Chapter 15

Plant Fibres for Textile and Technical Applications

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Additional information is available at the end of the chapter

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1. Introduction

Recently natural and made-man polymer fibres are used for preparation of functionalised textiles to achieve smart and intelligent properties. There are numerous application possibilities of these modified materials. Main pathways for functionalizaton of fibres are: inclusion of functional additives (inorganic particles, polymers, organic compounds); chemical grafting of additives on the surface of fibres and coating of fibres with layers of functional coatings. A new approach to produce new materials is by nanotechnology, which offers a wide variety of possibilities for development of materials with improved properties. Composites of cellulose fibres with nano-particles combine numerous advantageous properties of cellulose with functionality of inorganic particles, hence yielding new, intelligent materials. For preparing cellulose composite materials profound knowledge about fibres properties is needed. Besides, new fibre qualities are demanded to guaranty the modification efficiency. Therefore non-standard methods are involved to determine physical properties of fibres.

In addition to, manufacture, use and removal of traditional textile materials are now considered more critically because of increasing environmental consciousness and the demands of legislative authorities. Natural cellulose fibres have successfully proven their qualities when also taking into account an ecological view of fibre materials. Different cellulose fibres can be used for textile and technical applications, e.g. bast or stem fibres, which form fibrous bundles in the inner bark (phloem or bast) of stems of dicotyledenous plants, leaf fibres which run lengthwise through the leaves of monocotyledenous plants and fibres of seeds and fruits. Flax, hemp, jute, ramie, sisal and coir are mainly used for technical purposes. Recently, the interest for renewable resources for fibres particularly of plant origin is increasing. Therefore several non-traditional plants are being studied with the aim to isolate fibres from plant leaves or stems.

A review of different conventional and non-conventional fibres is presented. For extraction of fibres different isolation procedures are possible, e.g. using bacteria and fungi, chemical and mechanical methods. The procedure used influences fibres surface morphology. By fibre isolation procedures mainly technical fibres are obtained, which means that cellulose fibres are multicellular structures with individual cells bound into fibre bundles.

2. Plant fibres

Many useful fibres have been obtained from various parts of plants including leaves, stems (bast fibres), fruits and seeds. Geometrical dimensions of these fibres, especially the fibre length depends mainly on fibre location within the plant. Fibres from fruits and seeds are few centimetres long, whereas fibres from stems and leaves are much longer (longer than one meter) [Blackburn 2005].

With an exception of seeds' and fruits' fibres, plant fibres are sclerenchyma elongated cells which occur in different parts of plants, mainly in the stems and leaves. These are elongated cells with tapering ends and very thick, usually heavily lignified cell walls. Sclerenchyma gives mechanical strength and rigidity to the plant, since it is usually a supporting tissue in plants. Fibres are also associated with the xylem and phloem tissue of monocotyledonous and dicotyledonous plant stems and leaves.

All plant cells have a primary wall. During cell growth and after it has stopped, the cytoplasm in sclerenchyma cells dries while the cell wall becomes thickened by addition of a thick and rigid secondary cell wall which is formed inwards of the primary cell wall and constructed of cellulose fibrils. The secondary cell wall is formed by successive deposition of cellulose layers, which are divided in three sub-layers (S1, S2 and S3), of which the middle layer is the most important for fibres mechanical properties. It consists of helically arranged microfibrils. The diameter of microfibrils is between 10-30nm [John 2008]. An important parameter of the structure of the secondary wall is the angle that the cellulose microfibrils are making with the main fibre direction. Actually each of three fibres sub-layers has a different microfibrillar orientation [Krässig 1992, John 2008, Cuissinat 2008] which is specific for the fibre type. Due to the formation of a thick secondary wall, the lumen becomes smaller.

The cell wall in a fibre is not a homogeneous layer. The walls of plant cells (the primary and the secondary cell wall) can be considered as a composite consisting of cellulose fibrils embedded within a matrix of lignin and hemicellulosic polysaccharides [Krässig 1992].

Vegetable fibres are generally composed of three structural polymers (the polysaccharides cellulose, and hemicelluloses and the aromatic polymer lignin) as well as by some minor non-structural components (i.e. proteins, extractives, minerals) [Marques 2010]. Cellulose forms a crystalline structure with regions of high order i.e. crystalline regions and regions of low order i.e. amorphous regions. Middle lamellas composed of pectic polysaccharides are connecting individual cells in bundles [Caffall 2009].

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Retting which is the process of separating fibres from non-fibre tissues in plants, involves bacteria and fungi treatments and mechanical and chemical processes for fibres extraction. Despite good quality of fibres, dew retting is usually replaced by other more economic methods because the process is very time consuming and weather dependent. Instead of atmospheric retting chemical methods and enzyme retting with pectinases, hemicellulases and cellulases is used, however fibre properties depend on extraction conditions significantly.

2.1. Morphology of lignocellulosic fibres

Sclerenchyma cells possess fibre like form and are arranged longitudinally. The cells are long and narrowed at the cell ends and surrounded and protected by a cell wall which is a complex macromolecular structure. During cells growth the wall is thickened and further strengthened by addition of a secondary wall. Usually fibre cells are occurring in strands or bundles which are called technical fibres [Caffall 2009]. The cells are polygonal in transverse section and connected between themselves by sclerenchyma middle lamellas. The lumen or cavity inside mature, dead fibre cells is usually very small when viewed in cross section [Lewin 1998, Cook, 1993].

2.2. Fibre structure

The cellulose, hemicellulose and lignin content in plant fibres vary depending on the plant species, origin, quality and conditioning [Blackburn 2005].

Chemically unmodified cellulose is generally recognised to occur in four polymorphic forms. There is some evidence for the existence of others [Krässig1992, Lewin 1998]. The monoclinic spatial model for the unit cell of native cellulose is cellulose I crystal modification. The unit cell houses the cellobiose segments of two cellulose molecules, one being part of the 002 corner plane and the second being part of the 002 centre plane [Lewin 1998, Hu 1996]. The monoclinic unit cell has dimensions of 0.835 nm for the a – axis, 1.03 nm for the b-axis or fibre period, 0.79 nm for the c-axis, and 84^0 for the ß angle according to Meyer, Mark and Misch [Krässig 1992]. For natural cellulose a typical x-ray diffraction diagram is observed, that is, three equatorial diffraction peaks at the angles of about 14°, 16° and the strongest diffraction peak at an angle of 22° [Yueping 2010].

However, the crystalline dimorphism of cellulose and the existence of two families of native cellulose were confirmed lately. The crystalline phases I_α and I_β can occur in variable proportions according to the source of the cellulose. Phase I_β is a monoclinic unit cell having space group $P2_1$ and dimensions a = 0.801nm, b = 0.817nm, c = 1.036 nm, ß = 97.3º and very close to the cell proposed by Meyer, Mark and Misch. Phase I_α corresponds to a triclinic unit cell with space group P_1 and dimensions a = 0.674nm, b = 0.593nm c = 1.036nm, α= 117º, γ = 113º and ß = 97.3º [O'Sullivan 1997]. The celluloses produced by primitive organisms (bacteria, algae etc.) are classified by the I_α phase whereas the cellulose of higher plants (woody tissues, cotton, ramie etc.) consists mainly of the I_β phase. I_α and I_β were found to have the same conformation of the heavy atom skeleton, but to differ in their hydrogen bonding patterns [O'Sullivan 1997].

Regenerated cellulose II is obtained when native cellulose is treated with strongly alkaline solutions or precipitated from solutions, such as when producing man-made cellulose fibres. The cellulose III crystal structure is formed after treating the cellulose with liquid ammonia and cellulose IV lattice structure is obtained by treating regenerated cellulose fibres in a hot bath under stretch.

Furthermore, cellulose molecules are, during the course of biosynthesis, arranged in morphological units elementary fibrils. The fibrillar structure model is accepted for cellulose native and man made fibres however, there are some differences in the structural arrangement between different types of these fibres [Krässig 1992]. Elementary fibrils are strings of elementary crystallites which are associated in a more or less random fashion into aggregations. Isolated segments of the fibrils fringing from aggregations are forming a fibrillar network. By transition of cellulose molecules from crystallite to crystallite the longitudinal connections are achieved and coherence of the fibrils by hydrogen bonds at close contact points or by diverging molecules [Krässig 1992].

Microfibrillar orientation is different for different types of cellulose native fibres. It is a very important influence factor for fibres mechanical properties. Microfibrillar angle MFA of bamboo is 2^0-10^0, of coir 41^0-45^0, of flax 10^0, of jute 8^0, of ramie 7.5^0, of sisal fibres 20^0 [Blackburn 2005] and of cotton 20-30^0 [Morton 1993]. Besides microfibrillar orientation, fibres strength and stiffness depend on fibres constitution, cellulose content, crystallinity and degree of polymerisation. In addition to, fibres maturity and part of the plant from which fibres are obtained plays an important role.

Due to the imperfect axial orientation of the fibrillar aggregates, interfibrillar and intrafibrilar voids and less ordered interlinking regions between the crystallites inside the elementary fibrils the pore system of cellulose fibres is formed.

3. Conventional plant fibres

Textile fibres are broadly classified as natural fibres and man-made fibres, as shown in Figure 1. Natural fibres refer to fibres that occur within nature, and are found in vegetables respectively plants (cellulose fibres), animals (protein fibres) and minerals (asbestos). Man-made fibres are those that are not present in nature, although they may be composed of naturally-occurring materials. They are classified into three main groups: those made by transformation of natural polymers (regenerated fibres), those made from synthetic polymers (synthetic fibres), and those made from inorganic materials (fibres made of metal, ceramics, and carbon or glass) [BISFA.2006].

Nature in its abundance offers us a lot of materials that can be called fibrous. Plant fibres are obtained from various parts of plants, such as the seeds (cotton, kapok, milkweed), stems (flax, jute, hemp, ramie, kenaf, nettle, bamboo), and leaves (sisal, manila, abaca), fruit (coir) and other grass fibres. Fibres from these plants can be considered to be totally renewable and biodegradable. Plant fibres, which have a long history in human civilisation, have

gained economic importance and are now cultivated on a large scale globally [Blackburn 2005, Mather 2011, Hearle 1963, Mwaikambo 2006].

