Identification and Review of Downstream Options for the Recovery of Value from Fibre Producing Plants:

Hemp, Kenaf and Bamboo

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Table of Contents

List of Figures

List of Tables

List of Acronyms

BFRP - Bamboo fibre reinforced plastic

BMB - Bamboo mat board

BRFC - Bamboo fibre reinforced polymer composites

CBD - Cannabidiol

CIRTM - Co-injection resin transfer moulding

KSO - Kenaf seed oil

FDA - United States Food and Drug Administration

FRC - Fibre-reinforced concrete

GFRC - Glass fibre reinforced composites

MBM - Mat board

MDF - Medium-density fibre board

PFRC - Plant reinforced composites

PP - Polypropylene

RTM - Resin transfer moulding

S-RIM - Structural reaction injection moulding

SWB - Strand woven bamboo

THC - Tetrahydrocannabinol

VARTM - Vacuum assisted resin transfer moulding

1 Introduction

Over the past two decades, 6 000 mines have been abandoned and a large number are expected to be closed in the next ten years[1]. These mine closures create an economic vacuum, especially if the mines have been the only generator of economic activity in an area. Essential services, such as medical and health facilities, can also disappear if they were provided for by mining companies. Post-mining land uses such as agriculture have the ability to mitigate environmental and socio-economic impacts of mine closure, as well as stimulate economic growth beyond the life of a mine. Fibre producing plants such as bamboo and bast fibres are of particular interest due to their potential to create multi-product value chains and to selectively absorb metals from soils (Linger et al., 2002 and Kopittke et al., 2010). This presents an opportunity to simultaneously remediate and transform post-mining land into a restorative agricultural sector and dynamic manufacturing economy.

It is this opportunity that is being explored in a multi-disciplinary community of practice project at the University of Cape Town, under the auspices of the Department of Science and Technology (DST) and the National Research Foundation (NRF). This project[2] draws from different disciplines to explore the opportunities for developing multi-product value chains in the context of South African mining regions from an economic, environmental, engineering and legal perspective.

This specific report provides a review of the publicly available information on the products that can be generated from fibre-based plants, as well as the processes and technologies used to generate these products from the cultivated plant biomass. Fibre crops are typically classified by the part of the plant which produces the fibre, with the types of products and production processes being similar for plants falling under the same classification. This review focuses on the simultaneous generation of multiple products from bast fibre plants, kenaf and hemp (Section 2), and the grass fibre, bamboo (Section 3). Consideration is also given to the potential options for the recovery of phyto-extracted metals (Section 4).

[1] (https://theconversation.com/finding-ways-to-keep-communities-alive-after-mine-closures-98505)
[2] (http://www.resilientfutures.uct.ac.za/about-Towards-Resilient-Futures)

2 Bast Fibres: Hemp and Kenaf

The use of hemp by humans dates back to approximately 8000 B.C. and it is referred to by some as the fibre of a hundred uses. In fact, it was so important to 16th century England that King Henry VIII passed an act which ordered that farmers be fined for failing to grow the crop[3]. Although less well known in the Western world, kenaf has also been associated with many ancient cultures of the world and is often considered an alternative to hemp because of the similarities in the product properties. Today, the benefits of using natural fibres as a substitute for synthetic materials or other resources (such as hardwood and cotton) are being increasingly recognised, particularly in the context of sustainable development imperatives.

The section provides a review of the products that can potentially be generated from the bast fibre crops, hemp and kenaf (Section 2.1), as well as the processes and technologies used to generate these products from plant biomass (Section 2.2).

2.1 Products and Uses

Both hemp and kenaf are dicotyledons, which means that their stems or stalks have an outer bast or fibre and an inner woody core, also known as hurd and sometimes referred to as the core fibre (Figure 1). The bast fibre from bast fibre plants is composed of bundles and is obtained from the phloem, or inner bark the plant.

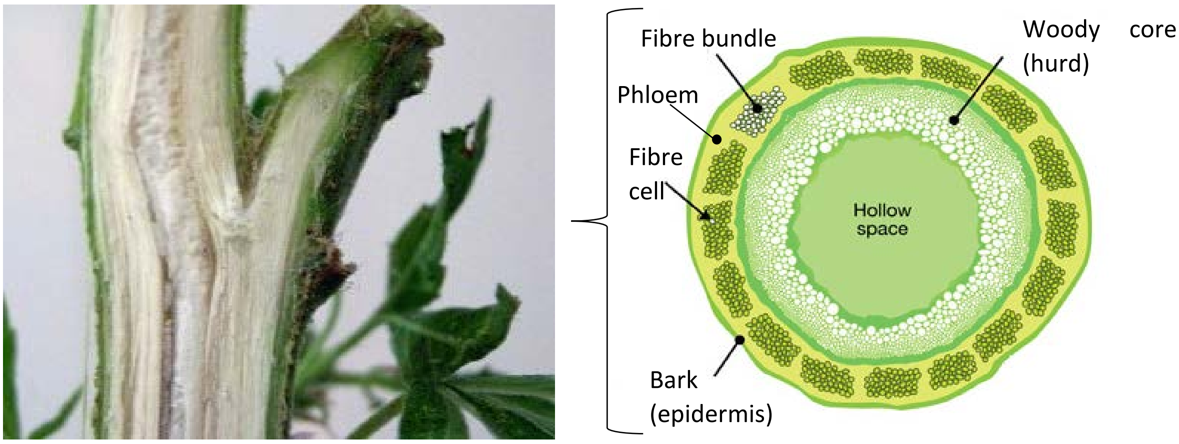

Figure 1: Bast fibre stem cross section (Sharma et al., 1999)

Although the whole plant can be used for bio-energy production as well as animal fodder in the case of kenaf, processing to separate the bast fibre from the woody tissue and other parts of the bast plant results in multiple products. The different parts of the plant (bast fibre, woody tissue or stem core, seeds and leaves) are used to manufacture various products of different levels of complexity, as shown in Figure 2 (Salentijn et al., 2015; Ingrao et al., 2015).

The processing of the bast plants generates both long and short bast fibres. Long fibres (varying from 15-50 mm) typically make up 70% – 90% of the bast and are characterised by a high cellulose content

[3] https://www.hemp.com/hemp-history/

of 50% – 70% (Chen and Liu, 2010; Papadopoulou et al., 2015), rendering them suitable for processing into traditional textiles (e.g. clothing and fabrics) or technical textiles such as geotextiles, nonwoven textiles and reinforcement in polymer-matrix or concrete composites (Salentijn et al., 2015). Short fibres typically comprise the remaining 10% – 30% of the bast and are characterised by a length of approximately 2 mm. Short fibres are typically used for cordage (ropes and twines) or for paper pulp. The woody tissue (also referred to as shives, hurds or core fibre) makes up the majority of the stem (60% – 75%) and is typically used to produce construction materials such as fibreboard, insulation and hempcrete, pulp for paper production, or for other industrial products such as agricultural mulch, animal bedding and fuel for boilers. The leaves are cleaned and processed for various uses such as vegetables, compost or medicines. Kenaf leaves are edible and are used as a vegetable in salads or cooked (Cross, 2014). Both hemp and kenaf seeds can be either used as a whole or crushed and pressed to produce oil and a residual seed cake, which is rich in protein. A more detailed configuration of hemp products is provided in Appendix I, whilst additional information on the key hemp and kenaf fibre-based products and by-products and their uses is provided in Sections 2.1.1 to 2.1.6 below.

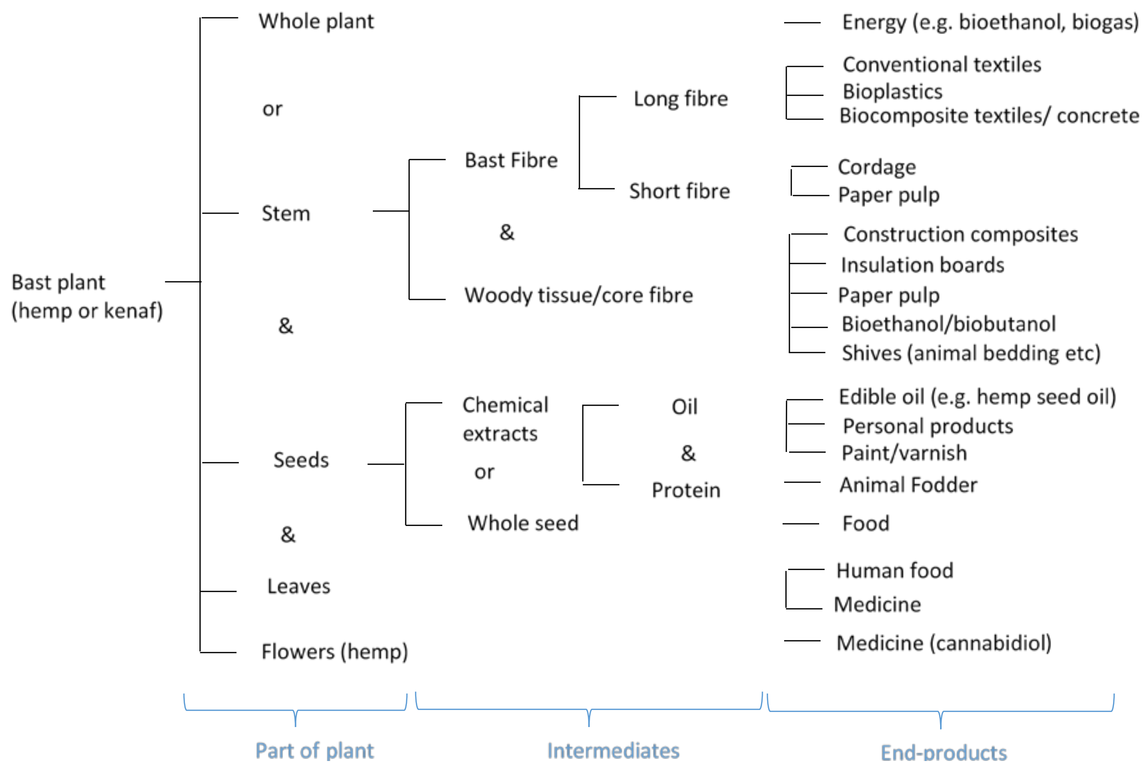

Figure 2: Multi-product value chains from bast fibre plants

Whilst hemp and kenaf have very similar product profiles and processing stages, the fibre structure is significantly different, resulting in different product properties and relative yields, as well as the size of the operating units. Whilst a kenaf stalk consists of approximately 40% bast fibre and 60% core fibre, only 25% of the hemp stalk is typically in the form of bast fibre, with 75% comprising core fibre or hurd. In general, the yield of fibre for kenaf is 2-3 times higher than that of hemp. Hemp bast fibre contains more cellulose and is longer and stronger than that of kenaf, although hemp fibres are not as long as those of flax and cotton. A comparison of the properties of fibres derived from hemp and kenaf plants is provided in Table 1.

Table 1: Comparison of yields and properties of fibre from hemp and kenaf plants

Properties	**Hemp**	**Kenaf**
Bast fibre (% in stalk/stem)	25-30	35-40
Fibre fineness (um)	25 to 40	20 to 35
Fibre length (mm) – long fibre	16 to 40	8 to 18
Cellulose (wt%)	70 – 74	45 - 57
Hemicellulose (wt%)	18 -22	21- 23
Lignin (wt%)	4-6	8-13
Tensile Strength (MPa)	550-1000	195-700

Sources: Sponner et al., 2005; Amaducci and Gusovius, 2010; Chen and Liu, 2010; Dicker et al, 2014; Pickering et al., 2016; Sisti et al., 2018

2.1.1 Conventional textiles

In the past hemp and kenaf have been used in sacking, canvas and sails for boats, due to their rot and mildew resistance, as well as their strength and durability. Until the nineteenth century, hemp was used in 90% of ships' canvas sails, rigging and nets (and thus it was a required crop in the American colonies). With modern technology, natural fibres have come a long way from the thick, burlap fibres that they were associated with decades past, and bast fibres are now used for a range of industrial and domestic textiles or woven into a variety of fine linen-like quality fabrics.

Fabrics

As a fabric, hemp and kenaf are breathable, warm, moisture-wicking, antibacterial, biodegradable and can be easily blended with other fibres such as cotton. Although bast fibre-based textiles are very durable and become softer with washing and wear, cotton-blended textiles are more aesthetically pleasing, lightweight, and have a softer feel. Fabrics made from hemp-cotton or kenaf-cotton blends have the appearance of linen. Currently cotton remains the major natural fibre used in the clothing industry, with fibres such as jute, wool, flax, silk, ramie, hemp, sisal and kenaf accounting for only 20% of the market. Other than cotton, flax is the only significant plant in terms of plant fibre production, and only 0.3% of the world plant fibre production was derived from industrial hemp in 1999. However, the demand for textiles from crops such as flax and hemp is predicted to increase due to the growing demand for "greener" textiles (Muzyczek, 2012).

Figure 3: (a) Hemp long fibre yarn (b) Kenaf long fibre yarn

Technical textiles

Currently cotton remains Technical textiles are functional textiles which include textiles for industrial applications such as automotive applications, medical textiles (e.g., implants), geotextiles (reinforcement of embankments) and agrotextiles (textiles for crop protection). For example, kenaf bast fibres have been used to make various types of environmental mats, such as seeded grass mats for instant lawns, mouldable mats for manufactured car parts and containers, and for geotextiles. Hemp nonwoven mats (see Figure 4) can be used as reinforcement, growing medium, underlayment, or erosion protection.

Geotextiles are the oldest example of technical textiles and have been in use for thousands of years, dating back to the Egyptian Pharaohs. They are permeable fabrics used for erosion control and to improve soil structure by acting as mulch, soil filter and absorption agent. Kenaf geotextiles can be used for soil erosion control, agromulching, protection of river banks and embankments, vegetation consolidation, land reclamation and road construction. Although polymeric geotextiles are typically made from polypropylene or polyester, kenaf fibre-based geotextiles have been reported to compete favourably with these on both a technical and commercial basis (Leão et al., 2012).

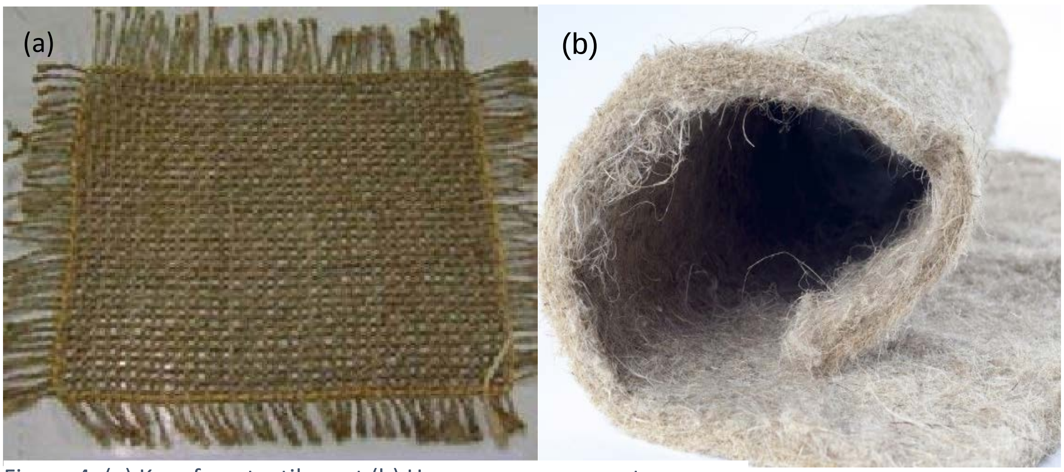

Figure 4: (a) Kenaf geotextile mat (b) Hemp nonwoven mat

2.1.2 Plant fibre reinforced composites

Both hemp and kenaf fibres have been applied in the production of plant fibre reinforced composites (PFRCs). PFRCs are composed of plant fibres embedded in a synthetic or biodegradable resin (Ramesh et al., 2017). PFRCs may potentially replace conventional glass fibre reinforced composites (GFRCs). Whilst comparable in strength properties, PFRCs have advantages over GCRFs in terms of renewability, abrasiveness to equipment, biodegradability, and low weight and cost (Frone et al., 2013; El-Shekeil et al., 2012). The physical properties of PFRCs may be adjusted depending on the required application by selecting appropriate process flow sheets, fibres, matrix and other additives (Ramesh et al., 2017), making them suitable for a wide range of applications.

One of the most common application of PFRCs is in the car manufacturing industry, with both hemp and kenaf bast fibres having been incorporated into thermoplastic matrix composites to replace flax fibres for use in the car industry (Summerscales et al., 2010). In the European Union, natural fibres are used in the moulded composites of automobiles to reinforce door panels, passenger rear decks, trunk linings, and pillars. In 1999, over 20 000 tonnes of natural fibre was used for these purposes in Europe, including about 2 000 tonnes of industrial hemp (Small and Marcus, 2002). Kaup et al. (2003) reported that the amount of hemp used for automotive composites in Germany and Austria increased from zero tonnes in 1996 to an estimated 2 200 tonnes in 2002. Total use of natural fibres for automotive composites in these two countries increased over four-fold in the same time period (from 4 000 to 17 200 tonnes). Kenaf bast fibres have also been used by Ford and BMW in a number of applications, including hybridized glass fibre polymer composites for the automotive component construction of a centre lever parking brake component (Mansor et al., 2013); exterior automotive parts such as front and back bumpers (Khan, 2011); spare tyre covers and deck boards; and petroleum-derived polypropylene (PP) resin in door trims. The door trim was found to have a reduced weight with the same durability as when manufactured with more conventional materials, as well as a high level of shock and heat resistance (Toyota, 2014). It has been estimated that 5 to 10 kilograms of natural fibres can be used in the moulded portions of an average automobile (excluding upholstery). Based on the present production of 16 million vehicles per year in Western Europe, Kaup et al. (2003) predicted a market growth potential of 80 000 to 160 000 tonnes per annum for natural fibres in press moulding in that region, at an annual growth rate of 10 to 20% until 2005 for the use of natural fibres in composite materials.

Figure 5: Natural fibres used in cars (Teles et al., 2015)

The potential also exists for the use of PFRCs in the manufacture of plastic grocery bags, food packaging materials, bottles, containers etc. (Ramesh et al., 2017). Kenaf fibre-reinforced composites, containing 15% – 20% kenaf, may be used in cell phone shells (Aji, 2008). According to a 2018 report by Grand View Research, the global natural fibre composites market is expected to reach USD 10.89 billion by 2024. The automotive segment is expected to remain the largest application by both value and volume. The main driving forces for the increasing use of PFRCs are government mandates for better fuel economy and end-of-life vehicles directives.

2.1.3 Paper

The first identified hemp-based paper dates back to the early Western Han Dynasty, which was around 200-150 BC. Both the bast and core (woody tissue) fibres from hemp and kenaf plants can be used to produce a wide range of paper and cardboard products (Mansor et al., 2015). Fibre paper is thin, tough, brittle, and rough. Paper made from kenaf bast fibre is reported to compare favourably to papers made from some softwoods and certainly to papers made from most hardwoods (Ververis et al., 2004), and is suitable for writing, printing, wrapping, and for packaging material (Saikia et al., 1997). Paper made from the core fibre or woody tissue (hurd) is not as strong, but is easier to make, softer, thicker and more adsorbent, and is suitable for uses such as wipes, tissues and hygiene products (Zaveri, 2004). Core fibres may be used to complement the higher mechanical strength of the bast fibres i.e. the whole stem could produce a pulp of good quality and strength. This pulp can also be mixed with conventional softwood pulps to produce a wide range of paper grades. When the whole stem is used, the pulping process is simple and costs are saved due to the absence of supplementary separation processes (Han et al., 1995; Kaldor et al., 1990).

