The Effect of Different Retting Methods on hop (*H. lupulus)* Fiber Quality for Small-Scale Textile Production.

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Abstract

Hops bines are a fiber-rich plant annually grown in the Pacific Northwest for the beer industry. Once harvested, the bines become byproducts and are typically mulched or composted. This research is aimed at gathering usable hops fibers to make woven textiles by using traditional biological and mechanical processes adopted from other bast fiber plants. Five different fiber extraction methods were compared; green processing, dry decortication, water retting, breaking to water retting, and dew retting. This research compared key characteristics including fiber length, width, linear density, breaking tenacity, elongation at break, modulus, fiber yield, spinnability, and woven fabric texture between the different methods. Green processing produced fibers that were 116.83mm ± 41.42 in length, a width of 331.9μm ± 188.51, an average linear density of 0.28D ± 0.18, breaking tenacity of 11.16 cN/tex ± 6.52, elongation at break of 3.99% ± 2.29, modulus of 309.1 cN/tex ± 264.83, and a fiber yield of 15.42g ± 7.88. This fiber was the least difficult to spin of the fiber producing methods and required a medium beat to weave. The warm water retting method had an average fiber length of 106.1mm ± 44.08, a width of 369.27μm ± 211.29, a linear density of 0.42D ± 0.39, an average breaking tenacity of 11.69 ± 4.92, elongation at break of 4.41% ± 2.73, a modulus of 387.53 cN/tex ± 215.84, and a fiber yield of 20.59g ± 8.02. These fibers were okay for spinning and woven with a medium beat. The breaking to warm water retting produced 134.21mm ± 55.49 length fibers, had an average width of 634.31μm ± 267.85, linear density of 0.49D ± 0.38, breaking tenacity of 12.49 cN/tex ± 5.81, elongation at break of 3.45% ± 1.07, modulus of 553.41 cN/tex ± 164.88, and fiber yield of 46.34g ± 20.32. The fibers were okay for spinning and were woven with a hard beat. Dew retting produced 79.42mm ± 24.13 length fibers, with average widths of 294.06μm ± 177.67, a linear density of 0.16D ± 0.09, breaking tenacity of 17.89 cN/tex ± 10.41, elongation at break of 3.38% ± 1.24, modulus of 869.55 cN/tex ± 321.11, and fiber yield of 4.58g ± 4.42. Breaking tenacity, elongation at break, and modulus are to be determined. The fibers were difficult to spin, and the yarn was woven with a medium beat. Depending on the end use, these fiber methods can be utilized to produce woven and nonwoven materials.

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Dedication

Thank you to my sweet Dave for keeping me laughing and well-nourished throughout this process. I'd also like to thank my friends and family for rooting me on from near and afar.

Table of Contents

List of Tables

List of Figures

List of Equations

Chapter 1: Introduction

The fashion and textile industries are one of the top polluting industries in the world accounting for 10% of global greenhouse gas emissions (European Parliament, 2020). This, in part, is due to the 400% increase demand in clothing consumption from fast fashion companies (Chen et al., 2021). What once were seasonable fashion trends have now turned into 52-week trends, which have resulted in low-cost disposable clothing to match consumer behaviors (Pookulangara & Shephard, 2013). The rise in fast fashion consumption has led to the use of low-quality materials and an oversaturation in production of these clothes. Overseas manufacturing in Third World countries take the brunt of the pollution to meet these fashion demands (Niinimäki et al., 2020), which in turn has an adverse effect on clean water, pollutes the air (Jaganathan et al., 2014), and presents dangerous working conditions for the workers (Bick et al., 2018).

The majority of textiles used to manufacture these clothes are polyester (a derivative of fossil fuel oil), which makes up 51% of total garment material content (Niinimäki et al., 2020). Polyester, "a fiber without an expiration date" (Burgess & White, 2019), is versatile and does not break down easily when handled, and thus can be shipped globally without damage (Niinimäki et al., 2020). However, the fact that it doesn’t break down easily adds to our ever-increasing landfill waste, especially when these clothes are made to be disposable (European Parliament, 2020). The current lifecycle of our clothing poses a huge health and environmental hazard because these textiles are resource-heavy to produce and have a considerable carbon footprint, which ultimately exacerbates greenhouse gas emissions. To combat this, using natural fibers provides a sustainable alternative to polyester-based textiles while creating an opportunity for reduced greenhouse gas emissions (Niinimäki et al., 2020).

Additionally, due to the commercialization of current industry practices, consumers’ relationship to their clothing has been separated for far too long. There are few consequences for consumers in developed countries to continue buying from fast fashion brands because they do not readily see the damages of their consumption. Reducing our dependence on overseas manufacturing will lessen the environmental and health risks that are imposed on these Third World countries. Likewise, a consumer behavior study conducted by Salfino (2021) found that goods manufactured domestically are seen as more appealing to consumers than imported goods. Buying domestically made garments may help consumers reconnect their relationship to their clothing. This was certainly the case for Rebecca Burgess, the fiber artist who coined the term “fibershed” and created a movement around locally sourced and manufactured textiles. A fibershed describes the network of fiber farmers and fiber artisans within a bounded geographic region. Burgess has made it her mission to connect local farmers, ranchers, dyers, artisans, designers, and textile mills (Burgess & White, 2019) and give these textile providers and artisans a platform in which they can keep business in the local community instead of selling out to overseas manufacturing. Burgess also challenged herself to create a wardrobe made from locally sourced textiles within a 150-mile radius of her location. Her successful completion of this year-long challenge has inspired other communities to look upon their regional textiles and resources to create their own local fibershed.

Within the Pacific Northwest, there are only two fibersheds: Pacific Northwest Fibershed in Portland, OR, and Vashon Fibershed in Vashon Island, WA. Pacific Northwest is focused on the revitalization of regional flax in the Willamette Valley (Pacific Northwest Fibershed, 2022), while Vashon Fibershed is geared towards animal fiber (Macrae, 2016). However, there is an untapped fiber-rich resource that has not been explored yet: hops. Hops is one of the major specialty crops grown within the Pacific Northwest states of Washington, Oregon, and Idaho for beer production. In 2022, 59,785 acres of hops were grown in the Pacific Northwest (Hop Growers of America, 2022). The fiber-rich stalks called bines can grow up to 20 feet in a single growing season. The cones, which make up only 15% of the grown plant (Korpelainen & Pietiläinen, 2021), are collected for beer production while the bines and leaves are mulched and composted. With the increase of hops growers in the Pacific Northwest due to the craft brewing industry (Mordor Intelligence, n.d.), there has been an excess of wasted byproduct that could be used towards value, particularly in the textile industry. Hops, like other bast plants, are characterized by producing fibers within the length of the stalk. These fibers can be extracted through retting processes that break down the lignin holding fiber bundles together. According to USDA (2022), there were 59,785 acres of commercially grown hops in the Pacific Northwest in 2022. Each hectare produces approximately 1.5 MT of hops bine (Haunreiter et al., 2021), allowing 36,291 MT of potential usable hops bine fiber. If this byproduct was used for a sustainable alternative for textile materials or products, then it could benefit the growers and fill a need for localized fiber sourcing.

A slowing down and localization of production with natural renewable fibers is essential for creating a more sustainable future for the fashion and textile industries. This can be achieved through the Fibershed movement that is emerging within fiber rich regions as it is one way to offset unsustainable fashion and textile industry practices. This research project contributed to local fiber systems by comparing traditional biological and mechanical bast plant retting processes and determined the most feasible method for hops fiber quality and quantity. Since documentation of hops fiber extraction methods were limited, the processes used were adapted from small-scale hand processing methods for bast plants such as: flax, hemp, and jute. If hops fibers could be extracted using the same techniques as other bast plants, then this could lead to a regionally sourced sustainable textile fiber. Furthermore, and of important note, this research expects that hops fibers processed using different techniques will produce different fiber qualities and quantities. Alternatively, adapted bast fiber processing techniques will not aid in the extraction of hops fibers, nor will there be a difference in fiber quality or quantity between the varying techniques. This mixed methods research project will quantitatively measure length, width, linear density, yield, and tensile strength of the fibers. Imitating these methods will allow for greater comparison of hops bines to well-used bast plants and will provide a foundation for others to replicate for small-scale production. Fibers extracted from each of the different processing methods were spun into a yarn, and a fabric swatch was woven from it. This swatch was used as a visual marker for potential hops fiber reintroduction as a textile material. Qualitative assessment of spinnability and weaving compared the different hand feel for each fiber type, ease of use, and potential marketability. This project could have major implications for regional textile sourcing, production practices, and waste reduction for a more sustainable supply chain.

