A Smart Textile Fibre from Biomass of *Brassica napus* L. and the Impact of Cultivar on Fibre Quality

by

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Abstract

Brassica (*Brassica napus* L.) fibre fits the profile as a sustainable and bio-degradable cellulosic natural fibre for application in industrial textiles and as a smart fibre. The current study investigated the effect of *Brassica napus* cultivars on textile fibre properties. Four different cultivars were germinated and harvested inside a greenhouse and water retting of the stems produced virgin-retted cellulosic fibres. However, different cultivars required different retting times. *B. napus* fibres have properties comparable to other commonly used textile fibres, and the potential to be used for apparel and technical textiles. Fibre properties differed among cultivars, such as fibre density and tensile strength showed a statistically significant variation. The most significant finding from this research is the discovery that *B. napus* fibres are lighter in weight (lower in density) than cotton, hemp, flax, and many industrial fibres, making *B. napus* an excellent choice for light-weight nonwoven fabrics or eco-composites. The discovery of fibre density for *B. napus* is a novel finding. The inherent lightweight characteristics of *B. napus* fibre classify it as a “smart fibre”.

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Dedication

This thesis is dedicated to Ar-Razzaq, Ahmad (sa), Ikra Ismah Mabsurah (Samha), Md. Iqbal Hossain Raju, and Dr. Mashiur Rahman (Bablu).

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Chapter 1. Introduction

Not all fibres can be used as textile fibres. A textile fibre must possess important properties, such as fibrous structure, spinnability, strength, fineness, colour, and the ability to react with acid or alkali (Klein, 2016; Trotman, 1984; Saville, 1999; Booth, 1968; Morton & Hearle, 2008). The quality of a cellulosic bast fibre may vary due to the intrinsic variabilities of its natural components such as fibrous nature, morphology of the fibre bundles inside plant stems, cellulose, and lignin (Rowell et al., 2000; Bonatti et al., 2004). Examples of such bast fibres are jute (*Corchorus capsularis*), hemp (*Cannabis sativa* L.), flax (*Linium usitatissimum* L.), ramie (*Boechameria nivea*) (Bergfjord & Bodil, 2010; Kozlowski, 2012a) that vary from each other in terms of cellulosic content as well as in many physical and chemical properties.

Brassica (*Brassica napus* L.), a lignocellulosic bast fibre (Tofanica et al., 2011) is the third most produced oleaginous plant in the world, ranks third worldwide as a source of vegetable oil and accounts for 16% of vegetable oil consumption all around the world after soybean (33%) and palm oil (34%) (Daun et al., 2011; Info-Prod Research, 2010; FAOSTAT, 2009; Edwards, 1967; Badani et al., 2006). *Brassica napus* is Canada's most valuable crop that contributes $26.7 billion to Canadian economy every year including $11.2 billion in wages (Canola Council of Canada, 2017a). Canada is the biggest *B. napus* producing country in the world with an annual production of 21.3 million metric tons (**Table 1.1**). The major use of *B. napus* is for edible oil production; the plant stems are considered biomass material following the harvest of the seeds for extraction of edible oil. Sevenhuysen and Rahman (2016) recently manufactured textile grade fibres from the stems of *B. napus* plants. However, no previous research work has been conducted on the effect of different *B. napus* cultivars on physical properties of the fibres, such as fibre density, diameter, and tensile strength.

Hence, this research work attempts to investigate the effect of different *B. napus* cultivars (HYHEAR 1, Topas, 5440, 45H29) on the textile fibre properties. Cromack (1998) investigated five different cultivars of hemp (Fedora 19, Felina 34, Uniko B, Futura 77, and Komopoliti) to determine the effect of cultivars on fibre yield and found that, there is an influence of cultivar on fibre yield percentage. Cultivar Komopoliti had the highest mean fibre yield (3.48 ton per hectare or 3.48 ton ha^{-1} or t ha^{-1}) and cultivar Felina 34 had the lowest mean (1.34 t ha^{-1}) among all the five cultivars with a seeding rate of 400 seeds/m^2. Similarly, variations among cultivars reveal variations in productivity and physical properties in cotton (Farag & Elmogahzy, 2009) and flax (Salmon-Minotte & Franck, 2005). Furthermore, fibres obtained from same cotton (*Gossypium*) bolls of any plant of cotton may display the tendency to differ in length, diameter, and fibre strength (Farag & Elmogahzy, 2009). After conducting research on eight different cultivars of hemp, Jankauskienė et al. (2015) concluded that fibre yield (%) is dependent on cultivar, where Beniko cultivar produced the highest (44%) fibre content and Fedora 17 produced the lowest (28.4%) fibre content. These facts (fibre yield, fibre content, length, diameter, strength) led to the hypothesis to be addressed in this current research that different cultivars of *B. napus* may have different fibre properties.

Table 1.1: Leading *Brassica napus* L. producing countries.

Country	***Brassica* production (in million metric tons)**
European Union (EU)	20.54[a]
Canada	21.3[b]
China	14.55[a]
India	7.09[a]
Japan	4.00[a]

[a] Statista (2018); [b] Canola Council of Canada (2017b)

Cotton is the dominant natural cellulosic fibre (Cook, 2012) and polyester (Polyethylene terephthalate, commonly abbreviated PET) is the most widely used synthetic fibre (McIntyre, 2005) in the global apparel industry. Despite being a synthetic petroleum-based fibre (Vadicherla et al., 2015), successful use of polyester in apparel consumer goods (Radhakrishnaiah et al., 1993) was made possible because of its cotton spinning properties (CSP) that enabled it to be spun in existing cotton spinning systems (Canoglu & Tanir, 2009). With the alarming phenomenon of global warming affecting the climate (Cox et al., 2000), the need for renewable sources of sustainable natural fibres is on the rise (Blackburn, 2009). *B. napus* could play a significant role as a sustainable source for textile grade cellulosic fibre. Like cotton, *B. napus* produces a cellulosic fibre with a cellulosic content of 61.3% (Tofanica et al., 2011). Unfortuantely, cotton requires an estimated of 550-950 litres/m^2 (World Wildlife Fund, 2000) of water for its cultivation, and up to 29,000 litres/kg of water to process one kilogram of the product as shown in **Table 1.2**.

Table 1.2: Water consumption of cotton lint and other crops[a].

Crops	**Water requirement for area (litres per m^2)**	**Water requirement for product (litres per kg)**
Cotton lint	550- 950	7,000- 29,000
Potato	350- 625	500
Wheat	450- 650	900
Sugar	1,000- 1,500	1,500- 3,000

[a] World Wildlife Fund (2000)

The raw materials required for manufacturing polyester fibres are extracted from the by-products of petroleum. Since *B. napus* is a cellulosic fibre, it could be an alternative fibre to cotton that does not involve huge water consumption because the fibre would be produced from the waste stems of the oil seed production. Furthermore, *B. napus* fibre does not depend on the byproducts of the global petrochemical production as polyester does (Watts, 2009).

This current research examines the textile fibre properties of cellulosic *B. napus* fibre, such as fibre thermal heat resistance, diameter, density, tenacity, strength index, breaking load, breaking tenacity, and tensile strength on four different *B. napus* cultivars (HYHEAR 1, Topas, 5440, 45H29).

1.1. Textile fibre

American Society for Testing and Materials (ASTM) defines textile fibre as “a generic term for any one of the various types of matter that form the basic elements of a textile and characterized by having a length of at least 100 times its diameter” (ASTM 2017). The polymer chain and polymer groups vary from fibre to fibre and it should be underlined that the fibre interior structural parameters like crystallinity index (Cr.I) control the physio-chemical properties of textile fibres. The properties vary from fibre to fibre, for example, Cr.I for flax, hemp, and kenaf is 64, 53, and 42, respectively (Bonatti et al., 2004).

A smart textile fibre is a fibre that possess one or multiple novel properties and is used for value added performance especially in transport, home textiles, construction, energy harvesting, and fashion (Decaens & Vermeersch, 2017). However, there is still no universal definition for a smart fibre. In the context of this research, a smart textile fibre has been characterized for exhibiting outstanding low-density profile in compraison to other industrial natural cellulose fibres, such as cotton, flax, hemp, and jute.

1.2. The fitness of textile application in diverse grounds

The term ‘textile’ or ‘textiles’ is not an ambiguous term. If anyone is asked about the definition of textiles, the answer would be quite predictable and would likely refer to a fabric or apparel that is used in daily life. However, application of textiles has flourished in many fields, such as composites, automotive, marines, aerospace, electronics, civil construction, nanotechnology, biomedical (Gajjar & King, 2014), as well as the apparel or clothing industry. In each case, the property of a textile is determined by its constituent fibre properties.

According to the end use, the modification or required fibre characteristics will vary and will be manufactured accordingly. For the potential application of composites, sisal, flax, banana, and jute fibres have been examined (Li et al., 2000; Pothan et al., 2003; Rana et al., 2003; Zafeiropoulos et al., 2002); for apparel application, kenaf, hemp, linen, jute have been examined (Buschle-Diller et al., 1999; Ramaswamy et al., 1995; Sinha, 1997; Watkins, 1998).

A textile fibre needs to have certain engineering attributes to comply with the end use application criteria. For example, for the aerospace industry, the required properties may be high tensile and high modulus (HT-HM) and the suitable fibres for this requirement are carbon fibres or glass fibres; for firefighting suits the required property is the fire retardancy and the suitable fibres for this requirement are aramid fibres; for smart wound healing, the wound dressing fabric needs to be flexible to provide comfort during the healing process and cotton fibre may act as an ideal substrate to produce the wound dressing fabric for minor wounds (but not for chronic wounds); for apparel application the fibre needs to be flexible, comfortable, breathable and for this cotton and silk are suitable choices.

Thus, not any fibre can be defined or used as a textile fibre, and a textile fibre must possesses certain attributes, such as physical properties: mechanical, thermal, or sorptive properties (Hatch, 1993) as well as some chemical properties like the ability to be dyed with colorants or pigments (Trotman, 1984; Broadbent, 2001).

1.3. Classification of textile fibres

A textile fibre can be classified into two main classes: natural and man-made fibres. These two classes can be expanded to other sub-classes, such as vegetable fibres, protein fibres, mineral fibres, natural polymer fibres, inorganic fibres, and synthetic fibres (**Fig. 1.1)**. The most basic manufacturing flowchart for producing a textile fabric is given in **Fig. 1.2**. The rectangle box represents the manufactured product and the diamond box represents the processing steps (chemical and mechanical) required to produce the product. Spinning process of fibres (**Fig. 1.3a)** produces a yarn (**Fig. 1.3b)**; the interlacing of warp and weft of yarns is used to construct woven fabric (**Fig. 1.3c)**, and the interlooping of yarns creates a knitted fabric.

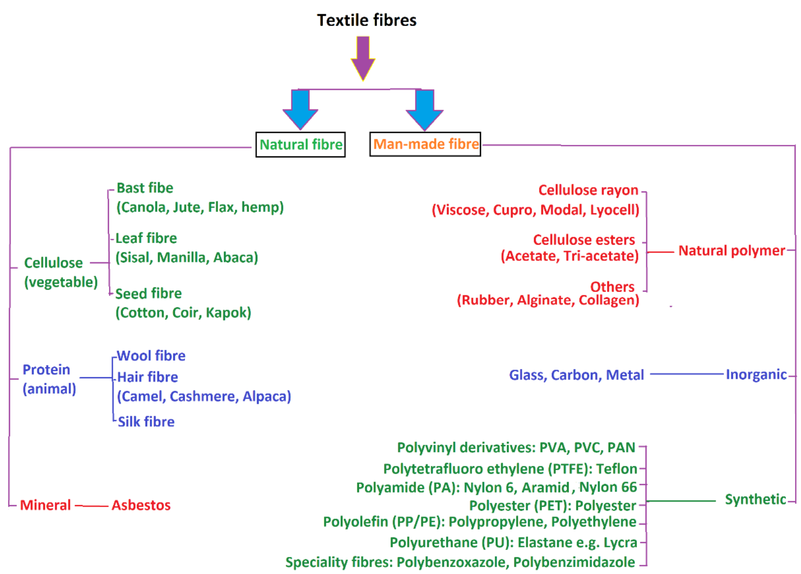


Fig. 1.1: Classes of textile fibres (artwork by author) (adapted from Mather & Wardman, 2011).

The constructions of knit and woven fabrics are discrete and each requires different industrial machinery set-up for production. There is another type of fabric which is called nonwoven fabric where the fibres are directly converted into the fabric. In the case of producing the nonwoven fabric, the intermediary textile yarns are not used or needed. Finally, apparel (**Fig. 1.3d)** is produced from fabrics.

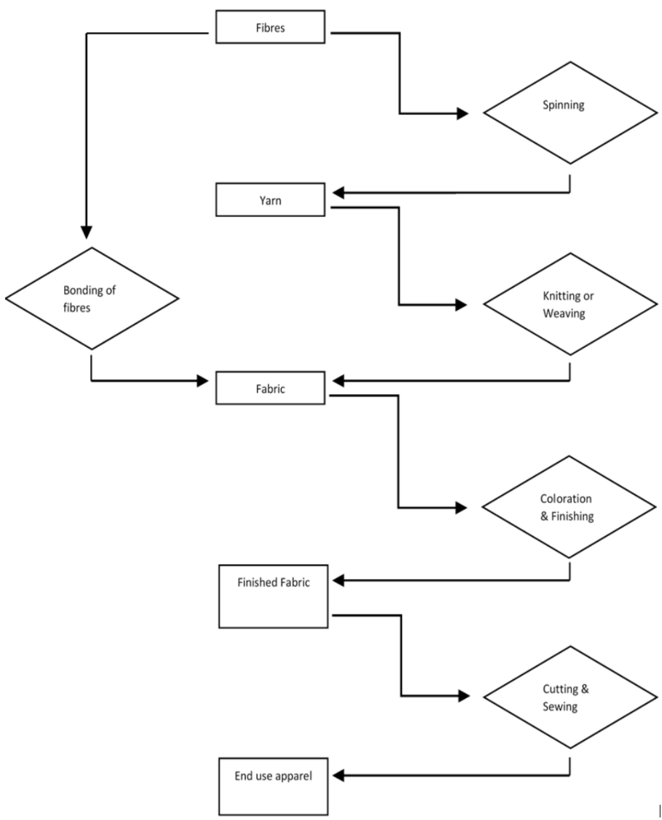


Fig. 1.2: Textile manufacturing flowchart.

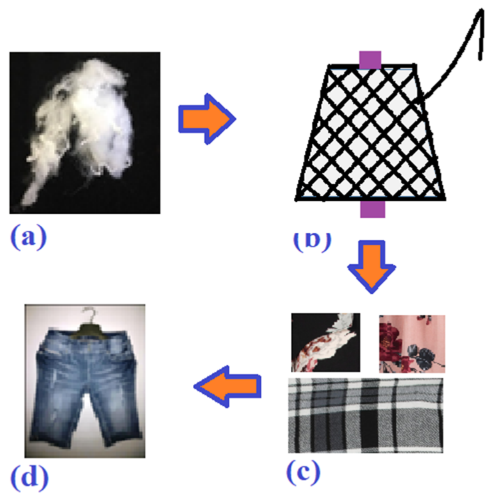


Fig 1.3: Textile manufacturing pipeline: (a) polyester fibre (Shuvo et al., 2017), (b) polyester yarn from polyester fibre, (c) woven fabric containing polyester yarn, (d) apparel containing polyester yarn.

1.4. The requirement of fibre formation

Morton and Hearle (2008) discussed the parameters required for a formation of fibre for textile application; fibres must be long, as short fibres cause loss of strength in the yarn **(Fig.1.4)**; fibres must be in parallel arrangement for ease of inserting twist to form a yarn, fibres must have an internal attraction to give cohesion to the structure, there should be freedom of molecular movement to provide required extensibility to fibre and sufficient openness for moisture absorption and dye uptake for coloration. **Fig.1.4** illustrates the positive effect of fibre length on improved fibre cohesion and increased strength as short fibres are prone to fibre breakage for having lots of void spaces along the polymer chain.

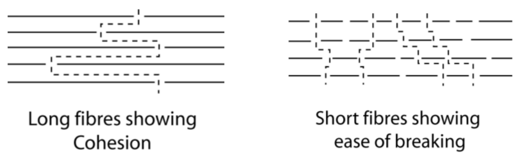


Fig. 1.4: Effect of length of fibres (or molecules) on strength (Morton & Hearle, 2008).

Morton and Hearle (2008) also discussed the molecular orientation within a fibre. A crystalline region in which molecules are in regular, ordered orientation, and an amorphous region in which molecules are disordered in orientation **(Fig. 1.5).** As an example, cotton is 65% crystalline and 35% amorphous. The amorphous region allows water particles to penetrate the fibre in the process of dyeing and the crystalline region contributes to fibre strength.

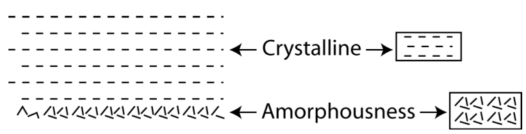


Fig. 1.5: Crystalline and amorphous regions inside a fibre (Morton & Hearle, 2008).

1.5. Chemical composition of lignocellulose textile fibres and their surface modification

Lignin and pectin are the prime impurities inside cellulose fibres, bonded with fibrils that hinder any fibre from becoming spinnable to form yarn for end use application and lignocellulosic fibres like cotton, jute, *Brassica*, hemp, cattail (*Typha latifolia*) or flax are miniature composites, formed from reinforcement of cellulosic fibrils, bound together by pectin gums in hemicelluloses and lignin matrices **(Fig. 1.6)** (Marriott et al., 2016; Kozlowski et al., 2012; Sridach & Paladsongkhram, 2014; Saha et al., 2010).

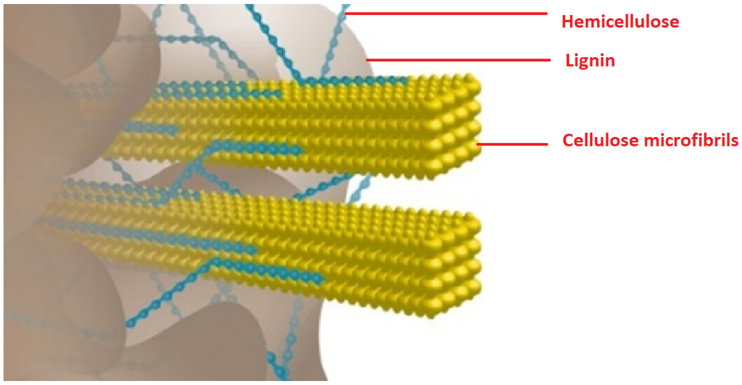


Fig. 1.6: Schematic representation of the general structure of a plant secondary cell wall. Cellulose microfibrils are shown in yellow, and the hemicellulose molecules are shown in blue. Hemicellulose molecules can bind to the surface of the cellulose microfibrils through hydrogen bonding and can link two or more microfibrils together. The lignin (shown in grey) coats and penetrates into the cellulose-hemicellulose network (Marriott et al., 2016).

Fig 1.7 displays jute bast fibre morphology. It can be seen that the jute fibre cell wall is composed of a primary cell wall (PCW) and a secondary cell wall (SCW) that contains the pure celluslosic microfibrils but in different architecture. The microfibrils in the SCW are arranged nearly parallel (7-9^{o}) to the cell axis while microfibrils in the PCW are present in a random or criss-cross manner (Kozlowski, 2012a).

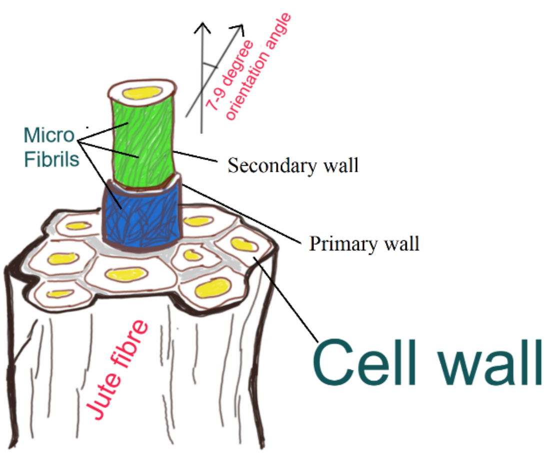


Fig 1.7: Morphology of jute bast fibre (artwork by author) (adopted from Kozlowski, 2012a).

Impurities like lignin, pectin and hemicellulose lie in between the intra-fibrillar regions of PCW or SCW (Kozlowski, 2012a; Meents et al., 2018) but the chemical synthesis of PCW and SCW is different **(Fig. 1.8)**. The deposition of lignification onsets during SCW synthesis only, whereas the presence of hemicellulose and pectin is still seen during the transition of plant cell starting from PCW to SCW in the plant biomass (Meents et al., 2018).

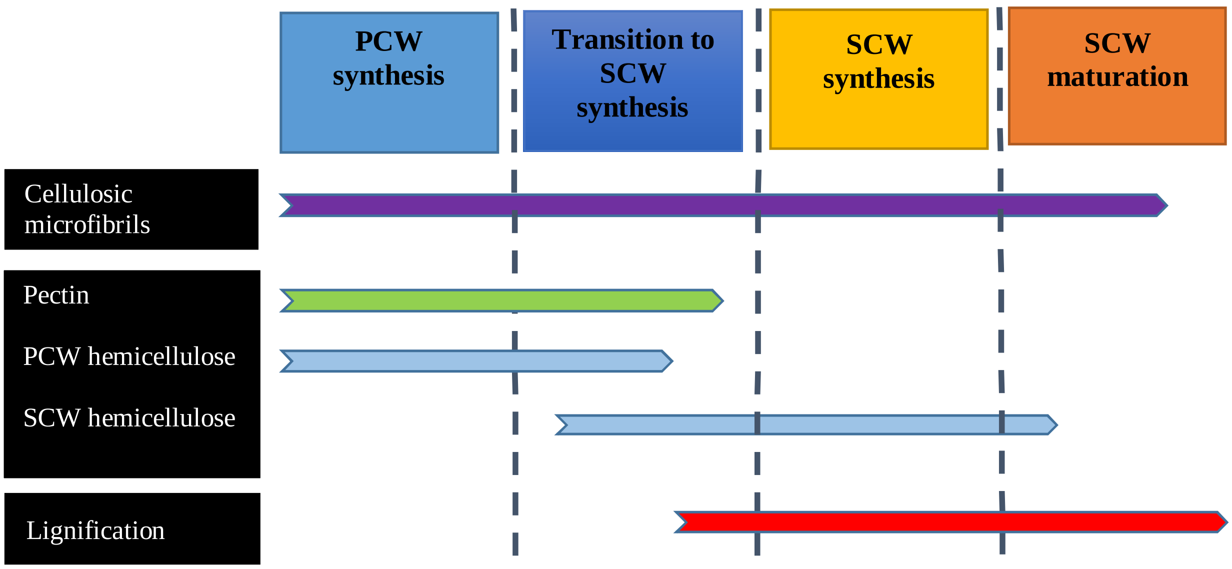


Fig. 1.8: The synthesis of the PCW (primary cell wall) and SCW (secondary cell wall) in plant biomass (artwork by author) (adopted from Meents et al., 2018).

Lignin makes the fibre stiff and hydrophobic; whereas, pectin binds the fibrils into bundles, preventing single fibre entity (Kozlowski, 2012a; Kozlowski et al., 2012). Hemicelluloses are bonded to the fibrils with a hydrogen bond (H-bond), cross-linking the fibrils with lignin and causing stiffness (Marriott et al., 2016). Hydrogen bonds are responsible for 20% strain energy inside cellulose (Tashiro & Kobayashi, 1991). By investigating the change of hydrogen bonds between impurities and fibrils inside cellulose fibres using FTIR spectroscopy before and after the chemical modification, it is possible to characterize fibres (Fan et al., 2012; Saha et al., 2010).

Table 1.3 shows the cellulosic and non-cellulosic materials (lignin, pectin, and hemicellulose) of different textile fibre interiors. Cotton has the highest cellulose content in the fibre interior compared to hemp, flax, *Brassica*, jute, and cattail **(Table 1.3)**.

