the length) (Van Der Velden et al., 2014). The energy required for weaving and knitting is a function of decitex as well (Van Der Velden et al. 2014). In a study by Van Der Velden (2016), the manufacturing stage (e.g., weaving, spinning and knitting) had the highest relative environmental impact compared to other stages of the textile product's life cycle. These findings are in contrast to those of earlier studies, which suggested that the use phase was the main environmental hotspot. Increased energy efficiency of household appliances and the trend towards "fast fashion" have reduced the relative impact of the use phase (Van Der Velden, 2016).

4.4 Composites

Compared to the previous applications, the use of biobased fibers in composites is a relatively complex field. Although carbon and glass fibers are the main products in use, even within these fiber types, a huge range of different variants (e.g., by fiber length or quality) are applied. Each fiber variant may represent a couple of applications for which this fiber may provide the required standards for a set of properties that determine the lowest possible price. Therefore, it is possible to assume that the technical properties of a fiber correlate with its application value. Ledl et al. (2014) considered the strength, fineness, density and modulus of elasticity of fibers to assess their value in composite applications by using regression models.

The results of recent comparative LCA studies illustrate that the environmental impacts associated with the production of natural reinforcement fibers is considerably lower than the impacts caused by synthetic fibers. For instance, the GHG emissions expressed in CO_2-equivalents (CO_2-eqv.) caused during the production of one ton of synthetic reinforcement fibers ranges between 2.6-92 kg CO_2-eq./kg, whereas it ranges from 0.4 to 1.9 kg of CO_2-eq./kg for natural reinforcement fibers (Duflou et al., 2012). Among synthetic fibers, the highest GHG emissions are caused by the production of carbon nanofibers (70-92 kg CO_2-eq./kg), followed by polyacrylonitrile-(PAN)-based carbon fibers (22.4-31 kg CO_2-eq./kg) and glass fibers with a carbon footprint of 2.6 kg CO_2-eq./kg (Duflou et al., 2012). In comparison, according to Duflou et al. (2012), jute fibers have the highest GHG emissions of natural reinforcement fibers (1.3-1.9 kg CO_2-eq./kg), followed by hemp fibers (without irrigation) (1.6 kg CO_2-eq./kg) and flax fibers with only 0.4 kg CO_2-eq./kg. Comparing the two fiber types according to their cumulative energy demand (CED) provides a similar result. Carbon nanofibers (654-1807 MJ/kg) are followed by PAN-based carbon fibers (286-704 MJ/kg) and glass fibers (45 MJ/kg). Hemp fibers (without irrigation) have the highest potential CED (6.8-13.2 MJ/kg), followed by flax fibers (with irrigation) (9.6-12.4 MJ/kg), sugarcane bagasse (11.7 MJ/kg) and jute fibers (3.8-8.0 MJ/kg) (Duflou et al., 2012). A comparison of five different hemp- and fossil-resource-based composites (e.g., hemp/PP vs GF/PP-mats) showed that the hemp-based product variants had a CED (cradle-to-gate) that was between 25-75% lower than the CED of the fossil-resource-based products (Carus and Partanen, 2017).

These advantages of natural fibers in the production phase can both decrease and increase during later processing steps (Barth et al., 2015); therefore, it is important to assess the environmental impacts throughout the whole product life cycle. For instance, an additional benefit of using natural fiber in composites can be the higher fiber content (when compared to the use of glass fibers at an equal performance level), which can reduce the need for base polymers and, thus, also its environmental impact (Joshi et al., 2004). Another benefit can arise from recovered energy during end-of-life incineration (Joshi et al., 2004). On the contrary, in cases where the majority of the environmental impacts of the products are caused during their use phase and where these impacts are closely related to their weight, such as is the case for aircraft parts, the environmental benefits of lightweighting can offset higher impacts during the production phase (Scelsi et al., 2011). When assessing the environmental impact of the whole life cycle, it is also important to specify the sourcing and production locations, the supply chain set up and the manufacturing methods. For instance, Schulz and Suresh (2017) compared ten different scenarios for the production of man-made cellulose fibers and showed that these factors significantly influence the LCA results. Therefore, environmental impacts should be assessed on a case-to-case basis, and a full life cycle perspective should be considered when comparing different types of fibers and composites.

4.5 Insulation materials for buildings

Insulation material is often composed of petrochemical-based material (mainly polystyrene) or natural substances of mineral origin (glass and rock wool). From the perspective of sustainability, natural or recycled material could contribute to a reduction in the use of non-renewable materials and energy and simplify reuse or recycling processes. Heat energy, thermal conductivity, coefficient of thermal conductance, thermal resistivity, thermal resistance (R-value), coefficient of heat transmission (U), permeance to water vapor and resistance to water vapor are important thermal properties for insulating materials.