Paper made from hemp and kenaf is reported to have several advantages over conventional paper. It is longer-lasting, whiter, stronger, resistant to staining, and has better ink adherence compared to conventional tree paper (Han et al., 1995; Kaldor et al., 1990). Consequently, it does not yellow, crack, or deteriorate like tree paper. Furthermore, the chemicals involved in making hemp paper are much less poisonous than the chemicals used in making wood pulp paper, and the paper can be recycled 7-8 times, compared to three times for wood pulp paper.

Despite these advantages, bast fibre plants have never been used for commercial high-volume paper production, with the pulp and paper industry being currently based predominantly on wood fibre. This appears to be due to a number of economic and structural issues which render the use of fibre from bast plants for mass applications, such as printing, writing and packaging, unviable (Fertig, 1996; Vantrese, 1998). Only 23 paper mills in the world are reported to use hemp fibre, located in the USA, UK, France, Spain, Eastern Europe and Turkey. These paper mills use hemp fibres to produce high-quality specialty papers including cigarette paper, bank notes, technical filters, hygiene products, art paper, and tea bags. In contrast to mass paper production, these products are believed to offer a highly stable, highly-priced niche market in Europe, where industrial hemp has an 87% market share of that sector (Small and Marcus, 2002).

2.1.4 Construction products

Construction materials based on hemp and kenaf range from insulating panels and nonwoven felts for acoustic damping or levelling from woody tissue/hurds, to fibre reinforced polymers for façade panels, oil-based varnishes and paint (leaves), and concrete products (Karus and Vogt, 2004).

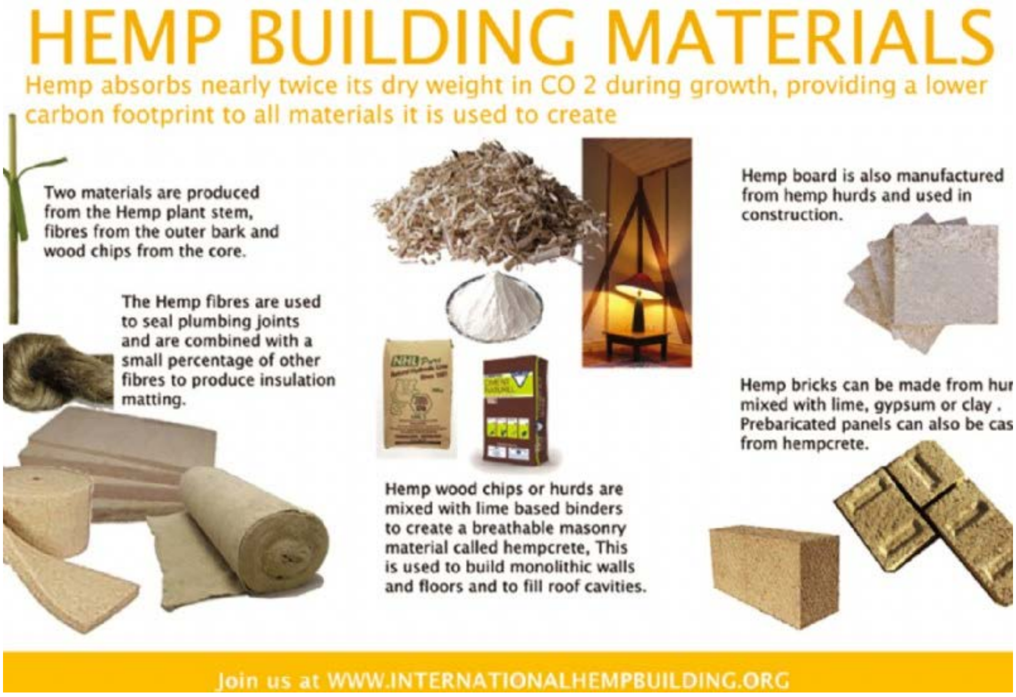

Figure 6: Hemp building materials (https://www.circulairfriesland.frl/agenda/lancering-basishandboek-bouwen-met-kalkhennep/2)

Fibre-reinforced concrete (FRC) is produced by mixing hydraulic cement, aggregates, water, and reinforcing fibres. Steel, glass and plastic fibres have been used to reinforce concrete for decades to reduce shrinkage and cracking.

The most commonly applied hemp product in the building and construction sector is hempcrete, also known as hemplime or hemp concrete (Chabannes et al., 2015; Arrigoni et al., 2017). Hempcrete is a biocomposite material made from a mixture of hemp hurds (shives) and lime. It is easy to work and provides a lightweight cementitious insulating material weighing about a seventh or an eighth of the weight of concrete. Using hempcrete in buildings is reported to create healthy (chemical-free and damp-free) indoor environments, and it is a "better-than-zero-carbon material", locking away more atmospheric carbon for the lifetime of the building than was emitted during its construction. However, hempcrete's density is only about 15% of that of traditional concrete and hence it must be used together with a frame of another material in load-bearing applications. In new houses, hempcrete is usually used to form walls in combination with a timber structural frame. It can also be used to create an insulating floor slab or roof insulation, allowing the entire thermal envelope of the building to be formed from hempcrete. Ronchetti (2007) summarises the main applications of hempcrete in the current building environment as: insulating wall infill, roof insulation, insulating wall plaster (internal/external), ground/intermediate floor insulating slab and insulating floor screed.

Figure 7: Hempcrete house https://ecopolproject.blogspot.com/2014/06/hempcrete.html)

2.1.5 Animal bedding/poultry litter/industrial adsorbent

The shives (woody tissue or, in the case of hemp, hurds) from bast fibres are highly adsorbent, do not produce dust and are easily composted. They are thus highly suitable as animal bedding, as absorbent for oil and waste spill clean-up, and for soilless potting mixes (Kozlowski et al., 2005; Lips et al. 2009). Small and Marcus (2002) attest that because hemp hurd is costly to produce (and animal bedding is a higher value use than industrial absorbent products), it is likely that animal bedding will remain the most important application of this product. An estimated 29 000 tonnes of hemp shives produced by members of the European Industrial Hemp Association were used to make animal bedding in 2002 (EIHA, 2003).

2.1.6 Seed and seed oils

Both hemp and kenaf seeds can be either used as a whole, or crushed and pressed to produce oil and a residual seed cake. Seed yield depends on the type of seed and climate. Yield of hemp seed varies from 0.6 to 2.4 tonnes per hectare, depending on the variety of legal industrial hemp seed, and is at least 5-7 times less productive for seed production than Cannabis Indica/Cannabis Sativa. Hemp grown for fibre generally produces lower yields of seed.

These seeds are rich in protein, fibre and healthy fatty acids, including omega-3s and omega-6s. Apart from nutritional benefits, hemp seeds also have a wide range of positive health effects. More specifically, they have been found to have antioxidant effects and may reduce symptoms of numerous ailments, improving the health of the heart, skin, and joints. Typically, the oil (known as hemp oil) produced from hemp seed is used to produce consumables like salad oil/dressing or grooming products such as soap, shampoo and cosmetics, but it may also be used to produce industrial products such as lubricants and paints (Salentijn et al., 2015). Hemp-based cosmetics and personal care products account for about one-half of the world market for hemp oil (de Guszman, 2001). Of the approximate one billion US dollars in gross sales that is reported annually by The Body Shop, about 4% of sales in 2000 were hemp products. On average, hemp seed contains around 30% oil by weight. The oil is typically green-coloured and is not psychoactive (Gibson, 2006). The residual material or seed cake is protein-rich as well as oil-poor and has been proven to be a good source of nutrition for animals (Salentijn et al., 2015). This seed meal does not contain THC (tetrahydrocannabinol), which is present in the leaves and flowering heads of industrial hemp plants. EIHA (2003) estimated that seed meal from 5 000 tonnes of hemp seed produced by members of the European Industrial Hemp Association was used in 2002 for animal feed. In 2011, the U.S. imported $11.5 million worth of hemp products, mostly driven by growth in the demand for hemp seed and hemp oil for use as ingredients in foods such as granola.

As in the case of hemp oil, kenaf seed oil (KSO) is approximately 20% of the total seed weight. It is mostly made up of polyunsaturated fatty acids and shows superior antioxidant behaviour compared to most traditional edible oils (Chan and Ismail, 2009).

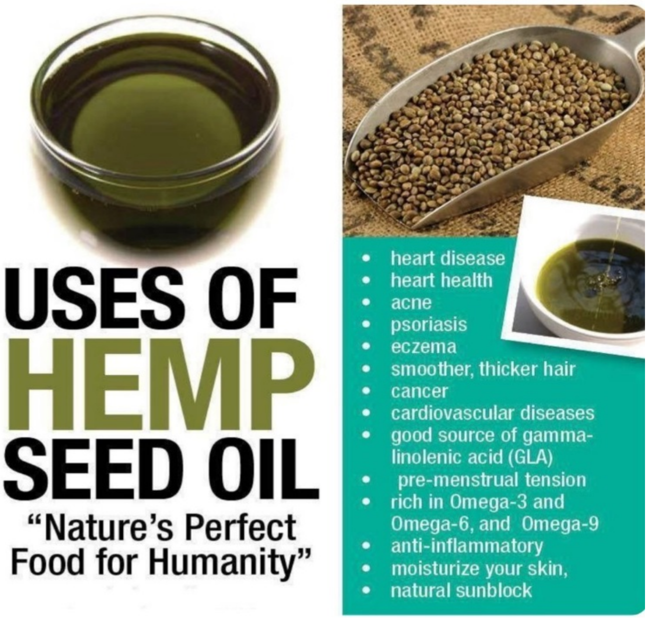

Figure 8: Uses of hemp seed oil (https://www.circlearanch.farm/products/100-pure-organic-cold-pressed-hemp-seed-oil)

2.1.7 Cannabidiol oil

Though hemp and kenaf are both bast fibre plants, kenaf is a hibiscus (*Hibiscus cannabinus L*.) whereas hemp is a cannabis plant (*Cannabis sativa*), and typically cannabidiols are produced from cannabis plants. Cannabidiol (CBD) is a phytocannabinoid which was discovered in the 1940s and is one of the many identified cannabinoids in cannabis plants (Adams and Hunt, 1940). CBD is made from the flowers or leaves of hemp and its uses are strictly medicinal. CDB is non-intoxicating and has a low concentration of tetrahydrocannabinol (THC), which is the psychoactive compound in cannabis species.

Cannabidiol is often sold as CBD oil and is often greenish or golden to dark brown in colour, but the oil can vary in viscosity depending on the extraction method used and concentration. CDB oil has been identified for its medicinal benefits relating to anxiety, inflammation, cognition, motor control, pain perception, nausea and appetite (Burstein, 2015; Pisanti et al., 2017). However, there has been a lot of controversy around CBD oil from hemp and the threshold THC concentration. Hemp that is grown specifically for CBD oils is required to be produced from certified seeds that are guaranteed to produce less than 0.3% THC in Europe and the US (Elsohly and Slade, 2005). In the United States, cannabidiol medicines for the treatment of epilepsy disorders were only approved by the Food and Drug Administration in 2018, however, CBD is still listed as a controlled substance (FDA, 2018).

Cannabidiol is extracted from hemp flowers either through the use of solvents or through supercritical/subcritical carbon dioxide processes (Attard et al., 2018). Extraction with supercritical CO2 has been noted to produce higher cannabinoid concentrations (Rovetto and Aieta, 2017).

2.2 Bast Fibre Processing

The separation of the fibrous and non-fibrous parts typically occurs in a number of stages, as shown in Figure 9. Firstly, harvesting is carried out to separate the stem or stalk from the leaves, seeds and roots. Thereafter the stems are pre-treated to soften the epidermis or bark (usually through a process known as retting) followed by a sequence of mechanical processes (collectively termed decortication) to separate the fibre from the woody tissue. Finally, the separated parts of the plant (leaves, seeds, long fibres, short fibres and woody tissue) are converted into products and by-products.

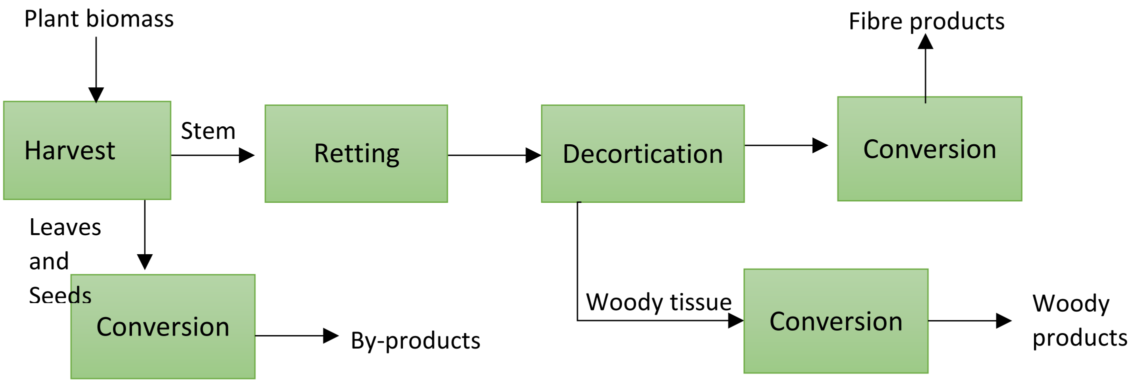

Figure 9: The main stages of bast fibre separation and processing (Sponner et al., 2005; Amaducci and Gusovius, 2010; Papadopoulou et al., 2015)

The production processes of fibre for textile and technical applications are more or less the same for bast fibre crops – an expanded flow sheet is summarised in Appendix II showing the different routes. There are, however, slight differences in the specific machinery used for the various bast fibre plants due to differences in the thickness of stalks and stem structures (Sponner et al., 2005). The different stages of the processing system are discussed in Sections 2.2.1 to 2.2.4.

2.2.1 Harvesting

Harvesting of bast fibres is a labour-intensive process and manual harvesting is still common in developing countries and in areas where production is not on an industrial scale (Amaducci and Gusovius, 2010; Pari et al., 2015). Mechanical harvesting is common for hemp and kenaf using crop cutting machinery, sometimes referred to as crop cutters, as shown in Figure 10 (Pari et al., 2015).

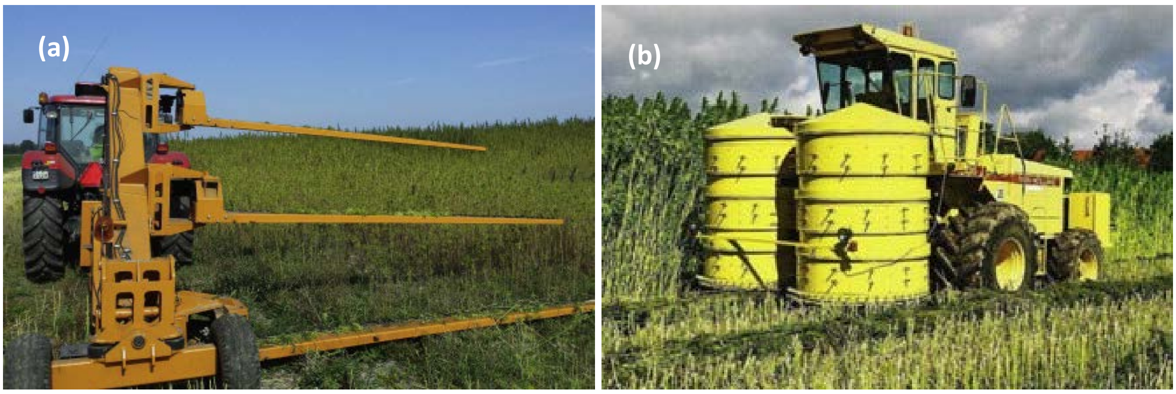

Figure 10: Examples of crop cutters used in harvesting bast fibres (Pari et al., 2015)

Small scale farmers still harvest manually by cutting the plants at 2 cm - 3 cm above the soil (Chen and Liu, 2010). The selection of cutters or mowers used for harvesting is dependent on the intended end-product. A cutter such as the one shown in Figure 10 (a) allows the stems to be cut in the same direction, which is important for maintaining length for textile applications. However, the cutter shown in Figure 10 (b) results in straws falling in different directions (Amaducci and Gusovius, 2010; Horne, 2012; Pari et al., 2015). The seeds and leaves are often recovered in this stage, using combine harvesters which simultaneously mow off the top of the plants and cut the stem (Pari et al., 2015).

2.2.2 Retting

During pre-treatment the epidermis is softened to allow fibre bundles to loosen. This is done through a process traditionally known as retting or degumming.

There are several pre-treatment or retting methods that can be applied, as shown in Figure 11. Water retting and dew retting are the commercial methods traditionally used, during which microbial activity causes a partial breaking down of the components binding the tissues together, separating the cellulosic fibres from non-fibre tissues (Sponner et al., 2005). Even though the fibres produced from water retting can be of high quality, the long duration and polluted water by-product have made this method less attractive. Various other alternative methods have been reported for this purpose with mixed results. These alternatives include enzymatic treatments, chemical treatments, physical treatment entailing high temperature and/or pressure, and mechanical treatments (shown in Figure 11).

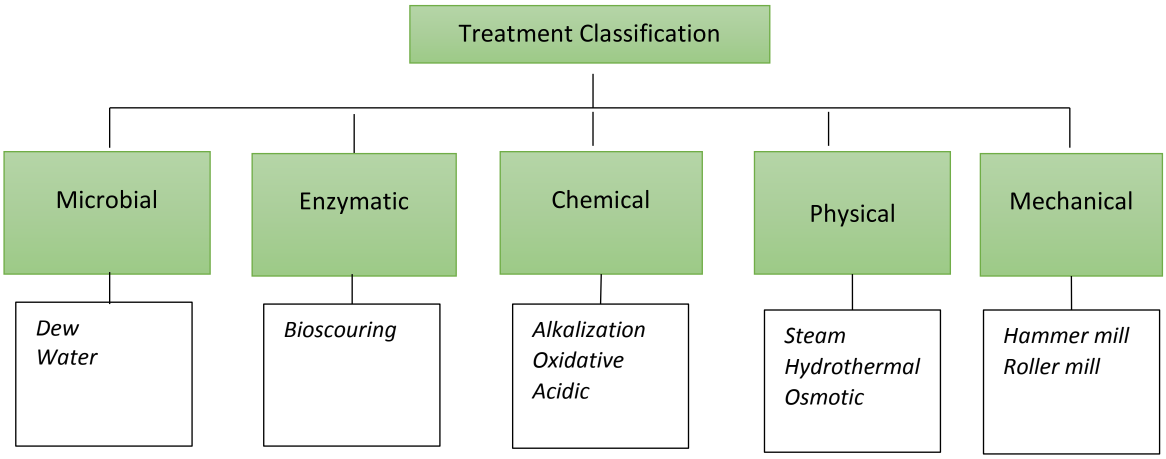

Figure 11: Classification of retting techniques (Paridah et al., 2011; Sisti et al., 2018)

The various methods of pre-treatment or retting tend to produce fibres of varying properties which has an effect on the efficiency of the downstream decortication process and the quality of the final products (Sisti et al., 2018). Whilst enzymatic processes show potential, it is likely that a combination of retting processes will be required to deliver products with optimum quality. A summary of the various retting methods and the key strengths and weaknesses is provided in Table 2. The various retting methods are discussed in further detail below.