Table 1.3: Chemical composition (%) of some lignocellulosic fibres.

Composition (%)	**Cotton** [a]	**Jute** [a]	**Hemp** [a b]	**Flax** [a b]	**Kenaf** [a b]	***Brassica*** [c]	**Cattail** [d]
Cellulose	83-99	51-78	55-68	64-84	44-60	61.3	42.61
Lignin	6	10-15	3.5-5.5	0.6-5	15-19	5.2	5.75
Pectin & Hemicelluloses	5	37	17	17-19	17-23	_	36.46

[a] (Kozlowski, 2012a); [b] (Bonatti et al., 2004); [c] (Tofanica et al., 2011); [d] (Sridach & Paladsongkhram, 2014)

The impurities in the textile fibre interior are destroyed during scouring or alkaline boiling at a high temperature (for example, virgin kenaf fibres treated with 6% NaOH at 95°C destroys impurities) causing destruction of lignin, pectin, and the breaking of hydrogen bonds (H-bond) between the hemicelluloses, breaking the cellulosic fibrils, leading to a better fibril separation for single fibre entity (Marriott et al., 2016; Edeerozey et al., 2007; Trotman, 1984). Destruction of these non-cellulosic impurities from the cellulose-hemicellulose-lignin matrix increases the breaking strength of cellulosic fibres and their flexibility (Zhang & Zhang, 2010).

Spicka and Tavcer (2013) conducted a one-bath pretreatment process of cotton fibres with an enzyme mixture producing excellent water absorbency and high tenacity of the treated cotton fibres. However, Hoque and Azim (2016) found that treating cotton fibres with enzyme alone does not remove much wax and mote (tiny dust particles) compared to an NaOH scouring process; nor can enzyme improve the whiteness of the fibre, making it suitable for dark shades only.

Mohiuddin et al. (1992) found enzyme treatment of jute bast fibres and found that treating the controlled fibres (diameter: 50.3 µm, bundle strength or Pressley Index: 1.79 lb/mg) with an enzyme (*A. terreus*) produced fine diameter fibres (42.5 µm), having improved bundle strength (2.2 lb/mg) better flexibility (no data available/ NDA), and softness (NDA). Basu et al., (2008) also found increased softness of jute bast fibres after treating them with enzymes. Ali et al., (2015) treated hemp bast fibres with enzyme and bleaching agents and found that enzyme-treated fibres reduced the least amount of non-cellulosic material, while bleaching treatment reduced the largest amount of non-cellulosic material. It was also found that enzyme-treated hemp fibres failed to produce single fibre entity and softness (Ali et al., 2015) suitable for CSP (Cotton Spinning Properties). Zhang et al., (2014) conducted an orthogonal experimental design to determine the optimum conditions (bath ratio, time, and alkali dosage) for reducing non-cellulosic material of hemp fibres and concluded that alkali treatment was the best and most efficient way to remove lignin. Wang and Postle (2003) concentrated on removing the pectin and lignin from hemp fibres through NaOH scouring, acid scouring, and bleaching, and concluded that NaOH could attack both pectin and lignin. Whereas, pectin was completely removed from hemp fibre interior by the NaOH boiling process, lignin was not completely removed, as a small portion of lignin was situated in the second wall layers of the fibres which cannot be accessed by NaOH. Hence, an attempt was made in this current research work to combine multiple chemical treatment processes on the water-retted virgin bast fibres of *B. napus* stems to achieve the optimum result for CSP of *B. napus* fibres.

1.6. *Brassica* growth and development stages

The vegetative and reproductive stages of *B. napus* plants are displayed in **Fig. 1.9**. *B. napus* seed imbibition (water absorption) is the first step of germination (Harperi, 1973). For adequate water absorption, it is important that the seed is in close contact with the moist soil and the soil should be low in inorganic salt and organic substances (Canola Council of Canada, 2017c). Several factors may influence the length of the growth stage, such as temperature, moisture, light, and nutrition (Edwards et al., 2011). Although *B. napus* is an agricultural cool season crop, temperatures below 5°C can hinder plant growth, and extremely low temperatures may cause frost damage as the favourable temperature for *B. napus* plant growth is between 12°C and 30°C with an optimum temperature of 21°C (Dickson, 2014).

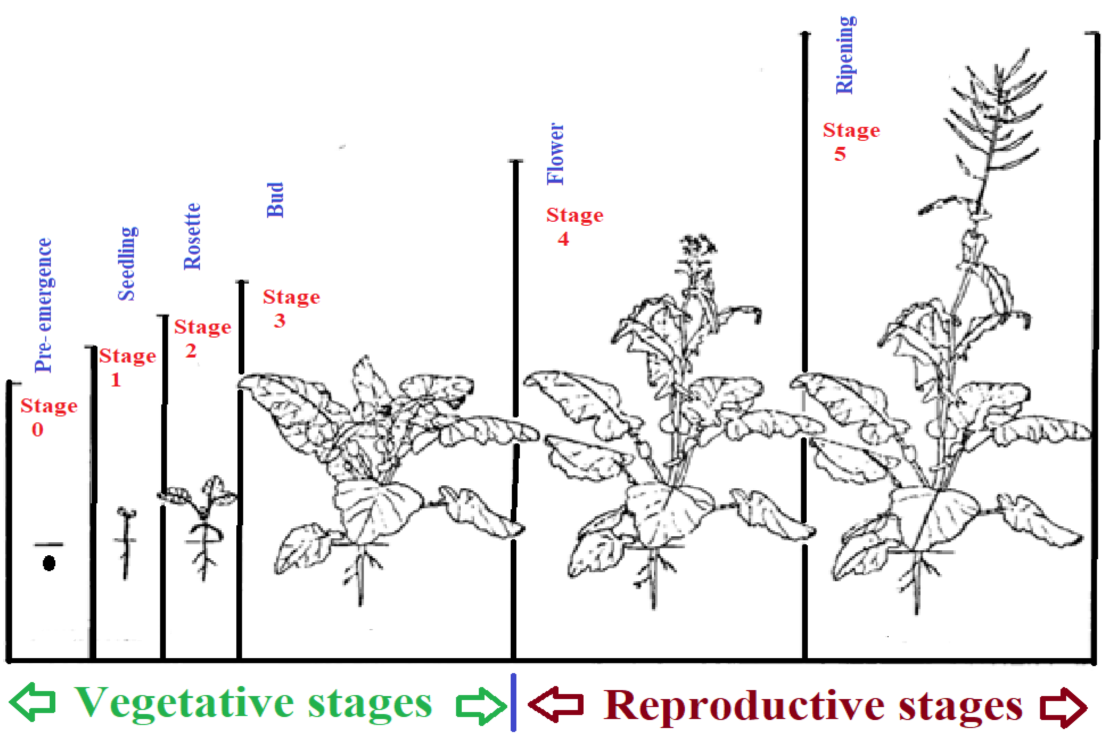


Fig. 1.9: Vegetative and reproductive stages of *Brassica napus* L. (Harperi and Berkenkamp, 1975).

Once seed imbibition is successfully completed, radicle root emerges from the seed and the root elongates downward and the root hairs along the elongated root help to anchor the development of the seed (Harperi, 1973; Harperi & Berkenkamp, 1975). Root growth is constant to 2 cm per day and 4-15 days (d) after seeding, the seedling develops a short 1.25 to 2.5 cm stem (Canola Council of Canada, 2017c). *B. napus* plants have a tap root system (Edwards et al., 2011), where the roots absorb water and nutrients from the soil they happen to be in contact with and transport them upward into the stem. Seedling starts from the emergence of the cotyledons to the unfolding of first true leaf (Knott, 2017; Harperi, 1973). Leaves are a major source of food for the growing plant as leaves are significant for photosynthstes required for *B. napus* species growth (Major, 1977) and loss of leaves negatively impact the seed yield growth (Freyman et al., 1973). At the bud stage, the stem starts to elongate and *B. napus* plants start growing taller (Knott, 2017; Theunissen & Sins, 1984; Berkenkamp, 1973). However, at this stage flower buds remain enclosed by young leaves and the secondary branches may appear from axial buds of the upper leaves or from lower nodes (Theunissen & Sins, 1984; Canola Council of Canada, 2017c). The next stage is the flowering (bloom) stage (Knott, 2017; Harperi, 1973; Harperi & Berkenkamp, 1975; Berkenkamp, 1973) where the plants also undergo pollination (self-pollination or cross-pollination via wind or insect or both) depending on the type of plant (Canola Council of Canada, 2017c) for producing seeds. Flowering stage is signaled by the opening of the first yellow flowers on the terminal bud (Edwards et al., 2011) after 41-54 d from the germination stage that lasts between 14 to 21 d on the main stems (Canola Council of Canada, 2017c). The plants grow moderaltely during the flowering stage (Harper, 1973) but height of the plants stop growing at the peak of flowering (Canola Council of Canada, 2017c). When lower pods start their elongation by mid-flowering (around 50% bloom), the stem becomes the major source of food for plant growth (Knott, 2017). Pods are also very important source of zinc, copper, magnesium for seeds (Edwards et al., 2011) and generate assimilates that are needed for producing seeds during pod-filling (Campbell &

Kondra, 1978). As the pod surface area increases, it leads to increased photosynthesis and pod walls and stems both contribute as a major source of food for the growing seeds (Edwards et al., 2011). Seed filling is completed after 35 to 45 d of the flower opening and the firm green seeds at this stage contain the adequate level of oil and protein for future germination (Canola Council of Canada, 2017c). Seed ripening is the final stage for *B. napus* species plant growth and development cycle where the seeds develop their final size with mature reddish-brown seed coat color (Harper, 1975). The stems and pods gradually become brittle and dry at maturity (Berkenkamp, 1973).

1.7. Influence and importance of fibre properties

A textile is the end product or finished good to any customer, and this end-product is the result of all the care starting from fibre processing quality, yarn processing quality, fabric quality control, fabric dyeing, and quality inspection prior putting the end product on display by retailers or wholesalers (Booth, 1968). If the constituent textile fibres fluctuate from the international textile quality schemes like ISO standards (Tested-Quality plan of Courtaulds Ltd) or USTER® *STATISTICS* (Booth, 1968), then the quality of the end product or textile will not satisfy the customer's requirements both in serviceability or economy. Hence, quality fibre properties are the most important factors controlling the end result of any textile product.

In the current research, the following textile properties are discussed and their importance during transformation and end uses are established: moisture regain, flexibility, single fibre entity, softness, fibre density, thermal properties, surface modification, diameter, and strength. In relation to *B. napus* fibre, the influence of retting and cultivar are also addressed.

1.7.1. Influence of moisture regain

Moisture regain is defined as the weight of water in a material expressed as a percentage of the oven dry weight of the material or the ratio of water in a material to the oven dry weight of this material (Booth, 1968). Moisture regain is related to the sorptive properties of any textile fibre (Hatch, 1993). Sorptive properties of a textile fibre refer to the hydrophilicity or water-loving; hydrophobicity or water-avoiding; oleophilicity or holding oil particles; heat of wetting; liquid, and water vapor absorption. Some water attracting groups inside a fibre interior are -OH, -NH, -CONH; some non-attracting groups are -CH, -COO, $-CH_3$, and some semi-attracting groups are -Cl, $-COCH_3$, -CN (Hatch, 1993). Moisture absorption affects three major properties of a fibre: fibre swelling, wet tenacity (tensile strength of fibre when it is wet), and wet modulus (modulus calculated for any fibre when it has absorbed the maximum amount of water) (Hatch, 1993).

Fibre with higher water absorption property exhibits higher swelling property (only in hydrophilic fibres) (Hatch, 1993). Swelling has a significant effect on the moisture absorption demonstrated by any textile fibre, where the water molecules penetrate the fibre interior to fill the spaces of more or less parallel polymer chains and exhibit a force outwards causing the fibre to swell (Booth, 1968). **Table 1.4** shows the dimensional changes of some textile fibres from swelling (Booth, 1968; Saville, 1999) and dimensional changes of fibres due to moisture absorption. The transverse (diameter and area) swelling (%) and volume swelling (%) values of the different fibres obtained by different studies display considerable discrepancies which reflect to the difference of their experimental methods or apparatus as well as the differences among their specimens of a given type of fibre (Saville, 1999; Morton & Hearle, 2008). It can be seen that hydrophilic fibres (cotton, wool, silk) are more prone to transverse and volume swelling than the hydrophobic fibres (nylon). Although the net result of swelling is shrinkage (decrease in length) (Booth, 1968) due to increased fibre diameter, the swelling behavior of a fabric is harnessed in designing waterproof fabrics (Saville, 1999) where the constituent yarns swell (when wetted by water) to close up the fabric structure for increased water impermeability.

Table 1.4: Dimensional changes of fibres due to moisture absorption from different studies[a].

Fibres	Dimensional changes of fibres			
	Transverse swelling (%)		Longitudinal swelling (%)	Volume swelling (%)
	Diameter (%)	Area (%)		
Cotton	20	40	1.1	42
Mercerized cotton	17	46	0.1	-
Acetate	9	6	0.3	-
Wool	14.8	25	1.2	36
Silk	16	19	1.3	30
Nylon	1.9	1.6	1.5	8.1

[a] (Morton & Hearle, 2008; Booth, 1968; Saville, 1999)

Wet tenacity is higher for some hydrophilic fibres, such as cotton and flax i.e., their breaking strength increases when they are wet in water (Hatch, 1993). Similarly, wet tenacity is lower for some hydrophilic fibres, such as silk and wool i.e., their strength reduces when they are wet in water (Hatch, 1993). **Fig. 1.10** dislays that wool fibre is weakened when it absorbs water and its breaking force drops in wet state compared to its dry state (Saville, 1999).

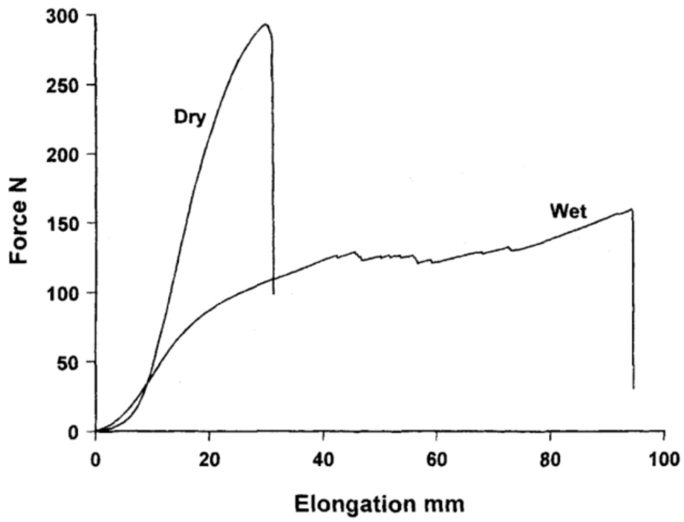
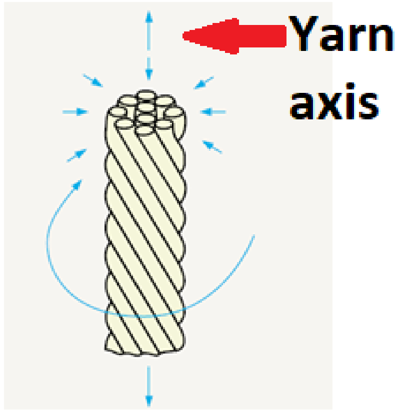


Fig. 1.10: The strength of dry and wet wool (Saville, 1999).

Laundering and drying methods for a fabric are indicated by the fibre wet modulus (Hatch, 1993). A low wet modulus fabric would not be hung for drying because of the tendency for the fabric to elongate under its own weight and not recover.

1.7.2. Influence of fibre flexibility

Fibres are spun in spinning machinery to produce yarn (Ziabicki, 1976; Klein, 2016; Chen, 2010). During spinning, the fibres are twisted to hold the constituent fibres together along the yarn axis **(Fig. 1.11)** and to impart strength (**Fig. 1.12**) to the yarn (Klein, 2016). The more flexible a fibre, the more twist it can undergo and the stronger a yarn will be produced. If the fibres are stiff, they will break down while twisting. Klein (2016) showed the relationship between the number of twists in a yarn and its strength for both cotton and polyester and also stated that the strength of a yarn drops down beyond the critical twist region (**Fig. 1.12**). This critical twist region varies from raw material to raw material for a yarn.



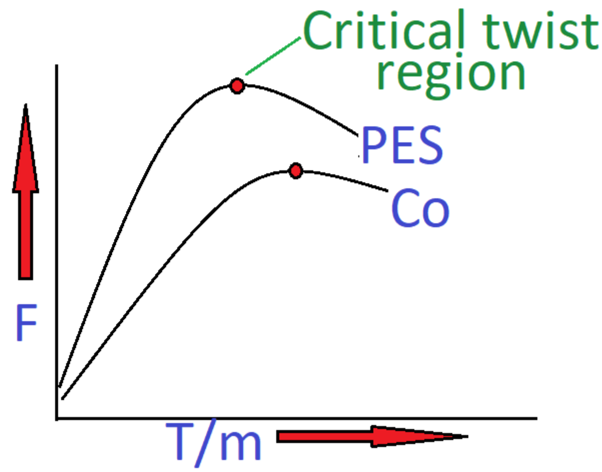


Fig. 1.11: Imparting strength to the yarn by twist (Klein, 2016).

Fig. 1.12: Relationship between the number of turns of twist and the yarn strength (F= yarn strength; T/m= Turns of twist per metre in the yarn; PES= Polyester fibres; Co= Cotton fibres). The critical twist region is marked by a red dot (artwork by author) (Klein, 2016).

A higher crystallinity in a fibre gives a fibre of higher stiffness or flexural rigidity or resistance to an external bending force. The highest flexural rigidity can be seen in Spectra (olefin) (1400-2000 g/denier or g/den) and the least in spandex (13-20 g/den); whereas, cotton (60-70 g/den) has a higher degree of stiffness than polyester (40-65 g/den) or nylon (5-58 g/den) (Hatch, 1993). The higher the crystallinity, the higher the tenacity, but the lower the flexibility. For example, about 437,000 bends (180-degree bends) are needed to break polyester fibres but only 900 bends for triacetate fibres before rupture occurs (Hatch, 1993).

1.7.3. Influence of single fibre entity

Neps (entanglements of fibres), thick places and thin places in yarn are classified as yarn faults (Yadave et al., 2015) or yarn defects (Chougule et al., 2016) which are strongly monitored during yarn quality control process (Stueber, 1985) in textile yarn spinning industries. Fibres that are not individualized (absence of single fibre entity) properly will create mass variation (thick and thin places) **(Fig 1.13)** along the length of the yarn and will ultimately lead towards yarn unevenness (Yadave et al., 2015) which will degrade the fabric quality for commercial application.

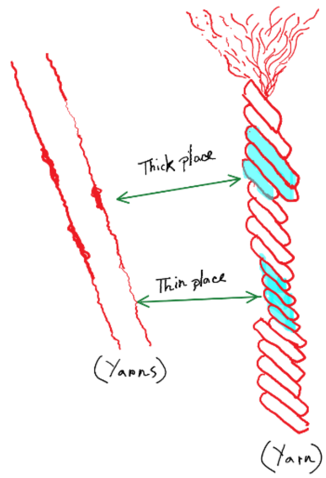


Fig. 1.13: Thick and thin places in a yarn causing yarn unevenness.

1.7.4. Influence of fibre softness

Soft fibre produces soft fabric which is highly comfortable to wear (Natarajan et al., 2005). Lyocell is a regenerated cellulosic fibre (produced by Tencel Inc., USA and Lenzing Ag., Austria) that displays softness like silk and such soft fibres are used in fashion textiles requiring high degree of softness and drape properties (Natarajan et al., 2005). Further, compression garments (that reduce swelling, fatigue, and soreness) used for medical patients also exhibit softness and comfort (Invista Inc., 2009). These compression garments comprise soft fibres like Lycra in their construction (Invista Inc., 2009). Hence, fibre softness has a significant influence on the aesthetic properties of a textile.

1.7.5. Influence of fibre density

Density is the mass per unit volume i.e., dense fibre will be heavier and vice-versa. This fibre property dictates different end user applications. As an example, E-glass fibre has a density value of 2.58 g/cc; however, a product that requires chemical or electrical resistance is made with another type of glass fibre, with higher density than 2.58 g/cc, which is E-CR glass fibre with a higher density of 2.72 g/cc (Gall et al., 2018). Fibre with lower density has higher moisture regain (due to higher amorphousness) and vice-versa (Morton and Hearle, 2008). **Table 1.5** provides an outline of the densities of different textile fibres (Saville, 1999).

Table 1.5: Density of different natural and man-made fibres[a].

Fibres	**Density (g/cc)**	**Fibres**	**Density (g/cc)**
Polypropylene	0.90	Acetate	1.33
Polyethylene	0.95	Silk	1.33
Nylon 11	1.10	Cotton	1.55
Nylon 6	1.13	Polyester	1.38
Wool	1.31	Viscose	1.52

[a] (Saville, 1999)

1.7.6. Influence of surface modification and chemical properties

Surface modification of a textile fibre is conducted with various chemicals to achieve many desirable properties, such as increased water absorbency. A cellulosic fibre may be subjected to an alkali treatment to increase its hydrophilicity as the alkali reduces the non-cellulosic impurities from the fibre interior (Trotman, 1984) that lead to water absorbency, which is required for subsequent fibre coloration.

Different fibres react differently to different chemicals. Polyester is resistant to dilute acids, while cotton is hydrolyzed (Hatch, 1993). Similarly, reactive dyes are used for cotton dyeing, but cannot be used for polyester dyeing (Broadbent, 2001).

1.7.7. Influence of thermal properties

Thermal properties refer to the response of a fibre toward temperature or heat. Different fibres respond differently to a similar temperature, such as cotton dyeing can be conducted at a lower temperature (60^{o}C-70^{o}C) with reactive dyes but polyester needs a higher temperature (120^{o}C-130^{o}C) to be dyed with disperse dyes (Broadbent, 2001; Trotman, 1984). The reason behind this high-temperature requirement of polyester is its highly crystalline interior structure that requires a high temperature to open up in order to make the dye particles accessible to the polyester interior.

Thermal properties also specify different fibre attributes such as the specific heat (heat required to increase 1^o C temperature), thermal conductivity (flow of heat through fibres), heat resistant temperature (temperature at which a fibre starts degrading), softening and melting temperature (fibre first softens with heat and then melts with increase of heat), decomposition temperature (degrades completely), and combustibility.

Natural fibres (cotton, wool) and many synthetic fibres (aramid) do not have softening or melting point and ignite (combustible temperature) between 415.6^{o}C-537.8^{o}C (Hatch, 1993), although there are many non-combustible fibres such as glass fibres, asbestos, and carbon (Hatch, 1993).

1.7.8. Influence of fibre length, diameter (micronaire value or MIC), and strength

Tallant et al., (1959) defined short fibres as having a length of 3/8 inch (9.53 mm) and shorter that do not break when the yarn ruptures, and found that short fibres decrease yarn and fabric strength. Klein (2016) stated that fibre length has an influence on fibre strength as well as on the spinning limit (the point at which fibres can no longer be twisted to produce yarn). Morton and

Hearle (2008) also found that longer fibres (within a limit) require less twist to cohere together to impart strength to yarn.

Thin fibres are called fine fibre and thick fibre are called coarse fibre. Long staple cotton fibres (length: 30-65 mm, MIC: 2.8-4.5, strength: 33-45 gram/tex or g/tex) are considered most thin/fine and best in quality, whereas short staple fibres are the thickest/coarsest (length: <20 mm, MIC: 4.5-6, strength: 14-18 g/tex) and used for lower quality fabrics (Kozłowski, 2012a). Saville (1999) states that finer fibres have more cohesion and so require less twist to form a strong yarn. However, coarse fibres have useful applications. It was found that acrylic carpets produced from coarser fibres provide better compression properties than finer fibres and are more likely to perform better under foot traffic (Celik, 2017). The most important effect of fibre fineness is on the fibre rigidity or stiffness, as the stiffness of a fibre increases with increasing fibre diameter leading to a reduced flexibility i.e., coarse fibre produces a substantial amount of fibre stiffness (Saville, 1999).