Asdrubali et al. (2015) described the utilization of unconventional fiber materials, being several residues from agricultural and production and processing industries (such as bagasse, and reeds) as well as recycled materials (for instance textile fibers). The majority of these materials have not yet been characterized completely (e.g., thermal properties, thermal conductivity, specific heat, fire classification, resistance to water vapor diffusion, sound absorption, fungal resistance and environmental impacts), which still makes comparisons difficult. However, there are indications that these materials could compete with conventional materials, and the local availability of these materials could also lead to a reduction in the economic and environmental impacts (especially regarding residues and by-products of the agricultural sector) (Asdrubali et al., 2015).

Using natural fibers in insulation generally reduces the consumption of resources and energy during the material production and fosters the recovery, reuse and recycling of the products before their final disposal (Ardente et al., 2008). Schiavoni et al. (2016) compared different insulation materials based on the data in the literature regarding their global warming potential (GWP) from cradle to gate (i.e., from raw material to the final product, neglecting the use and the end-of-life phase). They showed that synthetic insulation material had a consistently higher GWP than natural fiber-based materials. Specifically, extruded expanded polystyrene had the highest GWP (5.05 - 8.25 kg CO_2-eq./functional unit – f.u.), followed by that of expanded clay (loose) (10.31 kg CO_2-eq./f.u.), glass wool (9.89 kg CO_2-eq./f.u.), glass fibers (7.70 kg CO_2-eq./f.u.), expanded polyurethane (5.31 kg CO_2-eq./f.u.), expanded perlite (panels) (3.99 kg CO_2-eq./f.u.) and expanded vermiculite (loose) (3.36 kg CO_2-eq./f.u.). Among the natural fibers, kenaf had the highest GWP (3.17 kg CO_2-eq./f.u.), followed by that of jute fibers (2.79 kg CO_2-eq./f.u.), kenaf fibers (1.13 kg CO_2-eq./f.u.), cellulose (0.73 kg CO_2-eq./f.u.) and natural pumice (loose) (0.08 kg CO_2-eq./f.u.) (Schiavoni et al., 2016; Zabalza Bribián et al., 2011; Asdrubali, 2009; Ardente et al., 2008).

4.6 Food and feed

The applications described so far cover the largest share of fibers in technical applications. However, many fibers are used in food and feed applications. In contrast to the technical applications, these serve nutritional purposes. A comparison across technical and nutritional applications is difficult since they differ in their structure and valuation (Stern, 2009).

In food products, fibers are often inseparable contents of vegetables and fruits. Still, dietary fiber can be considered an additional ingredient (food additive) to processed food (e.g., bread, pasta, yogurt, cereals). Wood, for example, is widely used as a raw material for the production of food additives and ingredients. Probably the most well-known of these additives is cellulose (Slavin et al., 1980). In food, cellulose is mostly used as a thickener or binding agent. It can be derived from wood or woody plants, such as spruce or bamboo, or from alternative sources, such as cotton. Many modified cellulose derivatives (e.g., carboxymethyl cellulose) are used as emulsifying agents or stabilizers in food products. Within the European Union, these derivatives are classified by directive 87/107/EEC (European Community, 1988) as food additives E461 to E469, while cellulose itself is classified as E460. They are generally permitted as food additives under Annex I of directive 95/2/EC (European Community, 1995).

Fiber additives serve to improve the mechanical attributes of food, such as their stabilizing, binding, dispersing, or emulsifying properties (similar as in coatings and paints). Apart from these technical attributes, they also provide some health benefits since they are only (partly) indigestible. A company survey by Stern (2009) provided a list of 27 different kinds of dietary fibers in food products. Most frequently mentioned were inulin and other fructooligosaccharides (FOS). The second-most frequently mentioned group (23.4%) were fibers from apples, lemon fruits, sugar beets, potatoes, soybeans, oats and peas. Another aggregated group of dietary fibers were from different kinds of bran (10.5%), such as oat, wheat, rye, or rice. According to Stern (2009), the first and most important criterion that could be used to differentiate between the dietary fiber products on the market is the difference in their water solubility. The completely soluble products, including gum arabic and arabinogalactan, made up 60% of the surveyed products. Insoluble products accounted for another 40% of the surveyed products.

Niche strategies would provide smaller market volumes of 500 to 5,000 tons annually but higher prices (3.5 to 10 Euros/kilogram) while the substitution strategy would lead to price-based competition (down to even below 2 Euros/kilogram) and open up a 15,000- to 25,000-ton market. In general, the survey findings confirmed that dietary fiber additives are complex products that depend on their approved health claims, which need to be communicated clearly to the consumer. Consequently, these products require multistage marketing approaches, and particularly ingredient branding (Venkatesh et al., 1997).