Dew retting

Dew retting, also known as field retting (see Figure 12), is the oldest method of retting and was used by the Egyptians for millennia (Van Sumere, 1992). The stalks are left out in the field for 2-10 weeks to allow microorganisms, mainly filamentous fungi or aerobic bacteria present in soil and on plants, to act on the gum and pectic substances in the bast (Sponner et al., 2005; Ribeiro et al., 2015; Sisti et al., 2018). During the field retting process the straw is often turned 2 to 3 times to allow the process to occur uniformly on the stalks. Changing environmental conditions often make it hard to control the process and fibre produced from field retting is often a darker colour (Gebai et al., 2018). Dew retting is increasingly being conducted in controlled environments, with the control of parameters such as the type of microbes, temperature, and period of treatment (Pickering et al., 2007; Bleuze et al., 2018). Dew retting is less cost-intensive than water retting, and is still commonly used in regions of low water supply (Paridah et al., 2011; Sisti et al., 2018). However, dew retting often yields low and inconsistent fibre quality compared to other methods (Jankauskienė et al., 2015; Liu et al., 2015).

Figure 12: Dew retting of bast fibres in a field (Gebai et al., 2018)

Table 2: A Comparison of bast fibre retting methods

Retting process	Description	Key parameters				Advantages	Disadvantages
		Duration	Temp (°C)	Pressure (kPa)	pH		
Dew	Plants left out on the field for microbial retting	2-10 weeks[1,3]	ambient	ambient	~7	• Low-cost[3,9] • Efficient water usage[5,15]	• Inconsistent fibre quality produced[9] • Dependent on climatic conditions[9]
Water	Plants immersed in water tanks or moving streams	7-14 days [5,15]	15 – 30°C[1]	ambient	~7	• High quality fibre[3,9] • Uniform fibre produced[9]	• Large volume of water needed[5,9] • Extensive water treatment maintenance required[5,9]
Enzymatic	Modified water retting, enzymes directly added to a water tank	8-24 hours[2]	~32°C[5]	ambient	6[5]	• More control over fibre properties[4]	• Conditions highly sensitive to enzyme type[2]
Chemical	Treatment with chemicals such as sodium hydroxide	1-2 hours[12]	variable	ambient	9 >[5]	• Flexible and long fibres produced [3,14] • Short time [3,15,14]	• Fibres can easily discolour and deteriorate[3,14]
Mechanical	Fibres separated by hammer mill or roller mill	unknown	ambient	ambient		• High throughput[8]	• Higher energy cost[8] • Fibres are easily damaged in milling[6,8]
Physical	Steam explosion - saturated steam used	unknown	~200°C[12]	~1600kPa[12]		• Fast process[11] • Can be used with chemical retting[11]	• Can produce too many short fibres[15]
	Hydrothermal – water diffused in plant to crack stem lengthwise	unknown	170–200°C [11]	100–160kPa [11]		• Can be used as pre-treatment for enzymatic retting[10]	• High water requirement [11,15]

Sources: [1]Sponner et al., 2005; [2]Ouajai and Shanks, 2005; [3]Amaducci and Gusovius, 2010; [4]Foulk et al., 2011; [5]Paridah et al., 2011; [6]Hänninen et al., 2012; [7]Amel et al., 2013; [8]Deyholos and Potter, 2014; [9]Jankauskienė et al., 2015; [10]Liu et al., 2015; [11]Liu et al., 2016; [12]Liu et al., 2017; [14]Ramesh et al., 2015; [15]Sisti et al., 2018.

Water retting

This involves leaving the stalks in tanks or ponds of water for about 7–14 days to be acted upon by microorganisms at temperatures of about 25 to 30 °C, similarly to dew retting (Sponner et al., 2005; Paridah et al., 2011; Sisti et al., 2018). Alternatively, instead of tanks or ponds the stalks can be immersed in slow moving streams at temperatures of around 15 to 20°C for a longer time (see Figure 13).

Figure 13: Water retting methods: (a) Pond water retting (b) Stream water retting (Sisti et al., 2018)

The duration of the treatment often depends on the water type, temperature and the type of microbes present (Donaghy et al., 1990; Paridah et al., 2011). Elevated temperatures (between 30 °C to 40 °C) can reduce the time required to complete the degumming of the stalk to less than 7 days (Sponner et al., 2005; Horne, 2012). Water retting gives a more uniform quality product, which yields a higher-quality fibre than dew retting (Amaducci and Gusovius, 2010; Jankauskienė et al., 2015). However, water availability and waste water treatment need to be considered as water retting requires significantly more water than dew retting and the nutrients from the decaying stalks remain in the water (Zhang et al., 2008; Paridah et al., 2011; Jankauskienė et al., 2015). Efforts have been made to make this treatment less reliant on the availability of water resources. For example, sea water has been found to work as well as fresh water on retting hemp, but waste water management remains a challenge (Zhang et al., 2008; Van der Werf et al., 2008; Liu et al., 2017).

Enzymatic retting

Enzymatic retting, also known as bioscouring, is a modification of water retting in which enzymes are directly added to a water tank or in a bioreactor to free the fibres from other tissues (Sisti et al., 2018). The process takes 8-24 hours, but time can vary depending on pH, temperature, and enzyme type and concentration (Ouajai and Shanks, 2005; Paridah et al., 2011; Ramesh et al., 2015). Pectinases or pectinolytic enzymes, which are commercially produced from fungi, are mostly used in enzymatic retting (Jayani et al., 2005). One of the main advantages of enzymatic retting is that it is able to produce consistent high-quality fibres with variable fineness, which is beneficial for use in resins (Foulk et al., 2008; Foulk et al., 2011). Varying parameters such as the type of enzyme and composition of the enzyme mixture can be used to tailor make fibres/fibre bundles with specific properties, such as strength and fineness, for specific applications (Foulk et al., 2008; Fischer and Müssig, 2010; Foulk et al., 2011). Research on enzyme retting of bast plants is increasing and it has been shown that different enzymes and retting protocols are required for different fibre crops.

Chemical retting

Numerous chemical treatments can be performed on bast fibres depending on their type, the ensuing fibre recovery process and the final applications of the fibres. The dried plants are immersed in a tank with a solution of chemicals such as sodium hydroxide, sodium carbonate, high pH agents or mineral acids (Sisti et al., 2018). The fibres are loosened in a few hours, but close control is required to prevent deterioration and damage to the fibres. The commonly used chemical treatment is alkalisation, usually carried out with a sodium hydroxide solution ranging from 1% – 25% concentration (Parikh et al., 2002; Amel et al., 2013; Ramesh et al., 2015). Alkalisation produces stronger, more flexible and less brittle fibres than other chemical treatments, but the base concentration influences the fibre morphology and discolouration (Mwaikambo and Ansell, 2002; Amel et al., 2013; Ramesh et al., 2015). Low alkali concentrations have been shown to prevent the degradation of fibres (Ramesh et al., 2015). Treatment of bast fibres with acidic solutions (such as sulphuric acid or hydrochloric acid) is less popular due to the rapid degradation of the fibres (Shi et al., 2011).

Physical treatment methods

These methods involve varying parameters such as pressure and temperature, and include steam explosion, hydrothermal methods and osmotic degumming. Steam explosion involves the use of saturated steam at about 200^{o}C; the high temperature softens the material and the high pressure results in fibre separation (Thomsen et al., 2006). Steam explosion is a fast and well-controlled process that has been adapted for the processing of various fibres and is often applied in conjunction with other retting processes such as chemical retting (Thomsen et al., 2006; Zhang et al., 2008). It can be carried out downstream, after alkali treatments, to increase the efficiency of separation of the fibres (Thomsen et al., 2006; Liu et al., 2017). Steam explosion has also been widely used before enzymatic retting to improve enzyme catalysis (Jacquet et al., 2015).

Hydrothermal methods, on the other hand, involve using water at elevated temperatures (170–200 °C) and pressures (100–160 kPa) (Thomsen et al., 2006; Liu et al., 2016). This method is also often applied in combination with other retting processes, and has been noted to improve enzymatic retting in hemp without damaging fibre mechanical properties (Liu et al., 2016).

Osmotic degumming uses the diffusive penetration of water inside the stem, resulting in the epidermis cracking lengthwise without breaking or shortening the fibres (Konczewicz and Wojtysiak, 2015). This method has mostly been applied to flax, but due to the similarity in bast fibre structures, the process could be applied to other bast fibres by changing parameters such as temperature, flow velocity, and process duration (Konczewicz and Wojtysiak, 2015).

Mechanical treatment

In this process the stalks are either crushed between rollers or hammer mills (see Figure 14). This somewhat differs from the traditional definition of retting and is rather best defined as mechanical separation or mechanical treatment (Münder et al., 2004; Deyholos and Potter, 2014). Hammer milling can be conducted in a single drum or in multiple concurrent rotating drums: the stalks are crushed and then screened for the next stages of processing (Deyholos and Potter, 2014). In roller mills, the stalks are cracked between long cylindrical rollers with minimal damage to the fibres, producing uniform long fibres. Mechanical treatment tends to disrupt fibre cell wall structures, negatively affecting tensile mechanical properties (Münder et al., 2004; Hänninen et al., 2012; Sisti et al., 2018). The choice of the type of mill for mechanical separation depends on the type of fibre, final application and ensuing treatments. For example, hammer milling has a higher throughput capability (about 5–15 t/h straw input), but produces finer fibre than roller milling, whereas roller milling gives much greater length control, producing consistent long fibres while preserving the integrity of the fibres, but has a much lower throughput than hammer milling (Paridah et al., 2011; Hänninen et al., 2012; Deyholos and Potter, 2014; Sisti et al., 2018). Milling is also often used in conjunction with traditional retting processes, often after dew or water retting, especially to produce finer fibres for technical applications (Deyholos and Potter, 2014; Liu et al., 2017).

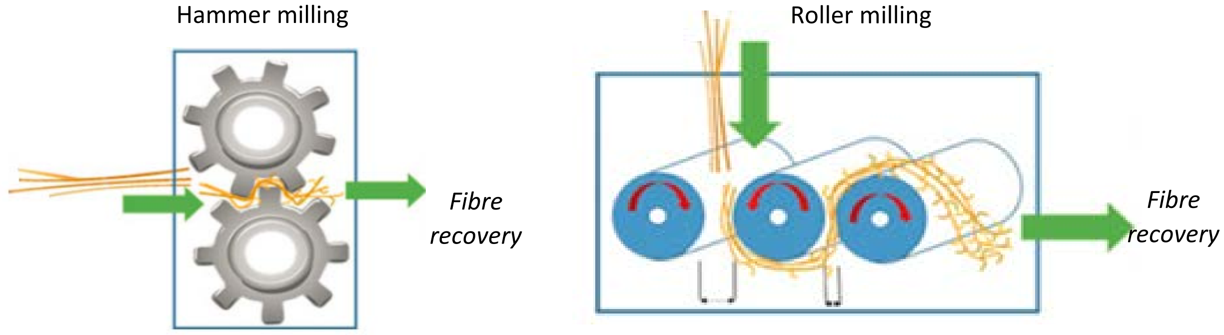

Figure 14: Mills used in the mechanical separation of bast fibres (Sisti et al., 2018)

2.2.3 Decortication

After pre-treatment the softened stalks are dried and then fed into a sequence of mechanical processes to separate the fibre from the woody tissue, a process known as decortication (Sponner et al., 2005; Amaducci and Gusovius, 2010). Traditional decortication consists of breaking, scutching and hackling (shown in Figure 15), from which the main products are long fibres, short fibres and woody tissue (or shives) which are further converted into finished products (Sponner et al., 2005; Chen and Liu, 2010; Horne, 2012; Deyholos and Potter, 2014). Waste products such as entrapped leaves, seeds and dust are also recovered as part of this process (Amaducci and Gusovius, 2010; Horne, 2012).

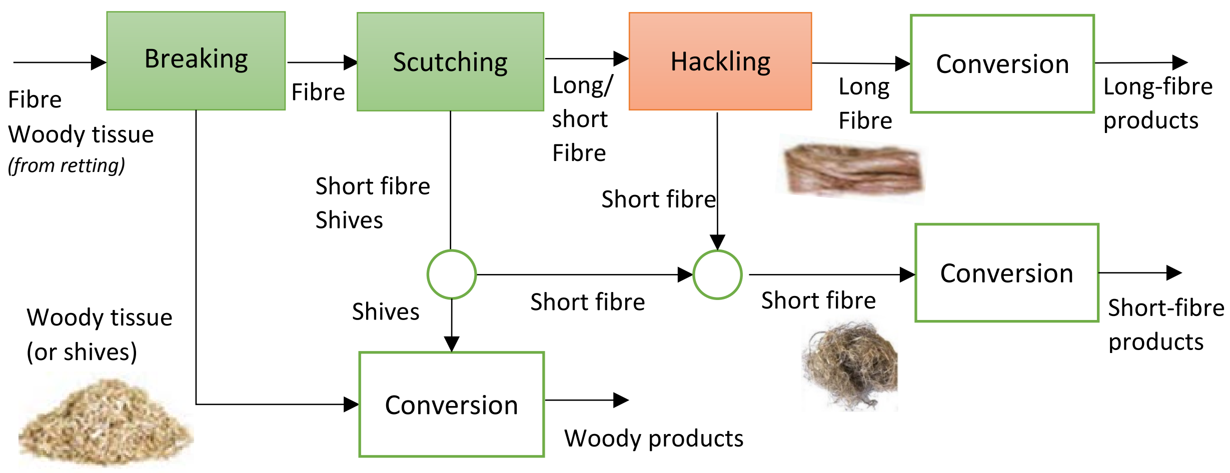

Figure 15: Bast fibre recovery process (Sponner et al., 2005; Amaducci and Gusovius, 2010; Chen and Liu, 2010; Horne, 2012)

The conventional process (shown in Figure 15) is more suited for the purpose of producing long fibres for conventional textile applications as the process keeps long fibres in the same direction (Amaducci and Gusovius, 2010; Horne, 2012; Deyholos and Potter, 2014).

The decortication process for the production of fibre for technical applications such as biocomposites or geotextiles is slightly different (see Figure 16). After the breaking step, the fibre is milled to produce finer material, then scutched, but the process often excludes the hackling step (Amaducci and Gusovius, 2010; Deyholos and Potter, 2014).

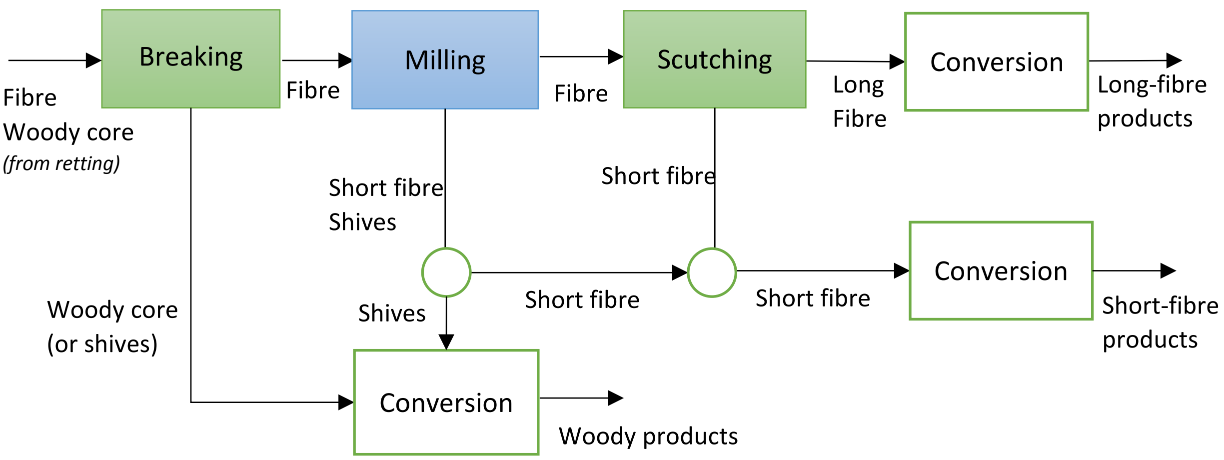

Figure 16: Bast fibre recovery process for technical applications (Amaducci and Gusovius, 2010; Horne, 2012; Deyholos and Potter, 2014)

The process in Figure 16 produces medium-sized long fibres and finer fibres compared to the process in Figure 15 (Horne, 2012; Deyholos and Potter, 2014). Finer fibres are often required more for technical applications such as biocomposites and bio-plastics (Amaducci and Gusovius, 2010; Deyholos and Potter, 2014). In both processes however, dust control is a huge concern. The dust is usually extracted by drum and baghouse filters and the collected dust may be compacted for other uses (Amaducci and Gusovius, 2010). The main steps involved in both processes are discussed in the following sub-sections.

Breaking

After pre-treatment, the dried stalks are placed on a conveyor which feeds them through several pairs of horizontal parallel rollers (Amaducci and Gusovius, 2010; Horne, 2012). The first breaking operation consists of splitting the stalks down their lengths by the action of pairs of smooth and ribbed (see Figure 17) rollers (Sponner et al., 2005; Amaducci and Gusovius, 2010). The pressure splits the stalks and in the second breaking operation, the ribbed rollers progressively breakdown the woody tissue into smaller pieces. Most of the woody tissue separates from the fibre and falls through the rollers and is screened out (Deyholos and Potter, 2014). Any leaves and seeds trapped amongst the stalks during harvesting also fall through the rollers and are screened out in this stage (Amaducci and Gusovius, 2010).

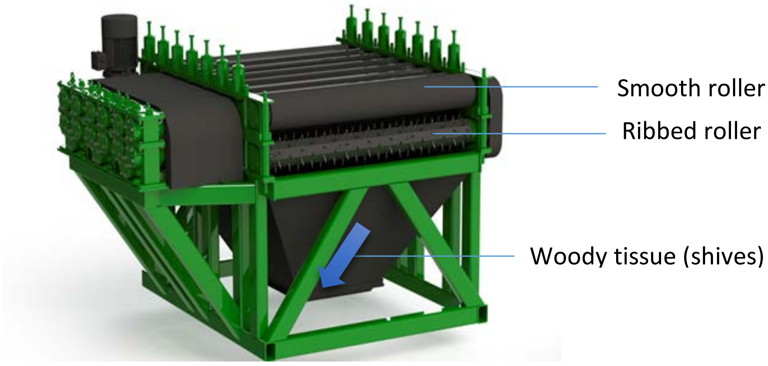

Figure 17: Example of breaking machine used in the decortication process

The effectiveness of the breaking process depends on the quality of the feed stalks. It is possible to break un-retted stalks, especially for the production of fibre for technical applications. However, breaking is more effective on uniformly retted stalks as the proportion of woody tissue is low and fibre content can exceed 50% (Sponner et al., 2005; Amaducci and Gusovius, 2010).