In **Fig 1.14** (Klein, 2016)**,** it can be seen that both ring-spun yarn and rotor-spun yarn are influenced by constituent fibre properties, as the fibre length, length uniformity, fibre strength, and micronaire value (MIC) (µg/inch) account for more than 60% of the yarn strength.

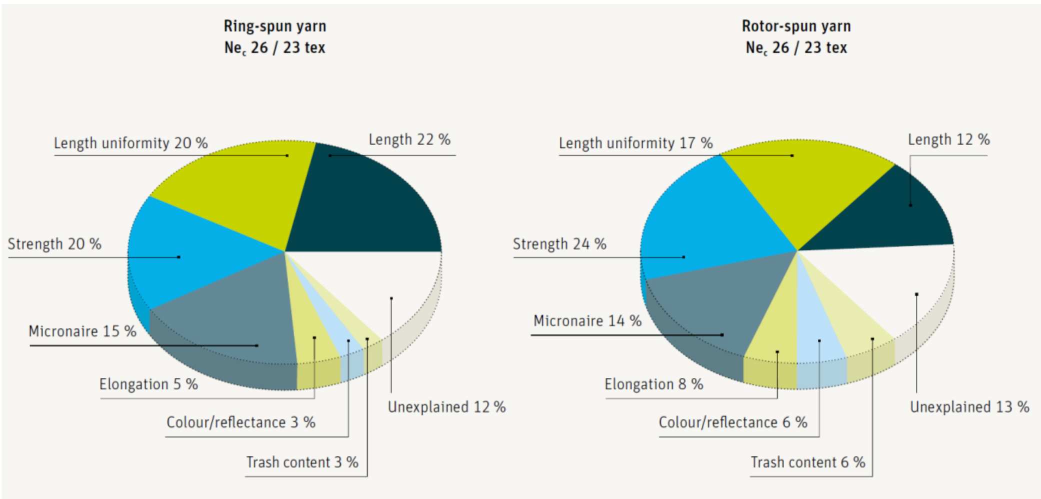


Fig. 1.14: Effect of fibre properties on yarn strength (Klein, 2016).

The correlation between fibre properties and yarn properties can be summarized in **Fig. 1.15** (Klein, 2016)**,** where the effect of fibre length, MIC value, nep content, trash content, breaking strength, elongation on the resultant yarn properties are compared. It can be seen from the **Fig. 1.15** that fibre color and trash content has no significant correlation with the yarn breaking tenacity. Further, El-Messiry and Abd-Ellatif (2013) found that the correlation coefficient between fibre breaking strength and yarn breaking strength was 0.76.

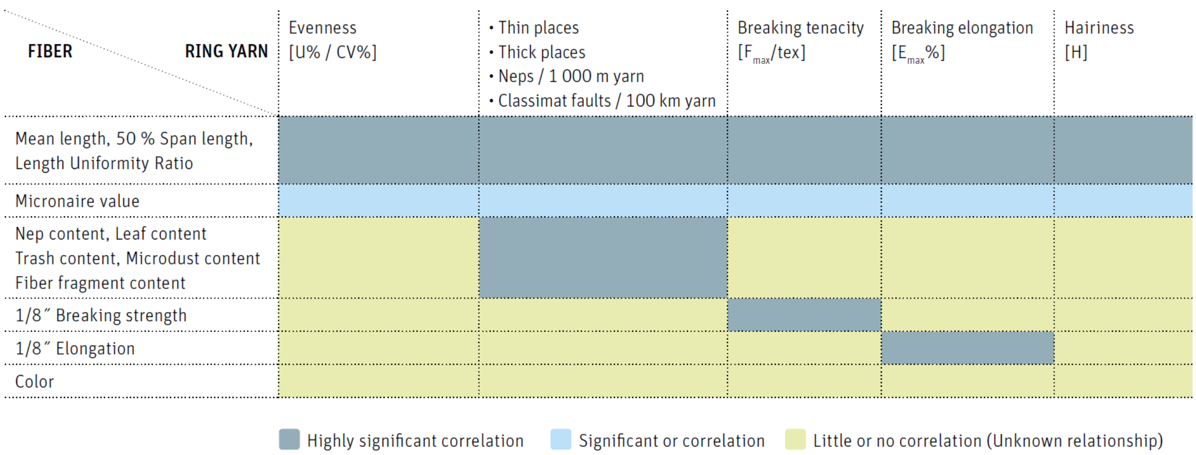


Fig. 1.15: Correlation between fibre properties and yarn properties according to USTER technologies (the CV% of the statistical results ranged between 15.50±0.00% - 16.85±0.05% but no data was available on the correlation co-efficent or correlation type) (Klein, 2016).

Mechanical properties of a textile fibre relate to different aspects like initial modulus (extending/elongating when small stress is applied), tenacity (ratio of load required to break a fibre and the linear density of that fibre) elongation at break, toughness (the capacity to resist the sudden impact of load or shocks-of-energy and accepting a large deformation without breakage). For physics, the term “stress” (force per unit area, where the S.I. unit is Newton/m^2=Pa) is used; for textile fibre engineering application, specific stress (also called tenacity) is used, where specific stress is the force per linear density and the S.I. unit for tenacity is Newton/tex. Reiter (2018) shows a linear relationship between fibre strength and yarn strength **(Fig. 1.16)**.

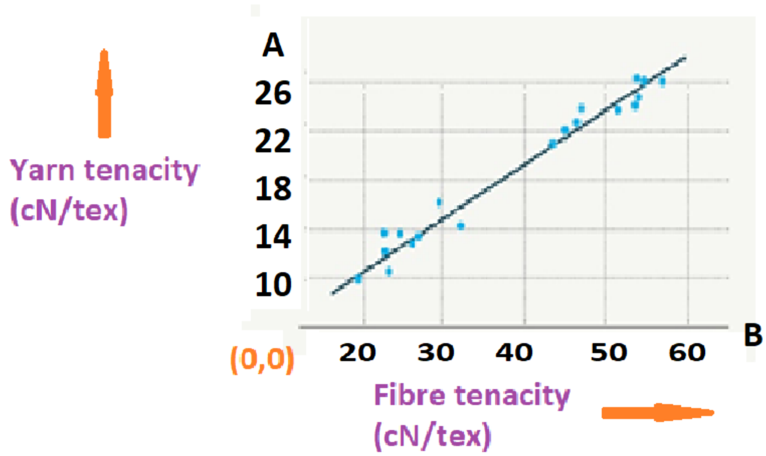


Fig. 1.16: Relationship between fibre tenacity (B) and yarn tenacity (A) in cN/tex (Reiter, 2018).

Yarn tenacity is less than its constituent fibre tenacity as yarn tenacity depends on several fibre properties **(Fig. 1.16)** (fibre length, MIC value, elongation as shown in **Figs. 1.14, 1.15)** and is not only a single function of fibre tenacity (El-Messiry & Abd-Ellatif, 2013). Further, fibre tenacity varies from fibre to fibre and from testing methodology to testing methodology, for example, mean fibre tenacity (cN/tex) of Egyptian cotton variety Giza 86, Giza 87, Giza 88 are 39.01, 37.13, 35.55, respectively when tested by a Vibroscope (single fibre testing methodology) and 43.1, 45.2, 45.1 when tested by a High Volume Instrumentation tester (bundle fibre testing methodology).

1.8. Impact of different retting methods on fibre quality

Different fibres require different extraction methods, for example, cotton is extracted from cotton bolls, silk from cocoons of the silkworm, and bast fibres from the plant stems by retting.

The cell wall of any plant stem consists of different components **(**see **Fig. 1.17)**: primarily cellulose, hemicellulose, and pectin (Zimmermann et al., 2004). Retting, the separation of the fibre bundles from the stem or woody core of plants (Thomas et al., 2011), can use various methods such as mechanical, chemicals, water, dew, and enzymes (Thomas et al., 2011; Akin et al., 2000; Akin et al., 2001).

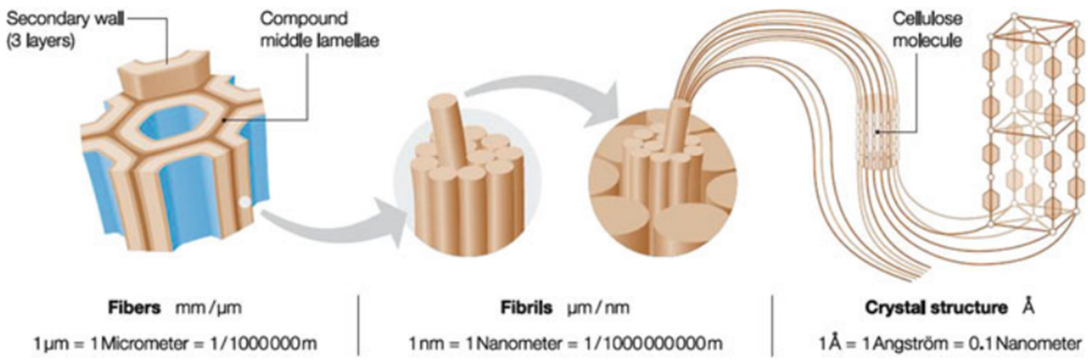


Fig. 1.17: Scheme of a wood cell wall showing the compound middle lamella (middle lamella and primary wall), and three layers of the secondary wall. Cellulose, the principal component of the cell wall, exists as a system of fibrils (Zimmermann et al., 2004).

Different retting methods have different effects on fibre quality (Akin et al., 2005; Van Sumere, 1992; Van de Weyenber et al., 2003; Thomas et al., 2011), such as cellulose and fibre yield of water and dew retted hemp fibres were found to be 81.7%, 3777 kg ha^{-1} and 78.4%, 3966 kg ha^{-1}, respectivey (Jankauskiene˙et al., 2015). Further, cellulose and tenacity of chemical (2% NaOH) and water retted nettle fibres were found to be 81.3%, 58.15 g/tex and 78.4%, 50.41 g/tex, respectively (Bacci et al., 2011). Ramaswamy et al., (1994) also found differences between bundle fibre tenacity of water retted kenaf fibre (28.2 g/tex) and chemical retted (7% NaOH) kenaf fibre (12.9 g/tex).

Jute fibre bundles, known as reeds (Roy & Lutfar, 2012), are separated by water retting of the stem stick **Fig. 1.18** (Roy & Lutfar, 2012). Using this model of jute water retting, the *B. napus* stems used in this research work were also water retted.

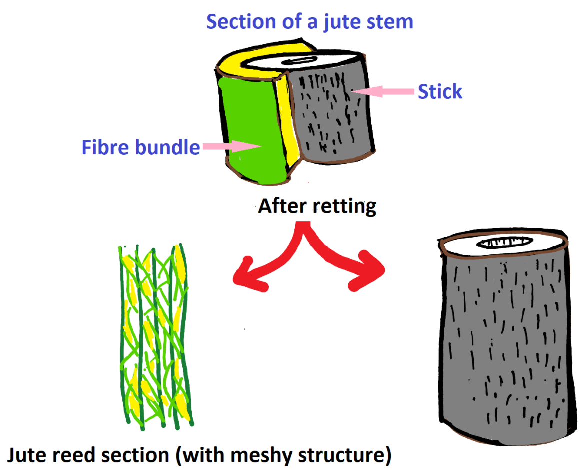


Fig. 1.18: Disintegration of jute stem into jute reed and a stick after retting (artwork by author) (adapted from Roy & Lutfar, 2012).

1.9. Cultivar effect on textile fibre properties

"Cultivar is a group of genetically similar plants, which by structural features and performances may be identified from other groups of genetically similar plants within a species" (Poehlman & Sleper, 1995). Different cultivars have different effects on textile fibre properties, and could ultimately affect the end use application of a textile. Fibre properties that are affected include fibre length (Cotton Incorporated, 2018), fibre strength (Messiry & Abd-Ellatif, 2013), MIC values (fineness or coarseness), color grade, and fibre yield (%) (Zonta et al., 2015).

1.9.1. Cultivar and variety variation effect on cotton fibre properties

Four major types of cotton of commercial importance are grown around the world; *Gossypium hirsutum* (commonly known as "American Upland" or "Long-Staple/LS" cotton) with fibre length of 2.22 to 2.32 cm; *G. barbadense* (commonly known as "American Pima" or "Extra-Long Staple/ELS" cotton) with fibre length of 3.16 to 4.78 cm; and *G. herbaceum* and *G. arboretum* with comparatively shorter fibre length of 1.27 to 2.54 cm (Cotton Incorporated, 2018; Messiry &

Abd-Ellatif, 2013). Both *G.hirsutum* and *G. barbadense* are native to North and South America; whereas, *G. herbaceum* and *G. arboretum* are native and grown only in East Asian countries. Other cultivar differences exist between American Upland cotton and American Pima cotton, one of which is the color. American Pima exhibits deeper yellow color inherently than the American Upland cotton (Cotton Incorporated, 2018); and the tenacity of Pima cotton (4.14 ± 0.59 N/tex) is higher than Upland cotton (3.19 ± 0.87 N/tex) (Farag & Elmogahzy, 2009).

In Egypt, most of the textile cotton fibres are produced from *G. hirsutum* (Long-Staple or LS) and *G. barbadense* (Extra-Long Staple or ELS) species (Messiry & Abd-Ellatif, 2013). Messiry and Abd-Ellatif (2013) conducted research on five varieties of *G. barbadense* or ELS Egyptian cotton (Giza 45, Giza 87, Giza 88, Giza 86, Giza 90) and found differences in the textile properties of these five varieties **(Table 1.6)**.

Table 1.6: Characteristics of five Egyptian cotton varieties of *Gossypium barbadense* species.

Cotton varieties [a]	**Fibre count dtex** [b]	**Tenacity cN/tex** [c]	**Young modulus g/den** [d]
G45 (*G. barbadense)*	1.33	37.88	32.11 (= 288.99 g/tex = 28.899 g/dtex)
G87 (*G. barbadense)*	1.51	37.13	42.59 (= 383.31 g/tex = 38.331 g/dtex)
G88 (*G. barbadense)*	1.62	35.55	43.55 (= 391.95 g/tex = 39.195 g/dtex)
G86 (*G. barbadense)*	1.76	39.01	42.09 (= 378.81 g/tex = 37.881 g/dtex)
G90 (*G. barbadense)*	1.64	32.75	34.30 (= 308.70 g/tex = 30.870 g/dtex)

[a] Abdellatif et al., (2012).
[b] Tex system is the linear density of yarn and is defined as the weight in grams per 1 km of yarn and decitex (dtex) is the weight in grams per 10 km.
[c] cN/tex: Centi-Newton; [d] Denier = (Tex × 9), g/tex = (g/den x 9), g/dtex = (g/den x.0.9).

Zonta et al. (2015) conducted research to investigate the cotton seed yield (kg ha^{-1}) and fibre percent (%) among four different *herbaceous* cotton cultivars (FiberMax 993, BRS 286, BRS 335, and BRS 336) grown in Brazil under different irrigation slides and concluded that FiberMax

993 (4,926.3 kg ha^{-1}) and BRS 286 (4,634.6 kg ha^{-1}) produced higher cotton seed yield than BRS 335 (4,183.8 kg ha^{-1}) and BRS 336 (4.070.5 kg ha^{-1}). The authors also found out that cultivar BRS 336 produced the lowest percentage of fibers (38.8%) compared to the other three cultivars: FiberMax 993 (43.1%), BRS 286 (43.1%), BRS 335 (42.5%).

1.9.2. Cultivar variation effect on hemp fibre properties

In Canada, three hemp cultivars namely Finola, Crag, and USO 14 are very popular for field production of seed (Hanks, 2008). However, hemp plants also possess high bast fibre content suitable for apparel and technical textile application (Werf et al., 1996), which may also be affected by cultivar variation. Sankari (2000) conducted research of Ukrainian monoecious Uso 11 hemp cultivar (an early maturing cultivar) with thirteen other hemp cultivars (dioecious and monoecious) originating from various parts of Europe to investigate the effect of cultivar on fibre yield (%), breaking tenacity, fibre fineness, and fibre elongation in the years of 1995, 1996, and 1997. Sankari (2000) found that there were significant differences in the bast fibre content in stem ($p < 0.001$), bast fibre yield ($p < 0.001$) among the fourteen cultivars. Sankari (2000) also identified variation in fibre fineness that varied from 15.1- 55.2 dtex in 1995 and 10.1- 60.2 dtex in 1996. The author also identified variation among the median breaking strength among the cultivars. Using **Figs 1.19a and 1.19b**, the median breaking tenacity of the fibres measured in 1995 varied between 41 and 61 cN/tex, and in 1996 they varied between 45 and 74 cN/tex. **Fig 1.19a shows** that in 1995, cultivar Uniko B showed the best normal distribution of breaking tenacity as its box-plot diagram showed the highest fibre in 1996 as shown in **Fig 1.19b**. French cultivars Fedora 19, Felina 34, and Futura 77 showed the best uniformity of fibres among all the cultivars.

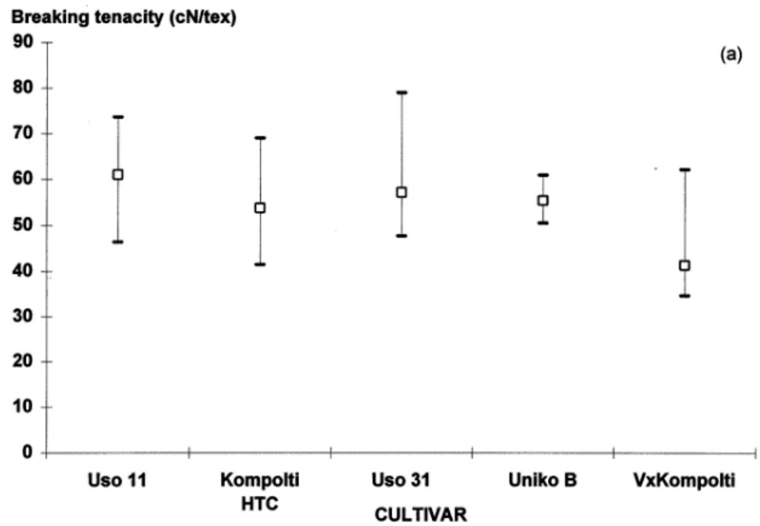


Fig. 1.19 (a): Median (□), 25th percentile (┴) and 75th percentile (┬) for breaking tenacity of the fibres (cN/tex) measured for 12 fibre samples of each cultivar in 1995 (Sankari, 2000).

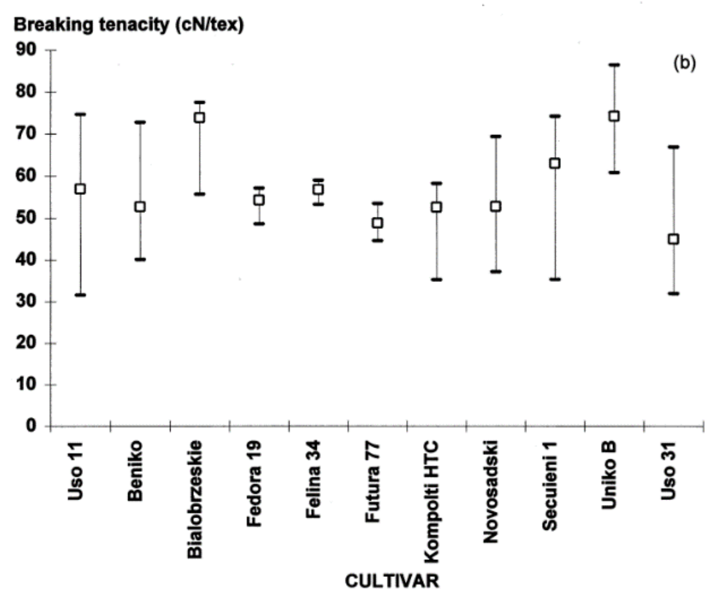


Fig. 1.19 (b): Median (□), 25th percentile (┴) and 75th percentile (┬) for breaking tenacity of the fibres (cN/tex) measured for 12 fibre samples of each cultivar in 1996 (Sankari, 2000).

Menge-Hartmann and Höppner (1995) reported variation in breaking tenacity among different unidentified cultivars of hemp varying from 48 cN/tex to 76 cN/tex. Bonatti et al. (2004)

conducted a histochemical and supramolecular studies among five different cultivars of hemp (Carmagnola, Fedrina, Felina, Fibranova, Futura) and found variation in cellulose (%) (**Table 1.7**).

Table 1.7: Chemical composition of different hemp cultivars (specimen plants were obtained from Istituto Sperimentale Colture Industriali, Italy but no data available on plant cultivation time)[a].

Cultivars	Cellulose (%)	Soluble lignin (%)	Insoluble lignin (%)	Ashes (%)
Carmagnola	59.1	0.1	18	4.1
Fedrina	62.2	0.1	20	2.6
Felina	62.4	0.1	19.3	3.1
Fibranova	59.3	0.1	19.2	3.1
Futura	57.7	0.1	19.9	3.9

[a] Bonatti et al. (2004)

In Denmark, Deleuran and Flengmark (2006) investigated comparative studies of fibre yield (t ha^{-1}), fibre yield (%), and stem yield (t ha^{-1}) of four different hemp cultivars namely Fedora, Fedrina, Felina, and Futura, which are reported in **Table 1.8.** They found that Futura gave higher fibre yield (32.3 t ha^{-1} and 3.7%) than all other cultivars with a seed rate of 32 kg ha^{-1}.

Table: 1.8: Effect of different hemp cultivars on fibre yield (%) (plants were grown and trials were carried out in Danish Institute of Agricultural Sciences, Denmark from 1998 to 2000)[a].

Cultivars	Stem yield (t ha^{-1})	Fibre yield (t ha^{-1})	Fibre yield (%)
Fedora	10.2	3.3	32.1
Fedrina	11.0	3.5	31.6
Felina	9.2	3.0	32.2
Futura	11.6	3.7	32.3

[a] Deleuran and Flengmark (2006)

A similar result was also found in Switzerland regarding stem yield (t ha^{-1}) but with higher seed yield of 250-1200 kg ha^{-1} (Mediavilla et al., 1999 cited in Deleuran & Flengmark, 2006). Variation among the hemp cultivars was also identified in Russia in terms of yield (%), and tolerance to cold (Sustrina, 1971 cited in Grigoryev, 2005) and further research focused on hemp cultivars that are more cold-tolerant, produce high yield (%) of fibres, and can be blended with cotton to produce fabric for the Russian market (Grigoryev, 2005).

1.9.3. Cultivar variation effect on flax fibre properties

The term "Flax" is an Anglo-Saxon word that means "to weave" (McCay, 1952 cited in Cruthers et al., 2006). The flax fibres contain non-cellulosic impurities such as lignin and hemicelluloses, which need to be dissolved in alkaline solutions for textile application. Many other processes are involved to make flax fibres usable for textile application such as scrapping, beating, washing, and dyeing (Pendergrast, 1987).

Variation in flax cultivars also causes variations in fibre properties, as investigated by Lowe et al. (2010). Due to the property variation of different flax cultivars, Mäori (the indigenous people of New Zealand) weavers use different flax cultivars for different end use applications: Tapamangu cultivar for baby shawls, and necklace ties; Arawa cultivar for excellent quality fibres; Takaiapu cultivar for medium quality fibres; and Takirikau cultivar for producing shiny fibres (Scheele & Walls, 1994).

Lowe et al. (2010) investigated tenacity of two different of cultivars (designated as B5 and F1) of New Zealand flax (*Phormium tenax*), which has been used by the Mäori for functional and cultural artifacts for a long time (Mead, 1999; Scheele & Walls, 1994) and found that the fibre tenacity was higher for B5 than F1. There was also a significant statistical difference between the tenacities of these two cultivars. ANOVA was conducted by the authors, where the *p*-value between B5 and F1 was found to be 0.037 for tenacity. It can be seen that the *p*-value is less than 0.05 that is an indication of a significant difference between the two flax cultivars. Similar results were found from the previous works of the author (Lowe et al., 2009) that supported this comparative difference in fibre tenacity between these two cultivars.