In comparison to applications in food products, the use of fibers as animal feed or in feed products is typically a mass-market application. In most cases, by-products from food processing (e.g., milling residues) are used. The price of these products is often based on the nutritional value of the product, with trade values typically below USD 300 per ton.

4.7 Market value and volume of selected fiber applications

Figure 12 presents a rough scheme that indicates the approximate bandwidths as well as relations between prices and volumes in the different application fields.

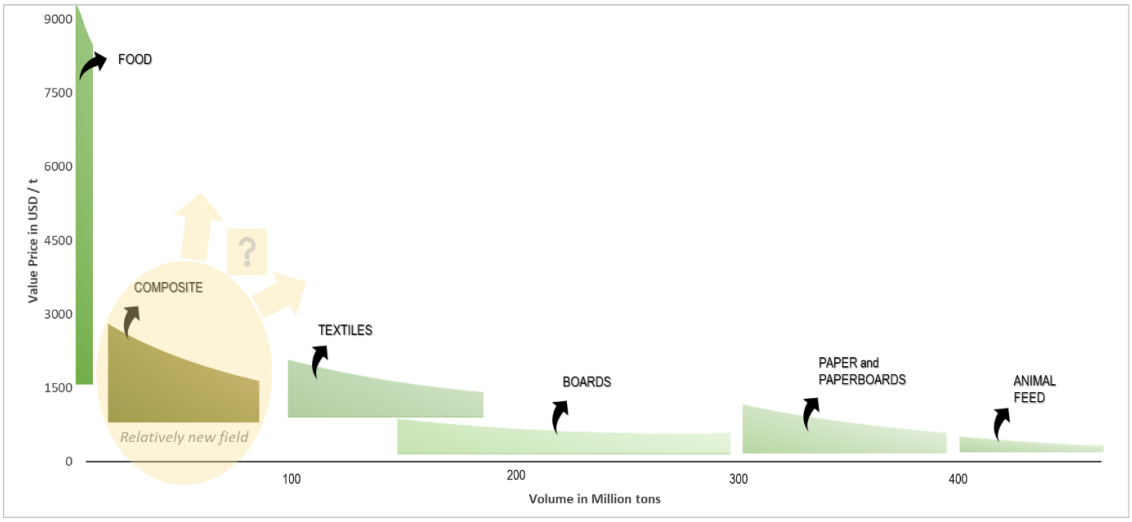

Figure 12: Schematic illustration of the volume and value relation of different fiber applications

This report is intended to serve as a guideline and provides a general overview of the relevance of fibers in biorefineries. Individual biorefineries (e.g., when they consider the utilization of side streams and by-products like fibrous residues) face individual site and framework conditions and, depending on these, they may have to consider varying individual aspects to be able to assess relevant criteria for their potential success on the market. Therefore, if decisions for an individual biorefinery have to be made, individual assessments can be carried out to answer specific questions for the individual case. Some examples for frequently occurring aims and questions, which require different methodical approaches, include choosing the most promising and sustainable application for a new material (where could the new material prevail on the market?), analyzing different conceivable future events and alternative outcomes (which conditions can be expected in the future and what are the optimal strategies?) and potential pricing of new biobased products (is the developed technology profitable?). Some useful approaches for case-to-case assessments are exemplified in *Table 9*.

A standardized basis is available for the characterization of biorefineries concerning their technical aspects and environmental, economic and social criteria ("classification and quality criteria of biorefineries", VDI-6310). This guideline is designed to be used for the evaluation and optimization of existing plants and can also guide the planning of future concepts. It is addressed to plant operators, technology developers and technology providers, planners and representatives of public authorities (VDI, 2016).

Table 9: Exemplarily illustration of several assessment methods for individual biorefineries and objectives

Feedstock / Fiber	**Product**	**Method**	**Result**	**Ref.**
Lignocell., residues (e.g., cashew nut shells)	Biopolymers: PLA, PHA, lignin, CNSL	Scenario analyses	Identification of key factors (targets: price reduction and sales volume increase) and how the targets could be achieved (range of probable outcomes, probability of occurrence)	Lettner et al., 2017
Flax fibers	Applications: textile (traditional) and technical	Market survey: qualitative (industry and research, 120 p.)	Identifying most important general fiber properties in tech. uses by focusing on market in interesting applications and by analyzing the nature of quality criteria or desired properties. Opinions (main function and secondary effects)	Smeder and Liljedahl, 1996
Cellulose nanofibers (Case study)	Different polymers (reinforcement)	Multi-criteria decision analysis	Evaluating several possible application fields and making predictions about their suitability for adoption of new materials; identifying and choosing most promising and sustainable applications for new materials	Piccinno et al., 2016
Fibers (32 different)	High-tech appl. (aeronautics), consumer goods (e.g., sporting goods)	Econometric	Assessing the monetary value of fibers to be used for reinforcement in composites by the relation of price and certain fiber properties; evaluation of the economic value of a reinforcement fiber by technical properties	Ledl et al., 2014