Chapter 2: Background Research

Sustainability & Small-Fiber Producers

There are many environmental problems associated with the production and life cycle of textiles and garments manufactured for the fashion and textile industries. Fabric production requires a lot of water, energy, and raw material resources that all negatively impact the air, soil, water, and environment. Fibers are acquired by either growing, shearing, chemical processing, or combing. They are then cleaned, spun into a yarn, and either woven or knit into a fabric. Next, the fabric is often dyed or printed and finished with treatments to create a desired look. The finished fabric is then cut, sewn, and made into the intended end use (Johnson et al., 2015). Waste can occur at every phase throughout the life cycle of textiles; from growing raw materials and garment production to consumer use and end of life. The environmental toll it takes to produce clothing is astronomical in and of itself-– to create one cotton tee shirt requires 2,700 liters of water, which is 2.5 years' worth of drinking water for one person (European Parliament, 2020; Mogavero, 2020). Moreover, the textile and garment production process contributes to global toxic wastewater, CO_2 emissions, and pollution from textile waste that is either sent to landfills or incinerated, all of which destroy the environment and are harmful to natural life. For example, 20% of the world's wastewater is a result of toxic textile dyes and finishes for the fashion industry, making it the world's second-largest water contaminator (Fibre2Fashion, 2022). Furthermore, CO_2 emissions of the fashion industry account for nearly 10% of the global CO_2 emissions at a staggering 1.7 billion tons a year (Centobelli et al., 2022). Not to mention the amount of waste generated at every step of the textile and garment manufacturing process which is exacerbated by the eventual end of life of a garment contributing to the total annual waste of 92 million tons (Centobelli et al., 2022).

A potential solution to reducing the environmental impacts of the current fashion industry can be through the use of more sustainable natural fibers. Natural fibers come from either plants or animals. Fibers are either extracted from the stems, leaves, or seeds of plants, or from the hair or cocoons of animals (Johnson et al., 2015). Some of the more common marketplace natural fibers are cotton, silk, wool, and flax (Johnson et al., 2015). Flax is an example of a bast fiber plant, which is classified under the same category as bamboo, hemp, jute, and ramie. Bast fiber plants require less water and energy resources with little or no pesticides to grow, and they generate high yields of fiber, provide nutrients to soil for regenerative farming, and are deemed biodegradable at the end of their lifecycle (Rana et al., 2014). In comparison, cotton, even though it's a natural fiber, is resource intrusive– to produce one kilogram of cotton requires 7,000-29,000 liters of water (Mogavero, 2020). Furthermore, growing one kilogram of cotton requires 457 grams of fertilizer and 16 grams of pesticides (Rana et al., 2014). For these reasons, bast fiber plants are more sustainable and have lower environmental impacts than other natural fibers (Rana et al., 2014).

Processing bast plants for fiber extraction is a lengthy and tedious process. The use of machinery and equipment is necessary for large-scale production. Since bast fibers have a long staple length, specialty equipment is needed to turn bast fibers into a textile fabric. Though the primary source of fabrics is made in mills, there are only a few sparsely scattered across the United States. For the small-scale fiber producer, the dearth of fiber and textile mills has created a bottleneck for nationally made fabric manufacturing. Furthermore, of the existing mills, most of these facilities only cater to animal fibers, thus further removing small-scale bast fiber producers from domestic textile production. Likewise, bast fiber processing facilities no longer exist in the Pacific Northwest (Pacific Northwest Fibershed, 2022). If bast fiber producers wanted their fibers made into a textile, they would have to send their fibers to an overseas manufacturer. This is an inefficient, impractical, and expensive method that is not sustainable for the small-scale bast fiber producer.

The fibershed movement gives small-scale producers and fiber artisans a network in which to connect and move the textile industry towards more renewable, sustainable, and regional material sourcing. In the case of bast fibers, this network can be key to the survival of domestic bast fiber production. There is a growing bast fiber movement in the US spearheaded by Chico Flax in California, Fibrevolution (part of the Pacific Northwest Fibershed) in Oregon, and the Rust Belt Linen Project in Ohio (Fibershed, 2019). These fibersheds aim to revitalize flax and hemp growing in these regions for the purposes of reconnecting communities to material origin (Rust Belt Fibershed, n.d.) and building a national bast fiber-to-textile supply chain (Fibrevolution, 2023).

With the backing of Fibershed, these communities can push the boundaries of fiber outreach that not only boost local economies but promote healthy regenerative ecosystems with Soil-to-Soil practices (Figure 2.1). Soil-to-Soil is a concept pertaining to everything involved in the life cycle of making a garment. The soil grows and feeds nutrients to the source of natural fiber, that is then dyed with plants grown on the land, and turned into garments built by designers and makers that will eventually be composted back into the soil at the end of its lifespan (Burgess & White, 2019). This concept enables consumers to fully see the extent of garment production and contemplate the sources in which their clothing is made. Impressing a regenerative culture upon consumers to seek a more resilient ecosystem with place-based textile production.

Figure 2.1 Cyclic concept of Soil-to-Soil practices. Photo credit: Burgess and White 2019.

Bast Plants

Although the growing of bast fibers for textiles in the United States has nearly diminished since the introduction of synthetic yarns in the 1930s (Kativa, 2016), there is hope for reviving this old tradition. The emergence of flax and hemp cultivation is a potential start. Although there are many bast plants, flax and hemp's versatility and adaptability make them ideal plants for fiber sourcing.

Flax and hemp are widely used bast plants with a rich history in textiles throughout the world. Bast plants are characterized by having an epidermis, cortex, phloem, xylem, and pith, which can be seen in cross section (Figures 2.2, 2.3). The xylem produces short coarse hurd fibers that can be used for nonwoven textiles. The long soft bast fibers extracted for woven textiles are produced in fiber bundles between the cortex and phloem (Figure 2.4). They are considered the primary fibers because they grow with the length of the plant (Mokshina et al., 2018). Secondary bast fiber bundles also exist but they are shorter than the primary fiber bundles (Manian et al., 2021) because they form with the girth of the plant after the plant has reached max elongation (Mokshina et al., 2018).

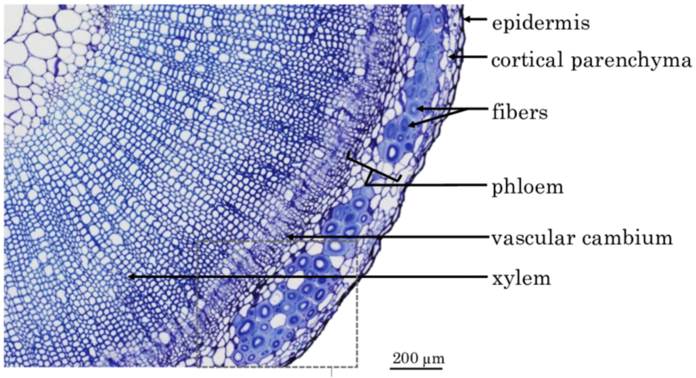

Figure 2.2 Cross section of flax. Photo credit: Goudenhooft (2019).

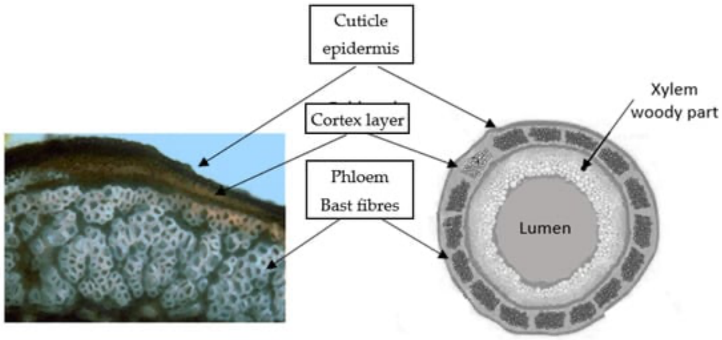

Figure 2.3 Hemp stem cross section. Photo credit: Zimniewska (2022).