Cruthers et al., (2006) conducted research on six cultivars of New Zealand flax (*Phormium tenax*), which were Tapamangu, Arawa, Paretaniwha, Makaweroa, Takaiapu, Takirikau, and investigated their length and diameter (**Table 1.9)**. The investigation exhibited a significant difference among the fibre lengths of the six cultivars ($p < 0.05$) and mean transverse-width of ultimate fibres ($p < 0.05$). The fibre length and width of Tapamangu and Arawa are quite similar but different than Makaweroa (**Table 1.9)**, which also resembles the findings of the previous research work of Carr et al. (2005).

Table 1.9: Mean length and width of fibres extracted from different flax cultivars[a].

Cultivars	**Mean length (µm)**	***p*-value**	**Mean width (µm)**	***p*-value**
Arawa	4513		11.2	
Makaweroa	4751		10.3	
Paretaniwha	3880	$p < 0.05$	12.8	$p < 0.05$
Takaiapu	4385		10.1	
Takirikau	3735		11.9	
Tapamangu	4041		11.2	

[a] Cruthers et al. (2006)

Previously, Carr et al. (2005) found that the cellulosic content, length, and width of the fibres of Tapamangu and Arawa are quite similar but the fibres of Makaweroa cultivar are comparatively longer than the Tapamangu and Arawa cultivars. Furthermore, the authors found no significant difference ($p > 0.05$) in the cellulosic content in these three cultivars (55.11±2.84% for Arawa, 53.34±3.15% for Makaweroa, 53.26±2.68% for Tapamangu) but found significant difference in fibre tenacity ($p < 0.001$) among these three cultivars (0.53±0.21 N/tex for Arawa, 0.56±0.48 N/tex for Makaweroa, 0.53±0.36 N/tex for Tapamangu). Similar research has been conducted in characterizing different cultivars of flax regarding length, shape, packing of the ultimate fibres, where inconsistency of fibre properties were identified (King & Vincent, 1996).

It appears from the above discussion that fibre properties and quality of hemp, flax or cotton vary from cultivar to cultivar. It is hypothesized that different *B. napus* cultivars may display different fibre properties, such as tenacity, density, tensile strength or other textile proerties of *B. napus* fibres may vary from cultivar to cultivar.

Hence, this current research paper addresses the effect of *B. napus* cultivar variation on textile fibre properties. This research was performed at Crop Technology Centre (CTC) and Textile Laboratory of University of Manitoba (U of M). As the research progressed, fibre characterization was conducted at the Composites Innovation Centre (CIC), Canada. The principal objectives of this investigation were to characterize fibre yield (%), moisture regain (%), thermal heat resistance, diameter, density, strength index, breaking tenacity, and tensile strength of the fibres extracted from four different cultivars (HYHEAR 1, Topas, 5440, 45H29) of *B. napus* biomass.

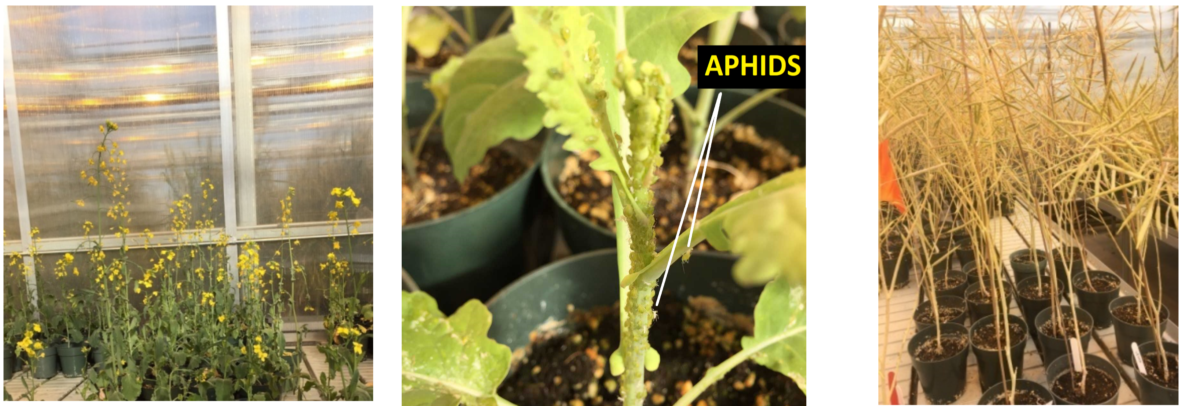
Chapter 2. Materials and methods

Four different cultivars of *Brassica napus* L. were used in this research work including HYHEAR 1, Topas, 5440, and 45H29. Ninety six (96) seeds per cultivar were germinated inside a growth chamber of Department of Plant Science, University of Manitoba (day temperature: 22^{o}C; night temperature: 17^{o}C). At the two-leaf-stage, the plants were transplanted to larger plastic pots (14.60 cm in height) and placed in the greenhouse of Crop Technology Centre (CTC) of University of Manitoba. Following harvesting, plant samples were brought to the Textile Laboratory in the Department of Biosystems Engineering at the University of Manitoba and assessed preliminary. *Brassica napus* fibres were extracted from the plant stems by water retting and different textile properties of the fibres such as moisture regain, thermal heat resistance, diameter, density, breaking load, breaking tenacity, strength index, and tensile strength were investigated in the Textile Laboratory as well as in the Fibre City of Composite Innovation Centre (CIC), Canada.

2.1. *Brassica napus* plant samples

The *Brassica* breeding program at the University of Manitoba supplied 96 seeds per cultivar. Eight plastic packs per flat were arranged so that 96 seeds per cultivar could be accommodated in each flat. The flats were filled with Sunshine® Professional Growing Mix (Sun Gro Horticulture, Canada) soil less mix and watered. The seeds were placed into a 1 cm hole in the soil, and the holes were closed gently so that the growth of the plant would not be hindered. The flats were put in a growth room and were watered daily. On 4th day and 10th day, the plants were watered with an aqueous solution of Plant Prod (20-20-20) fertilizer. When the plants reached the two-leaf stage (14 day after seeding), they were transplanted into 14.5 cm pots (using the same soil less mix used for the flats) in the greenhouse at CTC (Crop Technology Centre) of University of Manitoba and were again fertilized with aqueous solution of Plant Prod (20-20-20) fertilizer.

Manual watering of the soil less mix (to field capacity) was carried out everyday once in the morning until the 32nd day (after seeding) when automatic irrigation (by the flooding bench watering system in the greenhouse) was started on the greenhouse water benches. When flowering **(Fig. 2.1a)** started, all the plants were fertilized with aqueous solution of Plant Prod (20-20-20) fertilizer one last time.



(a) (b) (c)

Fig. 2.1: Topas plants during different growth stages in greenhouse: (a) flowering of Topas plants, (b) aphids attacking the grown Topas plants, (c) brown Topas plants prior harvesting.

In the 41st day (after seeding), thrips, aphids **(Fig. 2.1b)**, and powdery mildew appeared on the surface of the plants of the four cultivars. Hence, soil and chemical spray treatment were used to control the emergence of thrips, aphids, and powdery mildew. Bamboo sticks were tied with plant stems as lodging resistance on the 53rd day after planting. As the plants were growing taller and getting heavier due to the developing seed pods on the branches, some plants did not grow straight and were bending so the bamboo sticks were used to support them. Hand harvesting of all the cultivar plants was completed 116 days after planting once all the leaves were dead and had fallen off and the plants had turned brown in color **(Fig. 2.1c)**.

2.2. Water retting of the *Brassica* plant stems and their diameter analysis

The diameter of *B. napus* stem specimens was determined using a digital Vernier slide calliper (Mastercraft®, PN: 058-6800-4, Canadian Tire) **(Appendix I)** and their weight was measured using an electric balance meter at room temperature and tabulated before starting the water retting. The diameter of the stems was measured in three regions (top, middle and bottom). The mean diameter for each stem was calculated using the diameter value of these three regions. Finally, the grand mean of each cultivar was determined using the mean of 50 stems.

At room temperature, the *B. napus* plants of the four cultivars were water-retted in four different water containers. Each of the steel bowl container contained 5 L of water. Water retting of these samples started and stopped as a single batch (collection of all the specimens). All the stems were taken out at the same time after the retting (the point at which fibres don't cling to stem strongly but loosely adhere to the stem surface which can be easily extracted by hand without any pulling force). Water was added as needed during the process to maintain a constant water volume of 5 L. A circular lid with a weight on top forced the stems to be completely immersed in the water and to ensure adequate retting. A small space was remained open for air exchange.

To prevent over-retting and under-retting of the stems, regular inspection (after every 12 hours) was conducted as the retting experiment was in progress. During daily inspection of the retting bath, it was observed that fibres were coming out from the exterior of the stems at the bottom of the water bath sooner than the stems at the top. Hence it was expected that stems at bottom would reach the retting point slight sooner than the stems that are above and might cause over-retting of the stems situated at bottom of water bath. Hence, the stems were regularly rotated in position from bottom to top and top to bottom of bath to prevent over-retting or under-retting.

2.3. Extraction of *Brassica* fibres from water-retted *Brassica* stems by single-slit method

Each of the retting water baths was monitored daily to determine the end point of retting. With gradual progress to the end point of the retting process, fibres were naturally coming away from the stem exterior **(Fig. 2.2)**. The endpoint of retting for a stem was determined as the point at which the fibre skin could be removed easily or isolated with a soft and gentle rubbing. If proper retting time is not achieved, only a portion of the fibre skin **(Fig. 2.3)** will be isolated. Such retting may result in reducing fibre yield efficiency because of fibre wastage. When the retting endpoint arrived, a fine needle was used to make a single slit along the length of the stem **(Fig. 2.4)** to unravel the whole fibre skin from the stem exterior **(Fig. 2.5)** manually and prevent fibre loss.

Fig. 2.2: Fibres are slowly coming out naturally as water retting endpoint is approaching.

Fig. 2.3: Improper fibre extraction due to under-retting in water.

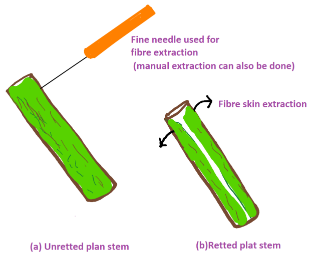


Fig. 2.4: Single slit method with a fine needle to extract *Brassica* fibre from stem exterior.

Fig. 2.5: Full-skin fibre extraction from stem exterior by the needle.

The extracted fibres were washed and dried at room temperature followed by 8-hour oven drying at 105°C inside an incubator according to ASTM D2495-07 (2012) standard, and the oven dried fibres were reweighed. Fibre yield (%) of the extracted fibres was calculated using the following mathematical formula **(Eq. 2.1)**:

$$\text{Fibre yield (\%)} = \left[100 \times \frac{\text{Weight of oven dried water retted fibres}}{\text{Weight of oven dried unretted stems}}\right]\% \quad \ldots\ldots \textbf{(2.1)}$$

2.4. Surface modification of water retted virgin *Brassica* fibres by 10% softener treatment

The experimental model for surface modification of the water-retted virgin *B. napus* fibres involves three consecutive treatment steps: alkaline scouring of water retted virgin *Brassica* fibres (1^{st} step); acidic treatment of the alkali-scoured *B. napus* fibres (2^{nd} step); softening treatment of the acid-scoured *B. napus* fibres (3^{rd} step).

Alkaline scouring involves treating the virgin-retted fibres with 400 ml solution of 5% NaOH (Sigma-Aldrich Corporation) and a 0.5% wetting agent (Glycerin), at 60°C for 60 minutes i.e., 20 gm solid NaOH and 2 ml liquid Glycerin were added to 398 ml distilled water to make the solution to treat the virgin-retted fibres. After this treatment, the fibres were rinsed for 15 minutes in distilled water and dried at room temperature.

Acidic scouring involves treating the alkali scoured fibres (Step 1) with 400 ml solution of 4 % acetic acid (Sigma-Aldrich Corporation) solution at 60°C for 30 minutes i.e., 16 ml acetic acid was added to 384 ml water; then the fibres were rinsed for 30 minutes in distilled water and dried at room temperature.

In the softening treatment, the acid scoured fibres (Step 2) were treated with 400 ml solution of 10% Tubingal 4748 (CHT BEZEMA) at 40^{0}C for 30 minutes at an acidic pH 4.5 (controlled by acetic acid) i.e., 40 gm softener was added to 400 ml water and the pH 4.5 was adjusted by adding adequate acetic acid. The softened fibres were rinsed for 15 minutes in distilled water and dried at room temperature. The treatment kinetic is given in **Fig. 2.6**.

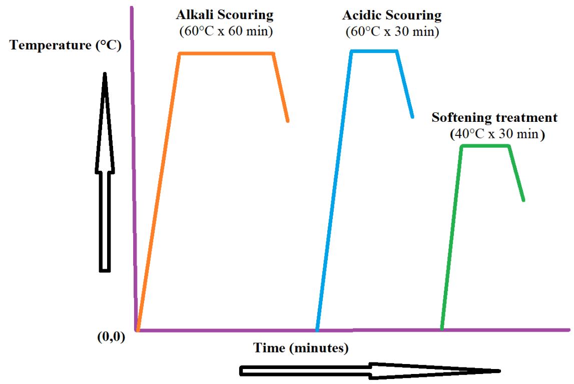


Fig 2.6: Temperature (°C)-time (min) curve of the 10% softener treatment kinetics.

2.5. Thermal heat resistance analysis of the 10% softener treated *Brassica* fibres

A thermal melting point analyzer (Linkam Scientific Instrument, UK) at the Biosystems Engineering Department of the University of Manitoba was used to assess the thermal heat resistance temperature of stem as well as the corresponding treated (10% softener) fibre. This melting point analyzer is comprised of heating plate controller connected to link pad (Model: T95 HS, UK), an imaging apparatus (Linkam , UK), and a color monitor (Dynax, Model: DX- 22L 150A11, UK). First, the samples were set on a glass slide in the machine **(Fig. 2.7)** and the temperature increased at a rate of 10° C/min. Thermal heat resistance in this research, refers to the temperature at which specimen loses its initial colour appearance and starts to have a blackish burnt appearance which was observed visually using the color display monitor.

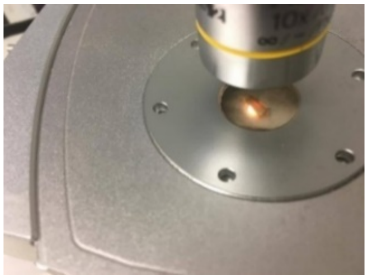


Fig. 2.7: Thermal resistance measurement of *Brassica napus* L. specimen by Linkam.

2.6. Diameter analysis of the 10% softener treated *Brassica* fibres by FibreShape

At Composites Innovation Centre (CIC), the diameter of the 10% softener-treated fibres was assessed using a FibreShape software (Innovative Sintering Technologies, Switzerland). The test equipment is comprised of a flatbed scanning system connected to a computer with FibreShape software for diameter analysis. The FibreShape diameter measurements are based on the entire image scanned, taking into account the entire sample of fibres seen in the image including different diameters of different fibres, and diameter changes along the length of the same fibre. The measurement is 2D, as it is based on a scanned image that is a profile view of the fibre (i.e., can only see what is presented to the scanner; it does not account for a non-circular cross-section, if the fibre is actually elliptical).

Specimen prepration for this test involved individualizing the *B. napus* fibres as much as possible using a fine comb prior to being placed on the scanning plate of the flatbed scanner for imaging. Fibres were tested in two stages per cultivar. The first stage involves testing individual fibres in an individualized state or single-fibre (SF) state **(Fig. 2.8)**. The second stage involves placing them on a scanner to scan them to determine their diameter using FibreShape software.

Fig. 2.8: Diameter measurement of *Brassica napus* L. fibre specimens by FibreShape: scanned image of *B. napus* fibres when tested as individual/single-fibre (N=22)

2.7. Density analysis of the 10% softener treated *Brassica* fibres by Gas Pycnometer

At CIC, the density of the 10% softener-treated fibres was assessed using an Automatic Gas Pycnometer (Quantachrome Ultrapyc 1200e, Quantachrome Instruments, USA) (**Fig. 2.9a**). After the fibre sample is weighed using an electronic balance, it is loaded into a cell **(Fig. 2.9b**) of known volume and the cell is loaded into the gas Pycnometer **(Fig. 2.9c).** This Pycnometer accurately and precisely measures the volume of the fibre specimen through N_2 gas displacement. Once the sample is loaded into the chamber of Pycnometer, N_2 gas is introduced to pass into the sample chamber to fill the void volume of the chamber including the tiny pores of the sample. The corresponding pressure is also measured by the Pycnometer. The difference between the void volume of empty cell chamber and the new void volume is the volume of the sample solid phase. The weight of the sample is measured using an electronic balance before loading it inside the Pycnometer. Therefore, the density of the specimen is determined by dividing the weight of sample by its volume.

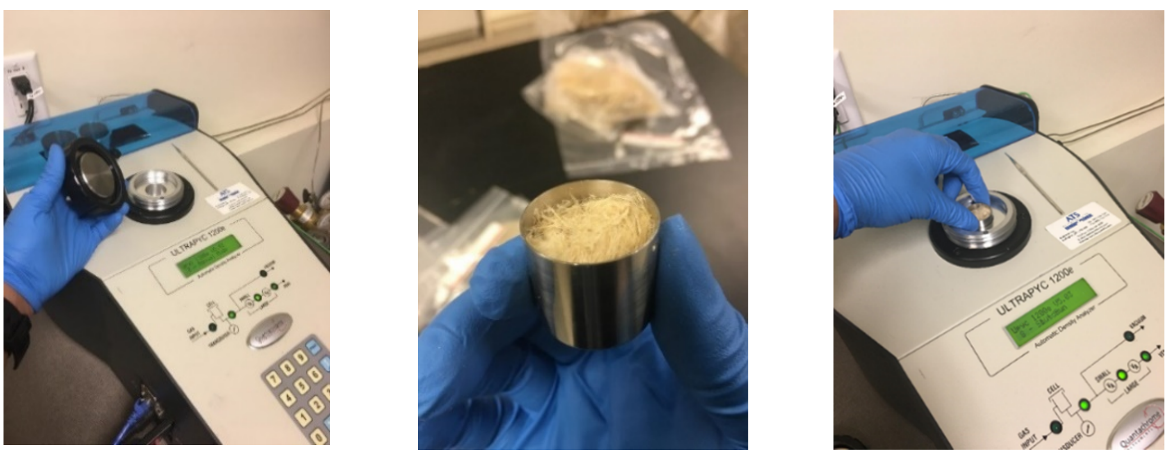
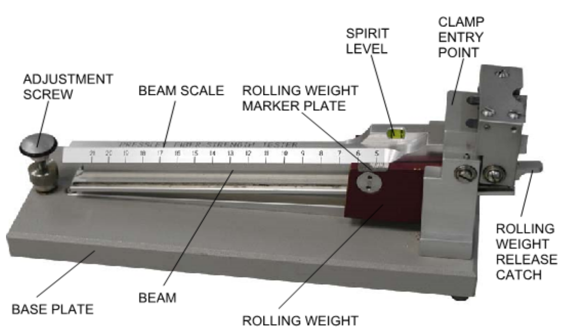


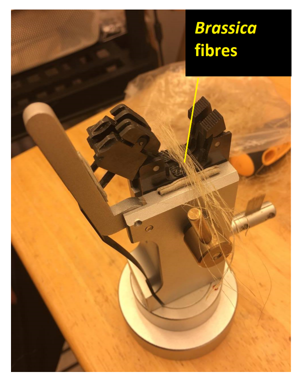
Fig. 2.9: Density measurement of *Brassica napus* L. fibre specimens by Quantachrome Ultrapyc 1200e Gas Pycnometer: (a) testing chamber lid, (b) *B. napus* specimen containing cell, (b) loading zone of the cell.

2.8. Tensile strength analysis of the 10% softener treated *Brassica* fibres by Pressley Strength Tester

In the humidity chamber (ENCONAIR GRC-40, Enconair Ecological Chambers Inc., Canada) (temperature: 23.0°C; relative humidity: 50.0%) of the Department of Plant Science of University of Manitoba, the breaking load of virgin and 10% softener-treated fibres was measured according to ASTM D1445M-12 (2012) standard using a Pressley Fibre Bundle Strength Tester (Model F215, SDL Atlas Instrument, USA) **(Fig. 2.10a)**. The Pressley tester comprised of a Torque vise **(Fig. 2.10b)** to hold the flat bundles of the fibre sample and a loading unit where the fibres are subjected to breaking loads (lb) in a free-rolling weight carriage designed to break the fibre bundles. There is also an applied load measuring beam scale on the Pressley tester that is calibrated in pound-force.



(a)



(b)

Fig. 2.10: Tensile property measurement of *Brassica napus* L. fibre specimens by Pressley Tester: (a) Pressley tester (photo is adopted from the F215 Pressley Fiber Bundle Strength Tester Instruction Manual provided by CIC), (b) torque vise to load the fibre on the tester.

To operate the Pressley tester, the fibre specimens are individualized and straightened as much as possible along the fibre axis using the fine comb mounted on the torque vise. The fibre bundles were placed between a pair of breaking clamps **(Fig. 2.10b)** in the form of a fibre ribbon of 6 mm wide (or 1/4-inch) with a clamp spacer (or gauge specimen) that is 3.2 mm (1/8-inch) wide. The excess fibre protruding from the clamps was cut and the clamps were placed between the jaws of the clamp to tightly lock the clamp by rotating the vice handle. The clamps were placed in the Pressley fibre bundle tester, and the rolling weight trigger catch was unlocked to break the fibres. The breaking load (lb) was recorded from the beam scale (lb), and the weight (in mg) of the broken fibres was measured using an electronic balance to determine strength index (lb/mg). Strength Index, breaking tenacity, and tensile strength were measured using the following formula:

Strength index (lb/mg) = Breaking load (lb) / Mass of specimen (mg) …… **(2.2)**

Breaking tenacity (gram-force/tex) = 6.8 x Strength index …… **(2.3)**

Tensile strength (MPa) = 9.807 x Fibre density (g/cc) x Tenacity (gram-force/tex) …… **(2.4)**

Eqs. 2.2 and **2.3** are in accordance with ASTM D1445M-12 (2012). This **Eq. 2.4** has been developed **(discussed in Appendix VIII)** to calculate the fibre tensile strength using the fibre density, because, in the textile industry, density is a very important factor as it is an indicator of weight of fibre (or fabric) being used or worn over human body. However, ASTM D144M-12 (2012) discussed the following **Eq. 2.5** to calculate tensile strength (in 1000 psi or pounds/inch^2**)**:

Tensile strength (1000 psi) = 2.016 x Tenacity (gram-force/tex) …… **(2.5)**

During this test procedure, there were three types of test failure observed (that are reported in **Appendices- IX, X**) while loading fibre specimens between the clamps, which were T1 (Type 1 test failure) due to loading insufficient amount of fibre specimen, T2 (Type 2 test failure) due to loading excess specimen beyond the loading capacity of the machine, and T3 (Type 3 test failure) due to loading too much brittle and stiff fibres, (seen only in virgin-retted fibres, but not in softened fibres). Proper and careful selection of fibre bundle samples was necessary while conducting tests with the Pressley tester.