Fibres that are produced on the seeds of various plants have been called seed hair or seed fibres. The most important fibre of this class is cotton. Other fibres of this group (kapok, floss from milkweed, dandelion, and thistle fibres) are not generally spun into yarns, but are utilized mainly as staffing in pillows and mattresses, and for life belts [Hearle1963].

NATURAL FIBRES		MAN-MADE FIBRES
VEGETABLE ORIGIN - **CELLULOSE FIBRES**		**NATURAL POLYMER BASED**
▪ **SEED FIBRES:** COTTON, KAPOK ▪ **BAST FIBRES:** JUTE, FLAX, HEMP, RAMIE, KENAF ... ▪ **LEAF FIBRES:** ABACA, SISAL, HENEQUEN ...		▪ **REGENERATED CELLULOSE**: ▪ VISCOSE, MODAL, LYOCELL, CUPRO ▪ **REGENERATED PROTEIN**: CASEIN, ARACHIN ZEIN ▪ **CELLULOSE ESTERS**: ACETATES ▪ **RUBBER:** ELASTODIENE ▪ **ALGINATE**
ANIMAL ORIGIN – **PROTEIN FIBRES**		**SYNTHETIC POLYMER BASED**
▪ **WOOL** ▪ **HAIR FIBRES:** ANGORA, MOHAIR, ALPACA ... ▪ **SILK**		ACRYLIC, ARAMID, CHLOROFIBRE, FLUOROFIBRE, MODACRYLIC, POLYAMIDE, POLYESTER, POLYETHYLENE, POLYIMIDE, POLYPROPYLENE, VINYLAL, POLYLACTIDE ...
INORGANIC:		**INORGANIC:**
ASBESTOS		CARBON, CERAMIC, GLASS, METAL

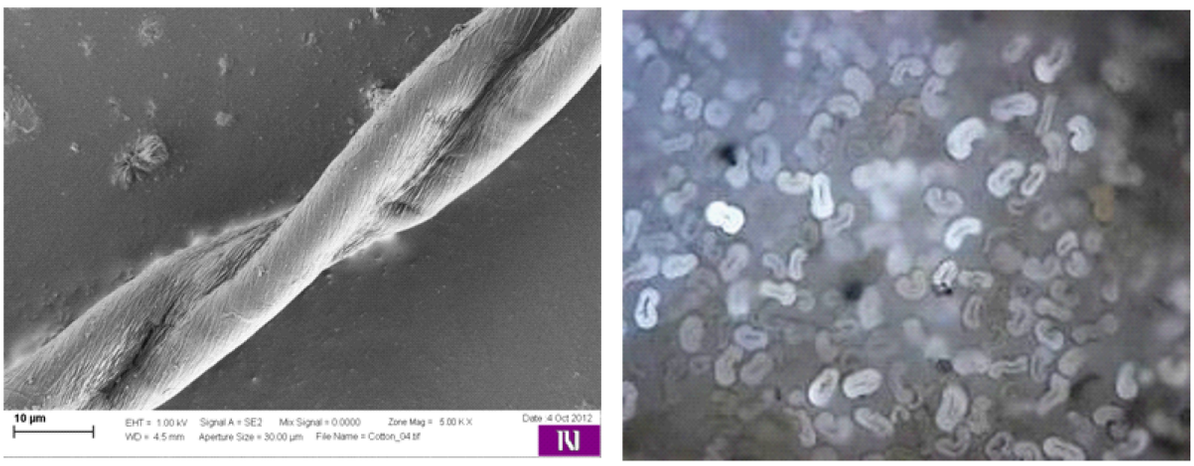
Figure 1. Classification of textile fibres

3.1. Seed fibres

3.1.1. Cotton

Due to fibres properties and low cost, cotton represents the most used textile fibre in the world. Fibres are obtained from seeds of the plant species *Gossypium*, which belongs to the *Malvaceae* family. Cotton fibres consist of unicellular seed hairs of the bolls of the cotton plant. Cotton fruit bursts when mature, revealing a tuft of fibres with the length from 25 to 60 mm and diameters varying between 12 and 45 μm. Cotton fibres have a pronounced three-wall structure. The cuticle layer consists of wax and pectin materials. This outer wax layer protects the primary wall, which is composed of cellulose crystalline fibrils. The secondary wall of the fibres consist of three distinct layers, which include closely packed parallel fibrils with spiral winding of 25 – 30° and represent the majority of cellulose within the fibres. Lumen is surrounded by the tertiary wall. The cross section of fibres is bean-shaped; however by swelling it is almost round when moisture absorption takes place (Figure 2).

Cotton fibres consist of 80-90% cellulose, 6-8% water, 0.5-1% waxes and fats, 0-1.5% proteins, 4-6% hemicelluloses and pectins and 1-1,8% ash [Lewin 1998, Hu 1996].



(a) (b)

Figure 2. a) Longitudinal view (5000× magnification) and b) cross-section of cotton fibre

Cotton is hydrophilic and the fibres swell considerably in water. Fibres are stable in water and its wet tenacity is up to 20% higher then its dry tenacity (25-40cN/tex). The toughness and initial modulus of cotton are lower compared to hemp fibres, whereas its elongation at break (5-10%) and its elastic recovery are higher. The fibres are resistant to alkali but degraded by acids. The microbial resistance of cotton is low, it burns readily and quickly, can be boiled and sterilized, and does not cause skin irritation or other allergies [Lewin 1998, Cook 1993].

3.1.2. Kapok

Kapok *(Ceiba pentandra)* is a highly lignified organic seed fibre, containing 35-50% of cellulose, 22–45% of hemicelluloses, 15–22% of lignin and 2–3% of waxes. It also contains smaller quantities of starch, about 2.1% of proteins, and inorganic substances, notably iron (1.3–2.5%). Kapok contains 70–80% of air and provides excellent thermal and acoustic insulation. The absolute density of a kapok cell wall is 1.474 g/cm^3, whilst the density of fibres by considering about 74% of lumen is only 0.384 g/cm^3 [Cook 2006]. Kapok is a smooth, unicellular, cylindrically shaped, twist less fibre. Its cell wall is thin and covered with a thick layer of wax. A wide lumen is filled with air and does not collapse like cotton. By the microscope observation kapok fibres are transparent with characteristic air bubbles in the lumen. The cross section of fibres (Figure 3) is oval to round. The kapok cell wall structure differs from other natural cellulosic fibres. A primary cell wall, which is directly related to the superficial properties of fibres, consists of short microfibrils, which are oriented rectangular to the surface of fibres. In the secondary cell wall microfibrils run almost parallel to the fibre axis. [Hearle 1963, Rijavec 2008, Fengel 1986, Khalili 2000, Fengel 1986/2]. Considering the content

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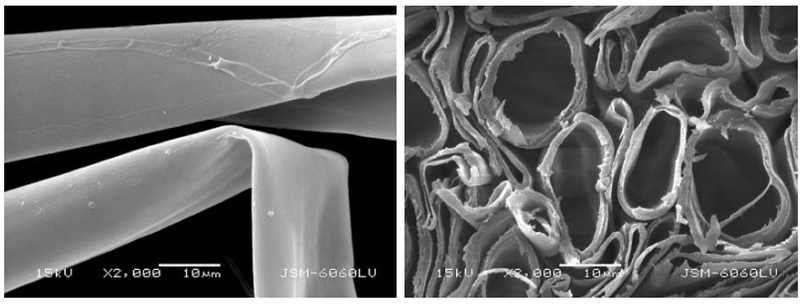
of alpha cellulose, kapok is more like wood than flax and other plant fibres. The average degree of polymerisation is 6600 [Fengel 1986]. Kapok fibres are 10–35 mm long, with a diameter of 20–43 μm. The cell wall thickness is about 1–3 μm. The tensile strength is 0.84 cN/dtex (93.3 MPa), Young's module 4 GPa, and breaking elongation 1.2% [Mwaikamno 2001].

Due to its wide lumen, kapok has an exceptional capability of liquids retention. Its excellent thermal and acoustic insulating properties, high buoyancy, and good oil and other non-polar liquids absorbency distinguish kapok from other cellulosic fibres. Kapok is mainly used in the form of stuffing and nonwovens; it is rarely used in yarns, mostly due to low cohesivity of its fibres and their resilience, brittleness, and low strength. New potentials of kapok are in the field of technical textiles, yachts and boats furnishing, insulating materials in refrigeration systems, acoustic insulation, industrial wastewaters filtration, removal of spilled oil from water surfaces, and reinforcement components in polymer composites [Rijavec 2008].



(a) (b)

Figure 3. SEM image of longitudinal view (a) and cross section (b) of kapok (2000× magnification) [Rijavec 2008].

3.2. Bast fibres

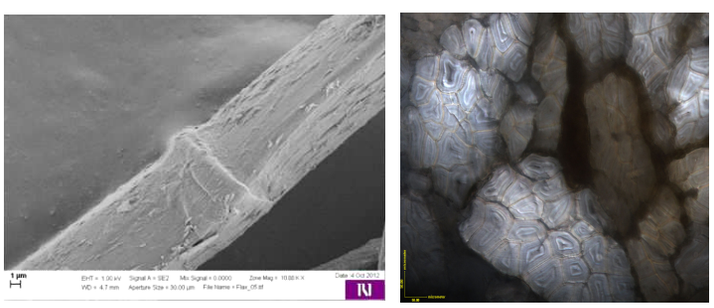
Bast fibres i.e. flax, jute, hemp, ramie, kenaf, and abaca are soft woody fibres, which are obtained from stems or stalks of dicotyledonous plants. The fibres occur in bundles or aggregates [Hearle 1963]. The bundles consist of 10 to 25 elementary fibres, with the length of 2 to 5 mm and a diameter of 10 to 50 μm. The bundles are connected by lateral ramification, which forms a three dimensional network. The elementary fibrils and bundles are cemented by lignin and pectin intercellular substances, which must be removed during the processing of fibres extraction [Mohanty 2005]. Bast fibres have a long utilization tradition. They have been used for more than 8000 years. Currently bast fibres are raw materials not only used for the textile industry but also for modern environmentally friendly composites used in different areas of applications like building materials, particle boards, insulation boards, food, cosmetics, medicine and source for other biopolymers etc.