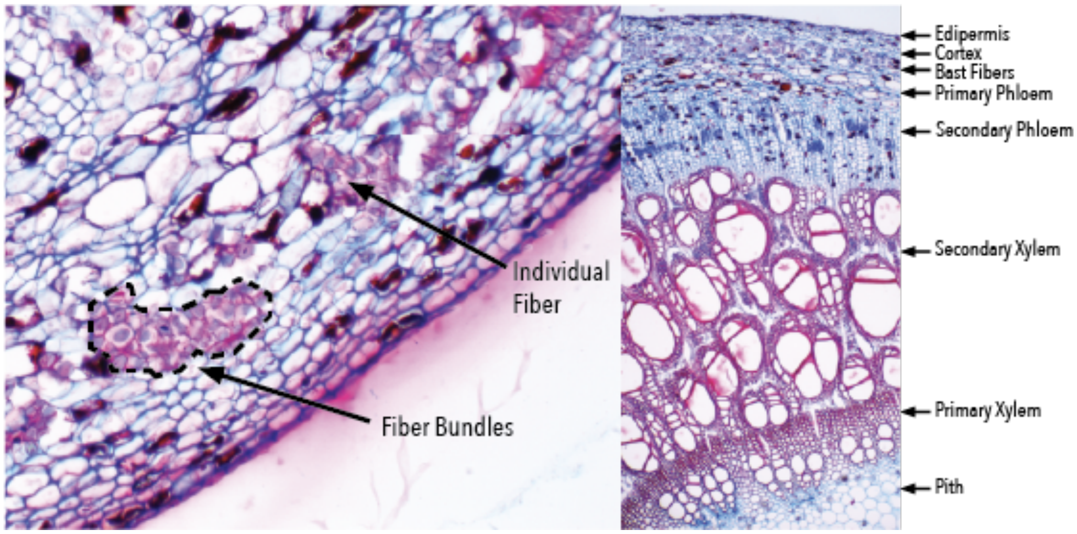

Figure 2.4 Cross section of hops stem and closeup view of hops fiber bundles. Photo credit: Dan Mottern.

Regardless of the visual differences in each plants’ cross section, bast plants all contain usable fibers. These plants all have different chemical compositions that effect the growth and fiber properties, making them distinguishable from one another. The major components affecting plant composition are cellulose, hemicellulose, pectin, and lignin. Cellulose, hemicellulose, and pectin are polysaccharides, or long chain carbohydrate molecules, and considered the “building blocks” of cell walls. Plants contain three main layers: the middle lamella, the primary wall, and secondary walls (Figure 2.5) (Rytioja et al., 2014).

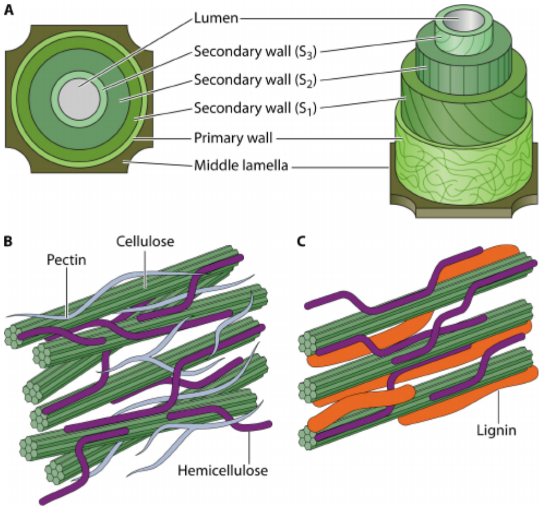

Figure 2.5 Plant cell wall structure. Photo Credit: Rytioja et al. (2014).

Cellulose, in the form of microfibrils, and hemicellulose provide rigidity to the primary and secondary walls' structures while pectin acts as an adhesive that binds cells and supports cell wall growth within the three main layers (Rytioja et al., 2014; Voragen et al., 2009). Lignin is found within the secondary cell walls and provides mechanical stability and stiffness to the cellulose microfibrils. Table 2.1 compares the chemical composition of flax, hemp, and hops.

Fiber	Cellulose %	Hemicellulose %	Pectin %	Lignin %
Flax[1]	62-71	16-18	1.8-2	2-2.5
Hemp[1]	67-75	16-18	0.8	2.9-3.3
Hops[2]	84 ± 1.6	–	–	6.0 ± 0.2

Table 2.1 Comparison of chemical composition for flax, hemp, and hops fibers.

A high lignin content impacts the mechanical properties of the plant, making them less elastic. Furthermore, a high cellulose content affects the tensile strength and density, while high hemicellulose affects the modulus, and high pectin affects the density and elongation of natural fibers (Karimah et al., 2021). Table 2.2 shows a comparative representation of the chemical composition of flax, hemp, and hops as they relate to length, width, linear density, breaking tenacity, elongation at break, and modulus.

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[1] (Ali, 2013)

[2] (Reddy & Yang, 2009)

Fibers	Length (mm)	Width (µm)	Linear density (denier)	Breaking tenacity (g/den)	Elongation %	Modulus (N/tex)
Flax	13-60[3]	12-30[3]	20.7-29.34[4]	2.6-8[5]	1.8-3.3[5]	8-25[6]
Hemp	5-55[3]	16-50[3]	17.1-27[7]	3-7[5]	1.7-2.7[5]	60[6]
Hops	115 ± 29[8]	20-24[9]	48 ± 19[8]	4.1 ± 1.9[8]	3.3 ± 1.2[8]	14.2 ± 5[8]

Table 2.2 Comparison of fiber properties for flax, hemp, and hops fibers.

Flax

Flax is one of the oldest known used bast fiber plants for textiles, with the earliest found evidence of yarn dating back 30,000 years ago (Melelli et al., 2021). Flax produces long lustrous fiber strands that are used for making linen textiles. Processing of flax has historically been done with water retting and hand processing techniques. Ancient Egyptians extracted fibers through water retting and spun them to create very fine flax fiber yarns (Melelli et al., 2021). The fineness of these yarns was used to weave soft textile fabrics which were highly regarded by the Egyptians (Melelli et al., 2021). In more recent years, dew retting has been the more common method, although the fibers extracted may contain pectin residues and are considered not as soft (Melelli et al., 2021).

Currently, the top producing flax fiber countries are France, Belgium, and Belarus (HelgiLibrary, 2023). Within the United States, flax for fiber production is predominantly grown in North Dakota and Montana (Agricultural Marketing Resource Center, 2022).

Hemp

Similarly, hemp has been an important fiber in textiles with first recorded evidence of fiber found in China in 4000 BCE (Kaufmann 2020). Cannabis sativa, the hemp producing plant, is extremely versatile– it grows quickly in various climates and has many nonwoven and woven applications such as building composites, paper, cordage, and textiles (Rana et al., 2014). Hemp was first introduced in the United States in the 1600s and was considered a cash crop because of its quick growth and multiple uses (Kaufmann 2020). Hemp was heavily used as sailcloth and rope for the US Navy during World War II in the 1940s, and farmers were encouraged to grow hemp for the war efforts (*US Hemp History*, n.d.). But by the 1960s, hemp was considered dangerous for its trace amounts of

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[3] (Manian et al., 2021)
[4] (Nair et al., 2013) Units converted for linear density.
[5] (Ali, 2013)
[6] (Schultze-Gebhardt & Herlinger, 2008)
[7] (Zimniewska, 2022) Units converted for linear density.
[8] (Reddy & Yang, 2009) Units converted for length, tenacity, and modulus.
[9] (Haunreiter et al., 2021)

psychoactive tetrahydrocannabinol (THC). This was exacerbated by the 1970s Controlled Substances Act that classified hemp and marijuana as indistinct varieties of the cannabis plant (*US Hemp History*, n.d.) and measures were taken to stop its cultivation. Because of this, hemp production in the United States took a downturn and hemp processing mills were shut down (US Department of Agriculture, 2000). While this was happening, cotton production grew and became the preferred fiber of the United States. However, despite hemp's tumultuous history in the US, hemp farmers are slowly regaining ground as governmental restrictions for hemp production lessen as a result of the passing of the bipartisan 2014 and 2018 Farm Bills (Kaufmann 2020). This, as well as more education around the benefits and uses of hemp, has allowed hemp production to increase and is projected to have a global annual growth rate of 15.8% by 2027 (Zimniewska, 2022). Currently, China is the largest producer of hemp with broader Europe as a close second (Zimniewska, 2022).