2.9. Moisture regain measurement of *Brassica* specimens

Before measuring the moisture regain of the *B. napus* specimens, all the sepcimens were kept at room temperature for 7 d (or days). Therefore, the room temperature weight of the specimen was measured, followed by oven-drying for 8-hour at 105°C inside an incubator according to ASTM D2495-07 (2012) standard, and the oven dried fibres were reweighed. Moisture inside the specimen was calculated from the difference of these two weights. The moisture regain of the specimen was calculated using the following formula **(Eq. 2.6)**:

$$\text{Moisture regain (\%)} = \left[100 \times \frac{\text{Weight of moisture in the specimen}}{\text{Weight of oven dried specimen}}\right]\% \quad \ldots\ldots \textbf{(2.6)}$$

During this test, the oven-drying end-point of the *B. napus* specimens was determined when a constant weight of the specimens was obtained during the oven-drying test. For example, during oven-drying of the *B. napus* stems, all the stems were oven-dried in the incubator at 105°C. After 6 hours, there was no change in weight from room temperature to oven dry weight (data not shown here) and after additional 2 hours (8 hours total) of incubation no changes in weight were obtained. Hence, a constant weight was obtained and reported after 8 hours for stems which is a pre-requisite for conducting moisture regain test. This method was followed to conduct every oven-drying tests throughout the research study for each applicable replication as illustrated in **Fig 2.11**.

2.10. Experimental design flowchart

Fig. 2.11 shows the experimental stages and replications per experiment of the current research. The entire characterization (moisture regain, thermal resistance, diameter, density, and tensile properties) of the *B. napus* fibre was conducted using 10% softener-treated fibres which were obtained from water retted stems of replication #2 as indicated in the following illustration (**Fig. 2.11**). At least three (03) replications or specimens per *B. napus* cultivar were used during each fibre characterization which are also illustrated in **Fig. 2.11**.

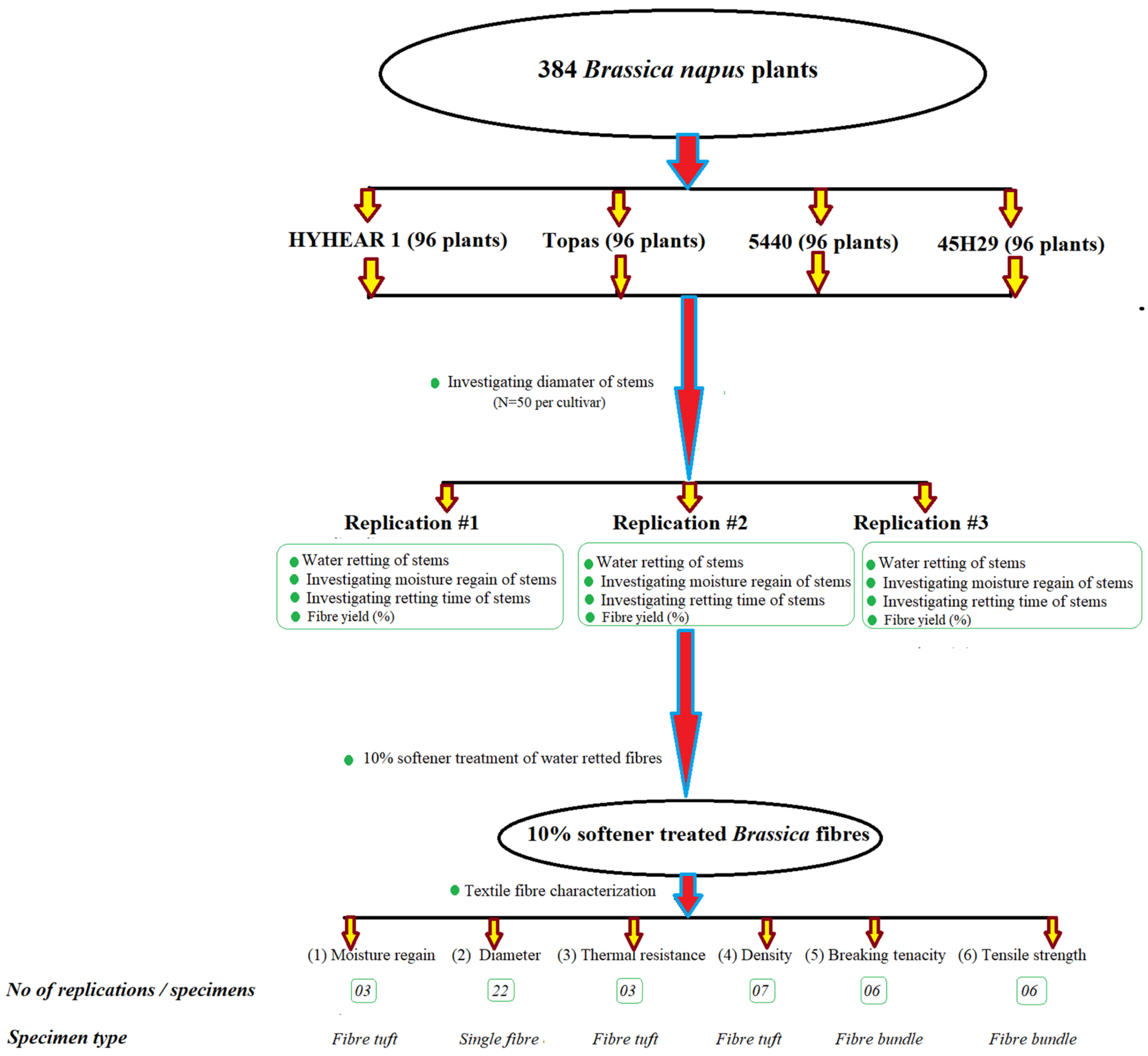


Fig. 2.11: Experimental design flowchart with *Brassica napus* L. cultivars in this research study.

2.11. Data analysis

ANOVA stasitical analysis (α=0.05) was conducted to determine the presence of any significance variation among the means and Fisher's LSD test (α=0.05) was conducted for pairwise comparion among the mean using Microsoft Excel software (Version- 2013, Microsoft Corporation, USA). Further, Microsoft Excel software was also used in calculating mean values, standard deviation, and co-efficent of variation (CV, %).

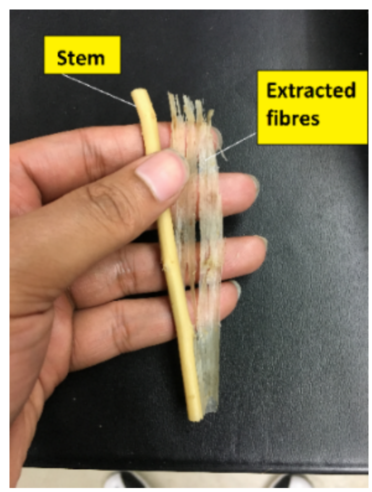
Chapter 3. Results and Discussion

3.1. Plant characterization

3.1.1. Effect of cultivars on the diameter (dia) of the stem samples

Table 3.1 shows the grand mean diameter (mm) of 50 plant stems (**Fig. 3.1)** of each of the *B. napus* cultivars with their standard deviations before water retting was conducted. The details of diameter values for each stem for each cultivar is given in **Appendix I (Table 1- Table 4)** and have been summarized (mean of three values). The results from **Table 3.1** depict that plant stems of 5440 had the highest mean diameter (5.01 mm), while HYHEAR 1 and 45H29 had the lowest stem diameter (4.61 mm). It was found that $F_{statistical}$ value (2.71) > $F_{critical}$ value (2.61) and $p < 0.05$, meaning that there is a significant difference among the means (**Table 3.1)**. Further, Fisher's LSD test exhibits that there is a significant difference between HYHEAR 1 and 5440 as well as between 5440 and 45H29.

(a)



(b)

Fig. 3.1: Stems (a) of *Brassica napus* L. cultivars and the extracted fibres (b) from the water retted stem.

Table 3.1: Grand mean diameter (mm) of the plant stems of the four different *Brassica napus* L. cultivars and statistical analysis (ANOVA and Fisher's LSD test).

Cultivar type	**Grand mean diameter (mm)** [A]	**CV, %** [B]	**LSD, α=0.05**
HYHEAR 1	4.61±0.77 [a s]		
Topas	4.92±0.60 [a]	4.35	0.36
5440	5.01±1.21 [a s q]		
45H29	4.61±0.91 [a q]		

[a] Mean ± Standard Deviation, N= 50; p=0.04 < 0.05; $F_{critical}$= 2.61 < $F_{statistical}$= 2.71;
[s, q] Significant variation (α=0.05)
[A] Appendix II; [B] CV stands for Coefficient of Variation

Fibre diameter is correlated to stem diameter. For example, hemp fibre diameter is larger at the bottom in comparison to the top (Kozłowski, 2012a). Further, the tensile strength of a natural fibre decreases when their diameter increases along stem length of a plant, because fibre defect (kinks) increases as their diameter increases (Liu et al., 2015). Therefore, the study of stem diameters (**Appendix I: Table 1- Table 4)** and their corresponding fibre diameters at different regions of a plant stem (bottom, top, middle) is significant to classify their end-use application in engineering.

3.1.2. Effect of cultivar on the moisture regain of the stems

Establishing atmospheric condition is very important for having constant weight (the weight of material that doesn't change at constant humidity and temperature with time) to obtain moisture regain (%) and fibre yield (%). For purpose of investigating the moisture regain (%) of the stems of the cultivars, all the stems were maintained at same moisture. **Table 3.2** displays the moisture regian of the cultivar specimens.

Table 3.2: Moisture regain (%) of the stems of four different *Brassica napus* L. cultivars and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	Cultivar type			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Overall mean	9.99±1.65 [a]	8.64±1.12 [a]	9.43±2.17 [a]	9.96±1.97 [a]
CV, %	6.64			
LSD, α=0.05	3.34			

[a] Mean ± Standard Deviation, N = 3; p=0.77 > 0.05; $F_{critical}$= 4.07 > $F_{statistical}$= 0.38

Table 3.2 demonstrates that the highest regain was exhibited by HYHEAR 1 (9.99±1.65 %) and lowest by Topas (8.64±1.12 %). However, there is no significant difference among the means of the moisture regain of the stems of the *B. napus* cultivars (p > 0.05; $F_{critical}$= 4.07 > $F_{statistical}$= 0.38). The moisture regain of *B. napus* plant stems is quite similar to the moisture regain of cattail plants as Chakma et al. (2017) reported moisture regain of virgin cattail plants to range between 9.6-10.6%.

3.1.3. Effect of cultivars on the retting time

Table 3.3 displays the retting time for stems of the four cultivars. The mean retting time was the shortest for Topas. Topas showed the lowest retting time (266±44.6 hours) followed by HYHEAR 1 (344.8±107.2 hours) and the highest retting time was demonstrated by 5440 (380.3±61.9 hours) followed by 45H29 (379±35.9 hours). However, there is no significant difference among the means of the retting time of the stems of the *B. napus* cultivars (p > 0.05). Khan's (2016) research on twenty different *B. napus* cultivars (excluding 5440, and 45H29) found retting time to range between 5-12 d (120-288 hours), and the retting times for HYHEAR 1 and Topas were found to be 9 d (216 hours) and 11 d (264 hours), respectively.

Table 3.3: Retting time (hours) of the stems of four different *Brassica napus* L. cultivars and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	**Retting time (hours) of the *Brassica* plant stems**			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Overall mean	344.8±107.2 [a]	266±44.6 [a]	380.3±61.9 [a]	379±35.9 [a]
CV, %		15.65		
LSD, α=0.05		128.4		

[a] Mean ± Standard Deviation, N= 3; p=0.2 > 0.05; $F_{critical}$= 4.1 > $F_{statistical}$= 1.9

The retting time variation of *B. napus* cultivars also resembles with the findings of Brown et al. (1986) who studied the retting time variation among five different flax cultivars, which were Ariane (26.3% pectic substances or PS), Belinka (32.5% PS), Hera (34.0% PS), Natajsa (28.2% PS), Regina (30.1% PS). Brown et al. (1986) found that Ariane retted rapidly among the five cultivars and Belinka, Hera were the slowest in glyphosate retting process.

Brown et al. (1986) sprayed the flax cultivars with glyphosate for purpose of retting, which were later tested for degree of retting by stem strength loss test (by Instron) and caustic weight loss test (by treating 1g of retted fibres by 50 ml 2M-NaOH). During their test, loss of stem strength (highest loss 63.2% for Ariane at 6.8 g/denier fibre strength and 28.3 dtex fibre fineness; lowest loss 44% for Hera at 7.3 g/denier, 27.4 dtex) and caustic weight loss of fibres (lowest loss 28% for Ariane and highest loss 31.1% for Hera) were considered as indications of degree of retting. Further, it was found that Ariane retted significantly faster (p< 0.05; no data given on retting time) among all the five cultivars while Natajsa and Regina retted significantly faster (p< 0.05; no data given on retting time) than Belinka and Hera. Enzymatic degradation of pectic compounds is responsible for retting (Allen, 1946 cited in Brown et al., 1986; Chesson, 1978). Brown et al. (1986) also identified the presence of pectic substances (PS) to be one of the major reasons for the variation of retting rate concluded that presence of higher amounts of pectic substances in the cell wall of Belinka (32.5% PS) and Hera (34.0% PS) than Ariane (26.3% PS), the cultivars Belinka and Hera took a long retting time to degrade their internal pectic compounds before a satisfactory degree of retting was obtained compared to Ariane. No previous work could be found that demonstrated the end point of water retting.

During the fibre extraction from the stems in this research work, it was observed that the force required to extract fibres was different for individual plant stems within the same cultivar. Some stems required less pulling force to extract the fibres, while others required comparatively more. Few plant-extracted fibres exhibited a softer hand feel due to over-retting, while others were under-retted and stiffer, although they were in same water bath.

3.2. Effect of cultivars on the fibre yield (%)

Table 3.4 contains the fibre yield (%) obtained from water retting experiments for each of the four *B. napus* cultivars. Following the retting of the stems, 45H29 produced the highest and 5440 produced the lowest fibre yield (%), which were 10.41±1.86% and 9.11±2.13%, respectively. However, there is no significant difference among the means of the fibre yield (%) ($p > 0.05$).

Table 3.4: Fibre yield (%) of the four different *Brassica napus* L. cultivars and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	Cultivar type			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Overall mean	9.37±1.74 [a]	9.60±0.74 [a]	9.11±2.13 [a]	10.41±1.86 [a]
CV, %			5.84	
LSD, α=0.05			3.20	

[a] Mean ± Standard Deviation, N= 3; p=0.21 > 0.05; $F_{critical}$= 4.07 > $F_{statistical}$= 1.85

Khan (2016) found the fibre yield (%) of twenty different *B. napus* cultivars (excluding 5440, 45H29) ranged 6.23-13.82%; the fibre yield (%) of HYHEAR 1 was 12.66% and for Topas 10.63%. Fibre yield (%) found in the current study is within this range reported by Khan (2016). Jankauskienė et al. (2015) conducted a comparative study among eight different cultivars of hemp bast fibres, which were Beniko, Bialobrzeskie, Epsilon 68, Fedora 17, Felina 32, Futura 75, Santhica 27, USO 31 and found Beniko produced the highest fibre yield (5700 kg ha^{-1}) and Fedora 17 produced the lowest (2768 kg ha^{-1}). This variation of fibre yield was also reported for other cultivars, such as Bialobrzeskie produced 3812 kg ha^{-1}, Epsilon 68 produced 3631 kg ha^{-1}, Felina 32 produced 3607 kg ha^{-1}, Futura 75 produced 3913 kg ha^{-1}, Santhica 27 produced 3816 kg ha^{-1}, and USO 31 produced 3723 kg ha^{-1}. However, statistical variation for fibre yield (%) was only identified between Beniko and Fedora 17 ($p < 0.01$).

3.3. Fibre characterization

In this current study, surface modifications of water-retted *B. napus* fibres (extracted from stems used in replication #2) were conducted using 10% softener treatment that produced fibres with single fibre entity and flexibility for all the four cultivars **(Fig 3.2)**. Although, numerous chemical treatments were conducted in this research but only the 10% softener-treated fibres were used for characterization of different textile fibre properties, such as moisture regain, heat resistance, diameter, density, and tensile properties. Further, moisture regain and mechanical properties of the water-retted virgin *B. napus* fibres were also measured.

Fig. 3.2: 10% softener-treated fibres (from left to right- HYHEAR 1, Topas, 5440, 45H29).

3.3.1. Effect of cultivars on moisture regain (%) of water-retted and softener-treated fibres

The moisture regain (MR) (%) of water-retted virgin fibres and the 10% softener-treated fibres for the four cultivars is shown in **Table 3.5**. HYHEAR 1 showed the highest (12.53±3.37%) moisture regain and 45H29 showed the least (9.31±3.40%) among the water-retted fibres, whereas HYHEAR 1 showed the highest (7.64±0.03%) moisture regain and Topas showed the least (6.03±0.05%) among the softener-treated fibres. **Table 3.5** shows there is no significant difference among the means of water-retted virgn fibres ($p > 0.05$) but there is a significant difference among the means of the softener-treated fibres ($p < 0.05$). Fisher's LSD test exhibits that there is a significant difference between every pairs of means except between 5440 and 45H29 for the softener-treated *B. napus* fibres.

Table 3.5: Moisture regain (%) of the water-retted (WR) virgin and softener-treated (ST) *Brassica napus* L. fibres and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	**Moisture regain (%) of *Brassica* fibres**							
	Water-retted (WR) fibres				**Softener-treated (ST) fibres**			
	HYHEAR 1	**Topas**	**5440**	**45H29**	**HYHEAR 1**	**Topas**	**5440**	**45H29**
Mean	12.53± 3.37 [a m]	9.38± 2.75 [a m]	10.32± 3.15 [a m]	9.31± 3.40 [a m]	7.64± 0.03 [a]	6.03± 0.05 [a]	7.21± 0.06 [a n]	7.18± 0.06 [a n]
CV, %	14.47				9.83			
p-value	0.59 (> 0.05)				0.00 (< 0.05)			
$F_{critical}$	4.07				4.07			
$F_{statistical}$	0.67				621.70			
LSD, α=0.05	5.98				0.09			

[a] Mean ± Standard Deviation, N= 3;
[m, n] No significant variation (α=0.05)

Sevenhuysen and Rahman (2016) reported virgin *B. napus* fibres with moisture regain (%) (MR) of 20- 30%, which is higher than the moisture regain obtained from this research work. MR of different fibres is given in the following **Table 3.6** that displays that MR of natural fibres like cotton, flax, hemp differ at different atmosphere which is also illustrated in **Fig. 3.3**.

Table 3.6: Moisture regain (%) of different textile fibres.

Fibres	**Commercial moisture regain (%) at (105±3) °C**	**Moisture regain (%) at 65% relative humidity and 20°C**
Brassica napus L.*	-	20- 30 [a]
Cotton	8.5 [b]	7-8 [c]
Flax	12 [b]	7 [c]
Hemp	12 [b]	8 [c]
Jute	13.75 [b]	12 [c]
Silk	11 [b]	10 [c]
Wool	13.6 [b]	14 [c], 16-18 [c]

[a] Sevenhuysen and Rahman (2016); [b] ASTM D1909 –13 (2013); [c] Morton and Hearle (2008)
*Commercial trade name (for textile application) for *Brassica napus* L. has not been established yet

Fig. 3.3 (Saville, 1999) displays that cotton exhibits around 6%, 8%, 23% MR at 60%, 80%, and 98% RH, respectively. It also displays that MR for viscose increased eight times when RH increased five times (around 5% MR for 20% RH and 40% MR for 100% RH). Further, MR of silk, wool, acetate and nylon also changes with the change of RH.

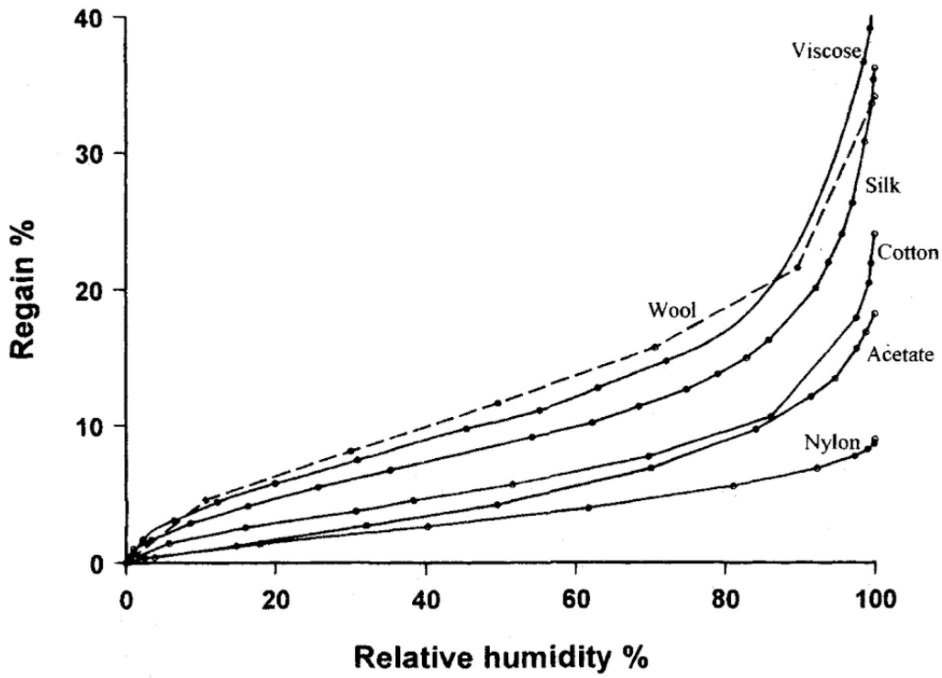


Fig. 3.3: Moisture regain of fibres in different relative humidity conditions (Saville, 1999).

By comparing the MR of water retted fibres and 10% softener-treated fibres, it can be seen that MR is comparatively lower for all the 10% softener-treated fibres than for the water-retted fibres which is in agreement with the work of Parvinzadeh et al. (2010). Parvinzadeh et al. (2010) conducted research by treating controlled cotton fibres (4.84% MR) with softeners and found a decrease of MR of the softener-treated cotton (3.52% MR) because of the increased hydrophobicity of the fibre surfce. The authors also confirmed there finding by SEM images where the softener particles aggregated on the fibre surface and decreased their hydrophilicity.

3.3.2. Effect of cultivars on the thermal heat resistance of stems and softener-treated fibres

Table 3.7 contains the comparative study of thermal heat resistance among the cultivar stems and their respective 10% softener-treated fibres. Heat resistance, is the temperature at which a material loses its initial colour and gives a burnt look **(Fig 3.4)**. It can be seen from the table that in every case, the heat resistance of 10% softener-treated fibre is less than that of the corresponding stem. Among the stems, highest heat resistance was shown by Topas (270.53±1.10^{o}C) and lowest by 45H29 (240.20±0.40^{o}C). Similar results were seen for the thermal resistance of fibres, where Topas showed the highest i.e., 257.23±0.51^{o}C, and 45H29 showed the lowest i.e., 237.63±0.51^{o}C. It can be also seen from **Table 3.7** that there is a significant difference among the means of thermal resistance of the plant stems (p <0.05) as well as among the softener-treated fibres (p <0.05) of the four *B. napus* cultivars. There is a significant difference between every pair of means for the thermal heat resistance of the four *B. napus* cultivars.