3.2.1. Flax

Flax fibres are obtained from the stems of the plant *Linum usitatissimum*. Fibres are running at the surface of the plant stem, which is about 1 m height and 2 – 3 mm thick in the diame-

ter [Blackburn 2005]. Like cotton, flax fibre is a cellulose fibre, however its structure is more crystalline, making it stronger, and stiffer to handle, and more easily wrinkled. Flax fibre properties are controlled by the molecular fine structure, which is affected by the plant growing conditions and the retting procedure that is applied.

The process of retting tends to separate the bundles of flax fibres into individual fibres, although many fibres remaining together in bundles [Hearle 1963]. Flax fibres are not as pure as cotton in terms cellulose content; indeed they contain only about 60 - 70% of cellulose. In addition they contain other substances such as hemicelluloses 17% and lignin 2-3%, as well as waxes 2%, pectins 10% and natural colouring matters [Mather 2011, Mohanty 2005]. Flax fibres have a soft handle and have fairly lustrous appearance. The length of fibres varies between 6 – 65 mm, but on average they are about 20 mm long. Their diameter is about 20 μm. Flax fibres are not as twisted as cotton fibres, but both have a lumen in the centre. Several dislocations that are areas of the cell wall in natural fibres where the direction of the microfibrils (the microfibril angle) differs from the microfibril angle of the surrounding cell wall, are observed on longitudinal images of fibres (Figure 4). These deformations are due to extraction procedures [Thygesen 2006]. The shape of fibres varies from polygonal to oval and irregular. Fibres cross-section form depends on variety, plant growth conditions and maturity. Flax fibres are amongst the strongest in the group of naturally occurring fibres (55 cN/tex and about 20% stronger in wet state), but they do not stretch much. Flax fibres elongation at break is only 1.8% and their moisture regain is 12% [Lewin 1998, Cook 1993].



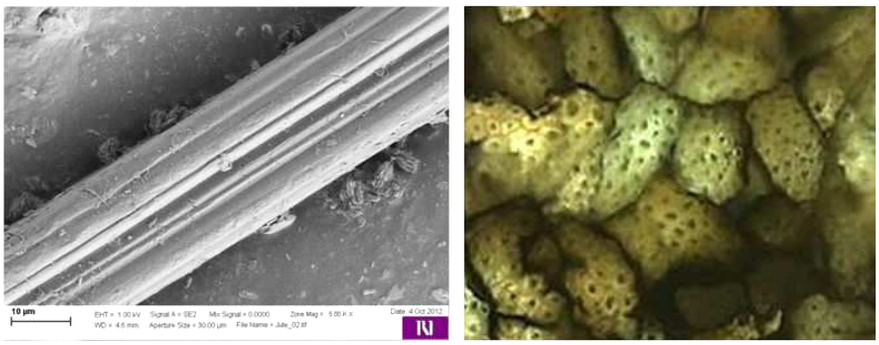
(a) (b)

Figure 4. a) Longitudinal view (10000× magnification) and b) cross-section (30× magnification) of flax fibre

3.2.2. Jute

Jute is a natural fibre obtained as an extract from the bark of the white jute plant *Corchorus capsularis* and to a lesser extent from tossa jute (*Corchorus olitorius*) [Mohanty 2005]. Jute is a long, soft and shiny fibre that can be spun into coarse, strong threads and is one of the cheapest natural fibres. It is also the most versatile, eco-friendly, natural, durable and antistatic fibre available. The plants are retted by the same method used for flax. The resulted jute strand, which are up to 3 m long, are composed of many very short fibres, elementary fibres (length between 0.5-6.0 mm, diameter 26-30 μm) held together by lignocelluloses. The fibres contain between 61-71% cellulose, large amount of hemicelluloses (14-20%) and lignin

(12-13%) and pectin (0.2%) [Mather 2011]. The cross-sections of bundles of jute fibres show a range in the size and number of fibres per bundle, in the thickness of the wall and in the shape and diameter of lumens. The fibre is generally smooth, with some dislocations. The individual fibres are mainly polygonal, with rounded corners and oval to round lumens (Figure 5) [Hearle 1963]. Jute has a moderate strength (30-45 cN/tex), however it is not as strong as flax or hemp. For fibres low extension at break (1-2%) is characteristic. Moisture regain of jute fibres is 12.6%, but it can absorb up to 23% of water under conditions of high humidity. Jute has high insulating and anti-static properties and low thermal conductivity [Cook 1993, Mwaikamno 2009].



(a) (b)

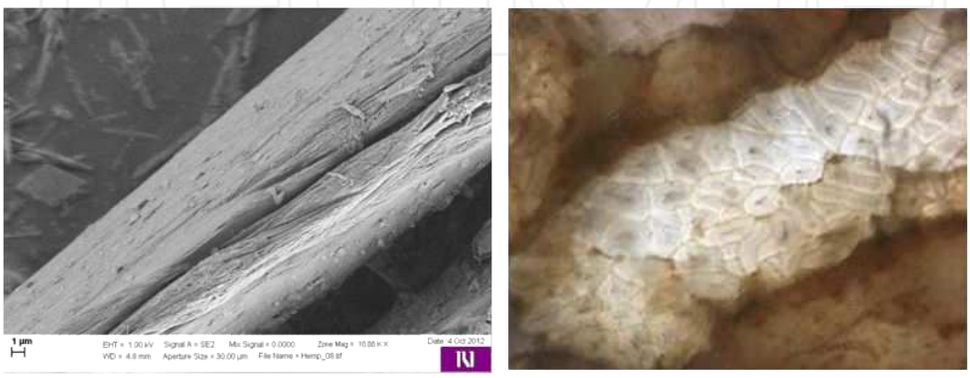
Figure 5. a) Longitudinal view (5000× magnification) and b) cross-section (180× magnification) of jute fibre

3.2.3. Hemp

Hemp is the bast fibre obtained from stems of *Cannabis sativa* L plants. It grows easily to a height of 4 m without agrochemicals and captures large quantities of carbon. The most important components of fibres are cellulose (77%), pectin (1.4%) and waxes (1.4%). Pectin is found in the middle lamellae and glues the elementary fibres to form bundles. The lignin (1.7%) is an incrusting component of the fibre. It is incrusting cellulose and contributes to the hardness and strength of fibres. It is located in the middle lamellae and fibre primary cell wall. Other components of hemp fibres are tannin, resins, fats, proteins etc. The content of these components is much higher in hemp than in cotton.

Therefore the processing of those fibres requires different technology [Blackburn 2005]. The diameter of the cell varies considerably from 16 to 50 μm, with broad flat lumen. The length of the individual or elementary fibres is ranging from 2 to 90 mm (average length is 15 mm). Elementary fibres are thick walled and the cross-section of fibres is polygonal with rounded edges (Figure 6). In longitudinal view, the fibre is roughly cylindrical, with surface irregularities and lengthwise deformations caused by dislocations. The ends of fibres are slightly tapered and blunt [Hearle 1963]. Hemp fibres are coarser when compared to flax and rather

difficult to bleach. The fibres have an excellent moisture resistance and rot only very slowly in water. Hemp fibres have high tenacity (53-62 cN/tex); about 20% higher than flax, but low elongation at break (only 1.5%) [Mohanty 2005].



(a) (b)

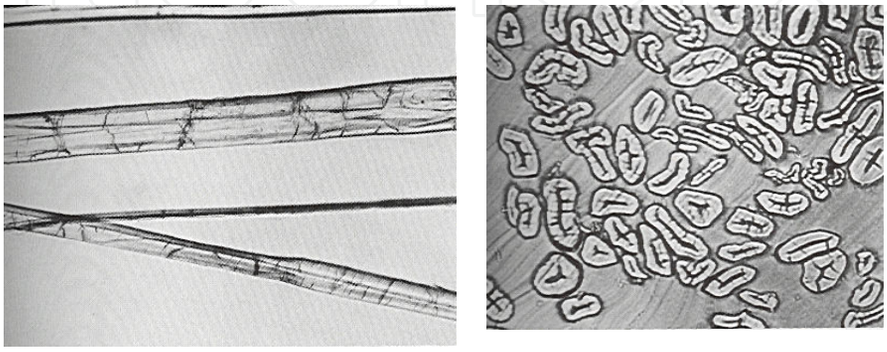
Figure 6. a) Longitudinal view (10000× magnification) and b) cross-section (200× magnification) of hemp fibre

In recent years because of the interest for alternative renewable resources, hemp gained again relevance. Beside the traditional textile application of hemp numerous new directions emerge: building and isolation materials, composite materials, special cellulose materials (papers), technical textile, geotextiles and agricultural textile, oil based products, items for agriculture and horticulture etc. [Blackburn 2005].

3.2.4. Ramie

Ramie is a herbaceous perennial plant in the nettle family *Urticaceae*, native to eastern Asia. Ramie fibres are extracted from the stem of the plant *Boehmeria nivea* of the nettle family. Individual fibre cells in stems are bound together in fibre bundles by waxes, hemicelluloses, lignin and pectins that are difficult to remove (Figure 7). Therefore the efficiency of the retting process usually used for e.g. hemp fibres extraction is not sufficient to extract ramie fibres from stems. But, a combined microbial and chemical treatment is very effective and economical. Chemical composition of ramie fibres is: cellulose (91-93%), hemicelluloses (2.5%), pectin (0.63%) and lignin (0.65%). Ramie fibres exhibit excellent mechanical properties, i.e. the best in the group of bast fibres (45-88 cN/tex) and, as most of the natural cellulose fibres the strength increases by 25% when fibres are wet. The ultimate fibre length is between 120-150mm and fibre diameter is 40-60 μm. Fibres are durable and they have good

resistance to bacteria, mildew and insect attack. The main disadvantage of ramie is its low elasticity (elongation at break is 3-7%), which means that it is stiff and brittle [Mather 2011]. Fibres are oval to cylindrical in shape and their colour is white and high lustrous. Fibres surface is rough and characterized by small ridges, striations, and deep fissures. Ramie fibre can be easily identified by its coarse, thick cell wall, lack of twist, and surface characteristics [Hearle 1963].