Milling

Milling can be performed by hammer mills or roller mills (similarly described under "mechanical treatment" in Section 2.2.2). Hammer mills are the preferred mills for the production of fibre for technical applications due to their higher output of finer fibre and higher throughput compared to roller mills (Paridah et al., 2011; Hänninen et al., 2012; Deyholos and Potter, 2014; Sisti et al., 2018). However, a combination of mill drums can be used in sequence in advanced decortication to produce very fine fibres (Münder et al., 2004; Deyholos and Potter, 2014). Advanced decortication can also be applied to un-retted stalks, but the fibre produced is often much shorter and very fine, and often results in damage to fibre cell walls (Hänninen et al., 2012; Amel et al., 2013).

Scutching

The main purpose of scutching is to separate the long (also known as 'line') fibre and short (also known as 'scutched tow') fibre, as well as to remove any remaining woody tissue or shives and any waste matter, such as dust and small particles (Chen and Liu, 2010). In scutching the fibre bundles are passed through revolving turbines (see Figure 18) with projecting bars that beat the fibre bundles, separating the long and short fibres and remaining shives (Sisti et al., 2018).

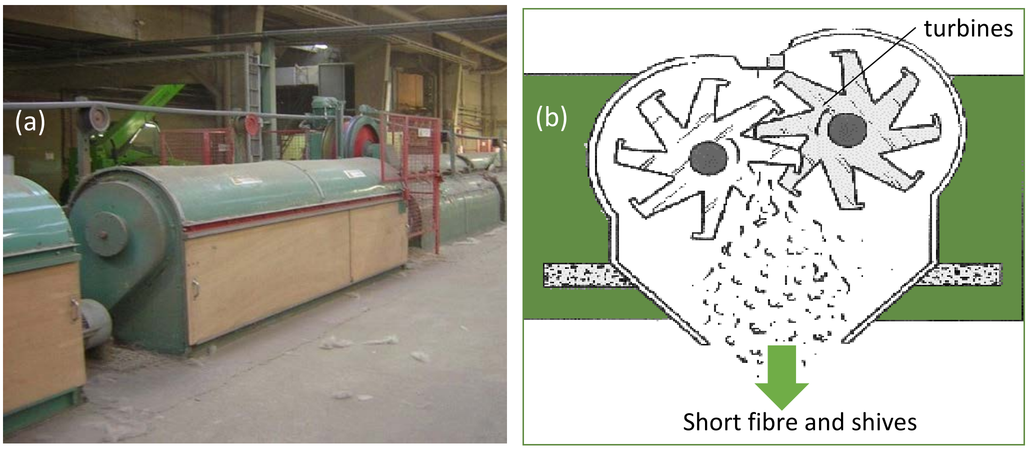

Figure 18: Scutching turbines and (b) cross section of scutching turbine (Sponner et al., 2005)

The effectiveness of scutching is dependent on the speed of rotation of the blades and the rate at which the stalks proceed through the two pairs of turbines (Sponner et al., 2005; Amaducci and Gusovius, 2010). The separation ratio of the long to short fibre is also more efficient for uniformly retted stalks; under-retting results in low separation during scutching and over-retting results in excessive fibre breaking, resulting in a higher proportion of short fibres (Amaducci and Gusovius, 2010).

Hackling

The main purpose of hackling is to complete the separation of the long and short fibres (Horne, 2012). Hackling is a combing action that removes smaller contaminants, aligns the long fibres and separates the bundles without destroying length. During hackling the fibres are separated over a series of combs of increasing fineness to clean the long fibres and separate the remaining short fibres (Deyholos and Potter, 2014). The fibre is placed in a clamp that moves the fibre between a hackling frame with opposing sets of pins and a series of brushes which "comb" the fibre bundles (see Figure 19) to detangle the long fibres, clean them and arrange them in the same direction (Sponner et al., 2005).

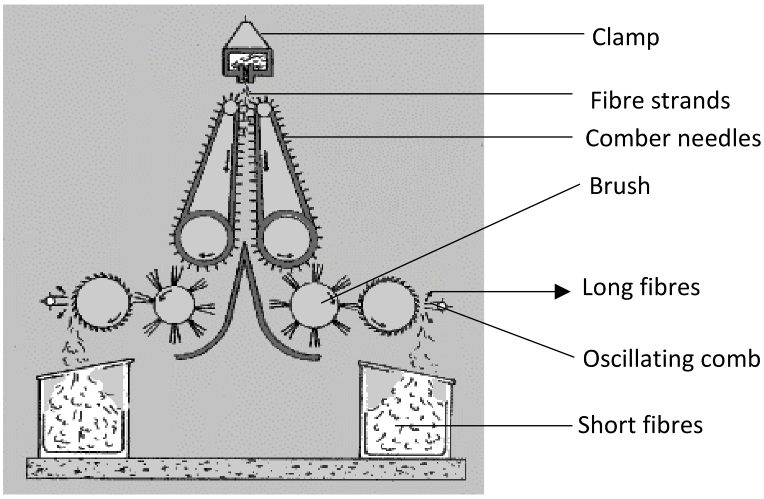

Figure 19: Example of hackling frame used to separate fibre bundles (Sponner et al., 2005)

The remaining short fibres not removed during scutching are collected, along with short fibres produced due to the breakage of some of the long fibres during hackling (Sponner et al., 2005; Horne, 2012). The long fibres that have been processed through hackling frames are assembled in slivers which can be stored and further processed/converted to finished products (Horne, 2012). During this process some remaining hurds and other impurities (such as dust and debris) are also removed (Amaducci and Gusovius, 2010).

2.2.4 Product conversion

Product conversion operations will vary for each product type. The processes for the conversion of the fibre and woody tissue into key products are described in the sub-sections below.

Conventional Textiles

Long fibres for use in textiles such as fabrics for clothing and furnishings and cordage go through a spinning process, which is the process of drafting and twisting natural (or man-made) fibres on spinning frames to produce yarn, also known as filaments. In the bast fibre industry, spinning can either be 'wet spinning' or 'dry spinning' (Sponner et al., 2005; Summerscales et al., 2010). The spinning process may however be problematic due to the thickness, stiffness and lack of uniformity of the fibre. The difficulties associated with spinning hemp into yarn are associated with the high lignin content of hemp. It is possible to reduce the lignin content from 8–10% to 0.2%, resulting in finer and softer fibres suitable for blending with other fibres such as cotton and wool or synthetic fibres. Hemp based yarns are knitted into fabrics that are similar in appearance and touch to linen, and are suitable for soft furnishings and curtains.

In the case of cordage, the short fibres are first prepared for spinning by removing the remaining woody tissue or hurds, untangling the fibres, forming slivers and coiling the material. Spinning is performed on frames similar to those used for the spinning of long fibres, except that the spinning frames are shorter. The resultant spun fibres are then twisted into cordage (Chen and Liu, 2010).

Geotextiles

Geotextiles can be woven, knitted or nonwoven, and varying manufacturing processes result in geotextiles with different properties suitable for different applications. Woven and nonwoven geotextiles are manufactured using techniques similar to the manufacturing of clothing textiles as shown in Figure 20. Woven geotextiles are produced by interlacing or weaving yarns of fibre, whereas nonwoven geotextiles are manufactured by cross lapping the fibres into a web and bonding the fibres together by methods such as needle punching, spun-lacing or thermal bonding (Desai and Kant, 2016).

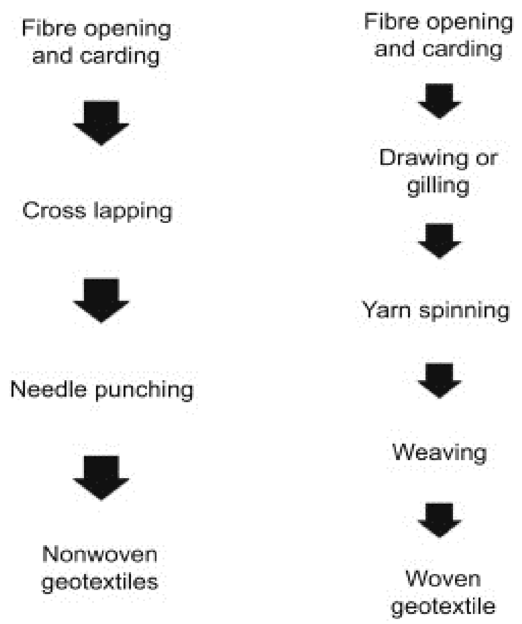

Figure 20: Flow diagram showing the manufacture of woven and nonwoven fibre geotextiles (Desai and Kant, 2016)

Composites

There are numerous methods for fabricating composite components, and although the criteria for the selection of the method may be different for PFRC's, many of the methods have been based on those used in the traditional polymer sector. Essentially composite fabrication entails some form of moulding to shape the resin and reinforcement. Reinforcements for composites can take the form of woven and nonwoven fibres.

The moulding process begins by placing the fibre preform on or in the mould, either as dry fibre or as a fibre/resin mix. Dry fibres are "wetted" with resin or the resin is injected into a closed mould. The mixture is then cured, either under ambient conditions or under conditions of elevated temperature and/or pressure. PFRC's are produced through conventional composite manufacturing processes such as pultrusion, injection moulding, hot press moulding, resin transfer moulding or compression moulding in an autoclave or hot press (Ho et al., 2012; Kabir et al., 2012; Salentijn et al., 2015). The selection of a suitable moulding process will therefore depend on the production rate and characteristics of the raw material (for example the type of polymer used) and, more particularly, the size and shape of the products (Ho et al., 2012). For small- to medium-sized components, injection and compression mouldings are preferred due to their simplicity and fast processing cycle. Larger structures are typically manufactured by open moulding and autoclave processes (Ho et al., 2012). Pultrusion is mainly used for producing long and uniform cross-section parts. Resin transfer moulding (RTM) has become increasingly popular due to its high-volume production and relatively low costs. RTM methods include vacuum assisted resin transfer moulding (VARTM), structural reaction injection moulding (S-RIM), co-injection resin transfer moulding (CIRTM) and other subsets where the basic approach is to separately inject the liquid resin into a bed of stationary preforms (Ho et al, 2012). Ho et al. (2012) provide a more detailed review of methods for the manufacture of PFCRs.

Paper

Paper from kenaf and hemp has been produced successfully with existing paper-making technologies, using either chemical or mechanical pulping processes (Papadopoulou et al., 2015). The commonly used process is based on Kraft technology (see Appendix III). This process is a chemical method for the production of pulp that employs an alkali solution (usually caustic soda and sodium sulphide) as the liquor in which the fibre is cooked in order to loosen the fibres. Kenaf fibres contain considerably less lignin than pine which allows easy and quick pulping via the Kraft process.

Hempcrete

As outlined by Gregor (2014), there are three methods of application of hempcrete currently used: pre-fabricated blocks/panels, spray-on application and infill cast into formwork around structural elements such as timber frames. Although prefabrication and new dry forms of timber frame construction seem very efficient, they are vulnerable to construction failure or heterogeneities in the blocks' series. On the other hand, spraying and mechanical mixing and tamping, which are considered as wet processes, provide a more continuous homogenous mass. Whilst there could be further differences within each method (e.g. order of mixing individual components, density, sizes of hemp wood, etc.) between different manufacturers and researchers, they all have in common the use of hemp, lime and water.

Pre-fabricated blocks are prepared by mixing CaO with water to obtain slaked lime, to which hydraulic lime and hemp shives are added. The mixture is then poured into moulds and blocks are formed by compaction in the moulds under vibration (Figure 21).

Figure 21: Device for pre-casting hempcrete blocks – mixer, forming process (Collet et al., 2013)

Spraying is a wet process and can make construction very fast. In the process proposed by Collet et al. (2013), hemp shives and lime-based binder are mixed together and constitute a dry mix that is blown along a pipe by a flow of compressed air. Water is added to the mix at the end of the pipe, the quantity of which may be controlled by the operator via one valve. An example of spraying hempcrete is shown in Figure 22.

Figure 22: Device for spraying hempcrete (Collet et al., 2013)

Various methods can be used to mix and tamp hempcrete into frameworks. Most commonly water is mixed with lime or hemp shives, usually in a pan mixer (as shown in Figure 23).

Figure 23: Mixing and tamping of hempcrete into a construction frame (Gregor, 2014)

3 Bamboo

Bamboo is a perennial woody grass with a hollow stem that belongs to the grass family. There are 1000–1500 bamboo species (Asia accounts for about 1000 species) within 75–91 genera of bamboo plants. Bamboo plants can be as tall as 30 m and as wide as 25 cm – 30 cm in diameter. Unlike other plants, bamboo develops in full diameter from the ground and continues growing up to maximum height. Traditionally, bamboo has mainly being associated with handicrafts, bamboo shoots, chopsticks and the production of bamboo and rattan furniture. However, the last quarter of a century has seen a mushrooming of the variety of commercially available products, with bamboo now being considered by the Food and Agriculture Organization of the United Nations (FAO) as one of the two most important "Non-Wood Forest Products", a term which encompasses all biological materials other than wood which are extracted from forests for human use (van der Lugt et al., 2009). Globally, bamboo currently has about 1 500 registered uses and is emerging as a major source of raw material for several processed products, primarily due to its fast growth, wide spread occurrence and multiple uses for the different parts of the plant.

This section of the report reviews the potential bamboo products and uses (Section 3.1), as well as the processes and technologies in conversion of bamboo plants into raw, intermediate and final products (Section 3.2).

3.1 Products and Uses

As in the case of bast fibre plants, the whole bamboo plant can be used for biomass to produce energy or biofuels such as bioethanol, biogas and charcoal, or the different parts of the plant can be pre-separated to provide opportunities for the development of multi-product value chains. The main parts of the plant used for multi-product generation include the stem or culm, branches, leaves and shoots (see Figure 24). The branches can be used to generate sticks which can be used to make brooms, chopsticks and other products; the leaves can be used as fodder or as a source of homeopathic medicine; and the shoots as a food. The majority of the multi-product value, however, originates from the culm, which is the source of both fibre and woody tissue situated between the exodermis and endodermis (Figure 24).

a) Main parts of a bamboo plant

b) Main parts of a bamboo culm/stem

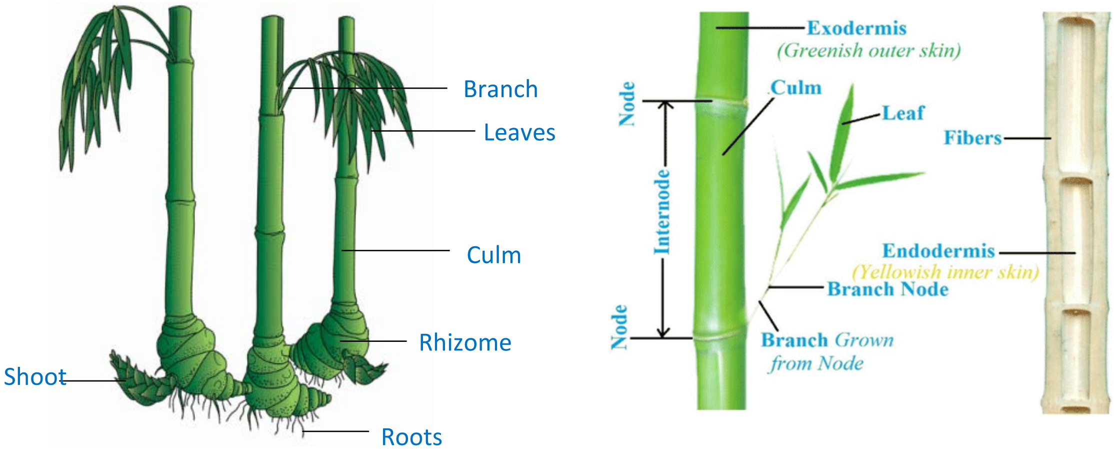

Figure 24: Main parts of a bamboo (a) plant and (b) stem

Each hollow cylindrical portion between two nodes is called an internode. The outer part of the bamboo stem, the exodermis, is comprised of the green portion with dense vascular bundles. The inner part of the stem, the endodermis, is comprised of the yellow portion with rare vascular bundles. The main cellulosic portion lies between the exodermis and endodermis. Bamboo has an average of about 60% cellulose content, with a lignin content of 12% – 30% depending on the different species (Khalil et al., 2012; Yueping et al., 2010). Bamboo fibres are embedded within a lignin matrix in the cellulosic portion between the exodermis and endodermis, as shown in Figure 25. Bamboo fibre vascular bundles are distributed non-uniformly throughout the culm and the bundles often vary within the culm wall, decreasing in density from the exterior to the interior. The size of single bamboo fibres are 10–30 µm in diameter and 1–4 mm in length (Wang et al., 2012).

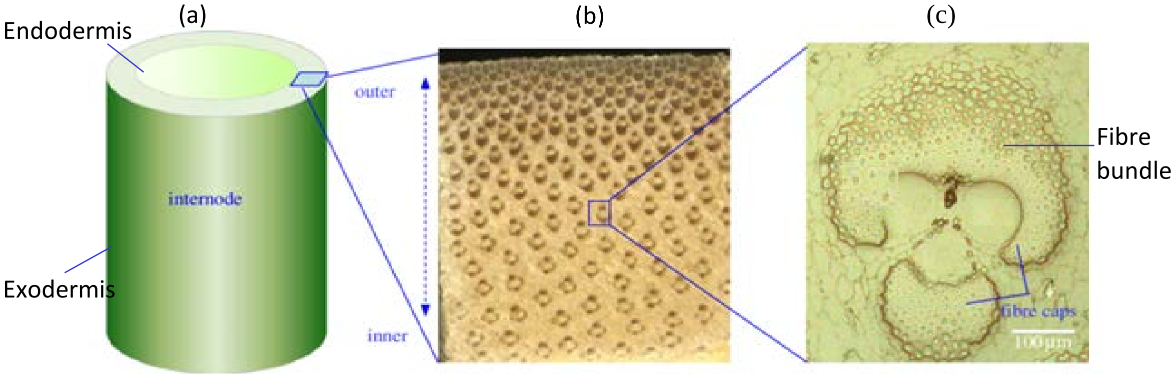

Figure 25: Structure of a bamboo culm (a) bamboo node (b) culm wall cross-section (c) fibre bundles (Wang et al., 2012)

Although bamboo grows faster than softwood, the culm has similar mechanical properties to hardwood. Just like wood, it may be used in its natural state in the form of poles and/or strips for the production of woven products (blinds, baskets and other handicrafts), or converted into a range of semi-finished engineered bamboo wood composites[4] (Figure 26). These raw and semi-finished products can be used as a timber substitute for the production of furniture, flooring and panels in the building and interior decorating sector, as well as in the production of sporting equipment and household and personal goods. Whilst wood-based products have traditionally dominated the bamboo product space, there is growing interest in the development of other bamboo products ranging from industrial uses such as paper, textiles, biochars, and natural fibre reinforced composites. Examples of bamboo products are presented pictorially in Appendix IV. Further information on the key wood-based, fibre-based, paper-based, energy-based products and by-products from the leaves and shoots is provided in Sections 3.1.1 – 3.1.4.