Table 3.7: Thermal resistance (^{o}C) of plant stems and softener-treated fibres of *Brassica napus* L. culitvars and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	**Thermal resistance (^{o}C) of *Brassica* cultivars**							
	Plant stems				**Softener treated fibres**			
	HYHEAR 1	**Topas**	**5440**	**45H29**	**HYHEAR 1**	**Topas**	**5440**	**45H29**
Mean	262.13 ±0.83 [a s]	270.53 ±1.10 [a s]	250.63 ±0.55 [a s]	240.20 ±0.40 [a s]	242.50 ±0.40 [a q]	257.23 ±0.51 [a q]	249.33 ±0.45[a q]	237.63 ±0.51 [a q]
CV, %	5.18				3.45			
p-value	0.00 (< 0.05)				0.00 (< 0.05)			
$F_{critical}$	4.07				4.07			
$F_{statistical}$	889.81				978.55			
LSD, α=0.05	1.45				0.89			

[a] Mean ± Standard Deviation, N = 3;
[s, q] Significant variation (α=0.05)

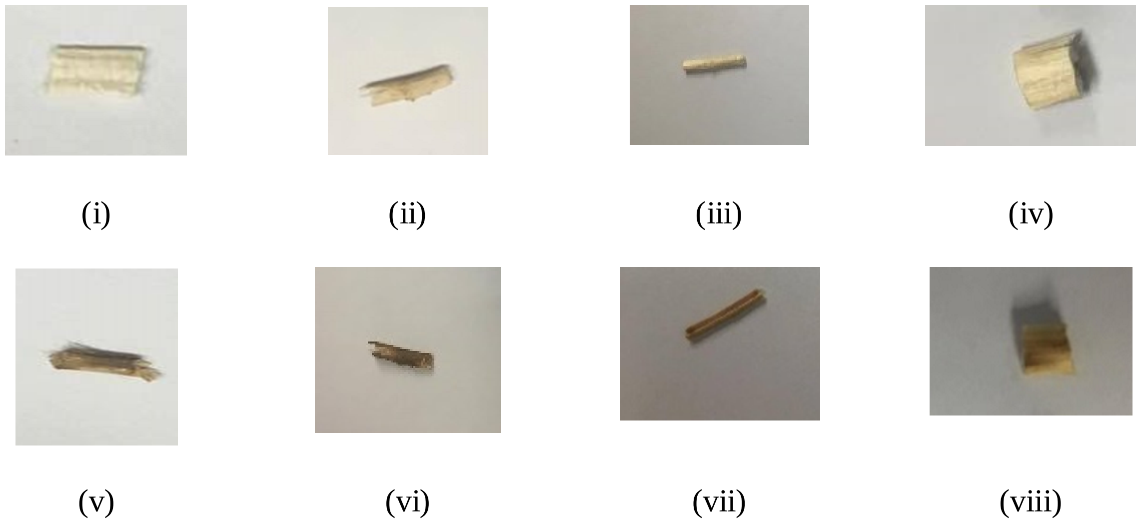


Fig. 3.4 (a): Thermal heat resistance of *Brassica napus* L. stems: (i-iv) pre-heated and (v-viii) post-heated stems of HYHEAR 1, Topas, 5440, and 45H29, respectively.

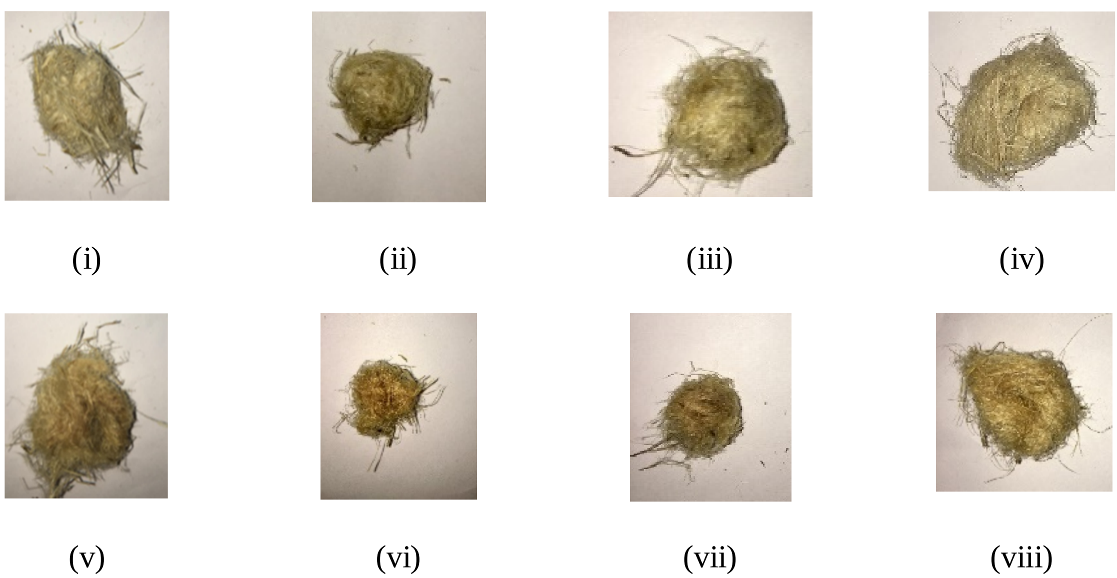


Fig. 3.4 (b): Thermal heat resistance of *Brassica napus* L. fibres: (i-iv) pre-heated and (v-viii) post-heated fibres of HYHEAR 1, Topas, 5440, and 45H29, respectively.

Khan (2016) also found a similar range of thermal decomposition temperature for some *B. napus* cultivars. The author found temperatures of 240.0^{o}C for virgin-retted Reston fibres, 260.0^{o}C for enzyme-treated Apollo fibres, and 225°C for enzyme treated Hero fibres. Sevenhuysen and Rahman (2016) reported the thermal resistance of virgin *B. napus* fibres of unknown cultivars to be up to 250.0°C.

3.3.3. Effect of cultivar on the diameter of softener-treated fibres

Table 3.8 contains the mean fibre diameter and minimum and maximum diameter (dia) of the four cultivars as determined by FibreShape software. As an individual fibre specimen, 45H29 showed the lowest fibre diameter (26.11 µm) and HYHEAR 1 showed the highest fibre diameter (213.60 µm) among all the *B. napus* cultivars. Further, HYHEAR 1 showed the highest mean fibre diameter (86.93±57.12 µm, N=22), whereas, 5440 showed the lowest mean fibre diameter (64.38±26.22 µm, N = 22) **(Table 3.8)**.

Table 3.8: Diameters (µm) of the softener-treated fibres of four *Brassica napus* L. cultivars using FibreShape software and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	**Cultivar type**			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Minimum dia [A]	30.39	33.35	27.32	26.11
Maximum dia [A]	213.60	146.67	109.25	207.33
Mean dia	86.93±57.12 [a]	81.54±31.78 [a]	64.38±26.22 [a]	78.37±47.79 [a]
CV, %		12.38		
LSD, α=0.05		25.51		

[a] Mean ± Standard Deviation; N= 22; p=0.34 > 0.05; $F_{critical}$= 2.71 > $F_{statistical}$= 1.13
[A] Appendix III

However, no significant differences among the fibre diameter of the four cultivars ($F_{statistical}$ = 1.13< $F_{critical}$ = 2.71; p-value > 0.05) were found as shown in **Table 3.8**. The detailed report on the results of the individual fibre diameter analysis obtained from FibreShape software has been recorded in **Appendix III** that have been obtained during the tests conducted at Composite Innovation Centre (CIC).

The diameter variation of *B. napus* fibres obtained from this research consistent with the diameter variation of other natural fibres. Diameter variations reported by Kozlowski (2012b) were 12-38 µm for cotton, 25-200 µm for jute, 25-500 µm for hemp, and 40-600 µm for flax. Sevenhuysen and Rahman (2016) found a mean diameter of 13.88 µm, 12.32 µm, 15.50 µm, 14.71 µm, 31.12 µm, and 26.207 µm for virgin *B. napus* fibres obtained from unknown cultivars, where the authors manually individualized the fibres and measured their corresponding diameters using a Bioquant Analyzer. The minimum diameter of the *B. napus* fibres found in this current study is close to the data found by Sevenhuysen and Rahman (2016). However, it seems that there is natural variation among the diameters for *B. napus* fibres, as found in this research. There may be other reasons for variation which are measurement technique (using different apparatus such as Bioquant analyzer or FibreShape)**,** *B. napus* specimen preparation method (single fibre or fibre tufts), and plant growing conditions. FibreShape may be used to determine fibre diameters in the single fibre where the test-specimens should be fully individualized and proper fibre individualization can be confirmed by scanning electron microscopy (SEM) for a consistent testing condition.

3.3.4. Effect of cultivars on the density of softener-treated fibres

Table 3.9 contains the fibre density of the 10% softener-treated *B. napus* fibres determined using a nitrogen gas Pycnometer. The mean value of the density was obtained from seven (N=7) replications per cultivar, and these data were obtained from the reports (**Appendices IV – VII**) produced by Pycnometer after analyzing the specimens. It can be seen from **Table 3.9** that the densities range between 1.34 g/cc and 1.43 g/cc for the four cultivars, with 45H29 having the highest density (1.43±0.0011 g/cc) and HYHEAR 1 the lowest (1.34±0.0009 g/cc). Statistical analysis shows significant differences among the mean densities of these four cultivars ($F_{critical}$= 3.01 < $F_{statistical}$= 10547.53 and p-value <0.05).

Table 3.9: Mean density (g/cc) of softener-treated fibres of four different *Brassica napus* L. cultivars using N_2 Gas Pycnometer and and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	Cultivar type			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Weight (g) [A]	1.25	1.58	1.65	1.16
Mean volume (cc) [A]	0.93 ± 0.0007 [a]	1.16 ± 0.0006 [a]	1.19 ± 0.0006 [a]	0.81 ± 0.0006 [a]
Mean density (g/cc) [A]	1.34 ± 0.0009 [a s]	1.36 ± 0.0007 [a s]	1.38 ± 0.0007 [a s]	1.43 ± 0.0011 [a s]
CV, %	2.80			
LSD, α=0.05	0.001			

[a] Mean ± Standard Deviation, N =7; p=0 <0.05; $F_{critical}$= 3.01 < $F_{statistical}$= 10547.53
[s] Significant variation (α=0.05)
[A] Appendices IV-VII

The results show that there is a significant difference between every pair of means of fibre densities; the cultivars can be ranked from the lightest to heaviest in the following stated order: HYHEAR 1> Topas> 5440> 45H29.

The current study is the first of its kind to measure the density of *B. napus* fibre in the world. Composites Innovation Centre (CIC) also used a gas Pycnometer to measure the density of flax fibres using the same testing procedure followed in this study (Truong et al., 2009). Considering fibre density, *B. napus* fibre is the lightest of all the natural cellulosic fibres recorded in **Table 3.10**. The density of *B. napus* fibre (1.34- 1.43 g/cc) **(Table 3.9)** is lower than cotton in all four cases: 1.54 g/cc (measured by Archimedes' principle, ASTM 2012), 1.509 g/cc (measured by N_2 gas Pycnometer), 1.743 g/cc (measured by He gas Pycnometer), and 1.55 g/cc (measured by density gradient tube). *B.napus* fibre density is also found lower than the fibre density of flax (1.50

g/cc, measured by N_2 gas Pycnometer) (Truong et al., 2009). Further, the density of *Brassica* fibre is lower than the densities of jute (1.44-1.50 g/cc) and hemp (1.48-1.49 g/cc) fibres (Houck, 2009 cited in Kozlowski, 2012a) (no data was found regarding the measurement method).

Table 3.10: Comparison of densities (g/cc) between *Brassica napus* L. and other natural cellulosic fibres.

Cellulosic fibres	**Fibre density (g/cc) measured by**			
	Archimedes' principle (ASTM D276-12)	**N_2 gas Pycnometer**	**He gas Pycnometer**	**Density gradient tube**
Cotton	1.54 [a]	1.509 [b]	1.743 [b]	1.55 [e]
B. napus	-	1.34 - 1.43 [c]	-	-
Flax	1.54 [a]	-	1.50 [d]	-

[a] ASTM D276-12 (ASTM 2012); [b] Onogi et al., (1996); [c] Table 3.9;
[d] Truong et al. (2009); [e] Preston and Nimkar (1950)

The density of fibre has great implications in many textile and smart textile applications. For example, in aerospace or in automotive applications, lightweight fibre reinforced composites will reduce fuel consumption and fuel expenditure (REF). The introduction of *B. napus* fibre composites can be a lightweight alternative to other currently-used bast fibre composites. For example, unsaturated polyester resin is used with hemp to produce hemp fibre reinforced composites (Qiu et al., 2011) and epoxy resin Kinetix R240 are used with flax, hemp and jutes for producing composites (Bambach, 2017). Textile fibres are used to manufacture industrial textiles, for example, jute geotextiles for road constructions (Horrocks & Anand, 2000). Manufacturers purchase fibres on the basis of weight to produce geotextile fabric in linear yards; however, the geotextile fabric is sold by fabric length. Therefore, the more light-weight a fibre can be (i.e., lower density), the more a manufacturer can buy and produce the fabric length at a lower price than heavy-weight (i.e., higher density) fibres. This commercial transaction gives huge economical savings using light-weight fibres to manufacture geotextile fabric. Based on the above stated features, *B. napus* may be termed as a "natural smart-fibre", whose feature can also be harnessed to produce biodegradable bags, wind turbines, and lightweight sports equipment.

3.3.5. Effect of cultivars on breaking load, breaking tenacity, and tensile strength of softener-treated fibres

The strength index ($S.I_{NDX}$), breaking tenacity, and tensile strength of the fibres were measured using the formulas stated in **Eqs. 2.2, 2.3,** and **2.4**, respectively, which has been discussed in **Chapter 2**.

The mathematical formula according to ASTM D1445/D1445M-12 (for strength index, breaking tenacity), and recommended by Composites Innovation Centre (CIC) (for tensile strength that is explained by the author) used for measuring these parameters in **Appendix VIII**. In this current study, a spacer was used in between the clamps while the fibres were tested by the Pressley Bundle Fibre Tester.

Table 3.11 and **Table 3.12** display the mean breaking load, strength index ($S.I_{NDX}$), and breaking tenacity of water-retted virgin *B. napus* fibres, and their respective 10% softener-treated fibres. The mean value of the fibre breaking load (lb), strength index (lb/mg), breaking tenacity (g-force/tex), and tensile strength (MPa) were obtained using six replications per cultivar. Breaking load of a textile fibres is not a correct representation of its tensile property while using a Pressley Bundle Fibre Tester; rather breaking tenacity (gram-force/tex or g-force/tex) of the textile fibre represents its actual and correct tensile properties. It can be seen from **Table 3.11** that Topas showed the highest breaking load (12.58±3.09 lb) as well as the highest breaking tenacity (16.85±2.69 g-force/tex) among all the virgin or controlled/untreated fibres; 5440 had the lowest breaking load (11.20±1.61 lb), but not the lowest breaking tenacity (12.33±2.13 g-force/tex) among all the fibres. 45H29 showed the lowest tenacity (12.04±1.56 g-force/tex), but not the lowest breaking load (11.30±3.09 lb). In terms of strength index ($S.I_{NDX}$) (lb/mg), 5440 had a $S.I_{NDX}$ of 1.81 but 45H29 had a $S.I_{NDX}$ of 1.77. Topas displayed the highest $S.I_{NDX}$ (2.48). All the data obtained from individual testing of the water retted virgin fibres of four cultivars are given in **Appendix IX (Tables 1a- 1d).** As breaking tenacity is important for textile industries, hence satatistcal analysis was focused only on the brekaing tenacities of the *B. napus* fibres.

Table 3.11: Mean breaking load (lb), strength index (lb/mg), and breaking tenacity (g-force/tex) of water-retted fibres of *Brassica napus* L. cultivars and statistical analysis of breaking tenacity (ANOVA test).

Parameters	**Cultivar type**			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Mean breaking load (lb) [A]	11.23±2.77 [a]	12.58±3.09 [a]	11.20±1.61 [a]	11.30±3.09 [a]
Mean strength index (lb/mg) [A]	1.99±0.79 [a]	2.48±0.39 [a]	1.81±0.31 [a]	1.77±0.23 [a]
Mean breaking tenacity (g-force/tex) [A]	13.52±5.35 [a]	16.85±2.69 [a]	12.33±2.13 [a]	12.04±1.56 [a]
CV,% (for tenacity)	16.11			
LSD, α=0.05	4.94			

[a] Mean ± Standard Deviation, N=6; $p=0.07 > 0.05$; $F_{critical}= 3.10 > F_{statistical}=2.72$
[A] Appendix IX (Tables 1a- 1d)

Table 3.12 displays the strength of 10% softener-treated fibres obtained using six (n= 6) individual readings per cultivar. 45H29 and 5440 displayed breaking tenacity of 12.51 g-force/tex and 9.57 g-force/tex. However, Topas had the highest breaking tenacity (13.15 g-force/tex) and HYHEAR 1 showed the lowest breaking tenacity (8.72 g-force/tex). $S.I_{NDX}$ variation influenced the breaking tenacity of the virgin fibres **(Table 3.11)**, which was also seen for the 10% softener-treated fibres **(Table 3.12)**. Fisher's LSD test exhibits that there is a significance variation between HYHEAR

1 and Topas, HYHEAR 1 and 45H29, and Topas and 5440, respectively. All the data obtained from individual testing of the 10% softener-treated fibres of four cultivars are given in **Appendix X (Tables 1a- 1d).**

Table 3.12: Mean breaking load (lb), strength index (lb/mg), and breaking tenacity (g-force/tex) of softener-treated fibres of four *Brassica napus* L. cultivars and statistical analysis of the breaking tenacity (ANOVA and Fiasher's LSD test).

Parameters	**Cultivar type**			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Mean breaking load (lb) [A]	10.68±3.40 [a]	10.99±1.98 [a]	9.88±1.79 [a]	11.48±2.53 [a]
Mean strength index (lb/mg) [A]	1.28±0.38 [a]	1.93±0.56 [a]	1.41±0.13 [a]	1.84±0.25 [a]
Mean breaking tenacity (g-force/tex) [A]	8.72±2.61 [a s x]	13.15±3.83 [a s q]	9.57±0.86 [a q]	12.51±1.73 [a x]
CV,% (for tenacity)	19.76			
LSD, α=0.05	3.02			

[a] Mean ± Standard Deviation, N=6; p=0.01 < 0.05; $F_{critical}$= 3.10 < $F_{statistical}$= 4.48
[s, x, q] Significant variation (α=0.05)
[A] Appendix X (Tables 1a- 1d)

One important finding was the change of $S.I_{NDX}$ and breaking tenacity of the water-retted virgin fibres after their softener-treatment. **Table 3.11** and **3.12** displays that, $S.I_{NDX}$ and breaking tenacity of the water-retted virgin fibres of HYHEAR 1, Topas, and 5440 are higher than their softener-treated fibres. However, 45H29 displayed different phenomenon than the other three cultivars as its $S.I_{NDX}$ and breaking tenacity improved after their softener treatment (virgin-retted fibres: 1.77 lb/mg, 12.04 g-force/tex; softener-treated fibre: 1.84 lb/mg, 12.51 g-force/tex). Khan (2016) used Instron to find tenacity of enzyme treated HYHEAR 1 (8.67 g-force/tex) and Topas (2.96 g-force/tex) in single fibre form which is less than the observed values of this study as the current study measured strength in bundle fibre form using a different apparatus (Pressley Tester).

Table 3.13 displays that Topas showed the highest tensile strength: 175.46 (±51.08) MPa and HYHEAR 1 showed the lowest: 114.74 (±34.42) MPa. However, ANOVA statistics show that there is a significant difference among the means of the tensile strength of the softener-treated fibres of four cultivars ($F_{critical}$= 3.10 < $F_{statistical}$= 5.22; p< 0.05).

Table 3.13: Mean tensile strength (MPa) of the softener-treated fibres of four different *Brassica napus* L. cultivars and statistical analysis (ANOVA and Fisher's LSD test).

Parameters	**Cultivar type**			
	HYHEAR 1	**Topas**	**5440**	**45H29**
Overall mean [A]	114.74±34.42 [a m]	175.46±51.08 [a n]	129.35±11.67 [a m]	175.20±24.22 [a n]
CV, %	21.08			
LSD, α=0.05	40.47			

[a] Mean ± Standard Deviation, N= 6; p=0.01 < 0.05; $F_{critical}$= 3.10 < $F_{statistical}$= 5.22
[m, n] No significant variation (α=0.05)
[A] Appendix XI

Table 3.13 also displays that there is no difference in tensile strength between 45H29 (175.20 ± 24.22 MPa) and Topas (175.46 ± 51.08 MPa) as the differences are only in the last two significant digits after the decimal. Fisher's LSD test displays that there is a significant difference in tensile strength between every pairs except HYHEAR 1 and 5440 as well as between Topas and 45H29.

The tensile strength of *B. napus* fibres is much less than that of other textile fibres: e.g. 287-800 MPa for cotton, 393-800 MPa for jute, 690 MPa for hemp, and 345-1500 MPa for flax (Kozlowski, 2012b), and Ali (2013) reported 310-390 MPa for hemp fibres, 900 MPa for flax, 220- 530 MPa for jute, and 280- 840 MPa for cotton, showing that variations can be seen. This variation can occur from different reasons, one of which could be the difference of the tensile strength testing principle i.e., Constant Rate of Extension (CRE) or Constant Rate of Loading

(CRL). For example, Booth (1968) showed a 60 denier nylon yarn requires 40 seconds (breaking stress 5.8 g/denier) to break when tested by a Scott Serigraph (CRL instrument) and 30 seconds (breaking stress 5.2 g/denier) to break when tested by Instron (CRE instrument).

Further, El-Messiry and Abd-Ellatif (2013) tested the single fibre tenacity (by a Vibroscope) and bundle fibre tenacity (by a High Volume Instrumentation or HVI tester) of five different varieties of Egyptian cotton fibres (Giza 86, Giza 87, Giza 88, Giza 90, and Giza 45) (as previously discussed in **Section 1.7.8, Chapter 1)**. The authors reported that, bundle fibre tenacity of cotton fibres were positively correlated with yarn tenacity with a correlation coefficient of 0.76, whereas the correlation coefficient between single fibre tenacity and yarn tenacity was 0.21. Reason behind this difference between correlation coefficients was the high degree of variability of tenacity among single fibres when tested by single fibre method and less when tested by bundle fibre method. The authors found that CV (coefficient of variation) of the tenacity of Giza 45, Giza 87, Giza 88, Giza 86, Giza 90 was 34.59%, 41.17%, 41.89%, 29.73%, 29.99% when tested by single-fibre testing method in Vibroscope and 3.3%, 3.6%, 3.9%, 4.9%, 4.0% when tested by bundle-fibre testing method in HVI tester. Therefore, tenacity of the *B. napus* fibre was measured in bundle fibre form using a Pressley Bundle Fibre Strength Tester in this current research.

3.4. Comparative study of mechanical properties between cotton and *Brassica*

Table 3.14 displays the comparative study of strength index or $S.I_{NDX}$ (lb/mg), breaking tenacity (g-force/tex or g-force/tex), and tensile strength (MPa) between cotton varieties (St Vincenta, Giza 12, Memphisa, Texas, Bengals) and 10% softener treated *B. napus* cultivars (HYHEAR 1, Topas, 5440, 45H29) when all of these nine different fibres are tested by Pressley Fibre Bundle Tester. **Table 3.14** provides a summary of strength index (collected from **Table**

3.12), breaking tenacity (collected from **Table 3.12**), tensile strength (collected from **Table 3.13**) of softener treated *B. napus* fibres as well as the $S.I_{NDX}$ of five cotton varieties (St Vincent: 8.98 lb/mg, Giza 12: 7.46 lb/mg, Memphis: 6.20 lb/mg, Texas: 6.48 lb/mg, Bengals 6.07 lb/mg) recorded by Gregory (1953). However, breaking tenacity and tensile strength of these cotton varieties were calculated using **Eqs. 2.3, 2.5** (discussed earlier in **Section 2.8, Chapter 2**).

Table 3.14: Comparative study of mechanical properties between cotton and *Brassica napus* L. fibres.

Fibres	**Mechanical properties when measured by Pressley Fibre Bundle Tester**		
	Strength index (lb/mg)	**Breaking tenacity (g-force/tex)**	**Tensile strength (MPa)**
St Vincent [a]	8.98	61.10	848.66
Giza 12 [a]	7.46	50.74	704.85
Memphis [a]	6.20	42.18	585.90
Texas [a]	6.48	44.10	612.53
Bengals [a]	6.07	41.29	573.47
HYHEAR 1 [b]	1.28	8.72	114.74
Topas [b]	1.93	13.15	175.46
5440 [b]	1.41	9.57	129.35
45H29 [b]	1.84	12.51	175.20

[a] Cotton varieties (Gregory, 1953); [b] *B. napus* cultivars

Table 3.14 displays that breaking tenacity (g-force/tex) and tensile strength (MPa) of the cotton varities St Vincent, Giza 12, Memphis, Texas, Bengals display 61.70 g-force/tex, 50.74 g-force/tex, 42.18 g-force/tex, 44.10 g-gorce/tex, 41.29 g-force/tex and 848.66 MPa, 704.85 MPa, 585.90 MPa, 612.53 MPa, 573.47 MPa, respectively, which are higher than the breaking tencity (HYHEAR 1: 8.72 g-force/tex, Topas: 13.15 g-force/tex, 5440: 9.57 g-force/tex, 45H29: 12.51 g-force/tex) and tensile strength (HYHEAR 1: 114.74 MPa, Topas: 175.46 MPa, 5440: 129.35 MPa, 45H29: 175.20 MPa) of all the four *B. napus* cultivars.