Hops

Hops is not a novel fiber in the textile industry, though it is currently underutilized as a bast plant fiber source. Due to the similarity in characteristics of other bast plants, hops seem to be a viable source for fiber. The theoretical percentage of bast fibers within a hops bine is 5%. Hops is a perennial plant within the Cannabaceae family. The genus, *Humulus,* contains three species of hops; *lupulus* (common hop), *yunnanensis* Hu. (Yunnan Hop), and japonicus (Japanese Hop) (Zimniewska 2022). All three species can be found in China, suggesting the root of their origins (Alonso-Esteban et al., 2019; Korpelainen & Pietiläinen, 2021).

Hops grow from rhizomes that send up shoots that eventually turn into stems. Unlike other bast plants that grow straight, the hops stems climb in a spiral motion up supports, typically coir rope, that sustain the development of the plant throughout the growing season. Hops produce cones that are more commonly collected for brewing beer. In commercial settings, these ropes are cut down when the cones of the plants are ready to be harvested.

In the past, the cones were not grown strictly for beer; they had also been used for medicinal healing and food preservation (Korpelainen & Pietiläinen, 2021). Other uses of hops have been explored for fiber use in cloth, rope, bedding, insulation, and paper applications (Korpelainen & Pietiläinen, 2021). Historically in Sweden, hops have been used as a substitute for more notable bast plants like flax and hemp. Due to the mandatory growing of hops from 1414 to 1860 (Lukešová et al., 2019), this overabundance resulted in new ways of using hops. One of these ways initiated the first documented woven hops textile (Skoglund et al., 2020). A chemise made of a hop-hemp blend and a fabric swatch made of hops is showcased at the Nordic Museum in Stockholm, Sweden (Skoglund et al., 2020).

Regardless of the artifacts, there is a dearth of documented historical literature on how these hops fibers were extracted and processed to make the woven textiles.

One promising utilization of hops is in the pulp and paper industry as previously conducted by myself and more formally by Haunreiter, Dichiara, and Gustafson (2021). From my previous research experience, I have been able to chemically break down an entire bine for the purposes of making a nonwoven textile in the form of a paper sheet. Using hops for pulp and paper is practical because the entire bine can be used. Furthermore, Haunreiter, Dichiara, and Gustafson (2021) determined that the strength and fiber quality of hops shows high potential for the paper making industry.

Preliminary work conducted by Reddy & Yang (2009) compared hops fibers to cotton and hemp. By testing the % crystallinity, fiber composition, structure, morphology, tensile properties, and moisture regain, Reddy and Yang (2009) concluded that hops fibers have similar properties to that of hemp. They also determined that hops fibers show promise for use in fibrous applications such as textiles, composites, and carpeting. The measured hops fibers had an average length of 11.5cm ± 2.9, fineness of 48 denier ± 19, tensile strength of 4.1g/den ± 1.9, and modulus of 161g/den ± 57 (Reddy & Yang, 2009). Reddy and Yang (2009) also found that hops had a high cellulose (fiber) content of 84% ± 1.6 and 6.0% ± 0.2 lignin (fiber binding agent) content. Although the hops fibers from this study were chemically extracted, this research sets baseline parameters for hops fiber comparison using the extraction method. They note that variety, plant maturity, and fiber extraction methods influence the fiber composition, therefore we should expect to see different results for this research. The following sections will explore the traditional processing methods for obtaining hops fibers.

Fiber Processing Methods

Although there are more advanced methods for fiber separation that contain chemicals, enzymes, steam explosion, and ultrasonification (Ramesh, 2018), the intent for this project was to provide a feasible means of fiber separation for small-scale production. Hence, the chosen processing methods required minimal equipment that were both easily accessible and inexpensive. Each of these methods also refer to historical and traditional processes that provided a better comparison of fiber quality and quantity.

With little information known on the historic processing of hops fibers, hand processing methods were adapted from other bast fiber hand processing methods. The methods for processing these bast plants will use dry decortication, dew retting, green processing, warm water retting, and breaking to warm water retting, a method that historically has not been used, but was tested in this research. Once the hops bines have undergone the retting process, they are ready for fiber separation. Fiber separation will be implemented by either decortication, breaking, hand peeling, or hackling until singular fibers are obtained. The following sections explore these historical methods in detail and how they will be applied to processing hops.

Dry Decortication

Dry decortication is the process of separating bast fibers from hurd fibers and woody materials in dried stems using machinery or hand tools (Ramesh, 2018). The dried stems are hand fed through implements that break up the stem and mechanically release the fibers from the wooden core. This process is known as decortication, and there are multiple implements that can be used depending on the type of raw material. Implements that are commonly used for breaking stems are decortication machines (machines with rotating beater rollers that smash the core and separate out fibers), crushing fluted rollers, hand breaking machines, and cutter mills (Sadrmanesh et al., 2019). Although this method can generate many fibers within a short amount of time (Sadrmanesh et al., 2019), the quality of fibers produced are coarser than other retting methods (Ramesh, 2018).

Following the decortication process, the fibers are hackled, or combed, to remove any impurities. The set of hackling combs range in size with a progressive reduction in spacing between needles. As the fibers are worked through each of the combs, shorter undesirable fibers are pulled out, which contributes to the tow. The tow can be collected and used for cordage or nonwoven textile applications. The ideal long bast fibers are collected at the end of the hackling stage.

Dew Retting

Dew retting is one of the oldest and most economical retting methods available. Dew retting is the process in which freshly harvested stems are lain in a field for an undefined period. Microorganisms and fungal bacteria in the soil enter the stomata of the plant and feed on the pectin holding the fibers together (Jarman, 1998). This process is dependent on weather conditions, thus making it difficult to control. Warm and humid conditions are ideal for ultimate fiber separation, which is a challenge in the Pacific Northwest. Dew retting is complete when the fibers can be easily separated from the woody core when the stems are broken. This process requires careful monitoring so as not to overret or underret the fibers (Ramesh, 2018). If that occurs, then the fiber quality is diminished.

Once fibers can detach from the main stem, the stems can be removed from the field and stored for drying. The stems will undergo decortication and hackling to obtain fibers. Fibers produced from this method are softer than mechanical retting, but do not produce as soft of fibers as water retting. However, it is still the preferred method for many farmers because of the low labor costs and sustainability associated with it (Ramesh, 2018).

Green Processing

Green processing comprises the immediate decortication and hackling of fibers once harvested. Contrary to other retting methods, this method processes stems on site when they are at peak moisture content. Processing the stems fresh instead of dry eliminates uncontrollable retting conditions as a result of weather or environmental concerns due to wastewater. This method has been adopted from Gusovius et al. (2019), who experimented with hemp stalks.

Water Retting

Water retting produces fine, uniform, and strong fibers (Manian et al., 2021; Tahir et al., 2011), however unfavorable environmental conditions and high labor costs are a consequence of this method. This method uses large quantities of fresh water which becomes quickly polluted during the retting process, resulting in bad smelling wastewater that is difficult to treat. However, despite the environmental concerns, this method is seen as the more favorable method because of the resulting fiber quality.

Water retting has traditionally been conducted in ponds, lakes, and rivers, and more recently in water tanks. Water tanks provide a better controlled environment for bacterial activity. Bundles of dried stems are submerged underwater for a set amount of time before they are removed and left out to dry. Ideal retting temperatures are between 21-32°C. Between these temperatures, water retting takes approximately 4 days for flax and 7-9 days for hemp (Jarman, 1998). Cooler water temperatures slow down bacterial activity and make the retting process take longer (7-14 days) (Ramesh, 2018). Warmer water temperatures speed up the retting process only taking 3-4 days (Ramesh, 2018). However, if the water gets too warm then it could kill the necessary bacteria.