(a) (b)

Figure 7. a) Longitudinal view and b) cross-section (100× magnification) of ramie fibre

3.2.5. Kenaf

Kenaf fibres are obtained from *Hibiscus cannabinus*. Kenaf contains two fibre types: long fibre bundles situated in the cortical layer and short fibres located in the ligneous zone. Elementary fibres are short; their fibre length ranges from 3 to 7 mm, with average diameter of 21 μm. The cross-sections are polygonal with rounded edges and the lumens are predominantly large and oval to round in shape [Hearle 1963]. The lumen varies greatly in thickness along the cell length and it is several times interrupted. Kenaf fibres contain about 45-57% of cellulose, 21.5% hemicelluloses, 8-13% lignin and 3-5% pectin. Kenaf fibres are coarse, brittle and difficult to process. Their breaking strength is similar to that of low-grade jute and is weakened only slightly when wet. There are many potential specific utilization possibilities for kenaf whole stalk and outer bast fibres, including paper products, textiles, composites, building materials, absorbents, etc. [Mohanty 2005].

3.3. Leaf fibres

Leaf fibres are often referred to as hard fibres, and have limited commercial value, mainly because they are generally stiffer and coarser texture than the bast fibres. The fibres are usually obtained from the leaves by mechanically scraping away the non fibrous material. Above all the leaves fibres are used for production of cordage and ropes. The most important fibres of this group are sisal, henequen and abaca.

3.3.1. Sisal

The sisal fibre is a "hard" fibre extracted from fresh leaves of sisal plant *Agave sisalana*. It is usually obtained by a decortication process, in which the leaf is crushed between rollers and then mechanically scraped. The length of the sisal fibre varies between 0.6 and 1.5 m and its diameters range from 100 to 300 μm [Mohanty 2005]. Cellulose content in sisal fibres is about 70%. The fibre is composed of numerous elongated fibre cells that are narrowed towards both ends. Fibre cells are linked together by middle lamellae, which consist of hemicelluloses, lignin and pectin. A sisal fibre in cross-section is built up of about 100 fibre cells. The cross section of sisal fibres is neither circular nor fairly uniform in dimension. The lumen varies in size but is usually well defined. The longitudinal shape is approximately cylindrical. Longitudinal view and cross-section of sisal fibres is demonstrated on Fig.8. Physically, each fibre cell is made up of four main parts, namely the primary wall, the thick secondary wall, the tertiary wall and the lumen. The fibrils are, in turn, built up of microfibrils with a thickness of about 20 μm. The microfibrils are composed of cellulose molecular chains with a thickness of 0.7 μm and a length of a few μm [Joseph 1999]. Sisal fibre is fairly coarse and inflexible. The tensile properties of sisal fibres are not uniform along its length. The fibres extracted from the root or lower parts of the leaf have a lower tensile strength and modulus. The fibres become stronger and stiffer at midspan, and the fibres extracted from the tip have moderate properties. The lower grade fibre is processed by the paper industry because of its high content of cellulose and hemicelluloses. The medium grade fibre is used in the cordage industry for making ropes, baler and binders twine. The higher-grade fibre after treatment is converted into yarns and used by the carpet industry.

(a) (b)

Figure 8. a) Longitudinal view (2500× magnification) and b) cross-section of sisal fibre

3.3.2. Abaca

Abaca or Manila hemp is extracted from the leaf sheath around the trunk of the abaca plant (*Musa textilis*). The commercial fibres are utilized in the form of strands, and the strands in turn are composed of bundles of individual fibres. Individual fibres, when removed from the strands by boiling in an alkali solution, are smooth and fairly uniform in diameter. The

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lumens are large in relation to wall thickness. Cross-marking is rare, and fibre tips pointed and often flat and ribbon –like. The technical fibres are 2 to 4 m long. The single fibres are relatively smooth and straight and have narrow pointed ends. Individual fibre diameters range from 14 to 50 μm and the lengths from 2.5 to 13 mm [Hearle 1963]. Chemically, abaca comprises 76.6% cellulose, 14.6% hemicelluloses, 8.4% lignin, 0.3% pectin and 0.1% wax and fat. Abaca is considered as one of the strongest of all natural fibres, being three times stronger than cotton and twice that of sisal, and is far more resistant to saltwater decomposition than most of the vegetable fibres. Abaca is a lustrous fibre and yellowish white in colour. Abaca fibres are used manly to manufacture ropes and handicraft goods [Blackburn 2005].

3.3.3. Henequen

Henequen (*Agave fourcroydes*) plant of the family agave is a close relative to the sisal plant. The henequen plant is native to Mexico, where it has been a source of textile fibre since pre-Columbian times. Many factors can influence the properties of the fibre including weather conditions, age of the plant, type of soil, extraction method, etc. Henequen fibre is composed of approximately 77% cellulose, 4-8% hemicelluloses, 13% lignin and 2-6% pectin and waxes by weight [Blackburn 2005, Aguilarvega 1995]. Fibres have variable diameter, being larger at the butt end and the smaller at the tip end of the fibre. Also, the diameter is connected with the fibre's origin, fibres cultivated at different locations have different diameters. The fibre cross-section changes from a beanlike shape at the butt end to rounded form at the tip end of the fibres. Like sisal, henequen fibres are smooth, straight, yellow, and easily degraded in salt water. Compared to other leaf fibres, henequen has low elongation at break and low modulus, but relatively high tenacity which makes them suitable as reinforcement for polymers [Blackburn 2005].

4. Non-conventional plant fibres

Lignocellulosic agricultural by-products are a promising and beneficial source for cellulose fibres. Due to the chemical and physical properties, composition and sustainability agro-based biofibres represent a potential for use in textile and paper industry for fibres, chemicals, enzymes and other industrial products. Annually renewable resources, e.g. corn, wheat, rice, sorghum, barley, sugarcane, pineapple, banana and coconut, etc. by-products are utilized as agro-based biofibres [Reddy 2005].

Also in non-conventional fibre plants elongated sclerenchyma cells are organized in a similar manner than traditional fibre cells like flax, hemp etc. These cells provide strength and support and are located next to the outer bark in the bast or phloem and serve to strengthen the stems. The fibres are in strands running the length of the stem.

To extract the fibre strands from other plant tissues the natural gum binding them must be removed by retting. The most common way is a biological treatment by an enzymatic or bacterial action on the pectinous matter of the stem.

Several techniques are used for extraction of conventional bast fibres: (i) Dew retting by the action of dew, sun, and fungi on the plants spread out on the ground, (ii) Water retting is conducted in rivers or pools through bacterial action and takes 2–4 weeks, (iii) For chemical retting solutions of different chemicals are used, e.g. sodium hydroxide, sodium carbonate, soaps, or mineral acids. The process takes only a few hours, (iiii) controlled biological or biochemical retting by addition of enzymes. The differences between the procedures are not only in expenses and process duration but the most important the quality and uniformity of retted fibres.

Ultimate fibres extracted from agricultural by-products are round, polygonal or elliptical in cross section and have a lumen in the centre. Their geometrical properties are conditioned by fibres origin and are different.

Reddy and Yang have collected structural characteristics and biofibres properties (Table1) [Reddy 2005]. Fibres obtained from pineapple leaves are the longest in this group and because of high crystallinity and high content of cellulose (70-82%) they express good mechanical properties (Young's modulus 400–627 MPa) [John 2008].

Fibre	Length (mm)	Width (μm)	Crystallinity (%)
cornhusk	0.5-1.5	10-20	48-50
pineapple leaf fibre	3-9	20-80	44-60
coir	0.3-1.0	100-450	27-33
bagasse	0.8-2.8	10-34	-
banana	0.9-4.0	80-250	45
wheat straw	0.4-3.2	8-34	55-65
rice straw	0.4-3.4	4-16	40
sorghum stalks	0.8-1.2	30-80	-
barley straw	0.7-3.1	7-24	-

Table 1. Properties of some non-conventional plant fibres [Reddy 2005]

4.1. Fibres from corn stover

As a kind of abundant and renewable agricultural residue, corn (Zea mays L.) stover, that refers a combination of corn stalk (stem) and leaf, could be a low-cost and sustainable source for energy and chemicals in future. For a long time (since 1929) fibres obtained from corn waste materials have been studied and utilized for pulp and papermaking [Li 2012].

Cornstalks as a potential for fibres extraction were studied by Reddy and Yang [Reddy 2005/2]. They have found, that natural cellulose fibres obtained from cornstalks have the structure and properties required for textile and other industrial applications.

The fibres obtained from cornstalks are composed of single cells bound together in cell bundles. Stronger fibres extraction conditions remove most of the binding substances resulting

in single cells that are too small to be used for high value fibrous applications. Elementary fibres with the length of 0.7 -1.5mm and cell diameter of 15 – 35 μm which is comparable to rice and wheat straw fibres were extracted and analysed. Fibres contain about 80% cellulose, 8% lignin and 8% moisture. The rest are minerals and pectin. The most important parameters for fibres properties, i.e. crystallinity and microfibrillar angle MFA condition fibres properties. The typical cellulose I structure is observed with the crystallinity of 52% and MFA of about $11^{0.}$ MFA is lower than that of cotton which has MFA in the range of $20–30^{0}$ depending on the maturity and cotton species. Due to high fibrils orientation tensile properties of fibres are good, i.e. they have high strength but low elongation. Elementary fibres form bundles with mechanical properties similar to that of kenaf and with moisture regain of about 7.9%, which is similar to that of cotton but lower than flax (12%) and kenaf (17%), respectively, are suitable for blending and processing with other common textile fibres to produce various products [Reddy 2005/2].