5. BIOREFINERY EXAMPLES

A set of five biorefinery examples has been selected to show the opportunities for sustainable processing of relevant biomass feedstock into a portfolio of marketable biobased products and bioenergy. The examples have been selected because natural fibers / fiber-based materials form an important part (in volume and/or profitability) of the total biobased product portfolio being produced, making the overall biorefinery market competitive. Both industrial best-practice examples and demo facilities are included to cover a large range of the diversity of biorefinery facilities in which natural fibers / fiber-based materials will provide part of the products outlet. The selected examples cover a number of feedstock, different technological or commercial readiness levels and distinct product portfolios, in which the role of fiber products is especially considered.

5.1 Industrial best practices

5.1.1 Lenzing Company (Austria) – biorefining beech wood to dissolving wood pulp, biochemicals and bioenergy

The Lenzing Group is a world market leader and has sites in all major markets as well as a worldwide network of sales and marketing offices. The company places a focus on supplying the global textile and nonwoven materials industry with man-made, plant-based, cellulose fibers. About 250,000 tons of cellulose fibers and 290,000 tons of pulp are produced each year at the Lenzing mill, which is located in the district of Vöcklabruck in Upper Austria.

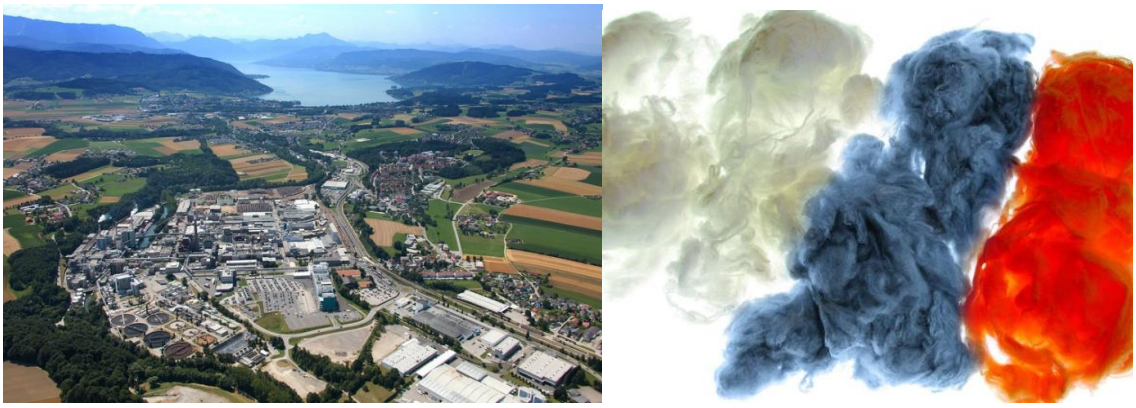

Figure 13: Lenzing AG, Austria and examples of staple fibers (both pictures © Lenzing AG)

The raw material of wood is processed into dissolving wood pulp and marketed under several brands: TENCEL™ for textile applications (e.g., women's outerwear, sportswear, home textiles), VEOCEL™ for nonwoven materials (e.g., hygiene products), LENZING™ for special fiber applications in other areas and other products, as well as innovations like REFIBRA™ recycling technology, the identifiable LENZING™ ECOVERO™-branded fibers and TENCEL™ Luxe-branded Lyocell filament yarn (Lenzing AG, 2018).

Lenzing uses 100% of the wood and, therefore, also produces considerable quantities of co-products in a biorefinery process: Besides the 40% dissolving wood pulp, 10% biochemicals and 50% bioenergy are produced. Examples are given in *Table 10*.

A key component of this globally unique biorefinery process, which is based on beech wood, is the so-called vapor condensate extraction plant. Since the vapor condensate extraction plant first came

on-stream (approximately 30 years ago), around 470,000 tons of acetic acid and 110,000 tons of furfural have been manufactured at the Lenzing site.

In cooperation with the company DuPont / Danisco, xylose is extracted on site from the spent sulfite liquor (high-purity crystalline powder), and hydrogenated later on to xylitol (in Finland). This product is used, e.g., as sweetener (such as for chewing gum and culinary purposes) and in the application areas of oral care and pharma (DuPont and Danisco, 2018). In recent decades, Lenzing has succeeded in increasing the utilization of the wood substances to enable more than half to be converted into high quality products. The environmentally compatible production process as well as the maximum attainable closed cycle and the optimal use of the raw material beech wood are unique in the industry. In addition, the residual, non-usable parts of the wood are used as fuel to gain electric and thermal energy. Thanks to the optimal exploitation of the raw material, non-fossil fuels comprised 83% of the energy mix used at the Lenzing site in 2015 (Lenzing AG, 2016).