Water retting is complete once test stems from a bundle can be dried and snapped between fingers along the length of the stem (Fisher & Van Alstyne, 2022). If they snap, then the bundles of stems are removed from the water and left out to dry completely (Fisher & Van Alstyne, 2022). If they do not snap, then they will require additional time in the water. This testing process is repeated so as not to over-ret the bundles. If overretting occurs, then the stems will appear slimy, and the fibers will be weakened. Once dry, the stems undergo mechanical breaking followed by hackling to obtain fibers (Jarman, 1998).

Breaking to Water Retting

Breaking the stems first through fluted rollers before submerging into warm water was a proposed method thought to accelerate the retting process. By breaking the stems first, layers of the stem become exposed, and water can penetrate the stem quicker. This method has been tried by Musio, Müssig, and Amaducci (2018) for hemp fiber extraction. In theory, by doing this, the bacteria that forms during water retting can work more efficiently to release the fiber bundles. This process follows the same steps as the water retting method up until fiber extraction. Since the stems are already decorticated, the core and fibers can be separated by hand peeling and then hackled with combs.

These methods were used for hops processing and the effect on fiber quality and quantity was measured as they relate to fiber extraction. These steps are detailed in the following section.

Chapter 3: Materials and Methods

Two hundred fresh Citra Hops bines were collected from Carpenter Ranches, LLC in Granger, WA. Hops cones were stripped on site with a hops harvesting machine and bines were driven to Moscow, Idaho for processing. All collected bines were dried outside for two days at 29.4°C and divided into five for the different processing methods with 50 bines per method. The hops bines were processed either by green processing, dry decortication, dew retting, warm water retting, or breaking to warm water retting. Once bines went through the retting phase, they were either decorticated with the decortication machine, broken with the fluted rollers, or hand-peeled, and then combed with a set of hackling combs until singular fibers were retrieved. The size of hackling combs were 13 mm, 11 mm, 9.5 mm, 3.2 mm, 0.5 mm, and 0.2 mm.

The decortication machine that was used was fabricated by the University of Idaho Machine Shop (Figure 3.1). This machine contains a roller with paddles that forcefully separates the bark from fibers when stems are fed through.

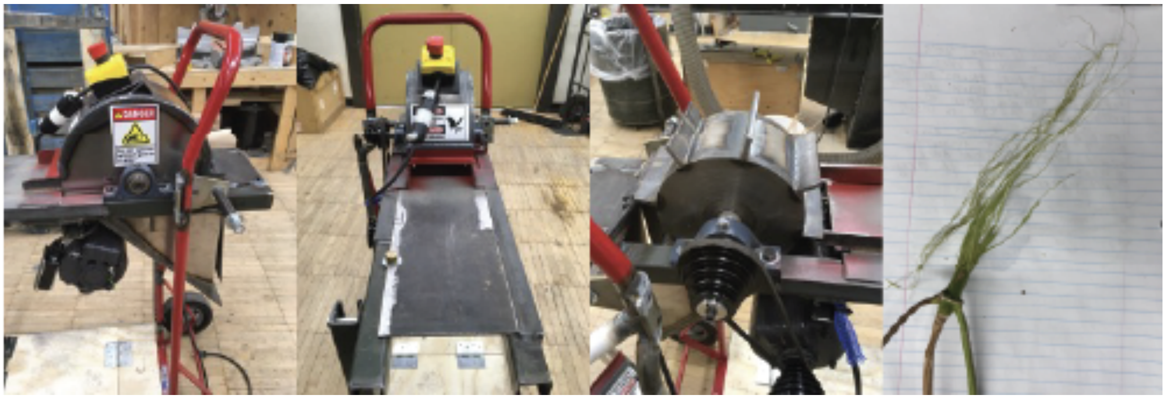

Figure 3.1 Lab-scaled decortication machine with an example of fiber separation from the beating roller.

A sugar cane juicer was used to break stems through three sets of fluted rollers (Figure 3.2). This machine compressed the core of the stems, making it easier to separate the outer bark from the woody pith.

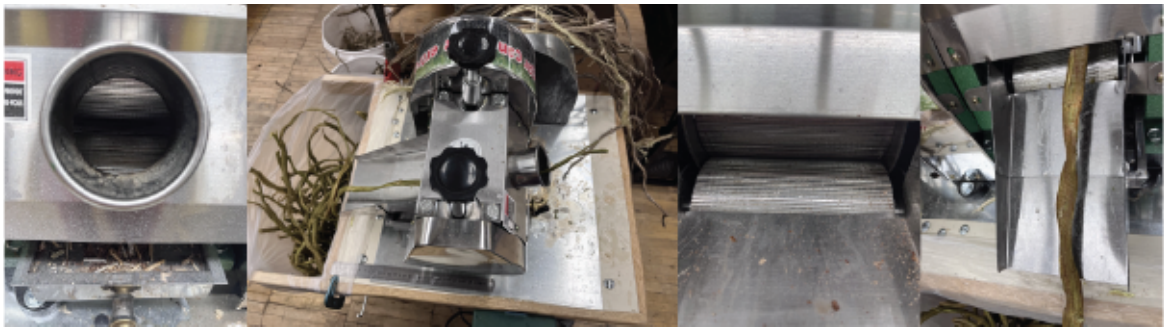

Figure 3.2 Sugar cane juicer with an example of hops bine after fluted rollers compression.

Four of the six hackling combs were made with nails (Figure 3.3). Nail combs are typical for hackling bast fibers like flax and hemp. The sharp points of the nails pierce the fibers making them finer (Merrow, 2015). The final two hackling combs are lice picks that can be bought in stores. These lice picks were used to reach ultimate singular fibers.

Figure 3.3 Hackling combs with sizes.

Fiber Extraction

Figure 3.4 is a visual reference of the five different fiber extraction processes that were used.

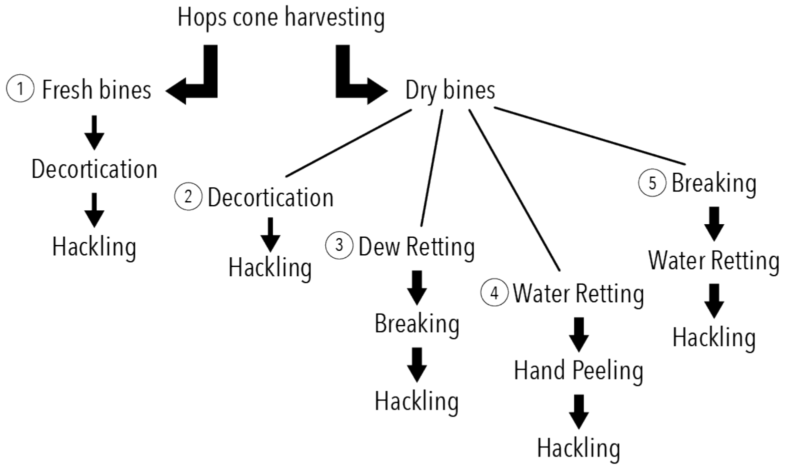

Figure 3.4 Schematic of hops processing methods used for this project.

Green Processing

Freshly harvested bines were collected from a local hops grower in Moscow, ID, and processed on-site. The variety of hops is unknown, and the weights of the full bines were not taken. Bines were decorticated in the decortication machine on site and taken to the lab where they were weighed and hackled with the 0.5mm and 0.2mm combs to single out individual fibers and weighed again.

Dry Decortication

Fifty bines were dried and decorticated through the decortication machine. Beginning bine weight, decorticated weight, and final hackled weight were unable to be recorded.