Although fibre properties of corn stover have been studied for decades, the first systematic investigation of cell morphology and fibre quality of different corn stover fractions was performed by Li et al. [Li 2012]. Individual fibres were connected in bundles by middle lamella with the highest lignin concentration. Obvious differences in cell morphologies and chemical compositions between four different plant fractions, i.e. stalk rind and stalk pith, and leaf blade and leaf sheath were observed. Fibres were shorter and finer in stalk pith and parenchyma and vessel content was the highest in this part of the plant. Therefore it was not suitable for papermaking, while morphological characteristics of fibres from corn stalk rind were appropriate as papermaking materials. There were also differences in lignification and hemicellulose content. Sclerenchyma cells in stalk rind were more lignified than those in other tissues. The lowest hemicellulose content was observed in stalk rind [Li 2012].

4.2. Wheat straw fibres

The microstructure, thermal and mechanical properties of wheat straw fibres have been examined and compared to flax straw fibres with an idea of using these natural fibres as reinforcing additives for thermoplastics [Hornsby 1997]. Of crucial importance in this regard is the manner by which their inherent mechanical properties alter on exposure to elevated temperatures, which are encountered during melt processing of the polymer. Under all test conditions flax straw was significantly stronger and stiffer than wheat straw. The tensile strength and elastic modulus decreased with increasing temperature up to 200^{0}C. This effect was minor for wheat straw than flax straw. The differences are due to fibres structural form. The form of wheat straw is much more cellular than flax. Due to different lignin content the thermal stability of flax fibres was significantly higher than it was for wheat straw [Hornsby 1997].

4.3. Fibres from hop stems

Hop (*Humulus lupulus* L.) belongs to the family *Cannabaceae* and genus cannabis that includes hemp. The use, production or properties of natural cellulose fibres from hop stems was studied by Reddy and Yang [Reddy 2009].

The single sclerenchyma cells in hop stem fibres are small. Their length is 2.0 ± 1.0 mm and width 16.5 ± 5.5μm. Fibres extracted from hop stems contain 84% of cellulose, 6% of lignin in 2% of ash. From the diffraction patterns of cellulose in hop stem fibres cellulose crystalline structure was determined. The crystallinity index is 44 ± 5% (65–70% for cotton and 81–89% for hemp cellulose) and microfibrillar angle of cellulose fibrils 8 ± 0.7^0. The diffraction pattern is very similar to the diffraction pattern of hemp. Cellulose crystallites in hop and hemp fibres are regularly distributed and are also parallel to the fibre axis and to each other.

Mechanical properties of hop stem fibres are close to that of hemp fibres. Shorter single cells and low crystallinity of cellulose in the fibres should be the major reasons for the lower breaking tenacity of hop fibres compared to hemp. Sorption properties of hop fibres are comparable to cotton properties and slightly lower than that of hemp [Reddy 2009].

4.4. Banana, sugarcane bagasse and sponge gourd fibers

Fibres from *Musaceae maturate rachis:* The fibrous structure of agro-industrial residues of two different types of *Musaceae* maturate waste rachises (banana -Musa AAA, cv 'Valery' and Musa AAB, cv 'Dominico Harton') has been studied by Gañán et al. Using an up-bottom approach, rachises, fibre bundles and conducting tissues, elementary or ultimate fibres, microfibrils bundles and cellulose microfibrils have been isolated [Gañán 2008]. For fibre bundles extraction biological retting followed by chemical treatment was used.

An important amount of vascular bundles that were formed by conducting tissues and fibre bundles was observed on rachis cross sections. Researchers are suggesting two groups of fibrous structures: the first at the microscopic level formed by conducting tissues, fibre bundles and their elementary fibres, and the second at nanoscopic or ultrastructural level where cellulose microfibrils are grouped in microfibril bundles. In addition to, on fibre surface calcium oxalates crystal structures were observed. Their occurrence on residue surfaces is related to the maturate state of samples.

The diameter of elementary fibres was 10-20μm and diameter of macrofibrils with helicoidal arrangement inside the secondary cell wall was less than 1μm. In addition to microfibril bundles with the diameter 40 – 60nm and cellulose microfibrils with the diameter 5-10nm were identified [Gañán 2008].

Three types of fibres, namely banana fibres (*Musa sapientum*) obtained from the pseudo stem of the plant, sugarcane (*Saccharum officinarum*) bagasse fibres and Brazil sponge gourd (*Luffa cylindrica*) fibre were studied by Guimarães and co-workers [Guimarães 2009].

The chemical structure of extracted fibres was determined. The cellulose content is the highest in Sponge gourd (66.59%±0.61%), Bagasse follows (54.87%±0.53%) and the lowest cellulose content was determined for Banana fibres (50.15%±1.09%). Cellulose crystallinity degree was between 39% and 50% for the analysed fibres. The most crystalline structure was observed in Sponge gourd fibres (50%), cellulose in Bagase was 48% crystalline and in banana fibres only 39%.

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A high content of lignin was observed for all types of fibres (17.44%±0.19% Banana, 23.33% ±0.02% Bagasse and 15.46%±0.02% Sponge gourd). Sorption properties of these fibres (banana and bagasse: 8.57±0.19 and 9.21±0.01, respectively) are very similar as cotton fibres, however moisture content in Sponge gourd fibres at standard climate conditions is significantly lower (4.79±0.02) [Guimarăes 2009].

4.5. Bamboo fibres

Bamboo is an abundant resource and it has always been used in agriculture, handicraft, paper-making, furniture and architecture. Recently attempts have been made to produce textile fibre from bamboo. Since a single bamboo fibre is 2 mm in length, it is used in textile production in the form of a fibre bundle. Bamboo is a very-fast growing grass. Environmental friendly fibres extracted from bamboo, which is renewable, fast growing, degradable, and does not occupy cultivated land are economically efficient and especially useful to grow in hilly areas.

After degumming through a chemical treatment, the cellulose content in the bamboo fibre reached more than 70%. Comparing chemical structure of hemp, jute and bamboo, lignin and hemicellulose contents in bamboo are far higher than that of the flax fibres, and almost as much as that of the jute fibres (Hemicellulose content: bamboo 12.49%, jute 13.53%, flax 11.62; lignin content: bamboo: 10.15%, jute 13.30%, flax 2.78%). Lignin in bamboo fibre bundles is reason for yellow colour of fibres and coarse fibre fineness [Yueping 2010].

Cross section of single bamboo fibre is round with a small round lumen. The bamboo single fibre width is 6–12 μm and the length 2–3 mm and it is smaller than that of flax (12–20 μm, 17–20 mm, respectively) [Yueping 2010].

By the x-ray analysis of bamboo fibres a similar x-ray diffraction pattern is obtained as it is of jute fibres. Two diffraction peaks are observed at the angles of 15–16° and 22° for the bamboo fibre and jute fibre. It is known that the crystalline structure of natural cellulose from various plants belongs to cellulose I with typical diffraction maxima at scattering angles 14°, 16° and 22°, respectively. Due to a high content of amorphous hemicellulose and lignin in the bamboo fibre and jute fibre an overlapping of the two peaks at angles of 14° and 16° on the diffraction pattern is observed [Yueping 2010].

The fine structure and mechanical properties of fibres within a maturing vascular bundle of moso bamboo Phyllostachys pubescens was studied by Wang with co-workers [Wang 2012].

Almost axially oriented cellulose fibrils were found in the fibre cell walls. This fibrilar arrangement maximizes the longitudinal elastic modulus of the fibres and their lignification increases the transverse rigidity [Wang 2012].

Because of high and different content of non-cellulose substances in various plant fibres the fibres' crystallinity is different. When comparing crystallinities of some plant fibres, the crystallinity of ramie is the highest, follows flax and cotton and the lowest crystallinity is observed for bamboo fibres and jute fibres. These structural differences are reflected on fibre

properties, i.e. density, moisture regain, tenacity, dyeing and thermal properties, etc. [Yueping 2010].

4.6. Quinoa fibres

Quinoa originates from Andes in South America and it belongs to the family Chenopodiaceae (Chenopodium quinoa Willd). It is a grain-like crop grown primarily for its edible seeds and it has become highly appreciated for its nutritional value. It has been recognized as a complete food due to its protein quality. It has remarkable nutritional properties; not only from its protein content (15%) but also from its great amino acid balance. It is an important source of minerals and vitamins, and has also been found to contain compounds like polyphenols, phytosterols, and flavonoids with possible nutraceutical benefits [Abugoch 2009]. The plant is not problematic and it can be cultivated everywhere. Quinoa has a high nutritional value and has recently been used as a novel functional food because of all these properties; it is a promising alternative cultivar.

The elementary fibres can be isolated from Quinoa stems. It is possible to use different processes for fibre isolation. Sfiligoj et al. reported about fibres which were obtained from untreated stems by mechanical isolation. Besides, stems were subjected to chemical treatment in alkaline medium (1%NaOH; different treatment times and temperatures were used; sample A – 1day treatment, room temperature; sample B – 11days treatment, room temperature; sample C – 1 hour T = 100^0C). In addition to they were water treated, respectively. Thereby the pectin structures connecting fibres with other plant tissues were loosed and the mechanical separation of the elementary fibres or fibre bundles was performed [Sfiligoj-Smole 2011].

Figure 9. Quinoa – ripe plant and the stem

Morphological characteristics of fibres were microscopically observed. Light microscopy tests were performed on whole stems and on ultimate fibres and fibre bundles. Different structures were observed on cross- sections and on longitudinal views of stems. Quinoa plant and its stem are shown on Figure 9. In addition to, stem's cross-section is demonstrated on Figure 10. Quinoa technical fibres, i.e. bundles of elementary cells were isolated from untreated and differently treated stems.