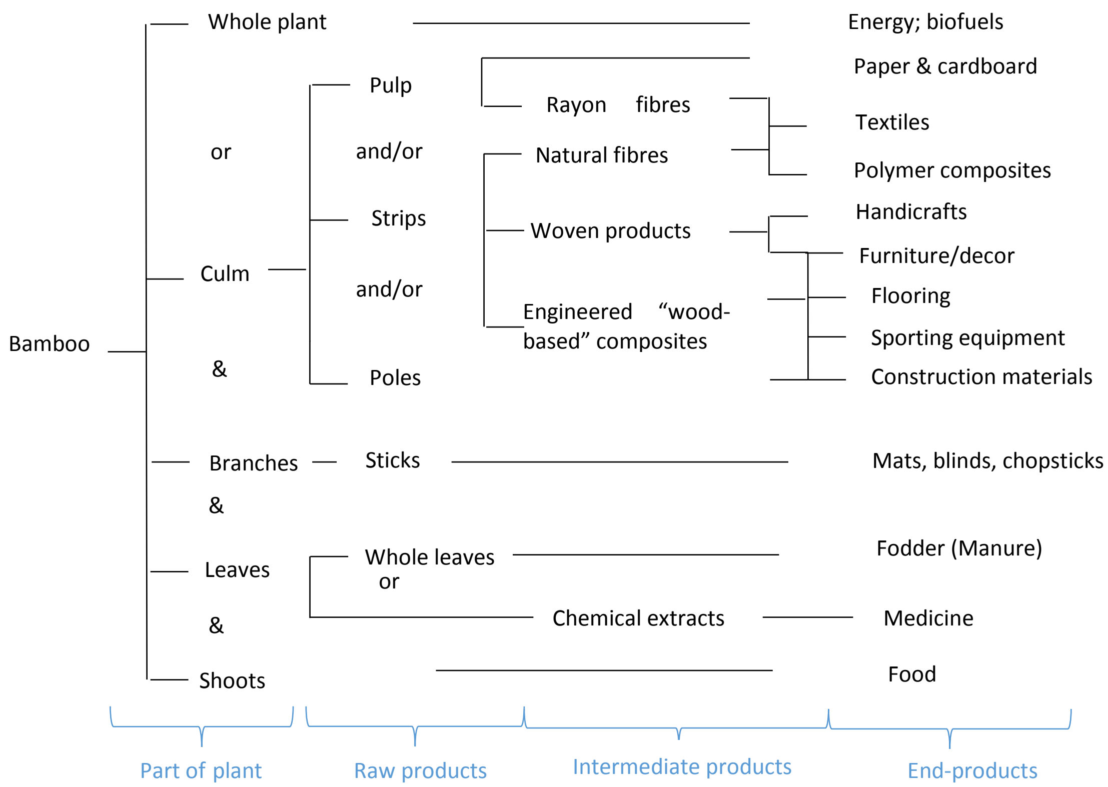

Figure 26: Bamboo multi-product value chains

High-end products such as natural fibre-based products and higher-value bamboo wood-based composites (such as plybamboo and veneers for flooring and furniture) generally require higher quality bamboo and are associated with lower product yields (more waste and off-cuts) than low-end products such as charcoal, poles, bamboo particle board and bulk paper production (Enterprise Opportunities Ltd, 2006). The versatility of bamboo in terms of uses is enhanced by the fact that different parts of the culm can be used for different products corresponding to different value-ranges, whilst the wastes or off-cuts from the production of high-end materials can be used in the manufacture of low-end materials. This versatility is illustrated diagrammatically in Figure 27.

[4] Where engineered bamboo composites are analogous to engineered wood, also called composite wood or manufactured board, terms used to describe a range of derivative wood products which are manufactured by combining wood and adhesives to form composite materials.

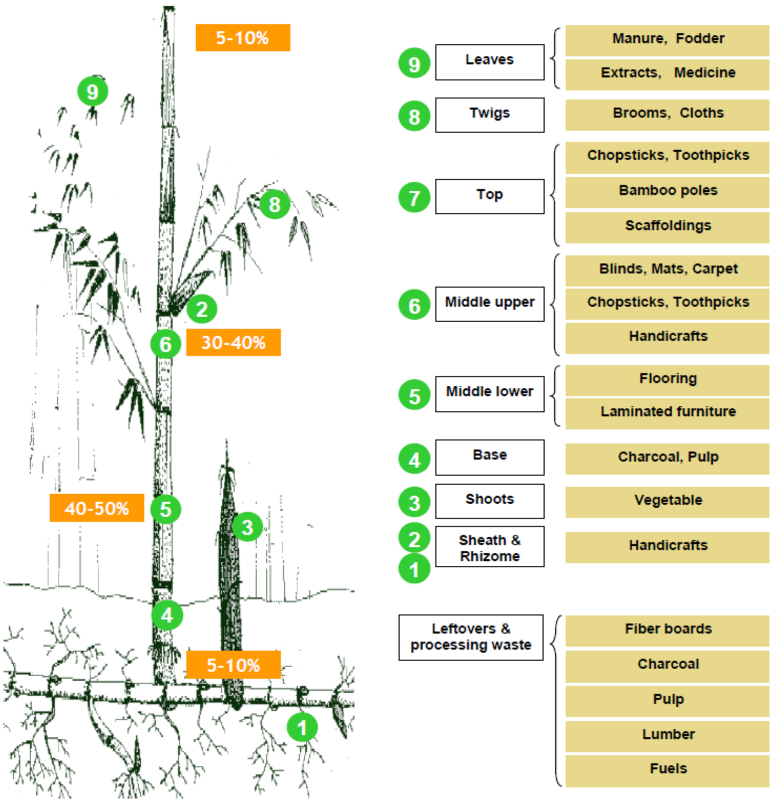

Figure 27: Multi-product capabilities for bamboo plants (Enterprise Opportunities Ltd, 2006)

It is also noted that, whilst most bamboo species have similar product profiles, not all bamboo species are suited for every single application. For example, some species are edible while most are not; some species can be used as structural timber while others can only serve for ornamental use or pulp.

Table 3 summarises a list of various common bamboo species and their economic importance. *Phyllostachys pubescens* (Moso bamboo) is perceived as being one of the bamboo species worldwide with the most commercial potential based on its availability, accessibility and potential for industrialisation (van der Lugt, 2009). Moso bamboo grows abundantly in temperate regions in China, can reach lengths of 10 m – 15 m and a diameter of 10 cm, and is very suitable for industrial processing to develop all kinds of industrial bamboo materials. The main source of bamboo products in South Africa is *Bambusa balcooa,* which was introduced to the country in the 1660's for paper pulp production and has since been naturalised to South Africa's climate, although its natural habitat is in more tropical climate areas. The plant itself can reach a height of 12 m to 20 m and a diameter of 6 cm to 15 cm. *Dendracolamus asper* is another commonly grown species in South Africa, and is suitable for a range of downstream products.

Table 3: Industrial applications and products of various species of bamboo (Benton, 2015)

		Applications									
Bamboo Species	Regions of Origin	Pulping	Land Rehabilitation	Household items	Furniture	Construction	Boards	Laminates	Edible Shoots	Textiles	Biofuels
B. bambos	South Asia	X	X	X							
Bambusa balcooa .	N.E. India and Bangladesh.	X			X	X					
Bambusa tulda	India, Bangladesh, Myanmar and Thailand.	X		X	X	X					
Bambusa vulgaris*	Global tropics. (the only pan-tropical bamboo.)	X		X	X	X					
Dendrocalamus asper	South East Asia (also elsewhere in tropical and sub-tropical regions)	X		X	X	X	X		X		
Dendrocalamus giganteus	Southern Myanmar and northern Thailand.	X		X	X	X	X		X		
Dendrocalamus strictus	India, Nepal, Bangladesh, Myanmar and Thailand.	X		X		X	X				
Guadua angustifolia	From Mexico to Argentina.	X			X	X		X			
Melocanna baccifera (Grove Forming)	Northeast India and parts of Myanmar and Bangladesh.	X		X					X	X	
Phyllostachys pubescens (Grove Forming) (Moso bamboo) #	China.	X		X	X	X	X	X	X	X	X
Phyllostachys pubescens (Grove Forming) Ochlandra spp	Native to the Western Ghats of southern India and southwestern Sri Lanka.	X		X							
Thyrsostachys siamensis	Myanmar and Indochina. Naturally in pure or mixed forests in monsoonal areas.	X		X	X	X			X		

* Grown for pulp on a 3-year rotation in plantations in Brazil.
# The most economically important bamboo species in China.

3.1.1 Wood-based products

Many species of bamboo have strong, light and flexible woody stems, rendering them suitable as a material to potentially replace traditional timber in various applications. Bamboo currently has many applications in the construction and building industries due to its woody nature and similar properties to timber. Bamboo wood-based semi-finished products are produced from the branches and the culm: the culm is either used whole as bamboo poles or split into strips for the production of woven products or engineered bamboo composites (see footnote 5). The latter include high-value products such as plybamboo and strand woven bamboo (SWB) veneer and boards, medium-value products such as bamboo mat board (MBM) and bamboo medium-density fibre board (MDF), and relatively low-value products such as bamboo particle board. Engineered bamboo wood composite products are used in a variety of applications, such as construction, flooring and furniture, but also in the manufacture of sporting and personal goods.

Bamboo poles

Bamboo poles are strong and durable, and often do not require intensive processing or finishing (Jayanetti and Follet, 1998). Bamboo culms are cured and dried for use as poles (shown in Figure 28) in various building and construction applications such as scaffolding, fencing, roofing and footbridges. However, construction and building with bamboo poles is limited by the variation in geometric and mechanical properties of poles, and there is often difficulty in making connections and joints suitable for round (and variable) sections, making it prohibitive for large scale construction (Sharma et al., 2015).

Figure 28: Bamboo poles: (a) Cured and treated poles (b) Various geometry and sizes of bamboo poles

Woven bamboo

Mats made by weaving treated natural bamboo strips are used for a wide range of purposes, including as wall or ceiling linings, lamp shades, wardrobe door linings, bed head inserts, table tops, bar and cupboard inserts, kitchen cabinets, doors and cupboard fronts, furniture, screens and feature panels and other imaginative purposes.

Figure 29: Woven bamboo mats

Plybamboo veneers and boards

As in the case of plywood, plybamboo is manufactured from sheets of cross-laminated veneer and bonded under heat and pressure with durable, moisture-resistant adhesives. By alternating the grain direction of the veneers from layer to layer, or "cross-orienting", panel strength and stiffness in both directions are maximised. Plybamboo started in China in the early 1990s and is mostly applied in flooring, furniture board and veneer. Plybamboo materials exist in many sizes, colours, layers and patterns. The most common differences are the thickness, ranging from 0.6 mm (veneer) to 40 mm (5-layer Plybamboo panel), the texture (plain pressed or side pressed) and the colour (the most commonly used colours are bleached and carbonised (see Figure 30).

Figure 30: Plybamboo veneers and boards

Strand woven bamboo

Strand woven bamboo (SWB) is a made from thin, rough bamboo strips that are glued in moulds under high pressure into beams or boards. An interesting feature of SWB is that there are no height requirements for input strips which means that, unlike the production of plybamboo, a large part of the resource can be used, thereby utilising the high biomass production of bamboo to the maximum. Due to the compression and addition of resin, SWB has a very high density (approximately 1080 kg/m3) and hardness, which makes it a material suitable for use in demanding applications (e.g. staircases in department stores), as well as outdoor furnishings. SWB flooring boards can also be made by pulping bamboo and mixing it with a resin prior to applying heat and pressure.

Figure 31: Strand woven bamboo boards

Bamboo mat board

Bamboo mat board (BMB) is made from thin bamboo strips or slivers woven into mats to which resin has been added. Pressed together under high pressure and high temperature, the mats become extremely hard boards, which during pressing can even be put in moulds to be processed into corrugated boards for roofing (see Figure 32). The production and density (1030 kg/m^3) of BMB and SWB are very similar and both materials use a large amount of resin.

Figure 32: Bamboo mat boards

Medium-density fibre board

As in the case of conventional timber, bamboo medium-density fibre board (MDF) is made by combining thin strand or "fibres" of bamboo with wax and a resin binder, thereafter forming panels by applying high temperature and pressure. MDF is a less expensive alternative to plywood, but is stronger than the least costly options, like particle board. Since the input material is chipped to small fibres, there are hardly any input requirements for the raw material. It is usually painted or covered with a veneer, for use in indoor furnishings.

Figure 33: Medium-density bamboo fibre board

Bamboo particle board

Bamboo particle board (shown in Figure 34) is one of the least expensive alternatives to plybamboo. Particle board has no layered construction – instead, it is comprised of small slivers of bamboo glued together to create a board. This is the type of material you usually find on inexpensive furniture pieces. Particle board is manufactured from bamboo chips, sawmill shavings, or even sawdust, and a synthetic resin or other suitable binder, which is pressed and extruded. A major disadvantage of particle board is that it is very prone to expansion and discoloration due to moisture, particularly when it is not covered with paint or another sealer.

Figure 34: Bamboo particle board

3.1.2 Fibre-based products

Fibres extracted from the culm of bamboo are typically used in textile products and in reinforced polymer composites.

Textiles

There are two different approaches to extracting the bamboo fibres and making bamboo textile. Fibres which are processed by mechanical and bacterial processes, or other methods similar to the retting of flax and bast plants, are termed mechanically-processed or natural bamboo fibres (Kaur et al., 2013; Zakikhani et al., 2014). Bamboo fabric made from this process is sometimes called bamboo linen. This process produces a material that is very durable and soft to the touch.

In contrast, fibres that are extracted using extensive chemical treatment similar to that used to manufacture rayon viscose are termed chemically-extracted, regenerated cellulose or bamboo rayon. Chemical methods produce a pulp and due to the extensive chemical processing involved, the final fibre bears little resemblance to natural fibres in plants. This has resulted in heated debate over whether textiles made in this way can actually be considered bamboo fibre products (Khalil et al., 2012; Rocky and Thompson, 2018), and the US Federal Trade Commission specifies that such products must be labelled as “rayon” or “rayon made from bamboo”. However, chemical methods are often less labour intensive and lower-cost, and are favoured by most industrial manufacturers (Rocky and Thompson, 2018). The majority of bamboo clothing is thus made from viscose rayon, processed from cellulose extracted from bamboo. Clothing made of bamboo rayon typically lasts even longer and holds its shape even better than clothing made of natural bamboo fibre.

Figure 35: Bamboo fibre

Bamboo fibre reinforced composites

As in the case of bast fibres, bamboo fibres can be used instead of synthetic fibres to reinforce natural or synthetic polymer matrices (Khalil et al., 2012). Considerable interest has been generated in the manufacturing of natural fibre-reinforced thermoplastic composites due to their good fracture toughness and thermal stability, with bamboo being used to reinforce polymers that are polyester, epoxy, phenolic resin, polypropylene, polyvinyl chloride or polystyrene based (Banga et al., 2015). In their review, Banga et al. (2015) reported that the tensile strength of bamboo fibre reinforced plastic (BFRP) composites is comparable to that of mild steel, whereas their density is considerably less, making them ideal for use in structural applications. Thermoplastic matrix composite materials offer an extended solution in different applications in the automotive industry, construction, electrical appliances and home/urban furniture (Banga et al., 2015). High density polyethylene composites, consisting of 70% recycled bamboo fibres, are stronger than wood and have been used to replace it in the manufacture of products such as decking, fencing and railings (Khalil et al., 2012). These polymer composites require low maintenance, are long lasting and not as flammable as wood (see Figure 36).

Figure 36: Various wood-replacement applications of bamboo fibre reinforced polymer composites (BFRCs)

3.1.3 Paper products

Bamboo is very similar to softwood in terms of fibre length and strength, although pulping conditions are very similar to hardwoods such as eucalyptus. Hence, shredded bamboo culm can be used to as a wood substitute or blended with hardwood sawdust to make a variety of paper products, using the Kraft pulping process. In the case of pulp production for paper, the annual yields per hectare for bamboo may be even higher than for the building and interior decoration industry, and significantly higher than conventional timber, since bamboo used for paper does not have to be mature.

3.1.4 Energy production

Bamboo has a number of desirable characteristics as a fuel for combustion, such as low ash content and alkali index compared to other bioenergy feedstocks. It has a heating value lower than many woody biomass feedstocks but higher than most agricultural residues, grasses and straws (Scurlock et al., 2000). As in the case of other biomass forms such as wood, it can be used directly as a fuel or processed into pellet form or other forms of fuels, such as biogas, bioethanol, and charcoal. In direct applications, off-cuts and bamboo processing waste can be used on-site to provide energy for other bamboo processing applications. Many industries make use of waste biomass to provide heat or raise steam for processes such as drying and heating, including the pulp and paper sector.

Torrefied pellets

A type of solid biofuel, a mild pyrolysis, or torrefaction, may be applied to biomass such as bamboo to improve its heating value (Chen et al., 2015). Torrefied pellets may be used as a substitute for coal in the generation of electricity and metallurgical processes. Also, a syngas may be produced from torrefied pellets in a gasification process. *Bambusa balcooa* may be torrefied, carbonised and co-fired with coal (Bada et al., 2015).

Bioethanol

Generally, bamboo is more productive compared to many other biofuel plants and large quantities of biomass may be harvested from bamboo plantations or natural stands of bamboo. This sustainable supply of raw material may be converted into biofuels (Littlewood et al., 2013). Moso bamboo (*Phyllostachys heterocycla var. Pubescens*), is fast growing and is easily propagated (Scurlock et al., 2000). It contains significant quantities of carbohydrates and once it has been pulped and de-lignified it may form a substrate for fermentation and the production of biofuels such as ethanol (Scurlock et al., 2000) and other biochemicals (Littlewood et al., 2013).

Bamboo charcoal

Bamboo charcoal is a solid, stable, carbon-rich material made by pyrolysing bamboo biomass. According to the types of raw material, bamboo charcoal can be classified as raw bamboo charcoal and bamboo briquette charcoal. Raw bamboo charcoal is made of bamboo plant parts such as culms, branches and roots. Bamboo briquette charcoal is made of bamboo residue, for example, bamboo dust, saw powder etc., by compressing the residue into sticks of a certain shape and carbonizing the sticks. Most bamboo charcoal for fuel is bamboo briquette charcoal, and the rest is raw bamboo charcoal. In China and Japan, many people use bamboo charcoal as cooking fuel, as well as to dry tea. Like all charcoal, bamboo charcoal purifies water and eliminates organic impurities and smells.

Figure 37: Bamboo charcoal

3.1.5 Leaf and shoot by-products

Pharmaceuticals from leaves

Flavone, a pigment in yellow plants, may be leached from bamboo leaf fibres. Flavone acts as a phytoestrogen and may play a role in cancer prevention (Arroo et al., 2017). Flavones are extensively used in the pharmaceutical industry (Gang et al. 2000). The incorporation of bamboo fibre into human and animal diets combats pathogens in the gut; consequently, a bamboo-based drug has been formulated for the treatment of gastrointestinal infections (Anping, 2005).