Water Retting

Fifty dried bines were fully submerged in a 32-gallon water tank of cold water for 8 hours. The water was drained, and warm water of 40°C was added to the tank. Bines were weighed down for total submersion in water and kept between 21- 32°C throughout the retting process. Partial water was drained from the bottom every few days and fresh warm water was added to the top. Water retting was completed once a sample of dried bines could be snapped with hand bending. After 35 days, the bines were removed from the tank, rinsed with cool water, and the bark was hand peeled from the core. The bark was left to dry in a conditioned lab at 21°C and combed with all the hackling combs to achieve singular strands of hops fiber. The weight of bark before and after combing was recorded and used to calculate fiber yield for this method.

Breaking to Water Retting

Fifty dried bines were submerged in a 32-gallon water tank of cold water for 8 hours. The water was drained, and the bines were run through fluted rollers that crushed the outer bark. The crushed bines were put back in the tank with warm water of 23.89°C. Bines were submerged using weights and the tank was left in the lab while the bines were water retting. Water was drained from the bottom every few days and fresh warm water was added to the top. After 20 days, bines were removed from the tank, rinsed with cool water, and left to dry in a conditioned lab at 21°C for 3 days. Once dry, the bines were hackled with all combs to achieve strands of hops fiber.

Dew Retting

Fifty dried bines were dew retted in a north-facing grass lawn for forty-five days. The dew point was recorded each day bines were retted. For mornings with little to no dew, bines were wetted using a water sprayer on a timed interval. The timer was set to spray at 3:30 am for 20 minutes each morning. Bines were rotated weekly to ensure equal dew and bacterial breakdown was achieved. Dew retting was complete once dried bines could be snapped with hand bending. Fully retted bines were brought to dry in a conditioned lab at 21ºC. Once dry, the bines were fed through fluted rollers to break up the bark and hackled with 3.2 mm, 0.5 mm, and 0.2 mm combs to achieve single strands of hops fiber. The beginning weight of bine batches before and after mechanical separation and the ending weight of hackled fibers were recorded.

Fiber Testing

A random sample of 100 fiber strands from each process were tested for fiber length, linear density, and tensile properties. An average width of 32 fiber strands from each process were also assessed.

Fiber Properties

Following ASTM Standard Test Method D5103, fiber lengths were taken with a ruler to an accuracy of 0.1 mm. Lengths were recorded and the average length (mm) ± one standard deviation was calculated per process method.

Linear density was calculated as directed by ASTM Standard Test Method D1577-07-Option B for the sampled fibers to describe fiber fineness. Linear density is a measure of the fiber's mass over length and is represented as the denier (D). The mass of each fiber was weighed using a Mettler Toledo scale to 0.0001mg. The linear density for each sample was calculated for 0.01 denier using the formula:

$$D = 9000 \times W/(L \times N)$$

Equation 3.1 Fiber linear density as denier.

Where D equals the average fiber linear mass density in denier, 9000 equals the constant multiplier of grams/fiber meter for denier, W is the mass of the fiber specimen (mg), L is the length of the specimen (mm), and N is the number of specimens.

The average linear density (D) ± one standard deviation was calculated per process method.

Fiber Morphology

A Zeiss Supra 35 Scanning Electron Microscope (SEM) was used to measure the longitudinal width of 32 fibers from each method. Four fibers were mounted on eight aluminum stubs for each method using double-sided carbon tape that were sputter coated with gold at a rate of 3 angstroms/sec for 180 seconds until 400 angstroms of gold coating were acquired. Three width measurements were taken for every fiber sample to generate an average that was used to calculate the average width (μm) ± one standard deviation per process method.

Tensile Properties

Following ASTM Standard Test Method D3822-07, strain rate tensile testing was conducted using a Q800 Dynamic Mechanical Analysis (DMA) instrument with fiber clamps on the green processed and water retted fiber strands. Breaking tenacity and modulus were recorded in N/tex units with computer generated data and converted to cN/tex, the accepted unit standard for textiles. The conversion for N/tex to cN/tex is (Schultze-Gebhardt & Herlinger, 2008):

$$1\ \mathrm{N/tex} = 100\ \mathrm{cN/tex}$$

Equation 3.2 Conversion for N/tex to cN/tex.

Elongation at break was recorded as a percentage. For each fiber processing method, the average tensile properties ± one standard deviation were calculated. Test parameters for the DMA were: 25 ± 1°C, gage length 9.05mm, pretension of 0.001 N, strain of 2%/min to 100%.

An Instron 5565 with flat jaws was also used for tensile testing of the breaking to water retted fibers and dew retted fibers. Elongation at break, breaking tenacity (cN/tex), and modulus (cN/tex) were recorded and analyzed using computer software. Test parameters for the Instron were: gage length 25.4mm, pretension 0.01N, strain of 0.5mm/min. An analysis of variance was conducted on JASP for breaking tenacity, elongation at break, and modulus between methods to find any statistical significance when $\alpha = 0.05$.

Fiber Yield

The beginning and ending fiber weights were recorded for each fiber batch. The percent fiber yield was calculated from this data for each process method using the following formula:

$$\text{Percent Yield} = (\text{Actual Yield})/(\text{Theoretical Yield})\ \text{x}\ 100$$

Equation 3.3 Calculation for percent fiber yield.

JASP was used to conduct an analysis of variance between retting groups for each of the five methods to find any statistical significance when $\alpha = 0.05$.

Fiber Usability

Spinning

The fiber types were single-ply spun by a local fiber spinner in Moscow, ID. The spinner has 12 years of experience spinning fibers on a drop spindle and spinning wheel. The spinner has spun fibers such as wool, alpaca, yak, bamboo, bison, silk, mohair, and nylon faux cashmere, and the spinner had previously spun hops fiber for the primary investigator for other experiments. The spinner was given a survey to fill out for each of the fiber types and an overall hops fiber spinning experience survey. The data from this survey was used to inform the fiber quality and spinnability of the different fibers, and if the spinner found any potential marketability for any of the fiber types.

Weaving

The spun yarn from the fiber types was woven on a table loom by the primary investigator, who has three years of weaving experience. The fiber types were assessed based on how usable the spun yarn was for weaving and the hand feel of the final woven structure.

Chapter 4: Results and Discussion

Quantitative Results

The duration of retting was different for each of the methods. The breaking to water retting took the least amount of time for the dry bines at 20 days. This was a significant time saver when compared to water retting (35 days) and dew retting (45 days). As previously mentioned, flax can take up to 4 days to water ret and up to 9 days for hemp to water ret. The green processing obviously took the least amount of time because it was processed day of. Overall, the retting process for hops took longer than other bast plants. The methods also produced different looking fibers. Figures 4.1-4.4 below show the visual comparisons of the usable combed fibers from each method.

Figure 4.1 Green processed fibers.

Figure 4.2 Water retted fibers.

Figure 4.3 Breaking to water retted fibers.

Figure 4.4 Dew retted fibers.

From here on forward, figure comparisons of the methods used shorthand names. Dew retting will be referred to as "dew," breaking to water retting will be referred to as "break," water retting will be referred to as "water," and green processing will be referred to as "green." Raw data and results for fiber testing can be found in Appendix A-N.

Length

A boxplot was created to compare the 100 samples of fiber lengths for each method (Figure 4.5). Of all the retting methods tested, dew retting produced the shortest fibers (79.42mm ± 24.13) and breaking to warm water retting produced the longest fibers (134.21mm ± 55.49). The green processing method had an average fiber length of 116.83mm ± 41.42, warm water retting method had an average fiber length of 106.1mm ± 44.08, and dry decortication did not produce any fibers. Green processed fibers had one fiber length outlier at 251mm, warm water retted fibers had one outlier at 290mm, breaking to water retted fibers had two outliers at 290mm and 319mm, and dew retted fibers had two outliers at 140mm and 185mm.

Compared to the 11.5cm ± 2.9 fiber lengths gathered by Reddy and Yang (2009), these fibers fall relatively within the given range except for dew retted fibers which came in shorter than the standard by 35mm, and breaking to water retted fibers were longer than the standard by nearly 20mm.