3.5. Summary of this current research study

3.5.1. Relationship between plant stems and their corresponding fibre characteristic

The detailed relationship between the *B. napus* plants and their corresponding fibre characteristics is beyond the scope of the current study as the majority of the plant characteristics were based on subjective assessment. Few data are available with objective measurements, such as plant stem diameter and stem moisture regain. However, a summary table (**Table 3.15**) has been prepared to compare cultivar and the corresponding fibre characteristics on a ranking scale of 1-4 (S1- Higher, S2- High, S3- Low, S4- Lower). It can be seen from the table that HYHEAR 1 had the highest moisture regain for plant stems (9.99%), water-retted virgin fibres (12.53%), and 10% softener-treated fibres (7.64%). The highest thermal heat resistance was demonstrated by Topas stems (270.53^{o}C) as well as by 10% softener-treated fibres of Topas (257.23^{o}C). The lowest thermal heat resistance was demonstrated by 45H29 stems (240.20^{o}C) as well as by 10% softener treated fibres of 45H29 (237.63^{o}C). Topas had the 2nd (highest) ranking among all the four cultivars regarding stem diameter (4.92 mm) and fibre diameter (81.54 µm). Future research is needed for a better understanding of relationship between plant stems and their corresponding textile fibre properties.

Table 3.15: Characteristics of stems and fibres exhibited by different *Brassica napus* L. cultivars (HYHEAR 1, Topas, 5440, and 45H29).

Properties	**Plant stem characterization**				**Properties**	**Fibre characterization**			
	HYHEAR 1	**Topas**	**5440**	**45H29**		**HYHEAR 1**	**Topas**	**5440**	**45H29**
Moisture regain, %[a]	9.99±1.65 (S 1)╙	8.64±1.12 (S 4) ╙	9.43±2.17 (S 3) ╙	9.961.97 (S 2) ╙	Moisture regain, %[b] (water retted virgin)	12.53± 3.37 (S 1) ╙	9.38±2.75 (S 3) ╙	10.32±3.15 (S 2) ╙	9.31±3.40 (S 4) ╙
					Moisture regain, %[b] (softener treated)	7.64±0.03 (S 1) ╙	6.03±0.05 (S 4) ╙	7.21±0.06 (S 2) ╙	7.18±0.06 (S 3) ╙
Heat resistance, °C[c]	262.13±0.8 (S 2) ╙	270.53±1.1 (S 1) ╙	250.63±0.5 (S 3) ╙	240.20±0.4 (S 4) ╙	Heat resistance, °C[c] (softener treated)	242.50±0.40 (S 3) ╙	257.23±0.51 (S 1) ╙	249.33±0.45 (S 2) ╙	237.63±0.51 (S 4) ╙
Diameter, mm[d]	4.61±0.77 (S 3) ╙	4.92±0.60 (S 2) ╙	5.01±1.21 (S 1) ╙	4.61±0.91 (S 3) ╙	Diameter, μm[e] (softener treated)	86.93±57.12 (S 1) ╙	81.54±31.78 (S 2) ╙	64.38±26.22 (S 4) ╙	78.37±47.79 (S 3) ╙

╙ Ranking: S 1- Higher, S 2- High, S 3- Lower, S 4- Low (based on actual data obtained from this current research work);
[a]Table 3.2;
[b]Table 3.5;
[c]Table 3.7;
[d]Table 3.1;
[e]Table 3.8.

3.5.2. Comparison of chemical and physical properties of *Brassica napus* L. with other natural fibres

Table 3.16 summarizes the effect of *B. napus* cultivar on fibre properties (that has been found from this current study) and compares their properties with other natural cellulosic fibres.

Table 3.16: Comparison of properties between *Brassica napus* L. fibre and other natural fibres.

Properties	***Brassica napus***	**Cotton**	**Jute**	**Hemp**	**Flax**
Moisture regain (%)	HY*: 12.53[d], 7.64[e] TO*: 9.38[d], 6.03[e] 54*: 10.32[d], 7.21[e] 45*: 9.31[d], 7.18[e]	8.5 [c]	12.0 [c]	8.0 [c]	7.0 [c]
Density (g/cc)	HY*: 1.34[e] TO*: 1.36[e] 54*: 1.38[e] 45*: 1.43[e]	1.54 [f]	1.44-1.50 [a]	1.48-1.49 [a]	1.54 [f]
Diameter (µm)	HY*: 30.39- 213.60[e] TO*: 33.35- 146.67[e] 54*: 27.32- 109.25[e] 45*: 26.11- 207.33[e]	12.0-38.0 [b]	25-200 [b]	25-500 [b]	40-600 [b]
Tenacity (g-force/tex)	HY*: 13.52[d], 8.72[e] TO*: 16.85[d], 13.15[e] 54*: 12.33[d], 9.57[e] 45*:12.04[d], 12.51[e]	41.3-61.1[g]	18-56.7[a]	27-63[a]	23.4-72[a]
Tensile strength (MPa)	HY*: 114.74[e] TO*: 175.46[e] 54*: 129.35[e] 45*: 175.20[e]	573-849 [g]	393-800 [b]	690 [b]	345-1500 [b]
Heat resistance of *Brassica* and ignition temperature for other fibres (°C)	HY*: 242.5[e] TO*: 257.2[e] 54*: 249.3[e] 45*: 237.6[e]	255.0[b] (ignition temperature)	193.0[a] (ignition temperature)	-	256.0[b] (ignition temperature)

[a] (Kozlowski, 2012a); [b] (Kozlowski, 2012b); [c] (Morton & Hearle, 2008); [d] Virgin retted fibres;
[e] Treated fibres suitable for textile application (treated with 5% NaOH, 4% acetic acid, and 10% softener);
[f] ASTM D276-12 (2012); [g] Gregory (1953);
* Different cultivars of *Brassica*: HY (HYHEAR 1); TO (Topas); 54 (5440); 45(45H29).

Chapter 4. Conclusion and future work

A new generation of lignocellulosic textile fibres produced from industrial biomass of *Brassica napus* L. plants is of growing interest because of its sustainability and the renewable source of cellulosic fibre. In context of global apparel and textile industries worth multi-trillions of dollars (PR Newswire, 2015), *B. napus* has the potential to become a global source of textile fibre, such as cotton or polyester. Four different *B. napus* cultivars (HYHEAR 1, Topas, 5440, and 45H29) were cultivated and harvested inside a greenhouse for this current research work. Ninety (96) plants per cultivar were water-retted at atmospheric condition to extract the fibres from the stem exteriors. Chemical and physical tests were conducted on the extracted virgin-retted fibres to measure their textile fibre properties and their variations among the four cultivars.

In the current study, fibre from HYHEAR 1 exhibited the highest moisture regain among all the cultivars, followed by 5400 for both virgin-retted fibres **(Table 3.5)** and softener treated fibres **(Table 3.5)**. 5440 and Topas displayed the most uniform fibre diameter among all the cultivars (**Table 3.8, Fig. 3.6)**. The observed value of fibre density showed that HYHEAR 1 was the most light-weight fibre among all the cultivars, followed by Topas **(Table 3.9)**. Further, Topas showed superior strength index, breaking tenacity, **(Tables 3.11, 3.12)** and thermal heat resistance **(Table 3.7)** among all four cultivars. Surface modification only increased the strength index and breaking tenacity of 45H29 among all the cultivars **(Tables 3.11, 3.12)**.

It appears that few *B. napus* cultivars possess few fibre properties superior to cotton: moisture regain of virgin-retted HYHEAR 1 fibre is higher than cotton **(TableS 3.5, 3.6)**; density of softener-treated *B. napus* fibre of all the four cultivars is lower than cotton fibre **(Table 3.9)**.

There are numerous theoretical relationships noticed in the current study. For example, the highest fibre yield % (10.41 ± 1.87) **(Table 3.4)** was obtained for 45H29 which might have come from the highest fibre density (1.43 ± 0.0011 g/cc) **(Table 3.9)**. Cultivar 45H29 also had the greatest number of branches as observed during harvesting. This may be an inherent genetic pattern that leads to its higher fibre density and higher fibre yield (%) during water retting. However, further study is required to confirm such a relationship.

Similarly, softener-treated HYHEAR 1 showed the largest moisture regain (7.61 %) **(Table 3.5)** and lowest fibre density (1.34 ± 0.0009 g/cc) **(Table 3.9)**. A lower density fibre displays a higher degree of amorphousness (disordered regions) in its interior, and ultimately leads to the tendency of a higher degree of moisture absorption (Morton & Hearle, 2008). Virgin-retted HYHEAR 1 fibres also did reveal the highest moisture regain (12.53 ± 3.37 %) **(Table 3.5)** among the virgin retted fibres of the four cultivars.

Softener-treated 45H29 exhibited the highest fibre density (1.43 ± 0.0011 g/cc) **(Table 3.9)**, the second largest tensile strength (175.20 ± 24.22 MPa) **(Table 3.13)**, and the second lowest moisture regain (7.13%) **(Table 3.5)**. The higher tensile strength of 45H29 may have come from its high fibre density (higher the fibre density higher is the crystallinity). Similarly, softener treated HYHEAR 1 had the lowest fibre density (1.34 ± 0.0009 g/cc) **(Table 3.9)**, the lowest tensile strength (114.74 ± 34.42 MPa) **(Table 3.13)**, and the highest moisture regain (7.61%) **(Table 3.5)**. As fibre density is inversely proportional to fibre volume and diameter, the fibre with a higher diameter should demonstrate a lower density. HYHEAR 1 had the highest mean diameter (86.93 ± 57.12 µm) **(Table 3.8)** and the lowest mean fibre density (1.34 ± 0.0009 g/cc) **(Table 3.9)**. 5440 displayed the lowest mean diameter (64.38± 26.22 µm) **(Table 3.8)** and the second highest mean fibre density (1.38 ± 0.0007 g/cc) **(Table 3.9)** among all four cultivars. A fibre with higher breaking tenacity may exhibit higher tensile strength: the strength index and breaking tenacity of the softened fibre ranked from high to low in the following order Topas> 45H29> 5440>

HYHEAR 1 **(Table 3.12)**; and the corresponding tensile strength ranked in the same order (from high to low) Topas> 45H29> 5440> HYHEAR 1 **(Table 3.13)**.

In terms of retting time, 5440 exhibited the highest retting time (380.33±61.88 hours) **(Table 3.3)**, perhaps due its highest grand average stem diameter (5.01 ± 1.21 mm) **(Table 3.1)** that accommodates a higher amount of non-cellulosic materials which require more time to degrade (Allen, 1946 cited in Brown et al., 1986; Chesson, 1978), leading to a higher retting time.

Furthermore, assuming all parameters are constant, a fibre with a larger diameter should demonstrate a higher breaking strength. In this regard, Topas displayed the second highest mean diameter (81.54 ± 31.78 µm) **(Table 3.8)** and the highest strength index (1.93 lb/mg) **(Table 3.12)** among all the four cultivars.

Topas displayed the highest thermal heat resistance temperature (271.6^{o}C) **(Table 3.7)** which might be due to its highest strength index (1.93 lb/mg) **(Table 3.12)** and highest tensile strength (175.46 MPa) **(Table 3.13)** among all four cultivars- perhaps an inherent genetic pattern that also contributed towards its lowest retting time among all the cultivars.

However, some discrepancies were also found. Softening treatment increased the breaking load (lb) and breaking tenacity (gram-force/tex) of 45H29 fibres (virgin-retted fibres: 11.30 lb, 12.04 gram-force/tex; softener treated fibre: 11.48 lb, 12.52 gram-force/tex) which was totally opposite to the other cultivars **(Tables 3.11, 3.12)**. The softening treatment lowered the breaking load and breaking tenacity of HYHEAR 1, Topas, and 5440 **(Tables 3.11, 3.12)**.

Finally, in line with the objectives of the current study, three major outcomes were achieved to understand the effect of cultivar on *B. napus* fibre properties. First, the discovery of density of the *B. napus* fibres which is the first and only of its kind in the world to date along with their tenacity and tensile strength. Secondly, the approach to identify the retting end-point (in hours) of the *B. napus* plants- an inception of *B. napus* retting study (as previously retting time was expressed by the number of days only). Thirdly, the diameter analysis of the four cultivars gives a basic knowledge on the fibre diameters of different *B. napus* cultivars.

Future work should concentrate on developing a relationship between the effect of cultivar on fibre properties and genetic variation. Further, efforts should be given on developing a standard method to determine the degree of retting and accurate retting end-point of *B. napus* stems, which can be the determination of stem strength loss and caustic weight loss of fibres as suggested by Brown et al. (1986). The Bioquant Analyzer machine at the Textile Lab of University of Manitoba can be used to study the microscopic diameter of the fibres. Dia-Stron can be also used to accurately measure the single fibre tensile strength with its corresponding fibre diameter for a better understanding of the synergy between fibre strength and diameter that may affect other textile properties of *B. napus* fibres. The relationship between stem diameter from different regions of a plant (bottom, middle, top) and their corresponding fibre diameters can be studied to classify the application of fibres (according to their diameter from different stem regions) for different engineering application as tensile strength of natural fibres decrease with increased fibre diameter from increased fibre defects (Liu et al., 2015). Further investigation into the structure and properties of *B. napus* fibres would broaden the current state of knowledge to develop strategies towards building broader textile fibre properties with the desired fibre flexibility. The potential of *B. napus* fibres for application in composite structures should be studied because of *B. napus's* superior lightweight characteristics compare to other natural cellulosic fibres. Consequently, *B. napus* will find uses not only for domestic, but also for technical textile applications.

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Appendix I

Table 1. Parameters of cultivar HYHEAR 1 samples.

Stem #	Diameter in regions	Diameter in mm	Average Diameter in mm	Weight of 50 samples in g	Oven dry weight in g
	a	5.45		32.41	29.42
1	b	6.05	5.506666667		
	c	5.02			
	a	5.2			
2	b	5.89	5.78		
	c	6.25			
	a	5.01			
3	b	6.13	5.65		
	c	5.81			
	a	4.6			
4	b	4.47	4.456666667		
	c	4.3			
	a	3.66			
5	b	3.59	3.523333333		
	c	3.32			
	a	5.72			
6	b	7.53	6.236666667		
	c	5.46			
	a	4.62			
7	b	4.91	4.463333333		
	c	3.86			
	a	3.76			
8	b	4.27	4.113333333		
	c	4.31			
	a	5.71			
9	b	4.51	4.846666667		

	c	4.32	
	a	4.69	
10	b	4.41	4.36
	c	3.98	
	a	5.15	
11	b	5.1	5.11
	c	5.08	
	a	5.51	
12	b	6.77	6.013333333
	c	5.76	
	a	4.61	
13	b	3.87	3.93
	c	3.31	
	a	5.73	
14	b	6.06	6.133333333
	c	6.61	
	a	2.56	
15	b	2.69	2.776666667
	c	3.08	
	a	4.31	
16	b	4.19	4.26
	c	4.28	
	a	3.59	
17	b	4.59	4.186666667
	c	4.38	
	a	4.69	
18	b	5.42	5.063333333
	c	5.08	
	a	5.23	
19	b	4.6	4.863333333
	c	4.76	
	a	5.01	

20	b	4.82	4.82
	c	4.63	
	a	2.61	
21	b	3.03	3.596666667
	c	5.15	
	a	4.02	
22	b	3.86	3.84
	c	3.64	
	a	4.35	
23	b	4.66	4.64
	c	4.91	
	a	4.21	
24	b	3.97	4.003333333
	c	3.83	
	a	4.58	
25	b	4.59	4.4
	c	4.03	
	a	3.96	
26	b	4.46	4.483333333
	c	5.03	
	a	5.1	
27	b	4.66	4.836666667
	c	4.75	
	a	4.68	
28	b	5.09	4.873333333
	c	4.85	
	a	4.92	
29	b	4.27	4.58
	c	4.55	
	a	4.6	
30	b	4.58	4.676666667
	c	4.85	

	a	4.91	
31	b	4.53	4.9
	c	5.26	
	a	3.44	
32	b	3.99	3.856666667
	c	4.14	
	a	4.89	
33	b	4.72	4.53
	c	3.98	
	a	3.54	
34	b	3.25	3.306666667
	c	3.13	
	a	4.94	
35	b	5.94	5.476666667
	c	5.55	
	a	4.63	
36	b	5.89	5.18
	c	5.02	
	a	5.51	
37	b	5.42	5.49
	c	5.54	
	a	5.08	
38	b	5.62	5.52
	c	5.86	
	a	4.13	
39	b	3.93	3.736666667
	c	3.15	
	a	4.33	
40	b	4.79	4.746666667
	c	5.12	
	a	4.32	
41	b	3.81	3.953333333
	c	3.73	

	a	4.18	
42	b	3.2	3.5
	c	3.12	
	a	3.41	
43	b	4.27	3.79
	c	3.69	
	a	4.6	
44	b	4.22	4.303333333
	c	4.09	
	a	4.51	
45	b	4.55	4.3
	c	3.84	
	a	4.24	
46	b	3.8	3.98
	c	3.9	
	a	5.53	
47	b	4.59	4.683333333
	c	3.93	
	a	5.73	
48	b	6.06	5.746666667
	c	5.45	
	a	4.59	
49	b	5	4.766666667
	c	4.71	
	a	4.51	
50	b	4.55	4.586666667
	c	4.7	

Table 2. Parameters of cultivar Topas samples.

Stem #	Diameter in regions	Diameter in mm	Average Diameter in mm	Weight of 50 samples in g	Oven dry weight in g
	a	5.21		39.00	35.51
1	b	5.1	5.336666667		
	c	5.7			
	a	4.37			
2	b	4.55	4.826666667		
	c	5.56			
	a	3.53			
3	b	3.66	3.646666667		
	c	3.75			
	a	5.02			
4	b	4.37	4.646666667		
	c	4.55			
	a	4.43			
5	b	5.17	4.88		
	c	5.04			
	a	3.43			
6	b	3.45	3.486666667		
	c	3.58			
	a	4.65			
7	b	5.12	4.883333333		
	c	4.88			
	a	6.22			
8	b	5.56	5.81		
	c	5.65			
	a	4.31			
9	b	4.31	4.31		
	c	4.31			
	a	4.87			

10	b	4.88	4.966666667
	c	5.15	
	a	4.69	
11	b	5	4.846666667
	c	4.85	
	a	6.24	
12	b	5.75	5.98
	c	5.95	
	a	5	
13	b	5.01	4.91
	c	4.72	
	a	4.4	
14	b	4.39	4.273333333
	c	4.03	
	a	3.81	
15	b	3.78	3.686666667
	c	3.47	
	a	4.76	
16	b	4.67	4.816666667
	c	5.02	
	a	5.22	
17	b	4.86	4.973333333
	c	4.84	
	a	3.13	
18	b	3.43	3.196666667
	c	3.03	
	a	5.82	
19	b	5.67	5.89
	c	6.18	
	a	4.55	
20	b	7.75	5.733333333
	c	4.9	

	a	5.64	
21	b	5.3	5.26
	c	4.84	
	a	5.12	
22	b	5.04	4.973333333
	c	4.76	
	a	5.51	
23	b	5.31	5.41
	c	5.41	
	a	4.33	
24	b	4.67	4.65
	c	4.95	
	a	4.81	
25	b	4.79	4.866666667
	c	5	
	a	5.72	
26	b	5.56	5.593333333
	c	5.5	
	a	5.56	
27	b	5.12	5.24
	c	5.04	
	a	5.13	
28	b	5.16	5.196666667
	c	5.3	
	a	5.02	
29	b	5.62	5.15
	c	4.81	
	a	5.26	
30	b	5.19	5.1
	c	4.85	
	a	5.07	
31	b	5.05	5.186666667
	c	5.44	

	a	4.88	
32	b	4.31	4.476666667
	c	4.24	
	a	4.66	
33	b	4.78	4.7
	c	4.66	
	a	6.11	
34	b	5.75	5.84
	c	5.66	
	a	5.07	
35	b	5.26	5.063333333
	c	4.86	
	a	4.53	
36	b	4.73	4.73
	c	4.93	
	a	4.62	
37	b	4.7	4.73
	c	4.87	
	a	5.45	
38	b	5.7	5.673333333
	c	5.87	
	a	5.09	
39	b	5.43	5.12
	c	4.84	
	a	5.75	
40	b	6.34	5.863333333
	c	5.5	
	a	4.09	
41	b	4.26	4.413333333
	c	4.89	
	a	5.36	
42	b	4.99	5.06

	c	4.83	
	a	5.71	
43	b	5.63	5.6
	c	5.46	
	a	4.18	
44	b	4.71	4.59
	c	4.88	
	a	4.88	
45	b	5.36	5.03
	c	4.85	
	a	5.04	
46	b	4.85	4.99
	c	5.08	
	a	4.63	
47	b	4.78	4.783333333
	c	4.94	
	a	4.81	
48	b	4.88	4.793333333
	c	4.69	
	a	4.85	
49	b	4.33	4.473333333
	c	4.24	
	a	4.31	
50	b	5.05	4.586666667
	c	4.4	

Table 3. Parameters of cultivar 5440 samples.

Stem #	Diameter in regions	Diameter in mm	Average Diameter in mm	Weight of 50 samples in g	Oven dry weight in g
	a	7.5		38.66	34.15
1	b	7.85	7.906666667		
	c	8.37			
	a	5.25			
2	b	5.88	5.693333333		
	c	5.95			
	a	4.43			
3	b	4.7	4.583333333		
	c	4.62			
	a	5.81			
4	b	5.37	5.563333333		
	c	5.51			
	a	5.31			
5	b	5.6	5.58		
	c	5.83			
	a	5.52			
6	b	5.18	5.416666667		
	c	5.55			
	a	5.36			
7	b	5.65	5.65		
	c	5.94			
	a	4.6			
8	b	4.63	4.456666667		
	c	4.14			
	a	4.23			
9	b	4.06	4.14		
	c	4.13			
	a	9.24			

10	b	8.51	8.953333333
	c	9.11	
	a	3.71	
11	b	4.26	4.173333333
	c	4.55	
	a	7.75	
12	b	8.57	8.433333333
	c	8.98	
	a	5.31	
13	b	5.42	5.61
	c	6.1	
	a	6.52	
14	b	6.67	6.626666667
	c	6.69	
	a	4.99	
15	b	5.09	4.936666667
	c	4.73	
	a	5.61	
16	b	4.18	4.653333333
	c	4.17	
	a	5.21	
17	b	5.37	5.423333333
	c	5.69	
	a	4.47	
18	b	4.21	4.2
	c	3.92	
	a	5.52	
19	b	5.67	5.646666667
	c	5.75	
	a	3.99	
20	b	3.79	3.77
	c	3.53	

	a	2.47	
21	b	3.12	2.84
	c	2.93	
	a	5.44	
22	b	5.35	5.253333333
	c	4.97	
	a	4.19	
23	b	4.23	4.146666667
	c	4.02	
	a	5.92	
24	b	5.98	5.876666667
	c	5.73	
	a	6.03	
25	b	6.4	6.066666667
	c	5.77	
	a	5.01	
26	b	4.62	4.686666667
	c	4.43	
	a	4.48	
27	b	3.78	4.193333333
	c	4.32	
	a	5.77	
28	b	5.07	5.22
	c	4.82	
	a	4.4	
29	b	3.83	4.36
	c	4.85	
	a	6.99	
30	b	5.79	6.243333333
	c	5.95	
	a	2.92	
31	b	2.72	2.866666667
	c	2.96	

	a	3.98	
32	b	3.48	3.73
	c	3.73	
	a	5.04	
33	b	4.84	4.983333333
	c	5.07	
	a	4.57	
34	b	4.61	4.713333333
	c	4.96	
	a	4.13	
35	b	4.17	4.28
	c	4.54	
	a	3.84	
36	b	4.05	4.023333333
	c	4.18	
	a	4.17	
37	b	4.56	4.446666667
	c	4.61	
	a	5.79	
38	b	6.02	5.923333333
	c	5.96	
	a	5.51	
39	b	5.39	5.53
	c	5.69	
	a	4.63	
40	b	5.03	4.843333333
	c	4.87	
	a	4.05	
41	b	4.26	4.226666667
	c	4.37	
	a	5.62	
42	b	5.53	5.576666667

	c	5.58	
	a	5.14	
43	b	5.22	5.056666667
	c	4.81	
	a	4.21	
44	b	4.6	4.466666667
	c	4.59	
	a	5.18	
45	b	5.49	5.23
	c	5.02	
	a	4.45	
46	b	4.24	4.156666667
	c	3.78	
	a	3.49	
47	b	3.72	3.676666667
	c	3.82	
	a	4.72	
48	b	3.81	4.266666667
	c	4.27	
	a	3.45	
49	b	3.42	3.346666667
	c	3.17	
	a	4.57	
50	b	4.86	4.916666667
	c	5.32	

Table 4. Parameters of cultivar 45H29 samples.