Food from shoots

High concentrations of fibre and proteins are found in the shoots of a number of species of bamboo. They are a well-known feature of Asian cuisine (Scurlock et al., 2000). *Phyllostachys* is the most important genus for the production of edible shoots (Diver, 2001). Culm flours may be produced from certain bamboo species. They provide sources of fibre and starch (Felisberto et al., 2017). Bamboo tea, bamboo wine and bamboo vinegar may be derived from bamboo (Diver 2001). The total carbohydrate content of bamboo leaves decreases throughout the growing season, remains stable for a while and then decreases once more during winter. With regards to protein in bamboo leaves, crude protein content is high during the growing season and decreases during winter. This suggests that bamboo leaves may provide winter feed for livestock such as goats. In addition, bamboo leaves used as fodder reduces the exposure of livestock to gastrointestinal parasites (Halvorson et al., 2011).

3.2 Bamboo Processing

The processing stages for the recovery of different targeted product types are outlined in Figure 38. The methods used in the main processing stages for key products are discussed in Sections 3.2.1 – 3.2.6. It is, however, recognised that, whilst a particular product-type (e.g. poles, fibre-based products, wood-based products, paper products or energy-based products) may be specifically targeted, it is possible to generate multiple product types from a single harvest by using different parts of the bamboo plant for different purposes and by re-purposing wastes from the production of a targeted product (e.g. higher-end product such as fibres) as feedstock for the production of another product type (e.g. lower-end product such as energy).

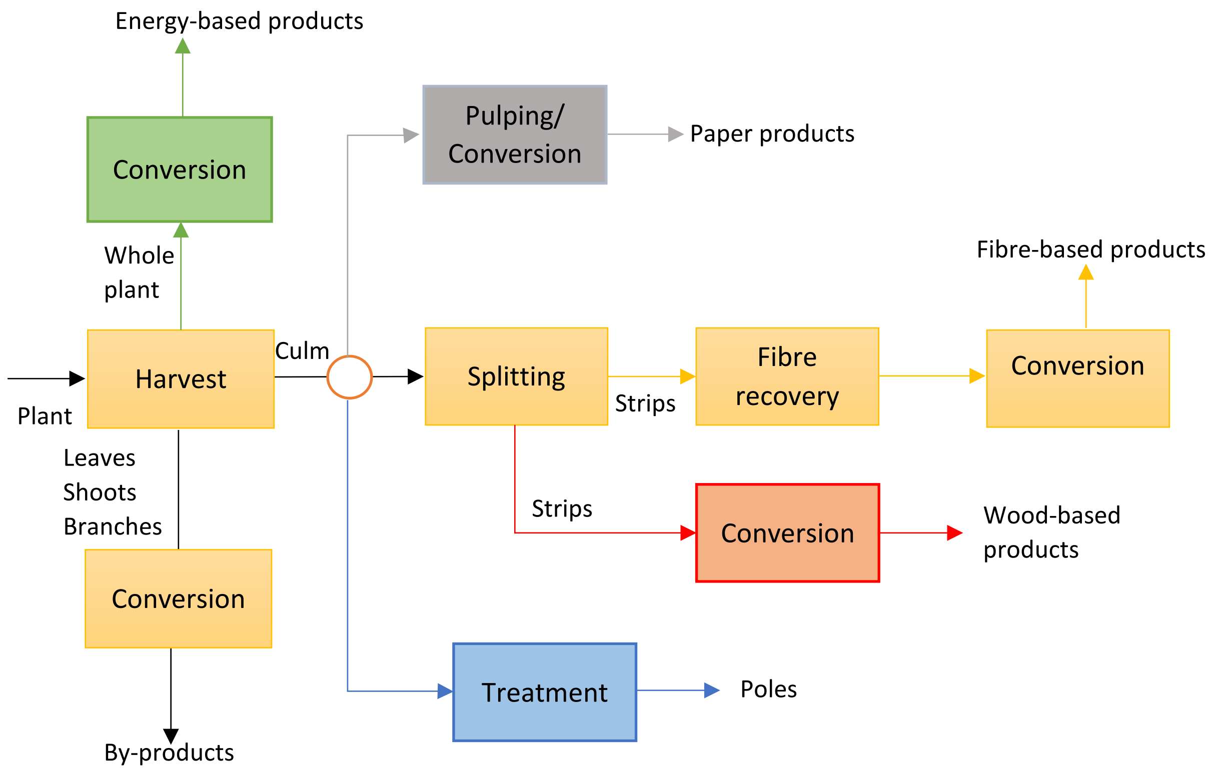

Figure 38: The main bamboo process stages for various products (adapted from Khalil et al., 2012; Rocky and Thompson, 2018)

3.2.1 Bamboo harvesting

Harvesting is the first step in the production of all bamboo products. Unless the whole plant is used for energy-production, harvesting allows for pre-separation of culm from the branches and leaves.

Most harvesting of bamboo is still un-mechanised and labour-intensive. Harvesting is performed manually during the dry season with bush knives similar to the traditional manual methods used for harvesting sugar cane (Bonilla et al., 2010; Guerra et al., 2016). Mechanisation of bamboo harvesting is difficult as the stems are strong and the plants grow either in clumps or as interconnected rhizomes, as shown in Figure 39 (Bonilla et al., 2010; Guerra et al., 2016; Akinlabi et al., 2017).

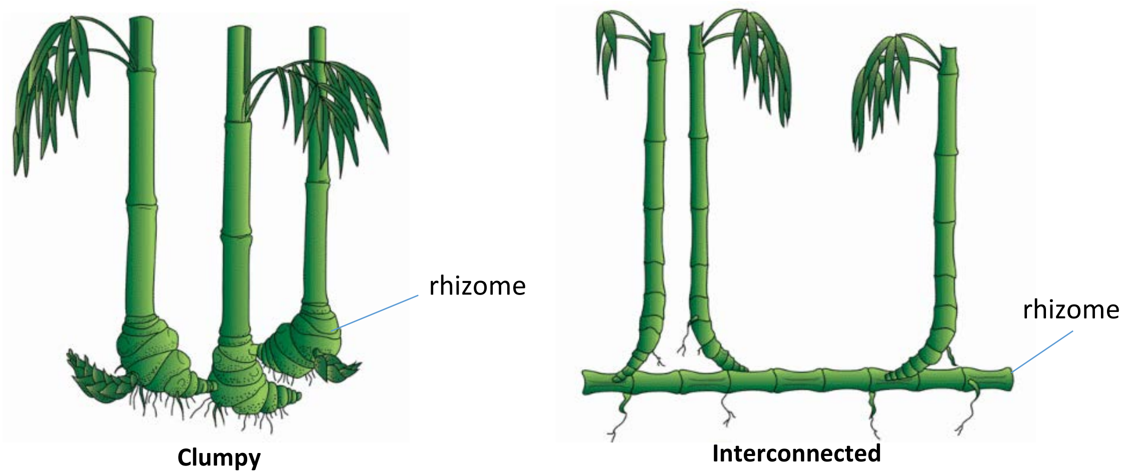

Figure 39: Bamboo plants (Akinlabi et al., 2017)

However, various cutting tools have been developed to optimise bamboo harvesting, as well as different cutting techniques (selective cut, horseshoe cut, and clear cut) which result in varying degrees of shoot and culm recovery (Darabant et al., 2016). The culms are cut at 30 cm – 40 cm above the rhizomes or just above the first node to prevent any accumulation of water in the hollow stubs, after which the culms are stripped of the twigs, and any shoots cut during harvesting are collected (UNIDO, 2009). The culms are then split or treated depending on the desired end-product; the culms either need to be split for fibre recovery and lumber products or can be processed for the use of the entire culm as bamboo poles (UNIDO, 2009).

3.2.2 Culm splitting

For the production of wood-based and natural fibre-based products, the bamboo culms are split mechanically into strips. Splitting can either be done manually (see Figure 40a) or by a splitting machine (see Figure 40b). Different splitting machines are often designed for culms within a specific diameter range. This limits the use of the same splitting machine across various bamboo species. However, some splitting machines which can adapt to differently sized culm diameters have been developed (Ahuja et al., 2012).

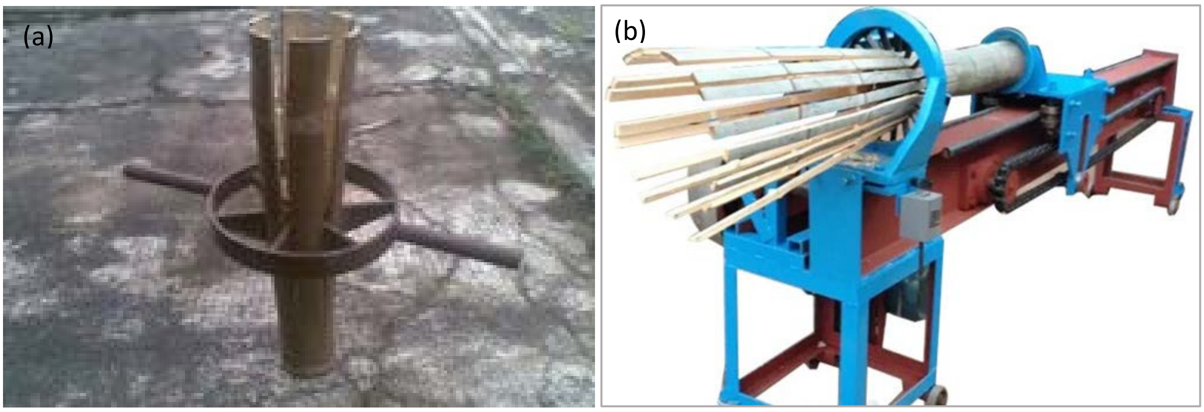

Figure 40: Bamboo splitting (a) manual splitter (b) splitting machine

Depending on the desired final product, the bamboo strips are then broken up for further processing to recover fibre (to be discussed under fibre recovery), or the strips are cut and/or treated for the production of wood-based products.

3.2.3 Recovery of fibre-based products

As indicated in Section 3.1, the main fibre-based products generated from bamboo are textiles and bamboo fibre reinforced polymer composites (BRFCs). The production of bamboo fibre as an intermediate product mainly comprises of cutting, fibre extraction, drying and combing, as shown in Figure 41. After splitting, bamboo strips are cut to increase the efficiency of fibre extraction. Fibre is then extracted using various methods and processes to generate either natural or rayon fibres (Waite, 2009; Yueping et al., 2010; Khalil et al., 2012; Rocky and Thompson, 2018). Thereafter the fibre is dried and combed before being converted into final products.

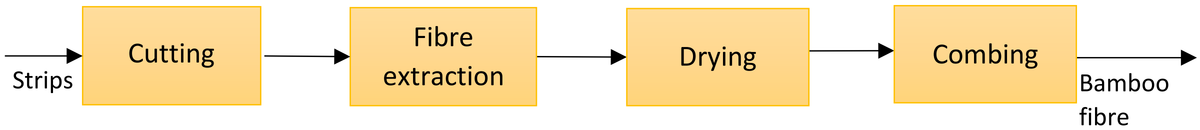

Figure 41: The main process stages of bamboo fibre recovery (Yueping et al., 2010; Khalil et al., 2012; Rocky and Thompson, 2018)

The methods used for extraction of natural fibres and rayon fibres, drying and combing, and fibre conversion into textiles and reinforced polymers are summarised in the sections below.

Natural fibre extraction

Bamboo fibre extraction requires the processing of the strips or bamboo chips to separate the fibre bundles from the remaining woody parts (exodermis and endodermis). Many of the methods used to extract natural fibre from bamboo culm are similar to those used in the retting or degumming of bast fibres, though bamboo fibre extraction is more intensive due to factors such as bamboo's strength and higher moisture content (Zakikhani et al., 2014). More intensive processing is required to maximise fibre recovery and often various combinations and/or sequences of the fibre extraction methods are applied (Phong et al., 2011; Kaur et al., 2013; Rocky and Thompson, 2018). The different extraction methods and potential combinations thereof are shown in Figure 42.

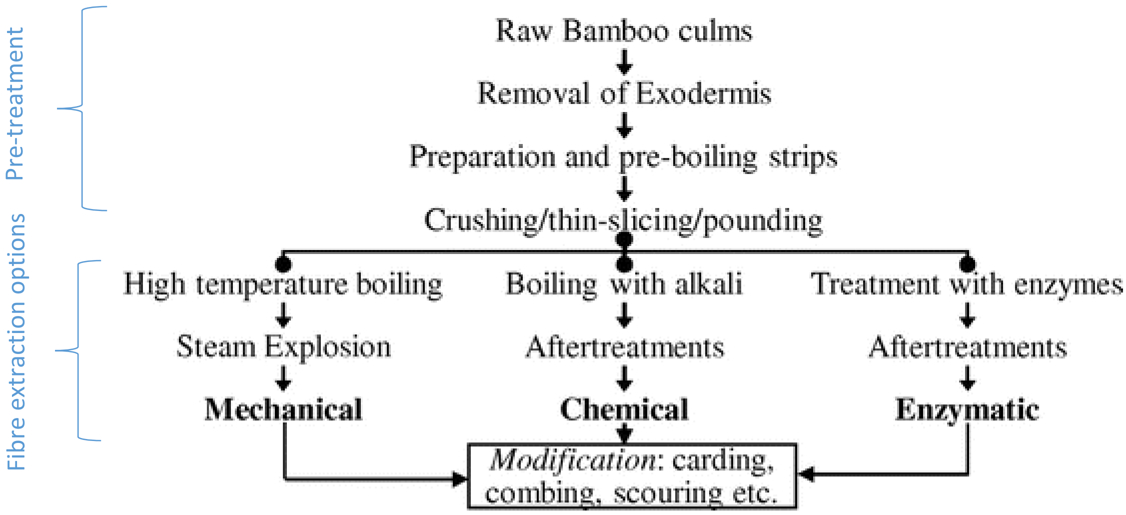

Figure 42: Examples of different processing routes for bamboo natural fibre extraction (Rocky and Thompson, 2018)

The first step to pre-treat the split bamboo culms usually involves removing the tough exodermis through a manual peeling or scraping process. However, depending on the bamboo species and hardness of the exodermis this step may not be applied. Thereafter, to further soften the strips, an additional boiling step can be applied, which entails heating in a water bath at about 90°C for 10-15 hours to loosen the vascular bundles (Rocky and Thompson, 2018). The strips are then broken into smaller pieces by means of a roller crusher, or manually by cutting the strips using cutting tools, especially in smaller-scale operations (Khalil et al., 2012). Depending on the ensuing fibre extraction process and the fibre end-use, the broken strips can be repeatedly passed through the roller crushers to start softening the fibre (Khalil et al., 2012; Zakikhani et al., 2014; Rocky and Thompson, 2018).

Subsequent fibre extraction processes are either mechanical, physical, microbial or chemical processes. These methods are typically used in combination to optimise fibre recovery (similarly to bast fibre extraction methods shown in Figure 11), with the combinations and sequence of different methods producing fibre varying in length, texture and diameter suitable for different end-uses (Zakikhani et al., 2014; Rocky and Thompson, 2018). For example, a combination of peeling, crushing, water heating and microbial treatment produces uniformly rough fibres suitable for textiles, whereas a sequence of water heating, microbial treatment and acid washing produces finer fibres used for more technical applications such as fibre composites (Yao and Zhang, 2011; Zakikhani et al., 2014).

The common microbial, mechanical or chemical methods used in bamboo fibre extraction are discussed briefly in subsections (i) to (iii).

(i) Microbial treatment

In this process the bamboo strips are kept in water tanks for up to 8 weeks, similar to water retting described under bast fibre separation. However, unlike bast fibres, bamboo cannot be field retted as bamboo rots easily (Kaur et al., 2013; Zakikhani et al., 2014). Microbes, which are either added to the water tanks or naturally present on the bamboo, degrade the cellular tissue to release the fibre bundles. The longer the bamboo is kept in the water, the easier it is to separate the fibres (Rao and

Rao, 2007; Fu et al., 2011). To speed up the process the bark can be manually peeled off before immersing the culms in water, which can reduce the time needed to a couple of days. This process produces long and coarse/rough fibres. However, the procedure is labour intensive and if the strips are not sufficiently softened they still need to be crushed after retting (Zakikhani et al., 2014).

(ii) Physical extraction

Bamboo extraction by "physical methods" usually involves steam explosion or heating the bamboo in water tanks (Zakikhani et al., 2014). During the steam explosion process, the cell walls of the fibres are cracked in a chamber or batch reactor and the bamboo fibres become soft, rapidly separating the fibrous and non-fibrous parts of the culms (Phong et al., 2011). This method produces a pulp often used in biomass production and has been adopted as a method for bamboo fibre production, usually for use in composites (Shao et al., 2008; Phong et al., 2011). Alternatively, the strips are heated in water for 10-15 hours at about 90°C to allow them to soften, but the strips need to be subsequently beaten or crushed (manually or in a mill) to completely loosen the fibre from the exo- and endo-dermis, making this method labour intensive (Rao and Rao, 2007; Rocky and Thompson, 2018).

(iii) Mechanical extraction

The bamboo strips can either be crushed, ground or milled, all of which result in fibres with different lengths, texture and tensile strength. Crushing is usually done with a roller crusher or pin-roller. However, this process yields short coarse fibres which can easily break if over-processed (Zakikhani et al., 2014). Grinding and milling are usually more efficient when not applied directly to the strips, therefore these methods are often applied after or before other fibre extraction methods (Phong et al., 2011).

(iv) Chemical extraction

Conventional chemical extraction procedures include alkali or acid retting, chemical retting and chemical assisted natural (CAN) degumming. However most of these treatments affect the quality of the fibre (Zakikhani et al., 2014). In the alkali procedure (i.e. alkalisation), bamboo strips or chips are often heated in a NaOH solution at about 70 - 80 °C for 7 to 12 hours, after which the bundles need to be washed before further processing (Zakikhani et al., 2014). This method causes the least damage to the fibre and produces fibre lengths suitable for textiles, however the waste water produced in this treatment poses environmental challenges (Waite, 2009; Phong et al., 2011; Kaur et al., 2013). The quality of the fibre produced can be controlled by varying parameters such as temperature, alkali concentration and time, which is often dependent on the end-use of the fibre (Kaur et al., 2013; Rocky and Thompson, 2018). In acid treatments the bamboo strips or chips are soaked or heated in inorganic acid or organic acid solutions at different temperatures (Kaur et al., 2013; Hong et al., 2013). However, with acid treatment the risk of fibre degradation is high, and this method is often used to produce a pulp (Hong et al., 2013). CAN treatment or retting speeds up the water retting process by using a chemical catalyst such as zinc nitrate or sodium nitrate (Kaur et al., 2013; Zakikhani et al., 2014). This procedure has been found capable of removing more lignin compared with alkaline and acid retting, but the moisture content of the treated fibres is higher, subsequently requiring longer drying periods or wet spinning (Kaur et al., 2013).