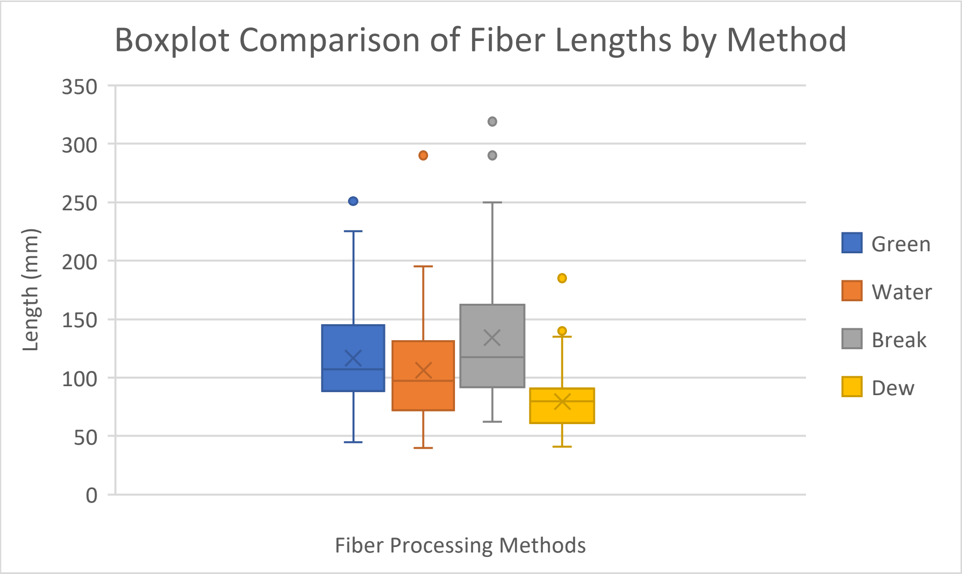

Figure 4.5 Boxplot of fiber lengths by method.

The most frequent fiber length was in the range of 76-107mm for the green processed fibers as seen in 37 fiber samples (Figure 4.6). Thirteen fibers had a length between 45-76mm, 22 fibers had a length between 107-138mm, 17 fibers had lengths between 138-169mm, five fibers had lengths between 169-200mm, four fibers were between 200-231mm in length, and one fiber had a length between 231-262mm.

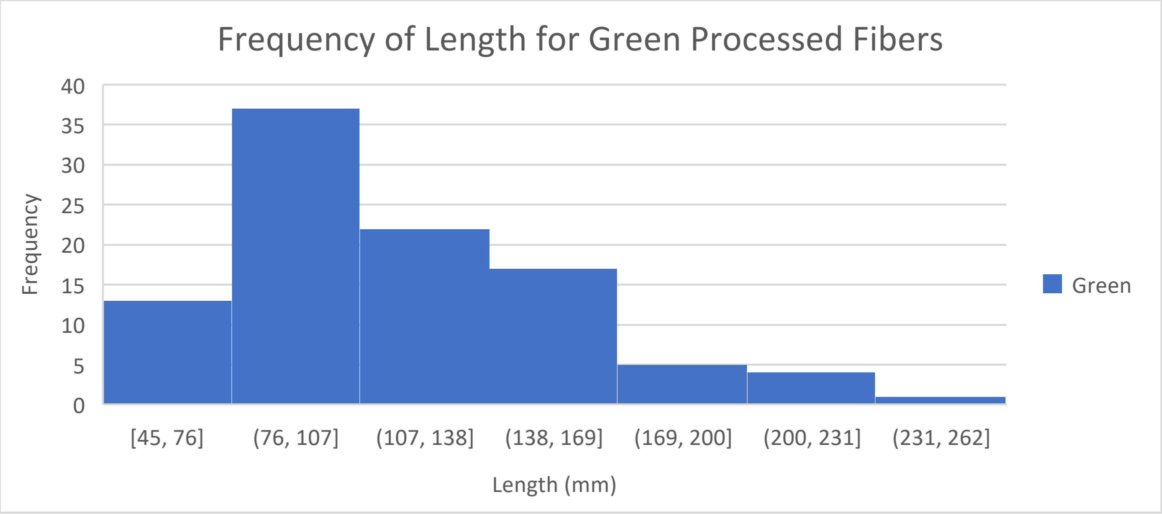

Figure 4.6 Fiber length histogram for green processed fibers.

The highest frequency fiber lengths for the warm water retted fibers were 28 and 29 fiber samples within the 40-73mm and 73-106mm range, respectively (Figure 4.7). Twenty-one fibers had lengths between 106-139mm, 14 fibers had lengths between 139-172mm, seven fibers were between 172-205mm in length, and one fiber had a length between 271-304mm.

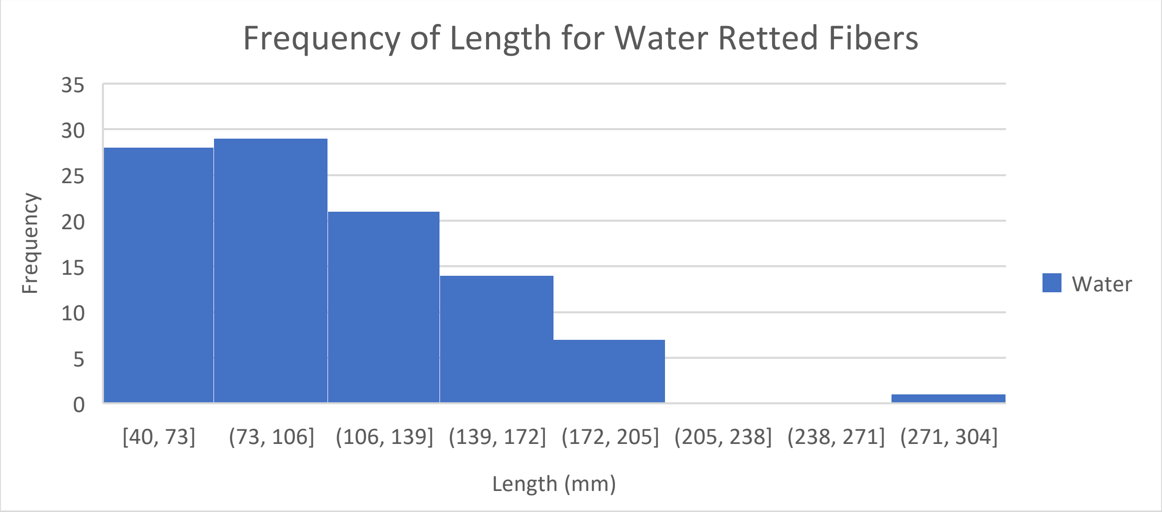

Figure 4.7 Fiber length histogram for water retted fibers.

Breaking to warm water retted fibers had the highest fiber length frequency in the range of 62-104mm with 36 fiber samples (Figure 4.8). Thirty-one fibers had lengths in the range of 104-146mm, 16 fibers had lengths between 146-188mm, 10 fibers were in range of 188-230mm, four fibers were between 230-272mm in length, one fiber was between 272-314mm, and two were between 314-356mm.

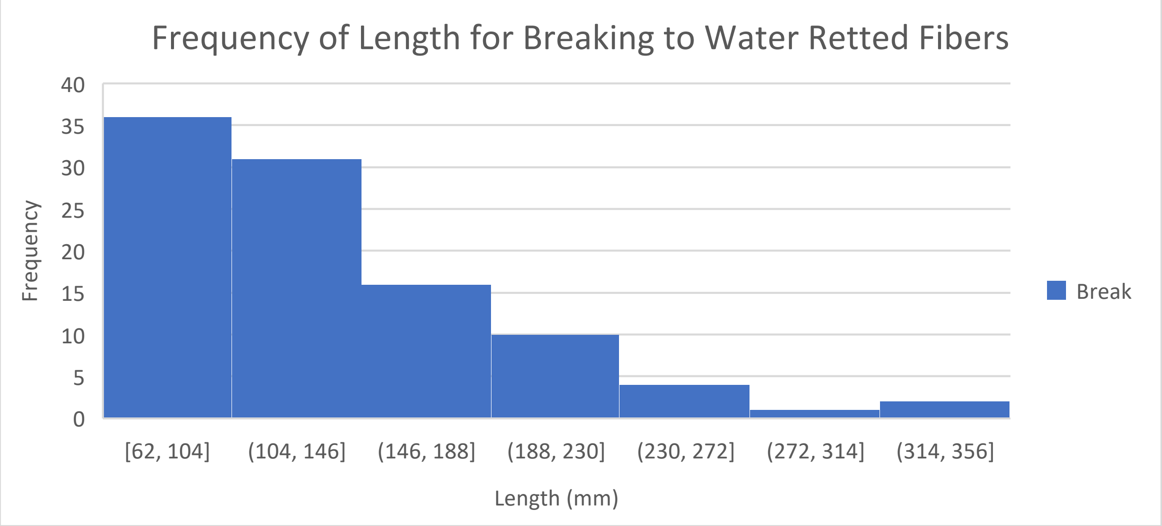

Figure 4.8 Fiber length histogram for breaking to water retted fibers.