Table 10: Examples for Lenzing AG biorefinery co-products

Co-products	Fields of application
Acetic acid	Food industry, pharmaceutical and cosmetics industry, chemical industry, solvents and textile industry
Furfural	Primary product for furfuryl alcohol, solvent in the refining of lubrication oil, solvent for anthracene and resins, distillation of butadiene, herbicide production
Mg-Lignosulfonate	Animal food industry, ceramics industry, production of fireproof bricks, tanning agent industry, clipboard and fiber board industry, auxiliary materials for the construction industry, fertilizer industry
Sodium sulfate	Detergent and cleaning agent industry, glass industry, cellulose and paper industry, textile industry, food and pharmaceutical industry, chemical industry
Soda ash	Glass industry, pulp and paper industry

5.1.2 Domtar Corporation, Plymouth Mill, (North Carolina, USA) – Biorefining of pine to fluff pulp and BioChoice™ lignin

Domtar's Plymouth Mill in North Carolina (*Figure 14*) has evolved into a modern Kraft pulp mill over decades (two pulp lines and an annual pulp production capacity of 470,000 tons), producing high quality fluff pulp from southern pine (mainly loblolly pine) for the production of baby diapers, adult incontinence products, air-laid nonwoven materials, and feminine hygiene products (Domtar Corporation, 2017). Their lignin separation facility is the first commercial-scale installation of the LignoBoost™ technology (advanced process that separates, purifies, washes and presses the lignin from the black liquor) worldwide, with a target capacity of 75 tons per day of lignin (approximately 25,000 tons per year).

Figure 14: Plymouth mill, North Carolina (© Domtar)

BioChoice™ lignin can be used as a biobased alternative to manifold fossil-resource-based compounds. The wide range of potential applications in the energy, materials and chemical categories include adhesives, agricultural chemicals, carbon products (such as carbon fiber, graphite and activated carbon), coatings, dispersants, fuels and fuel additives, natural binders, or resins.

5.1.3 Biowert Industrie GmbH (Germany) – biorefining meadow grass to insulation material, plastics, fertilizers and bioenergy

The grass biorefinery Biowert produces green electricity and innovative materials, namely composites, insulation materials and fertilizers. The philosophy is to use raw materials as efficiently as possible in a closed-loop recycling process, to avoid the generation of wastewater or waste products, only utilize minimum resources and produce ecologically, regionally and socially responsible products (Biowert Industrie GmbH, 2017). The plant is currently designed for an annual production capacity of 2,500 tons of cell fibers.

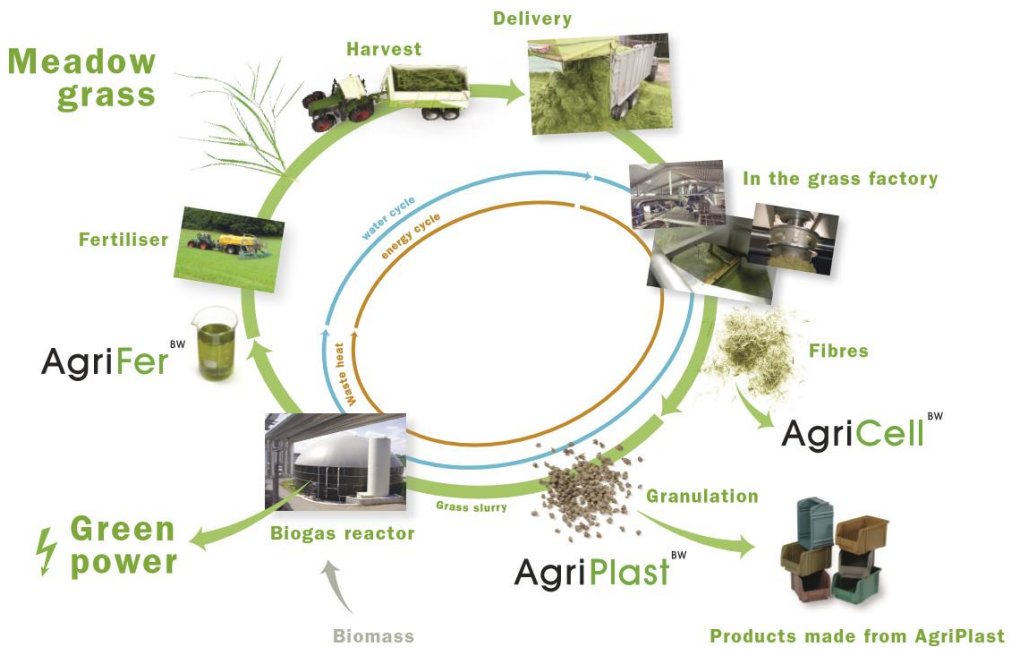

Figure 15: Biowert closed-loop manufacturing process (© Biowert GmbH)

The Biowert process is a grass factory; meadow grass is supplied by local farmers and processed in several stages into innovative materials (see *Figure 15*): AgriCell^{BW} insulation material, AgriPlast^{BW} plastic (e.g., for terrace boards) and AgriFer^{BW} fertilizer.