Stem #	Diameter in regions	Diameter in mm	Average Diameter in mm	Weight of 50 samples in g	Oven dry weight in g
	a	4		29.66	27.22
1	b	3.94	3.966666667		
	c	3.96			
	a	4.49			
2	b	4.64	4.463333333		
	c	4.26			
	a	4.27			
3	b	3.53	3.683333333		
	c	3.25			
	a	7.21			
4	b	6.67	6.813333333		
	c	6.56			
	a	4.37			
5	b	4.34	4.21		
	c	3.92			
	a	4.38			
6	b	5.18	4.92		
	c	5.2			
	a	4.72			
7	b	4.97	4.653333333		
	c	4.27			
	a	3.64			
8	b	3.73	3.703333333		
	c	3.74			
	a	3.79			
9	b	3.63	3.683333333		
	c	3.63			
	a	4.22			

10	b	4.78	4.443333333
	c	4.33	
	a	5.44	
11	b	5.25	5.213333333
	c	4.95	
	a	4.71	
12	b	4.83	4.993333333
	c	5.44	
	a	5.31	
13	b	5.42	5.263333333
	c	5.06	
	a	4.34	
14	b	3.84	4.043333333
	c	3.95	
	a	3.47	
15	b	3.26	3.533333333
	c	3.87	
	a	4.26	
16	b	4.3	4.156666667
	c	3.91	
	a	5.52	
17	b	5.44	5.583333333
	c	5.79	
	a	3.44	
18	b	3.01	3.19
	c	3.12	
	a	3.9	
19	b	4.08	3.97
	c	3.93	
	a	4.87	
20	b	4.48	4.736666667
	c	4.86	

	a	3.55	
21	b	3.78	3.7
	c	3.77	
	a	3.67	
22	b	3.69	3.786666667
	c	4	
	a	5.02	
23	b	4.69	4.74
	c	4.51	
	a	4.18	
24	b	4.43	4.393333333
	c	4.57	
	a	5.02	
25	b	4.76	4.763333333
	c	4.51	
	a	3.65	
26	b	3.61	3.666666667
	c	3.74	
	a	5.12	
27	b	5.14	5.173333333
	c	5.26	
	a	6.26	
28	b	6.08	5.886666667
	c	5.32	
	a	5.15	
29	b	5.81	5.523333333
	c	5.61	
	a	6.3	
30	b	6.99	6.723333333
	c	6.88	
	a	5.41	
31	b	5.15	5.336666667
	c	5.45	

	a	4.55	
32	b	4.59	4.616666667
	c	4.71	
	a	3.03	
33	b	2.96	2.96
	c	2.89	
	a	4.39	
34	b	4.55	4.373333333
	c	4.18	
	a	4.28	
35	b	5.19	4.75
	c	4.78	
	a	6.16	
36	b	7.25	6.986666667
	c	7.55	
	a	4.21	
37	b	4.28	4.2
	c	4.11	
	a	4.95	
38	b	4.8	4.816666667
	c	4.7	
	a	3.39	
39	b	3.6	3.523333333
	c	3.58	
	a	4.32	
40	b	4.03	4.253333333
	c	4.41	
	a	5	
41	b	5.08	5.043333333
	c	5.05	
	a	4.55	
42	b	4.83	4.626666667

	c	4.5	
	a	5.32	
43	b	5.57	5.573333333
	c	5.83	
	a	4.44	
44	b	3.6	4.023333333
	c	4.03	
	a	3.16	
45	b	3.46	3.316666667
	c	3.33	
	a	4.33	
46	b	4.35	4.22
	c	3.98	
	a	4.39	
47	b	4.91	4.91
	c	5.43	
	a	5.44	
48	b	5.72	5.56
	c	5.52	
	a	6.08	
49	b	6.04	5.903333333
	c	5.59	
	a	4.31	
50	b	3.9	4.106666667
	c	4.11	

Appendix II

Table 1. ANOVA and Scheffe test to compare the difference between pairs of mean of diameters of four *B. napus* cultivars.

ANOVA test

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HYHEAR 1 (1st)	50.00	230.38	4.61	0.59
Topas (1st)	50.00	246.24	4.92	0.36
5440 (1st)	50.00	250.56	5.01	1.46
45H29 (1st)	50.00	230.68	4.61	0.83

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.58	3.00	2.19	2.71	0.05	2.65
Within Groups	158.82	196.00	0.81			
Total	165.40	199.00				

Appendix III

Table 1: Diameters (μm) of the 10% softener-treated single fibres obtained using FibreShape.

HYHEAR 1	Topas	5440	45H29
170.08	73.39	57.41	71.86
183.86	54.59	46.47	76.02
213.60	76.26	33.68	107.75
211.63	115.47	83.99	71.36
35.93	103.30	92.00	26.11
56.30	75.25	86.72	53.76
54.76	143.18	70.75	33.04
44.28	124.10	49.08	36.47
30.39	58.88	102.68	62.71
124.88	146.67	92.44	122.52
64.64	33.35	50.76	53.74
94.30	95.85	27.32	58.80
49.89	43.21	70.88	57.04
69.39	45.51	80.64	51.51
33.01	105.98	109.25	68.22
38.26	88.93	38.01	98.48
52.40	94.06	58.47	49.50
81.45	74.69	103.19	105.14
80.12	61.99	41.82	83.01
69.72	53.63	28.41	198.86
64.75	49.71	59.72	207.33
88.74	75.84	32.55	30.84

Table 2: ANOVA for the single fibre (SF) diameter.

ANOVA test

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HYHEAR 1	22	1912.375	86.92614	3262.125
Topas	22	1793.837	81.53805	1009.859
5440	22	1416.252	64.3751	687.5833
45H29	22	1724.07	78.36684	2283.546

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6111.791	3	2037.264	1.125076	0.343666	2.713227
Within Groups	152105.4	84	1810.778			
Total	158217.2	87				

Appendix IV

Table 1: Density (g/cc) of 10% softener-treated HYHEAR 1 fibres.

```
                 QUANTACHROME CORPORATION
                    Upyc 1200e V5.03
                     Analysis Report

Wed Jan  3 17:35:58 2018
User ID:  IIS

Sample Parameters
     Sample ID:  HYHEAR1final
     Weight: 1.2541 g
Analysis Parameters
     Cell Size - Small
     V Added - Small: 12.9511 cc
     V Cell: 19.1442 cc
     Analysis Temperature: 27.2 C
     Target Pressure: 17.0 psig
     Type of gas used: NITROGEN
     Equilibration Time:  Auto
     Pulse Purge: 9 Pulses
     Maximum Runs: 10
     Number Of Runs Averaged: 7
     Deviation Requested: 100.0000 %
Analysis Results
     Deviation Achieved: 0.0614 %
     Average Volume: 0.9344 cc
     Volume Std. Dev.: 0.0007 cc
     Average Density: 1.3421 g/cc
     Density Std. Dev.: 0.0009 g/cc
     Coefficient of Variation: 0.0700 %
```

Run Data

RUN	VOLUME (cc)	DENSITY (g/cc)
1	0.9363	1.3394
2	0.9363	1.3395
3	0.9343	1.3423
4	0.9336	1.3434
5	0.9350	1.3412
6	0.9347	1.3418
7	0.9334	1.3436
8	0.9343	1.3422
9	0.9351	1.3411
10	0.9349	1.3414

Appendix V

Table 1: Density (g/cc) of 10% softener-treated Topas fibres.

```
                    QUANTACHROME CORPORATION
                       Upyc 1200e V5.03
                        Analysis Report

Wed Jan  3 14:58:40 2018
User ID:  IIS

Sample Parameters
     Sample ID:  TOPASfinal
     Weight: 1.5760 g
Analysis Parameters
     Cell Size - Small
     V Added - Small: 12.9511 cc
     V Cell: 19.1442 cc
     Analysis Temperature: 27.2 C
     Target Pressure: 17.0 psig
     Type of gas used: NITROGEN
     Equilibration Time:  Auto
     Pulse Purge: 9 Pulses
     Maximum Runs: 10
     Number Of Runs Averaged: 7
     Deviation Requested: 100.0000 %
Analysis Results
     Deviation Achieved: 0.0426 %
     Average Volume: 1.1582 cc
     Volume Std. Dev.: 0.0006 cc
     Average Density: 1.3608 g/cc
     Density Std. Dev.: 0.0007 g/cc
     Coefficient of Variation: 0.0483 %
```

Run Data

RUN	VOLUME (cc)	DENSITY (g/cc)
1	1.1594	1.3593
2	1.1580	1.3610
3	1.1587	1.3602
4	1.1586	1.3602
5	1.1587	1.3602
6	1.1579	1.3611
7	1.1572	1.3619
8	1.1588	1.3600
9	1.1583	1.3607
10	1.1577	1.3614

Appendix VI

Table 1: Density (g/cc) of 10% softener-treated 5440 fibres.

QUANTACHROME CORPORATION
Upyc 1200e V5.03
Analysis Report

Wed Jan 3 18:04:13 2018
User ID: IIS

Sample Parameters
- Sample ID: 5440CORRECT
- Weight: 1.6459 g

Analysis Parameters
- Cell Size - Small
- V Added - Small: 12.9511 cc
- V Cell: 19.1442 cc
- Analysis Temperature: 27.3 C
- Target Pressure: 17.0 psig
- Type of gas used: NITROGEN
- Equilibration Time: Auto
- Pulse Purge: 9 Pulses
- Maximum Runs: 10
- Number Of Runs Averaged: 7
- Deviation Requested: 100.0000 %

Analysis Results
- Deviation Achieved: 0.0428 %
- Average Volume: 1.1942 cc
- Volume Std. Dev.: 0.0006 cc
- Average Density: 1.3783 g/cc
- Density Std. Dev.: 0.0007 g/cc
- Coefficient of Variation: 0.0500 %

Run Data

RUN	VOLUME (cc)	DENSITY (g/cc)
1	1.2023	1.3690
2	1.1969	1.3751
3	1.1957	1.3766
4	1.1949	1.3774
5	1.1943	1.3781
6	1.1947	1.3776
7	1.1938	1.3787
8	1.1938	1.3787
9	1.1944	1.3780
10	1.1930	1.3796

Appendix VII

Table 1: Density (g/cc) of 10% softener-treated 45H29 fibres.

QUANTACHROME CORPORATION
Upyc 1200e V5.03
Analysis Report

Wed Jan 3 15:54:33 2018
User ID: IIS

Sample Parameters
Sample ID: 45H29final
Weight: 1.1601 g
Analysis Parameters
Cell Size - Small
V Added - Small: 12.9511 cc
V Cell: 19.1442 cc
Analysis Temperature: 27.2 C
Target Pressure: 17.0 psig
Type of gas used: NITROGEN
Equilibration Time: Auto
Pulse Purge: 9 Pulses
Maximum Runs: 10
Number Of Runs Averaged: 7
Deviation Requested: 100.0000 %
Analysis Results
Deviation Achieved: 0.0565 %
Average Volume: 0.8121 cc
Volume Std. Dev.: 0.0006 cc
Average Density: 1.4285 g/cc
Density Std. Dev.: 0.0011 g/cc
Coefficient of Variation: 0.0788 %

Run Data

RUN	VOLUME (cc)	DENSITY (g/cc)
1	0.8141	1.4250
2	0.8124	1.4280
3	0.8131	1.4268
4	0.8109	1.4306
5	0.8121	1.4285
6	0.8118	1.4290
7	0.8124	1.4279
8	0.8132	1.4265
9	0.8119	1.4288
10	0.8122	1.4283

Appendix VIII

Mathematical formula and calculations for strength testing of the fibre bundle

There are three values that we have been calculating and these are:

- Strength Index, S_{Indx} = Breaking Load (lb) / mass (mg)
- Breaking Tenacity (gram-force/tex), BT = 6.8 x S_{Indx} **(when a 1/8" spacer is added)**
- Tensile Strength (MPa) = 9.807 x Breaking Tenacity (gf/tex) x Density (g/cc)

(Note: Breaking tenacity formula is different if testing is done without the spacer in the clamps.)

Explanation: We know,

- 1 pound-force [lbf] =444.822161525477 centi newton [cN]
- 1 milligram (mg) = 1000 micro grams (µg)
- 1 cN = 1.0197 gram-force
- The tex system indicates grams per 1000 metres
- 1 tex = (1 grams/1000 meter) = 1 x (10^6 µg / 10^6 mm) = 1 µg/mm
- g= earth's gravitational acceleration= 9.81 ms^{-2}
- **1 m^3 = 10^6 cm^3 = 1 cc; 1 psi (psi= pounds/$inch^2$)= 0.00689476 MPa i.e., 1000 psi= 6.89 MPa**

a. According to ASTM D1445/D1445M-12, Strength index (S_{Indx})= (Load lb/mass mg) lb/mg
Or alternatively S_{Indx} = Y lb/mg = Y x (444.8222/1000) cN/µg = Y x 0.444822 cN/µg

b. According to ASTM D1445/D1445M-12, B. tenacity (BT) = [(S_{Indx} lb/mg) x 6.8] gram-force/tex
Or alternatively BT= [(breaking load in cN)/(mass of fibres in µg) x 15 mm] mm-cN/µg
= Y x 0.448222 x 15 mm-cN/µg = Y x 6.7 mm-cN/µg = Y x 6.7 x 1.0197 mm-gram force/µg
= Y x 6.8 mm-gram force/µg = Y x 6.8 gram force/$\frac{\mu g}{mm}$ = Y x gram-force/tex

c. According to ASTM D1445/D1445M-12, Tensile strength = (2.016 x BT in g-force/tex) 1000 psi

Alternatively, to calculate tensile strength by using density, the following formula has been developed.

Tensile strength = Z Pa = [F/A] Pa = (F/A) Nm^{-2} = (mg/A) Nm^{-2} = (mg/A) $kg.ms^{-2}/m^2$
Or Z (Pa) = (m kg x g ms^{-2}) / (A m^2) = [g ms^{-2}] x [m kg/ A $meter^2$]

⇨ Z (Pa) = [(9.81 ms^{-2}) x 1 meter] x [m kg / (A $meter^2$ x 1 meter)]
⇨ Z (Pa) = [(9.81 ms^{-2}) x 1 meter] x [m kg / Volume $meter^3$]
⇨ Z (Pa) = [(9.81 ms^{-2}) x (gram/gram) x 1 meter] x [ρ kg/m^3]
⇨ Z (Pa)= [(9.81 ms^{-2}) x (gram-force/gram) x 1 meter] x [ρ kg/m^3]
⇨ Z (Pa) = [9.81 ms^{-2} x $\frac{gram-force\ x\ 1\ meter\ x\ 1000}{gram}\ x\ \frac{1}{1000}$] x [ρ kg/m^3]
⇨ Z (Pa) = [9.81 ms^{-2} x $\frac{gram-force}{\frac{gram}{1000\ meter}}$ x 10^{-3} x ρ $\frac{10^3\ gm}{10^6\ cm^3}$] = [9.81 ms^{-2} x $\frac{gram-force}{tex}$ x ρ 10^{-3+3-6} $gram/cm^3$]
⇨ Z Pa = [9.81 ms^{-2} x $\frac{gram-force}{tex}$ x ρ gram/cc] x 10^{-6}= 9.81 ms^{-2} x $\frac{gram-force}{tex}$ x ρ gram/cc x 10^{-6} x $\frac{10^6}{10^6}$
⇨ Z 10^6 Pa = [9.81 ms^{-2} x $\frac{gram-force}{tex}$ x ρ gram/cc] x 10^{-6+6}
⇨ Z MPa = (9.81 ms^{-2}) x (gram-force/tex) x (ρ gram/cc)

Appendix IX

Table 1: Strength measurement of water-retted virgin/controlled/untreated fibres.

a. Cultivar HYHEAR 1 (controlled)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	T3	0		0.0043	4.3	0		0	
2	Success	11.1		0.0033	3.3	3.36		22.87	
3	Success	7.5	11.23	0.0031	3.1	2.42	1.99	16.45	13.52
4	Success	10.3		0.0059	5.9	1.75		11.87	
5	Success	12.5		0.0071	7.1	1.76		11.97	
6	T1	0	n=6	0.0031	3.1	0	n=6 but not 9	0	
7	T1	0		0.0069	6.9	0		0	
8	Success	10.2		0.0083	8.3	1.23		8.36	
9	Success	15.8		0.0112	11.2	1.41		9.59	

b. Cultivar Topas (controlled)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	T1	0		0.0038	3.8	0		0	
2	Success	17.2		0.0055	5.5	3.13		21.27	
3	Success	10.3	12.58	0.0051	5.1	2.02	2.48	13.73	16.85
4	Success	9.3		0.0043	4.3	2.16		14.71	
5	Success	12.6	n=6	0.0049	4.9	2.57	n=6 but not 7	17.49	
6	Success	15.3		0.0065	6.5	2.35		16.01	
7	Success	10.8		0.0041	4.1	2.63		17.91	

c. Cultivar 5440 (controlled)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	T3	0		0.0045	4.5	0		0	
2	Success	10.8		0.0068	6.8	1.59		10.80	
3	Success	10.4	11.2	0.0075	7.5	1.39	1.81	9.43	12.33
4	Success	14.2		0.0073	7.3	1.95		13.23	
5	T3	0		0.0123	12.3	0		0	
6	T3	0	n=6	0.0064	6.4	0	n=6 but not 9	0	
7	Success	9.7		0.0051	5.1	1.90		12.93	
8	Success	11.7		0.0051	5.1	2.29		15.60	
9	Success	10.4		0.0059	5.9	1.76		11.99	

d. Cultivar 45H29 (controlled)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	T3	0		0.0035	3.5	0		0	
2	Success	16.6		0.0102	10.2	1.63		11.07	
3	Success	10.4	11.3	0.0064	6.4	1.64	1.77	11.05	12.04
4	Success	11.9		0.0055	5.5	2.16		14.71	
5	Success	10.1	n=6	0.0055	5.5	1.84	n=6 but not 7	12.49	
6	Success	7.2		0.0047	4.7	1.53		10.42	
7	Success	11.6		0.0063	6.3	1.84		12.52	

Appendix X

Table 1: Strength measurement of 10% softener-treated fibres.

a. Cultivar HYHEAR 1 (10% softener-treated)

Test no	**Status**	**Breaking load (lb)**	**Mean (lb)**	**Fibre mass (g)**	**Fibre mass (mg)**	**Strength index (lb/mg)**	**Mean (lb/mg)**	**Breaking tenacity (gram-force/tex)**	**Mean (gf/t)**
1	T1	0		0.0058	5.8	0		0	
2	T1	0		0.0129	12.9	0		0	
3	Success	10.05	10.68	0.006	6	1.68	1.28	11.39	8.72
4	T1	0		0.0064	6.4	0		0	
5	Success	8.7		0.0091	9.1	0.96		6.50	
6	T1	0		0.011	11	0		0	
7	T2	0	n=6	0.0155	15.5	0	n=6 but not 11	0	
8	Success	7		0.0102	10.2	0.69		4.67	
9	Success	13		0.0092	9.2	1.41		9.61	
10	Success	16.3		0.0102	10.2	1.60		10.87	
11	Success	9		0.0066	6.6	1.36		9.27	

b. Cultivar Topas (10% softener-treated)

Test no	**Status**	**Breaking load (lb)**	**Mean (lb)**	**Fibre mass (g)**	**Fibre mass (mg)**	**Strength index (lb/mg)**	**Mean (lb/mg)**	**Breaking tenacity (gram-force/tex)**	**Mean (gf/t)**
1	Success	9		0.0054	5.4	1.67		11.33	
2	Success	10.15		0.0042	4.2	2.42		16.43	
3	Success	9.8	10.99	0.0041	4.1	2.39	1.93	16.25	13.15
4	Success	14.2		0.0102	10.2	1.39		9.47	
5	T1	0	n=6	0.0048	4.8	0	n=6 but not 7	0	
6	Success	12.6		0.0101	10.1	1.25		8.48	
7	Success	10.2		0.0041	4.1	2.49		16.92	

c. Cultivar 5440 (10% softener-treated)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	Success	11.5		0.0091	9.1	1.26		8.59	
2	Success	8.6		0.0065	6.5	1.32		9.00	
3	Success	11.4	9.88	0.0072	7.2	1.58	1.41	10.77	9.57
4	Success	9.3		0.0069	6.9	1.35		9.17	
5	Success	7.2	n=6	0.0052	5.2	1.38	n=6 but not 7	9.42	
6	T1	0		0.0045	4.5	0		0	
7	Success	11.25		0.0073	7.3	1.54		10.48	

d. Cultivar 45H29 (10% softener-treated)

Test no	Status	Breaking load (lb)	Mean (lb)	Fibre mass (g)	Fibre mass (mg)	Strength index (lb/mg)	Mean (lb/mg)	Breaking tenacity (gram-force/tex)	Mean (gf/t)
1	T1	0		0.0032	3.2	0		0	
2	T1	0		0.0049	4.9	0		0	
3	T2	0		0.011	11	0		0	
4	Success	10.9	11.48	0.0059	5.9	1.85	1.84	12.56	12.51
5	Success	11.1		0.0063	6.3	1.76		11.98	
6	T1	0	n=6	0.0028	2.8	0	n=6 but not 10	0	
7	Success	8.5		0.0049	4.9	1.73		11.80	
8	Success	11.1		0.0061	6.1	1.82		12.37	
9	Success	16.2		0.007	7	2.31		15.74	
10	Success	11.05		0.0071	7.1	1.56		10.58	

Appendix XI

Table 1: Tensile strength (MPa) of the 10% softener-treated fibres of four *B. napus* cultivars.

Breaking tenacity (gram-force/tex)	Density (g/cc)	Tensile Strength (MPa)	Mean (MPa)	S.D. (σ)
		a. Cultivar HYHEAR 1		
11.390	1.342	149.915	114.741	34.416
6.501	1.342	85.567		
4.667	1.342	61.423		
9.609	1.342	126.469		
10.867	1.342	143.027		
9.273	1.342	122.047		
		b. Cultivar Topas		
11.333	1.361	151.247	175.463	51.080
16.433	1.361	219.309		
16.254	1.361	216.911		
9.467	1.361	126.336		
8.483	1.361	113.211		
16.917	1.361	225.765		
		c. Cultivar 5440		
8.593	1.378	116.157	129.351	11.673
8.997	1.378	121.611		
10.767	1.378	145.533		
9.165	1.378	123.886		
9.415	1.378	127.268		
10.479	1.378	141.651		
		d. Cultivar 45H29		
12.563	1.429	175.995	175.195	24.215
11.981	1.429	167.845		
11.796	1.429	165.253		
12.374	1.429	173.348		
15.737	1.429	220.466		
10.583	1.429	148.262		