Rayon fibre extraction

As indicated in Section 3.1.2, bamboo fibre can be, and is more frequently, produced using extensive chemical treatment similar to that used to manufacture rayon viscose. The rayon method essentially follows the same process used to manufacture viscose using alkalisation followed by multi-phase bleaching steps to produce what is termed as regenerated bamboo fibre, which is silky like rayon (Waite, 2009). This process is shown in Appendix V. The use of carbon disulphide as a stabiliser in this process results in hazardous emissions to air and water. Due to the hazards involved, alternative and more eco-friendly methods and chemicals have been developed for the manufacture of bamboo rayon. The spinning loop process, which is like the Lyocell process, uses N-methylmorpholine-N-oxide (NMNO) instead of an alkali, and hydrogen peroxide (H_2O_2) is added as a stabiliser instead of sulphur compounds to produce regenerated bamboo fibre. While much more expensive, the Lyocell process substantially reduces the environmental threats associated with the viscose process, as the amine oxides are reported to be non-toxic to humans (Nayak and Mishra, 2016). Furthermore, 99.5 % of the chemicals used during the processing are captured and recycled, and virtually no waste is created. As a result, the Lyocell process is considered to be one of the leading methods of producing environmentally friendly regenerated fibres for textiles.

Post-extraction processing – drying and combing

After extraction, the fibres are typically dried at about 100^oC – 150^oC in a rotary drier (Zakikhani et al., 2014). After drying the fibres are then combed on a frame similar to a hackling frame described under bast fibres. This process often produces long and shorter fibres and is more suited for fibres intended for conventional textiles (Zakikhani et al., 2014).

Conversion of fibres into textiles and bamboo fibre reinforced polymers (BMRFs)

The regenerated bamboo fibre is spun into yarns for use as in textiles. Refined and spun cellulosic bamboo fibre with its low lignin content may be used in the manufacture of silky knitted and woven textiles (Yueping et al., 2010; Liu et al., 2011). These textiles may be used to manufacture a wide range of clothing items and other household items such as bedsheets, towels, blinds and table cloths.

Methods for the manufacture of bamboo fibre reinforced polymers are similar to those used for polymer composites made from other natural fibres (see Section 2.2.4). The main techniques used in the manufacture BMRFs include pultrusion, injection moulding, hot press moulding, resin transfer moulding or compression moulding in an autoclave or hot press.

3.2.4 Recovery of poles and wood-based products

As indicated in Section 3.1.1, bamboo culm can be used to make poles directly or split and converted to natural bamboo woven products (mats and handicrafts) or engineered wood intermediate products, the most common being plywood veneers and boards, strand woven bamboo, bamboo mat board, MDF and particle density board. Although the methods used vary according to the product, the same basic steps are used in the manufacture of natural or engineered wood-products, as shown in Figure 43. The first step in the production of almost all bamboo wood-based products is treatment to destroy any microorganism or bacteria and remove any remaining starch. In the case of some engineered wood-based products, preservation and colouring take place simultaneously. For the production of engineered wood products, the treated strips are subsequently contacted with resin before being compressed, cured, dried and finally shaped into boards, planks or other products. Bamboo mat board (BMB) is woven before being contacted with resin.

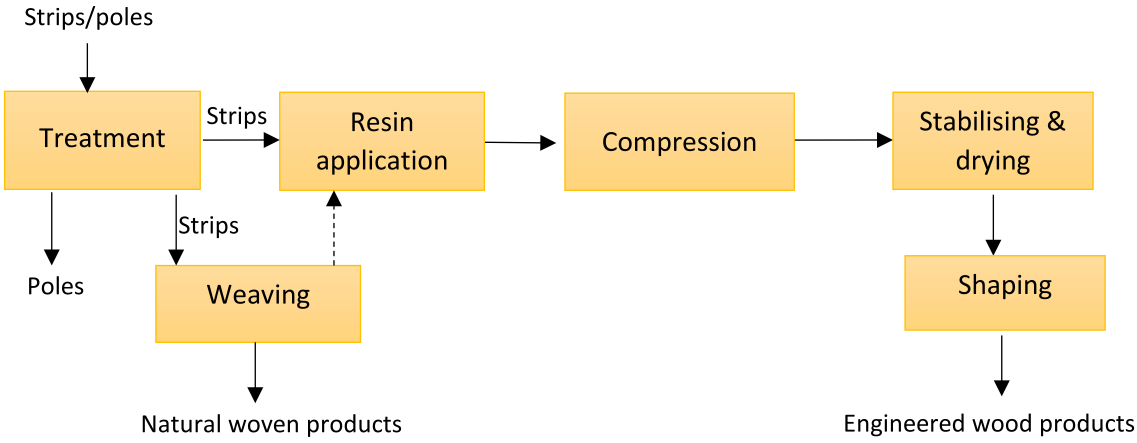

Figure 43: Manufacturing process for natural or engineered bamboo wood-products

Further details on the various methods for the manufacture of key wood-based bamboo products are provided in the sub-sections below.

Treatment

Poles, natural bamboo products and non-coloured engineered wood products are commonly preserved using a 1% solution of boric acid and borax in a 1:1 ratio. Boric acid and lime are also sometimes used. Another preservation process entails boiling in water. In some cases, bleaching or caramelisation is carried out, which simultaneously preserves and colours the wood. Caramelisation (also known as carbonisation) entails steaming using pressurised wet steam at 120-130°C, yielding a dark brown colour, whilst bleaching is conducted in a hydrogen peroxide bath at 70-90°C for 4 hours resulting in a lighter yellow colour. The coloured strips are then dried in drying chambers, before being processed further.

Figure 44: Boiling of bamboo strips process

Manufacture of plywood veneers and boards

Treated and dried strips are glued together using urea formaldehyde and polyurethane, before being pressed using hot presses (one-layer boards) and multi-layer cold presses (3 to 5-layer boards). The manufacture of plywood boards is presented pictorially in Figure 45.

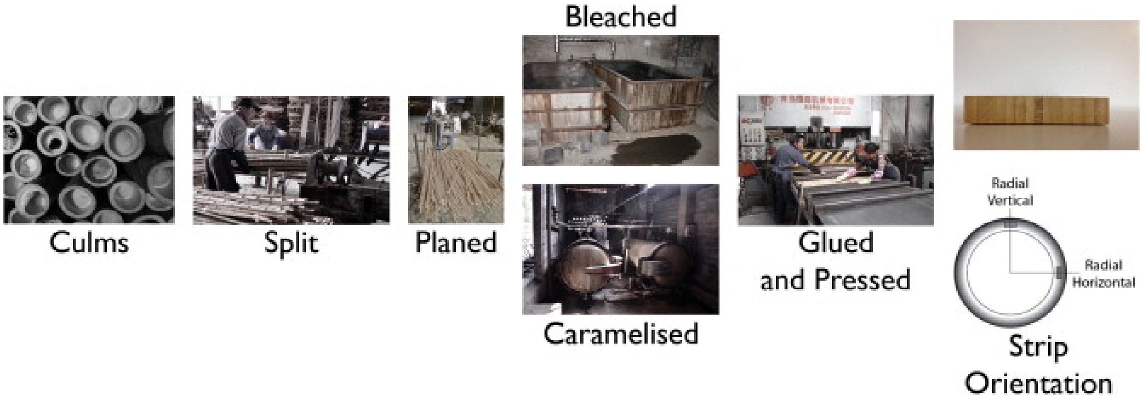

Figure 45: Bamboo board general manufacturing process (Sharma et al., 2015)

Manufacture of strand woven bamboo (bamboo scrimber)

Preserved natural or coloured bamboo strips are soaked in resin (normally phenol formaldehyde) and the glue-saturated strips placed in moulds and compressed under high pressure by a cold press. The compressed boards or beams are then heat cured in a large oven where the glue is activated at a temperature of 140-150 °C. Once the adhesive is fully dried, the boards or beams are sawn and sanded into the desired shape.

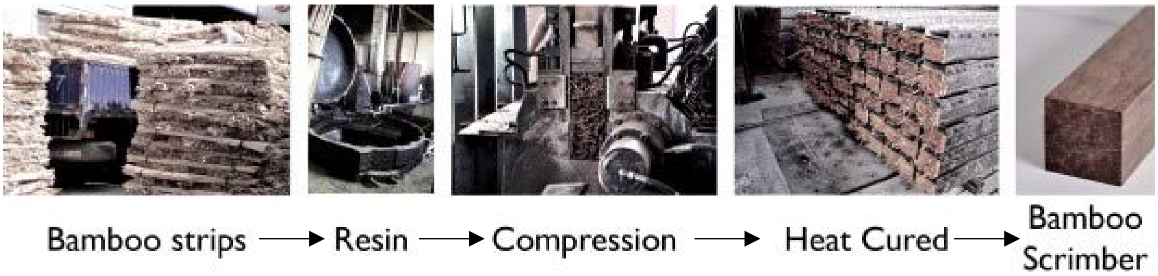

Figure 46: General manufacturing process for strand woven bamboo/bamboo scrimber (Sharma et al., 2015)

Bamboo mat board

Bamboo strips are (normally manually) woven into mats of different sizes and patterns. Some producers only treat the woven mats or boards after weaving. The dry boards are then dipped into resins and dried at temperatures of approximately 95°C to reduce the moisture content to 10%. Finally, hot pressing melts the resin in the mats and bonds them together tightly, before trimming and shaping.

3.2.5 Recovery of paper products

As in the case of hemp and kenaf, bamboo can be used to manufacture paper using the commonly applied Kraft process (Appendix III). This process entails treatment of wood chips with a hot mixture of water, sodium hydroxide (NaOH), and sodium sulfide (Na_2S), known as white liquor, that breaks the bonds that link lignin, hemicellulose, and cellulose. The technology entails several steps, both mechanical and chemical, with the key processes being digestion (or pulping) and bleaching.

3.2.6 Recovery of biofuels

As discussed in Section 3.1.4, bamboo biomass (in the form of whole plant or waste) can be used to generate steam and heat, or to produce biofuels, such as bioethanol, charcoal and torrefied pellets.

The process of conversion to biofuels and chemicals is relatively difficult due to the hardiness of the plant and the consequent necessity of various pre-treatments (Littlewood et al., 2013). One such pre-treatment is wet torrefication, a mild form of pyrolysis at temperatures typically between 200 and 320°C. Torrefication enhances the quality and handleability of the fuel. After pre-treatment, the mature bamboo and bamboo shoots may be hydrolysed to glucose and xylose using cellulases and xylase (Li et al., 2015). The resulting sugars may then be fermented to ethanol.

A key biofuel product is bamboo charcoal. Today, the technology of producing charcoal from bamboo is a highly specialised process where dried bamboo is carbonised in a kiln at a very high temperature (800 °C or more, according to the performance desired), reducing it to charcoal.

4 Metal Recovery Potential

Generally metal recovery from plants (agro-mining or phyto-mining) has not been applied to fibrous plants, but rather made use of hyperaccumulator plants (Bhargava et al., 2012; Hunt et al., 2014; Sheoran et al., 2009). Most of the literature appears to have been focused on nickel, although agro-mining of gold has also been proposed, and in principle As, Se, Cd, Mn, Tl and Zn all have hyperaccumulator plants (Sheoran et al., 2009; van der Ent et al., 2015). Hyperaccumulators for Cu, Co, La and Pb have poor uptake characteristics (van der Ent et al., 2015).

Recovering metals from hyperaccumulators generally entails drying and ashing (preferably with heat recovery) at temperatures of >500^{o}C, concentrating the metals by 10-20 times, followed by pyrometallurgical and/or hydrometallurgical processing to recover metals (Sheoran et al., 2009; van der Ent et al., 2015). Some plant-sequestered metals are kept as pure metallic nanoparticles within the biomass and an interesting alternative is the in-situ utilisation of metal nano-particles (such as Au, Ni, Zn, PGMs) within the biomass as catalysts i.e. plant-synthesised nano-particles (Hunt et al., 2014). Plant synthesised TiO_2 particles have been used to generate syngas. Volatiles such as Cd, As and Zn may be collected in the fumes during incineration (Rodrigues et al., 2016).

A number of processes have been developed for the recovery of nickel in particular, with ashing producing a "bio-ore" containing up to 20% Ni in the form of NiO, and recovery of Ni in the form of a metal using reductive roasting, sintering or through acid leaching and electrowinning (Houzelet et al., 2017; Sheoran et al., 2009; Zhang et al., 2016). An alternative that has received extensive attention is the production of Ammonium Nickel Sulphate Hexahydrate (Houzelet et al., 2017; Sheoran et al., 2009; Zhang et al., 2016). Plant-synthesised Zn and Ni nanoparticles have also been produced, although the biomass was treated by ashing before being used as a catalyst (Hunt et al., 2014).

AngloPlatinum was the first company to demonstrate the use of agro-mining on a large scale in 1996. An indigenous plant, *B.coddii,* was used to phytoremediate Ni contaminated land near the Ni refinery, – the biomass was collected and incinerated or ashed to produce a bio-ore and subsequently blended with the conventional Ni concentrate before being fed to the smelter (Sheoran et al., 2009).

Essentially, conventional metal recovery from plant processes are destructive, so the integration of metals recovery into a fibre processing plant would need to focus on the leaves, shoots and roots (on the assumption that most of the metals will have accumulated there). Metals or contaminants reporting to the stalks/culm may be (at least partially) leached out during the retting process, particularly if slightly more aggressive methods (high temperature or chemical retting methods) are used, offering an opportunity for metal recovery. Potential options to integrate metals into the multi-product value chains for fibre plants are outlined in Figure 47.

However, downstream treatment of wastewaters containing relatively low levels of metals and contaminants may be quite onerous and expensive. An alternative would be to use hyperaccumulators to explore options for phyto-mining of metal-contaminated land in the first instance, prior to cultivation of the fibre plants.

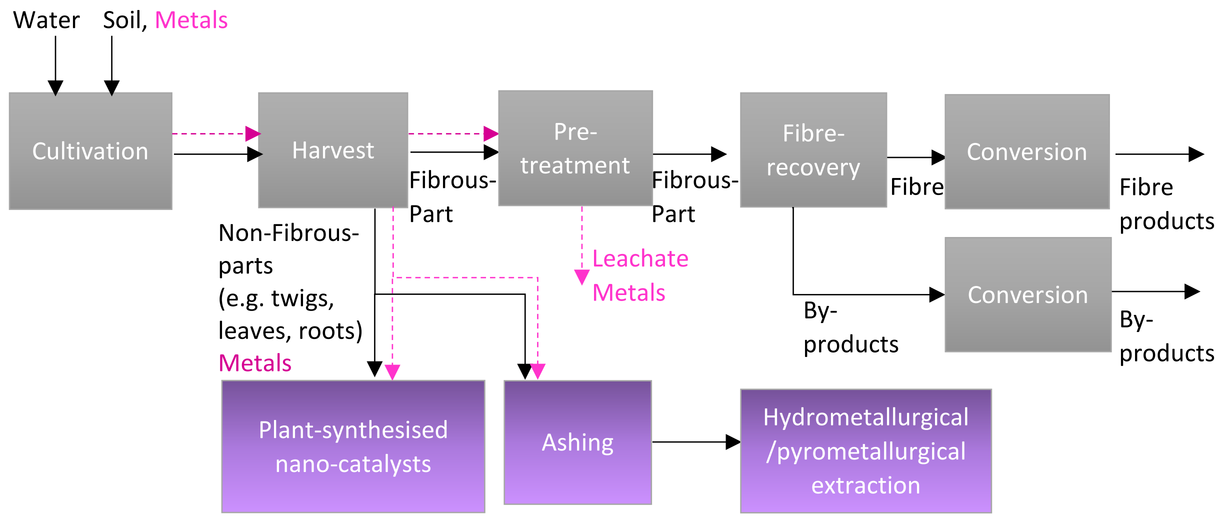

Figure 47: Potential processing flow sheet for simultaneous fibre-based product and metal recovery

5 Summary of Findings

This paper provides an overview of the processes and uses of biomass from fibre-based plants, specifically the bast fibres, hemp and kenaf, and the grass fibre, bamboo. The use of fibre-based plants dates back to the Bronze Age, with plants such as hemp and, in particular, bamboo remaining an important natural resource for traditional applications such as construction and decoration, and even textile and paper production, in many parts of Asia. Over the past 10-15 years, scientific and technological advances have led to the development of more durable products, as well as new high-end applications such as polymer and advanced wood composites. These developments, coupled with an enhanced awareness of the need for the development of "greener" materials, have resulted in a wide spectrum of niche bamboo, hemp, and even kenaf products on the markets.

Whilst all fibre plants are capable of generating multiple products from different parts of the plant, the range of possible products and the targeted markets will vary according to the different class of plant. In the case of bast fibres, a single plant can be processed to simultaneously generate long bast fibres (for the manufacture of high-end materials such as textiles and polymer composites), short bast fibres (for the production of medium-value materials such as paper or cordage), woody tissue or core fibres (for the production of lower-end or bulk materials such as hempcrete, insulation boards, animal bedding and paper), as well as seed oil. The relative extents to which these different product-types (long bast fibre, short bast fibre, woody tissue or seed oil) are generated and their suitability for final use will, however, be dependent on the methods used to process this biomass, with different processing methods affecting fibre length, colour, quality and strength.

In the case of bamboo, products are mainly generated from the stem or culm, and can be grouped as fibre-based products (including natural and "rayon" or regenerated cellulose fibre products for textiles and polymer composites), wood-based products (including natural wood and engineered wood composite products for construction, furnishings and sporting equipment) and bulk processing products, such as energy and paper. For bamboo, multi-product opportunities arise through the generation of different products from different parts of the culm – with the higher-quality parts of the stem being used for higher-end products such as fibre-based products and higher-value wood composites – and by re-purposing processing wastes and off-cuts for the manufacture of lower-end and bulk processing products. As in the case of the bast fibre plants, the methods used for bamboo processing will be highly dependent on the targeted products and associated specifications. Bamboo requires more intensive processing than bast fibre plants for the production of similar products, with the processing of higher-end products being more extensive than for lower-end products.

These findings clearly indicate that the effective exploitation of fibre-based plants will depend on the selection of desired products and by-products (and combinations thereof), as well as a comprehensive understanding of the relationship between the properties of the fibre biomass, the required processing methods, and the quality of the intermediate and final products. Product selection should, furthermore, take into account socio-economic as well as environmental considerations. To date, however, there appear to be few holistic or systemic studies to facilitate selection of products and processing of biomass from fibre plants. Further studies will also be required to investigate the effect of possible contaminates on the quality of products or the compositions of processing emissions in the event of fibre plants being cultivated on contaminated land. In cases where land contains high levels of metal contaminates, it may be more effective to use hyperaccumulator plants to recover metals prior to the cultivation of fibre plants for multi-product generation.