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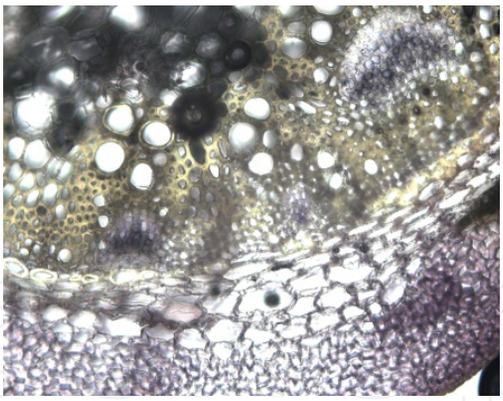

Figure 10. Cross – section of the quinoa stem

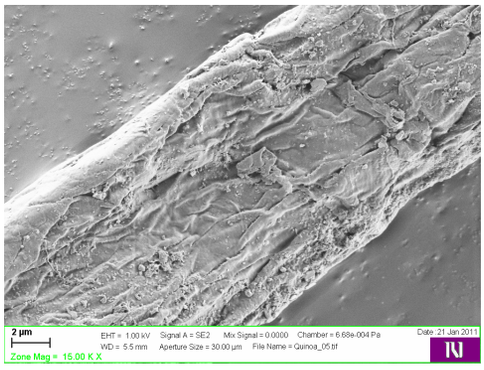

Figure 11. SEM image of surface morphology of isolated fibres from quinoa (fibres obtained by decortication from untreated stems)

The fibre bundles were mainly inhomogeneous and sclerenchyma cells were often accompanied by tracheary elements. Fibres surface morphology was strongly dependent on isolation process (Fig. 11, 12, 13 and 14). Fibres obtained by decortication, i.e. by only mechanical isolation show totally different surface morphology when compared to the fibres obtained from water and alkaline treated stems. In addition to, thermal conditions of the treatment influenced the surface morphology (cf. Fig. 13 and Fig.14).

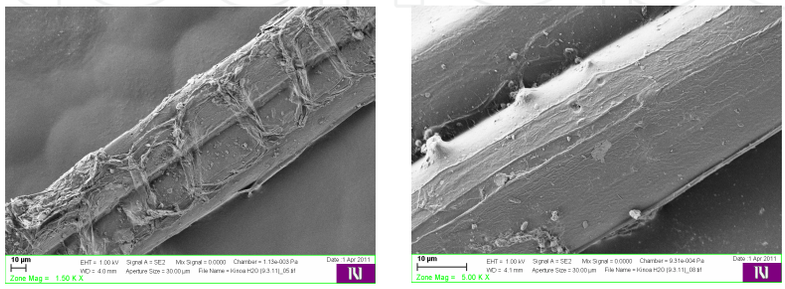

Figure 12. SEM images of surface morphology of differently isolated fibres from quinoa (fibres from water treated stems)

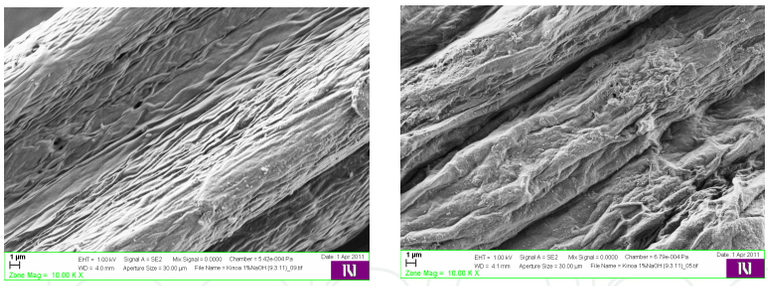

Figure 13. SEM images of surface morphology of differently isolated fibres from quinoa (fibres from NaOH treated stems)

Fibre dimensions were measured on microscopy images. Fibres' diameters are dependent on the procedure of fibres isolation. When untreated stems were processed fibre bundles were formed from a bigger number of cells and a mean diameter of 164μm was determined for these fibres. Pre-treatment of stems facilitates sclerenchyma cells separation from other plant tissues, and fibres' diameter for fibres isolated from pre-treated stems was 42.61μm. The variation of fibres' diameter is very high (variation coefficient is 43.76%).

In addition to, geometrical and mechanical properties of isolated fibres and fibre bundles were determined. The measurements were performed on Lenzing apparatus Vibrodyn and Vibroskop according to standard test methods. Ten parallel samples were measured. Fineness of fibre bundles was between 24.66 and 96.84 dtex depending on the isolation method used for fibres extraction. The fineness variation is related to different number of cells in the bundle and quality of fibre extraction process which is connected with the presence of different non-cellulose compounds on fibres.

It was important to obtain a representative sample for testing due to the inherent variability of most biological materials and extensive mechanical damage due to the isolation process. As mechanical and geometrical properties vary considerably according to temperature and humidity, all samples for testing were conditioned and prepared in the ISO standard atmosphere for textile testing of 65 ±2% relative humidity and 20 ±2ºC according to ISO 5079 was used [ISO 5079 (1995)].

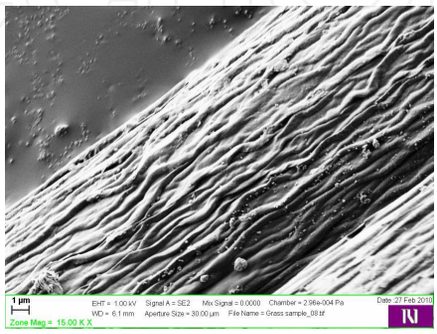

Figure 14. SEM images of surface morphology of differently isolated fibres from quinoa (fibres from stems, treated in NaOH at T = 100^0C)

Fibres' elongation is low and breaking strength high. The elongations vary between 1.41 % to 2.11 % and tenacities from 13.78 to 32.19cN/tex. The obtained values are comparable with the mechanical properties of some textile bast fibres, e.g. jute, hemp or coir. Ultimate fibre cell in hemp is 13 – 26 mm long; its diameter is between 5 and 32 μm, tenacity 29 – 47 cN/tex and elongation 1.8% [Sfiligoj-Smole in press].

In addition to, the powder X-ray diffraction spectra of quinoa fibres, which were obtained by the fibres extraction by water treatment and mechanical isolation, exhibit a diffraction pattern typical of cellulose I, with a diffraction peak of the 2θ angle at about 22^0, which can be assigned to the 002 reflection. However, the two diffraction maxima of 101, 10-1 reflections at diffraction angles 14 and 16^0, respectively, typical for native cellulose are not pronounced. The diffraction pattern is very similar to the pattern obtained by x-ray scattering of bamboo and jute fibres [Yueping 2010]. It is assumed that accompanying substances were not removed sufficiently and therefore the remaining amorphous hemicellulose and lignin are origin of overlapping of these two peaks [Sfiligoj-Smole in press].

4.7. Grass fibres

Grass because of its huge available amounts represents a great potential. It is an annual plant with bundles of elementary fibre cells bound by pectin middle lamellae. Parenchyma cells separate fibre bundles from each other.

The most important representatives in the group of grasses are: Perennial Ryegrass (*Lolium perenne*), Italian ryegrass (*Lolium multiflorum*), Hybrid ryegrasses (*Lolium perenne x multiflorum*), tetraploid varieties of perennial and Italian ryegrass, Timothy (*Phleum pratense*), Cocksfoot (*Dactylis glomerata*), Fescues (Meadow fescue - *Festuca pratensis*; tall fescue – *F.arundinasea*; red fescue – *F.rubra*), Bromes (*Bromus willdenowii*) [Holmes 1989, Petersen 1981]. Legumes are presented by: White clover (*Trifolium repens*), Red clover (*Trifolium pratense*), Lucerne (*Medicago sativa*) [Holmes 1989].

The elementary grass fibres were studied. They were isolated from different grass and legumes sorts, i.e. Ryegrass (*Lolium hybridum* Gumpenstein), Trefoil (*Trifolium pratense*) and Lucerne (*Medicago sativa*) [Sfiligoj-Smole 2005, Sfiligoj-Smole 2004]. The fibre-samples were obtained in a bio-refinery, after the liquid phase containing proteins and lactic acid was eliminated from the ensiled and green grasses, respectively. For the isolation of elementary grass fibres different processes were used. Cross section of a Trefoil stem is presented on Fig.15.

On the microscopy images of grasses cross sections stem area, lumen area, fibre area and fibre content was determined. A high content of fibres was detected in stems regardless the fibres origin. The highest fibre content was determined in Ryegrasses (39.5%), Lucerne followed (34.5%) and the lowest content of fibres was observed in the cross-section of Trefoil (20.2%) [Sfiligoj-Smole 2005, Sfiligoj-Smole 2004].

4.8. Alfa or esparto fibres

Esparto fibres, esparto grass or Alfa are cellulose based fibres extracted from esparto *Stipa tenacissima* leaves. It is a fast growing perennial plant from poaceae family that grows in

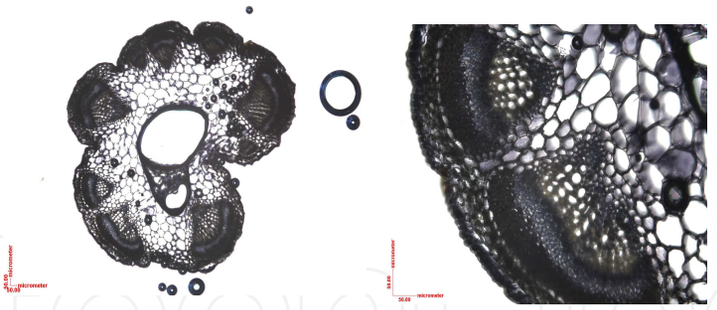

Figure 15. Cross section of a Trefoil stem [Sfiligoj-Smole 2005].

North Africa and southeast Spain. Leaves which reach up to 1m are rich with fibres [Belkhir 2012]. Fibres are extracted for cellulose pulp and paper manufacturing and therefore fibres and pulp were extensively studied. Pulp properties, chemical composition and cell wall architecture was researched. It was found that fibres morphological variability (length and width) is related to growth conditions, i.e. growth location, season and leaf level. Average length of fibres is 1-2 mm and fibres width varies from 14-17μm [Belkhir 2012].