The insulation material is made from 100% natural cellulose and suitable for walls, floors and ceilings. The plastics contain cellulose from regional fibers (up to 75%) and a variable thermoplastic polymer matrix that can also consist of recyclates or biodegradable plastics. The material is suitable for injection molding and extrusion for a variety of light, dimensionally stable, dye-able and temperature resistant products: terrace boards, toys and boxes or casings for technical equipment are some examples (illustrated in *Figure 16*).

Figure 16: Biowert products (© Biowert GmbH)

5.2 Demonstration and research

5.2.1 PULP2VALUE (Royal Cosun, NL) – biorefining of sugar beet pulp into micro-cellulose fibers, arabinose, galacturonic acid, animal feed and bioenergy

Sugar beet pulp is a major residual stream from the sugar beet industry (approx. 13 million tons per year in Europe) and is currently valorized as low value feed and/or green gas.

Figure 17: Sugar beets, Pulp2Value (© Pulp2Value, © nova-Institute)

Pulp2Value (processing underutilized low value sugar beet pulp into value-added products) is a demonstration project funded by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program (Bio-Based Industries, 2017).

The main objectives of the project are the isolation of more valuable products from the side stream, establishment of value chains based on microcellulose fibers, arabinose and galacturonic acid (illustrated in *Figure 18*), local cross-sectoral value chains involving the sugar, chemical and food industries, demonstration of an integrated and cost-effective cascading biorefinery system to refine sugar beet pulp and isolate high-value products (detergents, personal care, oil and gas, paints and coatings from MCF, flavor and food products from arabinose or cosmetics from galacturonic acid) and achieve a significant increase in the sugar beet pulp value by demonstrating applications for approximately 65% of its mass in high-value markets (increasing its current value by as much as 20–50 times).

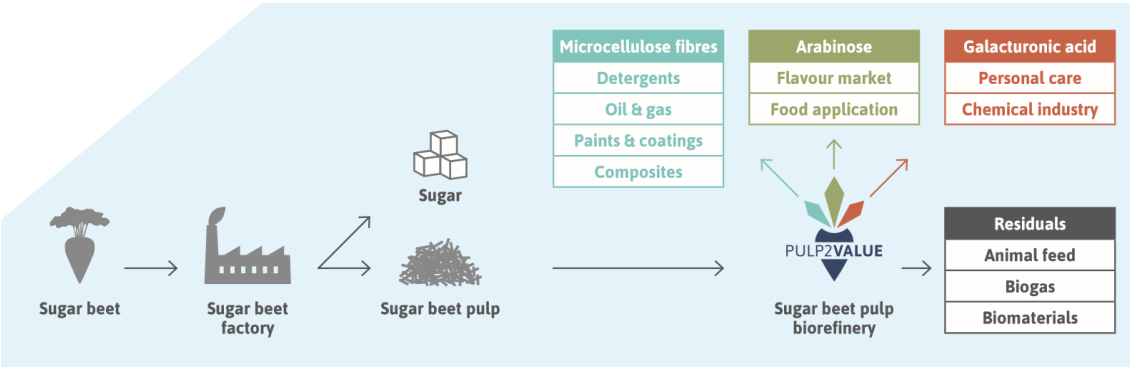

Figure 18: Pulp2Value sugar beet biorefinery (© Pulp2Value)

Nine new value chains for the processing of sugar beet pulp into bioproducts with a market potential of 350,000 tons and 200 million Euros should be demonstrated. Further impacts anticipated are the valorization of side streams from production of sugar beet, reduction in the carbon footprint through the use of MCF and chemical building blocks (replacing, e.g., glass, or Kevlar), rural development in sugar-beet-growing areas by connecting various industries, increased resource efficiency through the diversified use, an expanded European portfolio of value-added products and innovative products with a low environmental impact.

5.2.2 VELICA (Regione Lombardia, Italy) – biorefining of hemp and flax into fiber-based green composite building materials and oil-based fatty-acids, fuels and chemicals

VeLiCa (Vegetali Lino Canapa) is a strategic project in Italy that aims to create a biorefinery that produces materials and products for the future, using the ancient crops hemp and flax as feedstock (*Figure 19*). The project is funded with a 5 million Euro budget and involves the cooperation of five research centers.