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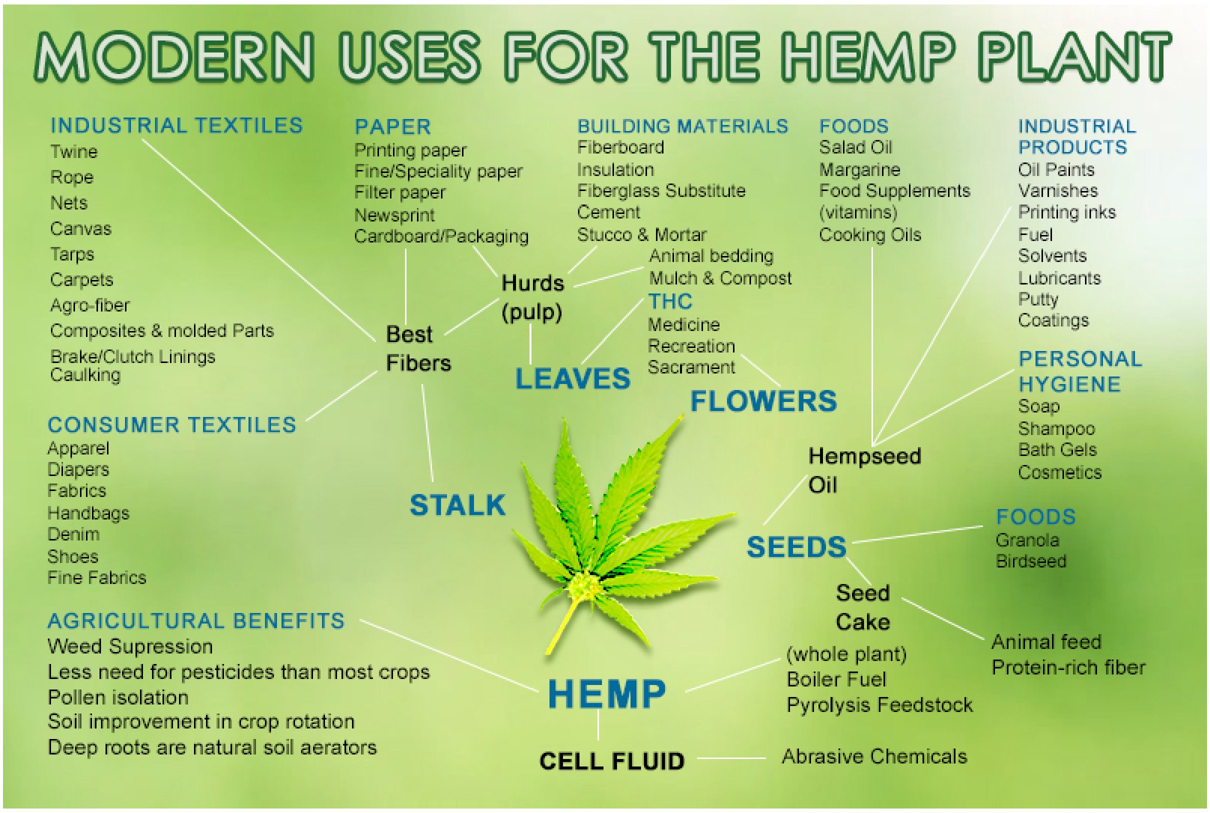
7 Appendices

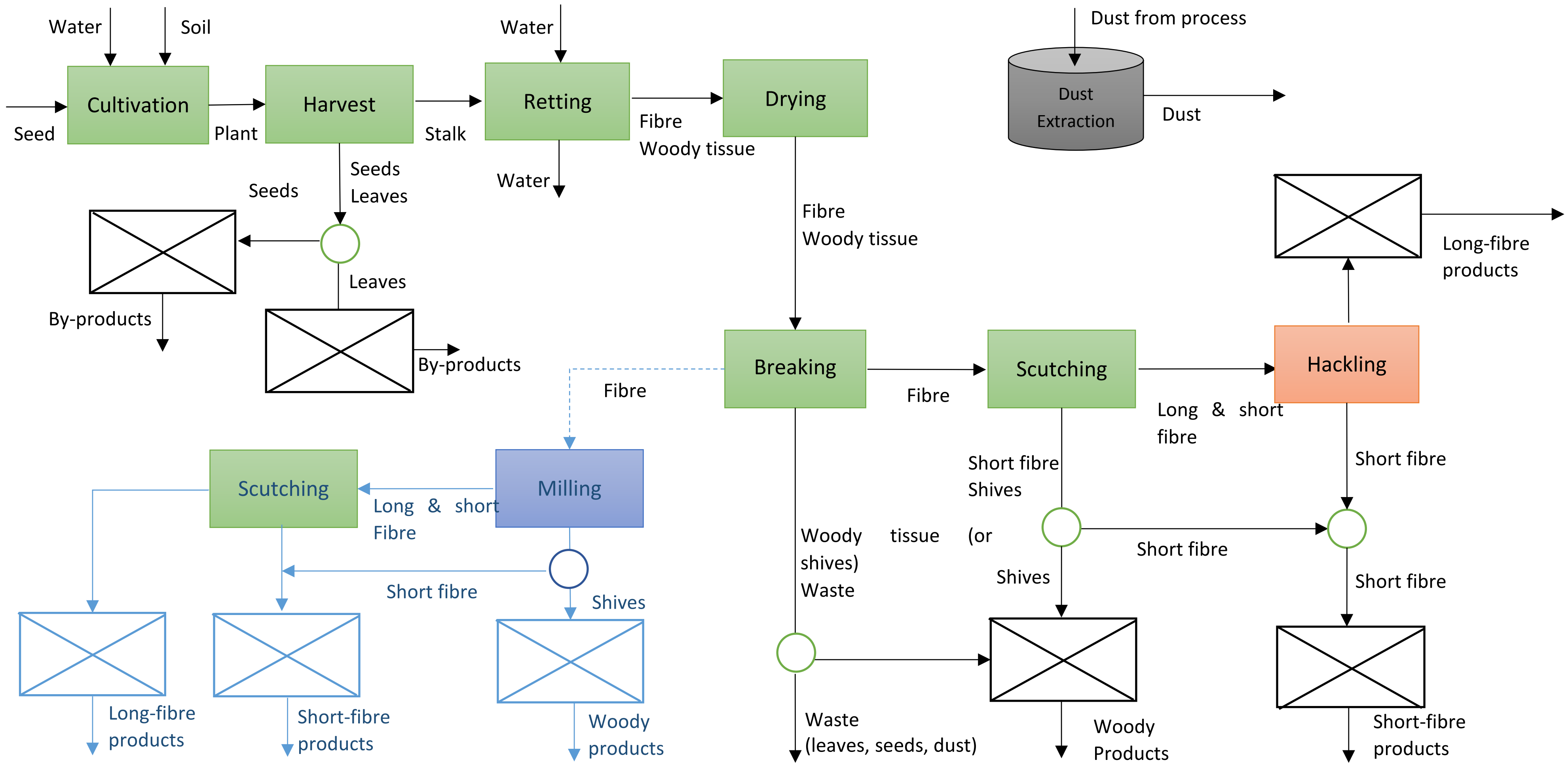
Contents

APPENDIX I: HEMP PRODUCTS AND USES

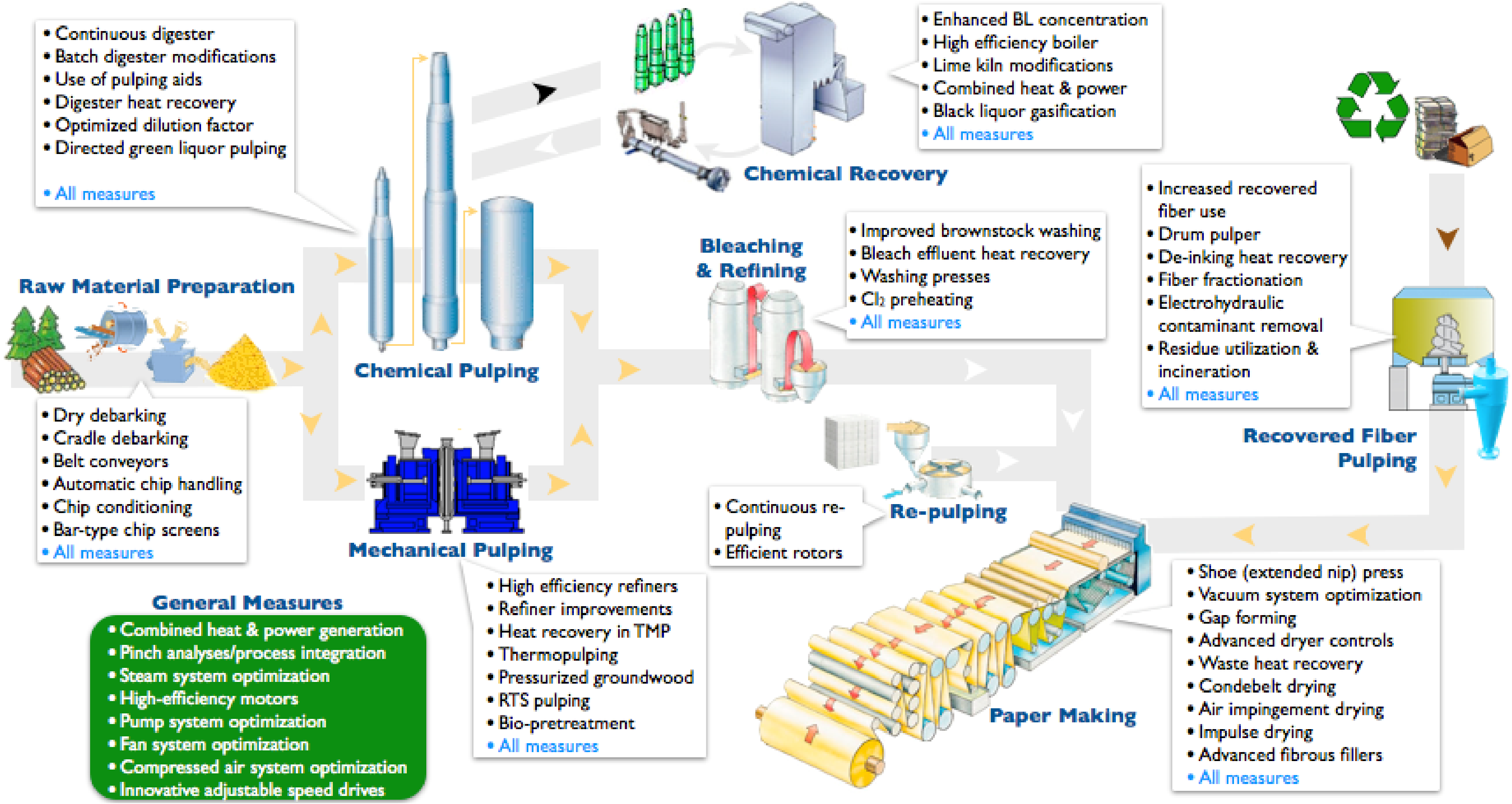


http://www.nkytribune.com/wp-content/uploads/2015/02/hemp.jpg

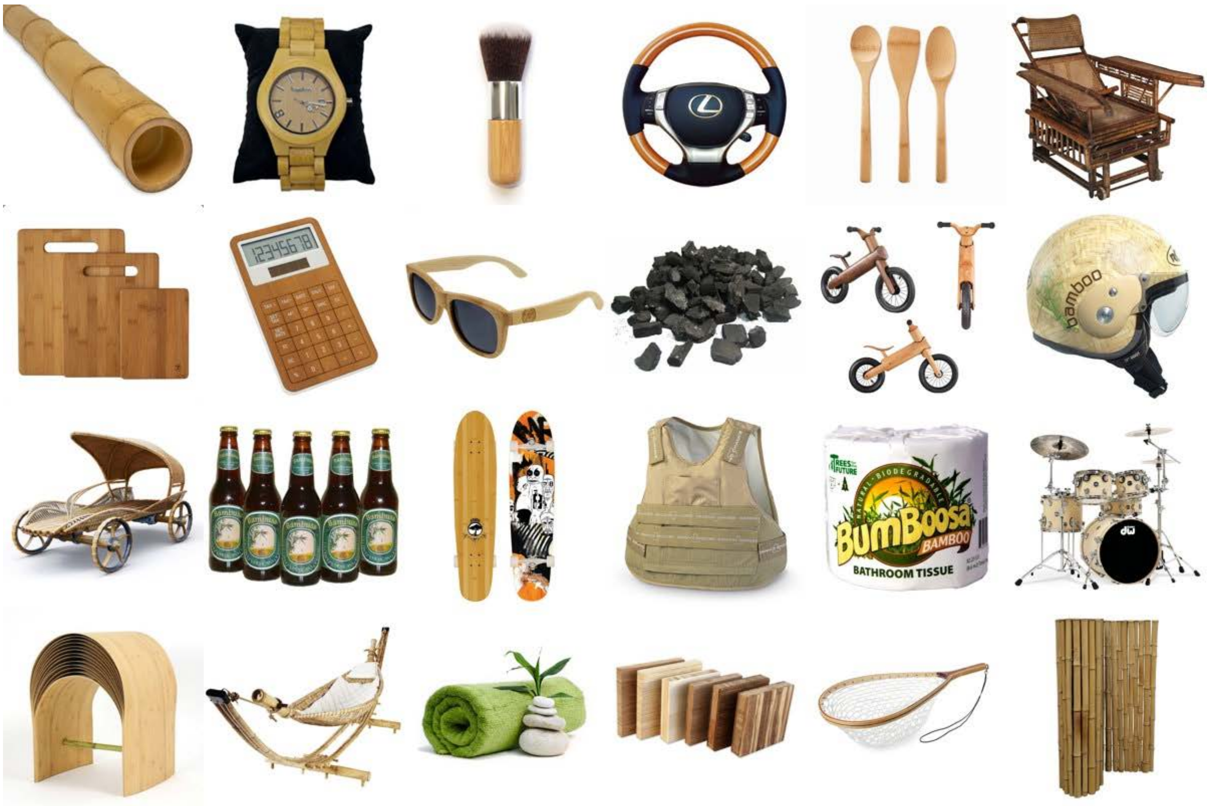
APPENDIX II: SUMMARY OF BAST FIBRE MULTI-PRODUCT PROCESS FLOWSHEET



APPENDIX III: PAPER PRODUCTION PROCESS

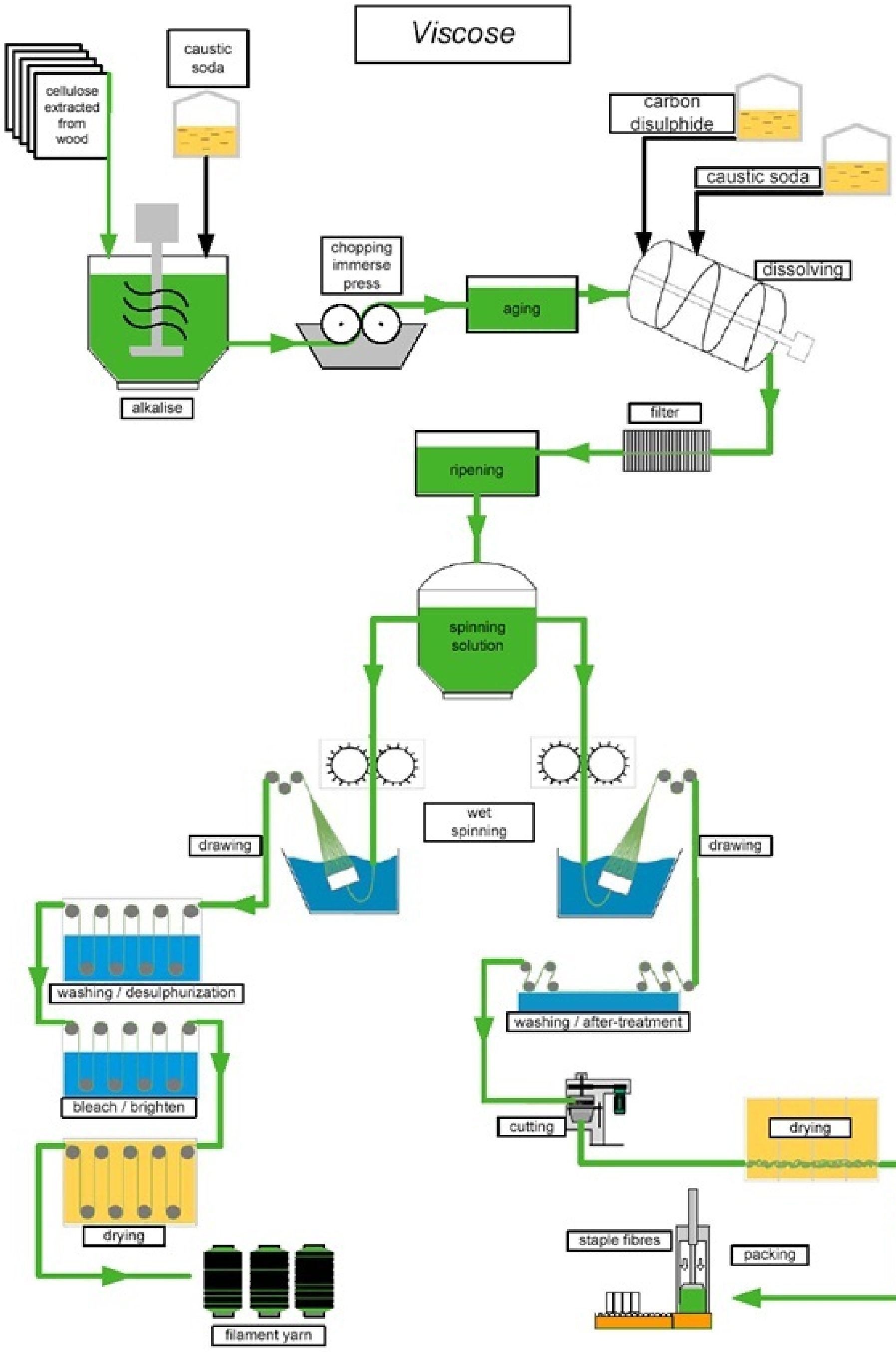


APPENDIX IV: EXAMPLES OF BAMBOO PRODUCTS AND USES



https://www.bambooimport.com/en/blog/products-made-from-bamboo

APPENDIX V: CONVENTIONAL PROCESS FOR VISCOSE PRODUCTION



https://oecotextiles.wordpress.com/category/fibers/viscose/

Process description for viscose production

The bamboo leaves and the soft, inner pith from the bamboo plant are extracted and crushed. The crushed bamboo cellulose is then soaked in a solution of 15% to 20% sodium hydroxide, at a temperature of 20^{o}C and 25^{o}C. This soak will last between 1 and 3 hours and will turn the bamboo cellulose into alkali cellulose. The bamboo alkali cellulose is then processed to remove excess sodium hydroxide. The mash that is left over is crushed by a grinder, before being left to dry for 24 hours. After the drying process, about a third of carbon disulfide is then added to the dry bamboo alkali mash. This causes the compound to sulfurise, and it turns it into a gel-type mixture. At the end of this step, any remaining carbon disulfide is evaporated and removed due to decompression. The resulting mixture is sodium xanthogenate. The next step is to add a diluted solution of sodium hydroxide to the sodium xanthogenate. The sodium hydroxide dissolves the sodium xanthogenate to create a viscose mixture. This mixture consists of 5% sodium hydroxide, and 7% – 15% bamboo fibre cellulose. The viscose bamboo cellulose is then forced through nozzles into a large container of diluted sulfuric acid solution, which then hardens the viscose bamboo cellulose sodium xanthogenate.

APPENDIX VI: SUMMARY OF BAMBOO MULTI-PRODUCT PROCESS FLOWSHEET