4.9. Sea grass – Zostera marina

Researchers report about different new cellulose sources, however mainly from terrestrial plant origin. But fibres from marine sources offer addition options when appropriate species are identified. Sea grasses belong to angiosperm and are found in most of the oceans. Among sixty different species *Zostera marina* called eel-grass is the most widespread. [Davies 2007].

P.Davis et al. reported about Baltic species of *Zostera marina* which was collected on the German Baltic coast. The diameter of the plant stem was about 2-5 mm and it was 3-8 times branched. The plant was up to 1.2 m long.

In *Zostera marina* a very interesting plant structure was observed. Fibres were reinforcing a matrix and thereby forming a composite structure. Fibres were organized in bundles. Individual fibres with the diameter around 5μm and approximately circular cross section were mechanically extracted from sea grass *Zostera marina*. Fibres are composed of 57% cellulose, 38% of non-cellulosic polysaccharides (10%pectins and 28% hemicellulose) and 5% of residual matter [Davies 2007]. Single fibre stiffness was determined. It was 28 GPa [Davies 2007].

Due to sea-grass fibres mechanical properties and its low density fibres present an attractive reinforcement for composite materials, especially when bio-degradability is required.

5. Applications of non-conventional cellulose fibres

Depending on their physical properties and cellulose content lingocellulose fibres can be used for various applications. The typical fibre morphology with a lumen in the centre, re-

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duces the bulk density, thereby acoustic and thermal insulation properties of biofibres are increased and therefore these fibres are preferable for lightweight composites for noise and thermal automobile insulators.

In addition to insulation, these materials are used in Civil Engineering as building materials. From industrial hemp Cannabis Sativa L useful cellulose fibres to manufacture fibre cement products for roofing are obtained. The disadvantages of some cellulose fibres are: lower modulus of elasticity, high moisture absorption, decomposition in alkaline environments, they are susceptible to biological attack, variable mechanical and physical properties. Hemp fibres with a higher durability than traditional cellulose fibres are more suited for this kind of application, and therefore a lot of research was performed about the use of hemp fibres as reinforcement for building materials based on cement. In addition to, hemp core fibres from agricultural waste industrial hemp straw with the length between 5-10 mm were studied by Jarabo et al. [Jarabo 2012].

An important aspect of natural fibres is associated with their hierarchically built anatomies developed and optimized in a long term evolution process. A variety of non-wood plants offer multiple possibilities in dimensions, composition and morphology of fibrous structures that can be useful for pulp and paper making industries [Gañán 2008]. Therefore based on high cellulose content they are replacing wood pulp in paper and fibres production. Grass stems and leafs fibres could be utilized for this purpose [Saijonkari – Pahkala 2001].

Natural fibres are currently attracting a lot of attention for reinforcement. Fibre reinforced composites consists of fibre as reinforcement and a polymer as a matrix. Their special advantage is their low cost, low density, good mechanical properties, biodegradability, etc. The advantage of natural fibre composites includes lack of health hazards and non-abrasive nature [Sreenivasan 2012]. Natural fibres provide stiffness and strength to the composite and are easily recyclable. Hemp fibres represent a good potential for this utilization. The use of hemp fibres as reinforcement in composite materials has increased in recent years as a response to the increasing demand for developing biodegradable, sustainable and recyclable materials [Shahzad 2012]. Hemp fibres are used for reinforced thermoplastics (composites hemp fibres - polypropylene PP, polyethylene PE, polystyrene PS, hemp fibres - maleated polypropylene MAPP, kenaf-hemp nonwoven impregnated with acrylic matrix., etc.), thermosets (polyester, epoxy resin, vinylester, phenolics) [Shahzad 2012] and biodegradable polymers (thermoplastic starch, polyhydroalkanoates (PHA), polyactides (PLA), lignin based epoxy, soy based resin, etc [Shahzad 2012].

Also other natural cellulose fibres have been used for composite preparation. Polymers including high density polyethylene (HDPE), low density polyethylene (LDPE) polypropylene (PP) polyether ether ketone (PEEK), have been reported as matrices [Li 2007].

A major disadvantage of cellulose fibres is their highly polar nature which makes them incompatible with non-polar polymers. These fibres therefore are inherently incompatible with hydrophobic thermoplastics, such as polyolefins [John 2008]. This characteristic results in compounding difficulties leading to non-uniform dispersion of fibres within the matrix which influences composite properties. To achieve strong adhesion at the interfaces which is

needed for an effective transfer of stress and load distribution through out the interface, sometimes surface modification is needed. Surface modifications include (i) physical treatments, such as solvent extraction; (ii) physico-chemical treatments, like the use of corona and plasma discharges or laser, and UV bombardment; and (iii) chemical modifications, both by direct condensation of the coupling agents onto the cellulose surface and by its grafting by free-radical or ionic polymerizations [John 2008].Therefore different coupling agents which introduce chemical bonds between the matrix and fibre are involved (e.g. silane, isocyanate and titanate based products, alkaline treatment, acetylation, benzoylation, acrylation, maleated coupling agents, permanganate, etc) [51]. or methods of physical fibre treatments (e.g. surface fibrillation, plasma treatment) are used [George 2001]. An additional possibility is to impregnate cellulose fibres in monomer solution, follows the in-situ catalyst, heat or UV polymerisation [George 2001].

Different natural fibres species have been used for preparation of composites. Some examples are: aspen fibre, abaca fibre, bagasse fibres, bamboo fibre (BF), banana fibre, etc.

Unidirectional isora fibre reinforced polyester composites were prepared by compression moulding. Isora is a natural bast fibre separated from the *Helicteres isora* plant by a retting process. Untreated and alkali treated fibres were used for composite preparation and influence of fibre content on composite properties was studied. It was observed that the pretreatment process conditions the fibre content for achieving optimum composites mechanical properties [Joshy 2007].

Green composites were prepared from pineapple leaf fibres and soy-based resin. The addition of polyester amide grafted glycidyl methacrylate (PEA-g-GMA) as compatibilizer increased the mechanical properties of composites. For preparing composites from pineapple leaf fibres in natural rubber fibres were pre-treated in NaOH solutions and benzoyl peroxide (BPO) of different concentrations. It was found that all surface modifications enhanced adhesion and tensile properties [Joshy 2007].

Elephant grass (*Pennisetum purpureum*) is available abundantly in nature and is renewable. It is a tall grass growing in dense clumps along lake and riverbeds up to 3 m height. The diameter of the stem is 25 mm and leaves are 0.6 to 0.9 m long and about 25 mm wide. It represents a potential and economic source compared to other natural fibers, however it is still underutilized, therefore K. Murali Mohan Rao with co-workers suggest fibres from the grass for reinforcement of polyester composites [55]. The density of the elephant grass fiberres is very low compared to other lignocellulose fibres.

This property is a good base for designing lightweight material from these fibres. The diameter of fibers is between 70 lm to 400 μm. Fibres mechanical properties are: tensile strengh is 185 MPA, tensile modulus is 7.40 GPa and elongation at break 2.50% [55]. The positive impact of elephant grass fibres on tensile strength of fiber reinforced

composites was determined and it was found that composite mechanical properies increase with percentage volume of fibers. Whereas the fibre extraction is simple, fibres are cheap and of appropriate properties elephant grass is also suitable for composites used for lightweight structures preparation [55].

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Cellulose nanofibres and crystals have gained a large interest, not only in the academic research society but also in industries, during the last few years [Oksman 2012].

It is well known that isolation of nanocrystals from cellulose is possible by strong acid hydrolysis. Under controlled conditions, acid hydrolysis allows removal of the amorphous regions of cellulose fibres whilst keeping the crystalline domains intact in the form of crystalline nanoparticles [Sheltami 2012].

The diamensons of nanofibres are usually around 20–30 nm in diameter with the length of few μm. Nanocrystals are much smaller. Their length is about 200nm and diameter about 3–5 nm [Oksman 2012]. Cellulosic nanomaterials are obtained form different resources, i.e. wood, bioresidues and annual plants, e.g. wood fibres, sisal, pineapple leaves, coconut husk fibres and bananas, mengkuang leaves (*Pandanus tectorius*) [Sheltami 2012], mulberry bark [Li 2009]. The use of isolated cellulose nanocrystals as reinforcements in the field of nanocomposites has attracted considerable attention since it was first reported in 1995 [Sheltami 2012]. Natural fibre reinforced composites can be applied in the plastic, automobile and packaging industries [Li 2007].

6. Conclusions

Lignocellulosic natural fibres have a very long tradition for textile materials manufacturing. Especially are these fibres important for technical textiles production. The series of plants yielding conventional textile fibres, e.g. flax, hemp, etc. has been recently extended by several abundant plant species traditionally not-connected with fibres extraction. Of huge interest are especially agricultural wastes from cultures which are primary grown for food industry, and their plant wastes additionally containing fibres. Different fibres have been studied by several authors; their properties were determined and compared to the properties of conventional fibres. Regardless of the origin fibre cells are elongated sclerenchyma cells of different geometrical characteristics, associated in fibre bundles with adequate mechanical properties. Several plant species were suggested for utilization from different geographic areas.

Natural fibres from conventional and unconventional source are considered as potential replacement for man-made fibres in composite materials for their reinforcement. Natural fibres from annual plants have advantages of being low cost and low density and therefore they are light. They are a renewable material. In addition to, an important advantage of these materials is their biodegradability and low toxicity. It was confirmed by many researchers that properties of natural fibres of different origin improve composites properties, e.g. the mechanical properties of natural fibres - polymer composites are superior to those of the unreinforced materials.

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References

[1] Abugoch James L.E. Quinoa (Chenopodium quinoa Willd.): Composition, Chemistry, Nutritional, and Functional Properties; Advances in Food and Nutrition Research 2009; 58 1–31.

[2] Aguilarvega M., Cruzramos C.A. Properties of cellulosic henequen fibres. Journal Of Applied Polymer 1995; 56 (10) 1245-1252

[3] Belkhir S., Koubaa A., Khadhri A. Ksontini, M,., Smiti, S. Variations in the morphological characteristics of Stipa tenacissima fiber: The case of Tunisia. Industrial Crops and Products 2012; 37 (1) 200-206 .