Figure 19: VeLiCa project for a hemp and flax biorefinery in Northern Italy (© VeLiCa)

The main goal of the VeLiCa project is to relaunch the plantations of flax and hemp in Regione Lombardia (Northern Italy) and design biorefinery schemes for full biomass exploitation. The development of different products with different added values, upgrade of agricultural residues and wastes, set up of new productive chains, establishment of a network of expertise, establishment of a bioproducts portfolio and training of new specialists are additional goals of the project.

The project consists of the selection of the most productive genotypes, the extraction of oil from the seeds to be used for the production of biodiesel, bio-lubricants with high flash point, polyols as intermediate for the synthesis of polyurethanes and bio-polymers. Additionally, selected enzymes are used to isolate ω-3 and ω-6 components from the oil, obtaining valuable oils for the nutraceutical market. The fiber in this project is used to produce composites with waste wool. These composites are both thermo- and phono-insulating materials, show good fire behavior, are free-standing and resistant to mold and insects due to the alkaline treatment used to produce them. Moreover, they are suitable for anti-seismic buildings, are recyclable and compostable. For these reasons, they are highly applicable as green building materials. The biorefinery approach of the project (fiber products emphasized) is schematized in *Figure 20*.

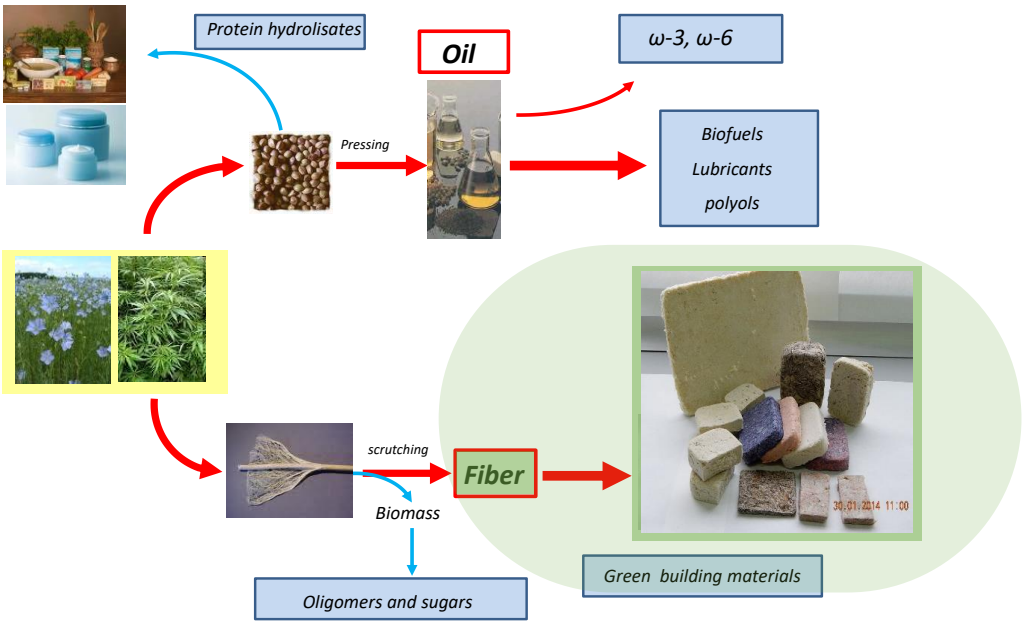

Figure 20: VeLiCa scheme, fiber composites (modified from Ravasio; IEA intertask meeting, Sardinia 2015; © VeLiCa)

6. Discussion and conclusions

The concept of sustainably processing biomass into a spectrum of marketable biobased products is a rather old one, and fiber-related products played a large role in these early biorefineries. Fibers and fiber-based materials also played important roles in the industrialization of biorefineries. However, the term "biorefinery" did not emerge until the 1990's and it then mostly referred to concepts that placed a focus on biofuels and chemicals.

While gaseous biofuels and liquid transportation fuels have a large market volume (especially the latter) the product unit value created in these applications is limited. In contrast, biochemicals and biomaterials tend to represent smaller markets, although these cover a large range from commodities to specialties and certain niche markets. However, as commercial biorefinery examples as well as economic simulations suggest, a single biorefinery tends to develop product portfolios based on several high-value-added by-products, considering the rather limited production volumes of a single mill. In contrast, the main product (in conjunction with the regional feedstock availability) defines the scale operation and, hence, more often directs the focus toward larger markets.

Therefore, those responsible for the individual biorefineries are confronted with decision-making processes whenever they consider the utilization of side streams and by-products such as fibrous residues. Three major aspects are in general relevant for such decision-making processes. Firstly, the feedstock utilized in individual biorefinery concepts largely determine later options. Secondly, large varieties of fibers of biogenic and non-biogenic origin are known and available on the markets. Hence, the selection and valuation of new fibers and fiber-based materials orient the decision-makers towards the use of existing products. Thirdly, there are only few major application fields for fibers and fiber-based materials, which largely determine sales value and volumes.

Based on a review of 657 abstracts from scientific articles published on the topic of biorefineries between 2010 and 2016, the importance of lignocellulosic feedstock in biorefinery development was dominant. Of all the types of feedstock mentioned, most referred to lignocellulose, which was mainly derived from dedicated lignocellulosic crops and residues. Fibers tended to be mentioned in the context of biorefineries related to residue utilization (especially from common agricultural crops like corn, wheat and sugarcane). Concerning residuals from starch and sugar crops, a strong focus was noted on energy utilization (fuels) compared to material exploitation. However, products such as composites, pulp and paper were also mentioned. Residuals from oil crops were more often used as fiber material (in 50% of the abstracts), for instance, due to their favorable self-bonding properties as insulation fiberboards. Composite reinforcements, nanomaterial, boards (mainly for insulation), pulp and paper products, carbon fibers from lignin, feed and dietary fibers are applications that were relatively frequently mentioned in the abstracts.

The fiber applications described begin from large market volume applications (e.g., pulp and paper, boards) towards more value-added applications (e.g., composites, textiles) and reached the highest added value in food applications. Within each application, certain niches can be considered as the most interesting market entrance options for new biorefinery-related fibers.

Most feedstock that provide a source for natural fibers (e.g., cotton, flax, hemp, jute) are suitable for biorefinery concepts but are not often considered in biorefinery development. The supply of these traditional natural-fiber feedstock is rather limited; therefore, the resulting biorefinery concepts are difficult to develop. In contrast, agricultural feedstock that are widely available, like wheat or maize, are more often utilized in biorefinery concepts but fiber products were rarely considered as an option in the product portfolio development.

Compared to other biorefinery products like fuels, the applications and markets associated with fiber products must be considered as relative diverse and complex. In contrast to, for example, the fuel-bio-fuel substitution, the replacement of glass fibers (as well as petroleum-based carbon fiber) is less dependent on cost. Therefore, fiber products open opportunities for future biorefinery development pathways.

A future economy that sustainably uses biobased resources instead of fossil fuels to meet people's needs will be dependent on the production of a variety of products such as food, feed, materials, chemicals and energy from limited resources, such as the cultivation land available. To produce "almost everything from almost everything," although due to the scarcity of resources (such as land, energy, water and nutrients), these should be used as efficiently as possible. Therefore, well-developed technologies, tailored management and logistics, optimized product portfolios, but also sustainable consumption patterns, fair distribution and circular economy issues need to be considered.

In particular, several future issues and upcoming technologies will most probably affect the topic of fibers and fiber-based materials in biorefineries. The production of micro- and nano-fibrillated cellulosic materials, for example, could lead to manifold promising applications (such as films, nanocomposites, coatings, pharmaceuticals, separation membranes, rheological modifiers and biomedical applications). Lightweight, high-performance materials in vehicles are a prominent topic that can be explored to address energy issues in the transportation sector, e.g., in the context of e-mobility. In this field, natural-fiber reinforced composites are of increasing interest. Carbon fibers are already produced to a small extent from natural resources (e.g., wood-based rayon), but also lignin from wood biorefineries is a potential precursor for biobased carbon fiber production. The strong growth of mail-order businesses leads to the necessity of packing products safely. Therefore, fibrous packaging materials such as paper board will remain relevant while the development of smart biobased packaging materials can also be expected. The so-called fast fashion trend has supported the production of cheap synthetic and cotton fibers in recent years while, in contrast, certain segments of the textile industry (e.g., fair fashion, outdoor clothing) have begun to consider sustainability as a major issue. Driven by increasing consumer awareness, the sustainable production of textiles, e.g., from natural fibers grown on a regional level, is becoming increasingly relevant. This could be another opportunity for the use of sustainable fibers from biorefineries.

Lignocellulosic materials are often used for energy production; however, there are several options for sustainable energy production, whereas a tremendous amount of materials used in everyday life still only depend on fossil resources. In the long term, biobased fibers and fiber-based materials could become more prominent in established fields once they are successful in niche markets and, therefore, be requested in higher volumes. Fiber industries that already produce high volumes of biobased fiber products might refine and diversify their product portfolio as well as ameliorate their conventional products in terms of their performance and sustainability.

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