[4] BISFA. Terminology of man-made fibres, 2006 Edition. Brussels: BISFA; 2006.

[5] Blackburn R.S., editor. Biodegradable and sustainable fibres. Cambridge: Woodhead Publishing Series in Textiles: 47, The Textile Institute; 2005.

[6] Caffall K.H., Mohnen D. The Structure, function, and biosynthesis of plant cell wall pectic polysaccharides.; Carbohydrate Research 2009; 344 1879-1900. Cellulose 2008; 15 (1) 67-74.

[7] Cook, J.G. Handbook of Textile Fibres, Natural Fibres: Merrow Publishing; 1993.

[8] Cuissinat C., Navard P. Swelling and dissolution of cellulose, Part III: plant fibres in aqueous systems.

[9] Davies P., Morvan C., Sire O., Baley C. Structure and Properties of fibres from Seagrass (Zostera marina). J.Mater.Sci 2007; 42 4850-4857.

[10] Fengel D., Wenzkowski M. Studies on kapok. 1. Electronmicroscopic observations. Holzforschung 1986; 40 137–141.

[11] Fengel D., Przyklenk M. Studies on kapok. 2. Chemical Investigation. Holzforschung 1986; 40 325–330.

[12] Gañán P., Zuluaga R., Cruz J., Velez J. M., Retegi A., Mondragon I. Elucidation of the fibrous structure of Musaceae maturate rachis. Cellulose 2008; 15 131–139.

[13] George J., Sreekala M. S., Thomas S. A Review on Interface Modification and Characterization of Natural Fiber Reinforced Plastic Composites. Polymer Engineering and Science 2001; 41 (9) 1471 – 1485.

[14] Guimarães J.L., Frollini E., da Silva C.G., Wypych F., Satyanarayana K.G. Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil. Industrial Crops and Products 2009; 30 407–415.

[15] Hearle J.W.S., Peters R.H. Fibre structure. London: The Textile Institute Butterworths; 1963.

[16] Holmes W. Grass, its Production and Utilization. Oxford, London, Edinburgh: The British Grassland Society, Blackwell Scientific Publications; 1989.

[17] Hornsby PR., Hinrichsen E., Tarverdi K. Preparation and properties of polypropylene composites reinforced with wheat and flax straw fibres .1. Fibre characterization. Journal of Materials Science 1997; 32 (2) 443-449.

[18] Hu X.P., Hsieh Y.L. Crystalline Structure of Developing Cotton Fibers. Journal of Polymer Science: Part B Polymer Physics 1996; 34 1451-1459.

[19] ISO 5079: (1995) Textile fibres -- Determination of breaking force and elongation at break of individual fibres

[20] Jarabo R., Fuente E., Monte M.C. Use of cellulose fibers from hemp core in fiber-cement production. Effect on flocculation, retention, drainage and product properties. Industrial Crops and Products 2012; 39 89-96.

[21] John M. J.; Anandjiwala R. D. Recent developments in chemical modification and characterization of natural fiber-reinforced composites Polymer Composites 2008; 29 (2) 187-207.

[22] John M. J.; Anandjiwala R.D. Recent developments in chemical modification and characterization of natural fiber-reinforced composites. Polymer Composites. 2008; 29 (2) 187-207.

[23] John M.J., Thomas S. Biofibres and biocomposites. Carbohydrate Polymes 2008; 71 343-364.

[24] Joseph P.V., Joseph K., Thomas S. Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites. Composites Science and Technology 1999; 59 (11) 1625-1640.

[25] Joshy, M.K., Lovely M., Rani J. Studies on interfacial adhesion in unidirectional isora fibre reinforced polyester composites. Composite Interfaces 2007; 14 (7-9) 631-646.

[26] K. Murali Mohan Rao, A. V. Ratna Prasad, M. N. V. Ranga Babu, K. Mohan Rao and A. V. S. S. K. S. Gupta Tensile properties of elephant grass fiber reinforced polyester composites. Journal of Materials Science 2007; 42 (9) 3266-3272.

[27] Khalili S., Daniel G., Nilsson T. Use of soft rot fungi for studies on the microstructure of kapok (Ceiba pentandra) fibre cell walls. Holzforschung 2000; 54 229–233.

[28] Krässig H.H. Cellulose, Structure, Accessibility and Reactivity. Switzerland, USA: Gordon and Breach Science Publishers; 1992.

[29] Lewin, M.; Pearce, E.M. Handbook of Fiber Chemistry. New York: Marcel Dekker; 1998.

[30] Li R., Fei J., Cai Y., Li Y., Feng J., Yao J. Cellulose whiskers extracted from mulberry: A novel biomass production. Carbohydrate Polymers 2009; 76 94–99.

[31] Li X., Tabil G.L:, Panigrahi S. Chemical Treatments of Natural Fiber for Use in Natural Fiber-Reinforced Composites: A Review Journal of Polymers and the Environment 2007; 15 (1) 25-33.

[32] Li Z.Y. ; Zhai H.M. Zhang Y., Yu L . Cell morphology and chemical characteristics of corn stover fractions. Industrial. Crops and Products 2012; 37 (1) 130-136.

[33] Marques G., Rencoret J., Gutiérrez A., Río J C. del. Evaluation of the Chemical Composition of Different Non-Woody Plant Fibers Used for Pulp and Paper Manufacturing. The Open Agriculture Journal 2010; 4 93-101.

[34] Mather R.R., Wardman R.H. The Chemistry of Textile fibres. Cambridge: RSC Publishing; 2011.

[35] Mohanty A.K., Manjusri M., Drzal L.T. Natural fibres, Biopolymers and Biocomposites. Boca Raton: CRC Press, Taylor & Francis Group; 2005.

[36] Morton W.E., Hearle J.W.S.Physical Properties of Textile Fibres. Manchester: The Textile Institute; 1993.

[37] Mwaikambo L.Y. Review of the history, properties and application of plant fibres. African Journal of Science and Technology, Science and Engineering Series 2006; 7 120–133.

[38] Mwaikamno, L.Y., Ansell M.P. The determination of porosity and cellulose content of plant fibers by density methods. Journal of Material Science Letters; 2001; 20 2095–2096.

[39] Mwaikamno, L.Y. Tensile Properties of Alkalized Jute Fibres. Bioresources 2009; 4(2) 566-588.

[40] Oksman K. Nanocelluloses and their use in composite materials, eXpress Polymer Letters 2012; 6 (9) 687.

[41] O'Sullivan A.C. Cellulose: The Structure Slowly Unravels. Cellulose 1997; 4 (3) 173-207.

[42] Petersen Asmus. Die Gräser als Kulturpflanzen und Unkräuter auf Wiese, Weide und Acker. Berlin: Akademie Verlag; 1981.

[43] Reddy N., Yang Y. Biofibers from agricultural byproducts for industrial applications. Trends in Biotechnology 2005; 23 (1) 22-27.

[44] Reddy N., Yang Y. Structure and properties of high quality natural cellulose fibers from cornstalks. Polymer 2005; 46 5494–5500.

[45] Reddy N., Yang Y. Properties of natural cellulose fibers from hop stems. Carbohydrate Polymers 2009; 77 898–902.

[46] Rijavec T: Kapok in technical textiles. Tekstilec 2008; 51 (10–12) (In Slovene) 319–331.

[47] Saijonkari – Pahkala K. Non-wood plants as raw material for pulp and paper. Dissertation. Faculty of Agriculture and Forestry, University of Helsinki; 2001.

[48] Sfiligoj-Smole M., Kreže T., Hribernik S., Pointner B., Stana-Kleinschek K., Ribitsch V. Characterization of natural cellulose fibres from quinoa. In: Valant M., Gardonio S., Fabbretti E., Pirnat U.(ed) Slovenian-Italian Conference on Materials and Technologies for Sustainable Growth: Proceedings book., 4-6 May 2011, Ajdovščina, Slovenia. Nova Gorica University; 2011.

[49] Sfiligoj-Smole M., Kreže T. Hribernik S., Kurečič M., Stana-Kleinschek K. Properties of Quinoa fibres; in press

[50] Sfiligoj-Smole M., Kreže T., Strnad S., Stana-Kleinschek K., Hribernik S. Characterisation of grass fibres; J. Mater. Sci. 2005; 40 (20) 5349-5353.

[51] Sfiligoj-Smole M., Stana-Kleinschek K., Kreže T., Strnad S., Mandl M., Wachter B. Physical properties of grass fibres. Chem. biochem. eng. q. 2004; 18 (1) 47-53.

[52] Shahzad A. Hemp fiber and its composites - a review, Journal Of Composite Materials 2012; 46 (8) 973-986.

[53] Sheltami R.M., Abdullah I., Ahmad I., Dufresne A., Kargarzadeh H. Extraction of cellulose nanocrystals from mengkuang leaves (Pandanus tectorius). Carbohydrate Polymers 2012; 88 (2) 772–779.

[54] Sreenivasan V.S., Ravindran D., Manikandan V., Narayanasamy R. Influence of fibre treatment on mechanical properties of short Sansevieria cylindrica / polyester composites; Materials and design 2012; 37 111-121.

[55] Thygesen L.G., Bilde-Sørensen J.B., Hoffmeyer P. Visualisation of dislocations in hempfibres: A comparison between scanning electron microscopy (SEM) and polarized light microscopy (PLM). Industrial Crops and Products 2006; 24 (2) 181–185

[56] Wang X., Ren H., Zhang B., Fei B., Burgert I. Cell wall structure and formation of maturing fibres of moso bamboo (Phyllostachys pubescens) increase buckling resistance. J. R. Soc. Interface 2012; 9 (70) 988-996.

[57] Yueping W., Ge W., Cheng H., Tian, G.L. Liu, Z , Xiao, Q.F. , Zhou, X.Q., [4]; Han, X.J. Gao, X.S. Structures of Bamboo Fiber for Textiles. Textile Research Journal 2010; 80 (4) 334-343.

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