The majority of dew retted fiber lengths were below 95mm. The greatest fiber length frequency was 34 fiber samples in the range of 77-95mm (Figure 4.9). Twenty-two fibers were in the length range of

41-59mm, 24 fibers were between 59-77mm, 14 fibers were between 95-113mm, three fibers were 113-131mm, two fibers were between 131-149mm, and one fiber was between 167-185mm.

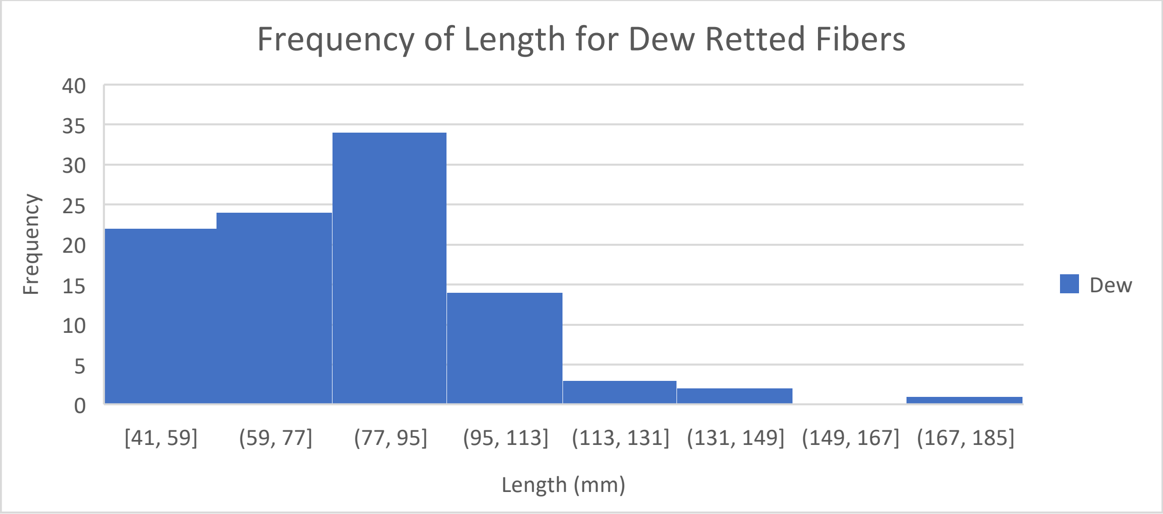

Figure 4.9 Fiber length histogram for dew retted fibers.

Width

Longitudinal widths were measured for 32 fibers from each method using SEM imagery. The average width for green processed fibers was 331.9µm ± 188.51, water retted fibers was 369.27µm ± 211.29, breaking to water retted fibers was 634.31µm ± 267.85, and dew retted fibers was 294.06µm ± 177.67 (Figure 4.10). There was one outlier for the green processing method at 1.024 mm, and four outliers for the dew retting method at 496.3µm, 540.5µm, 695.8µm, and 941.6µm. The fiber widths for these fibers were much greater than the 20-24µm fiber widths collected from Reddy & Yang (2009).

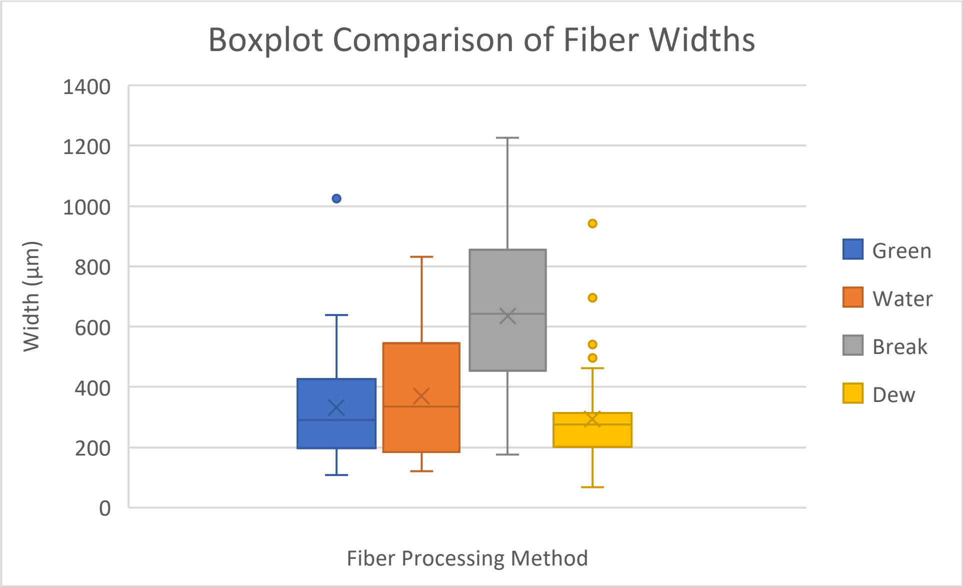

Figure 4.10 Boxplot of fiber widths by method.

Green processed fibers (Figure 4.11) had 17 fiber widths within the range of 107.08-317.08µm, 11 fiber widths between 317.08-527.08µm, three fiber widths between 527.08-737.08µm, and one fiber with a width between 947.08-1157.08µm.

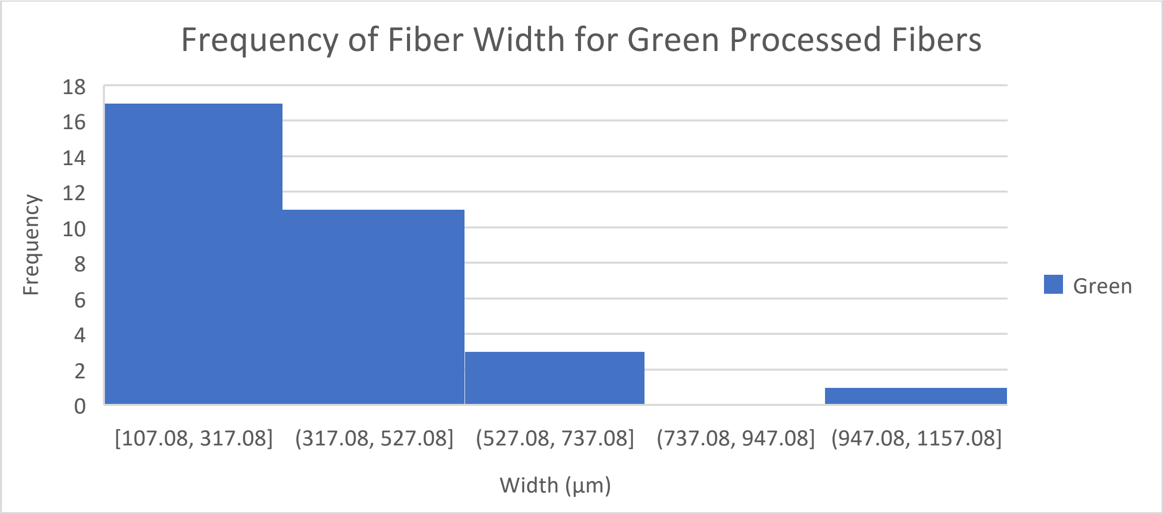

Figure 4.11 Fiber width histogram for green processed fibers.

The greatest frequency of water retted fiber widths was within the range of 120.87-350.87µm with 18 fibers (Figure 4.12). Eight fibers had a width between 350.87-580.87µm, five fibers had a width between 580.87-810.87µm, and one fiber had a width between 810.87-1040.87µm.

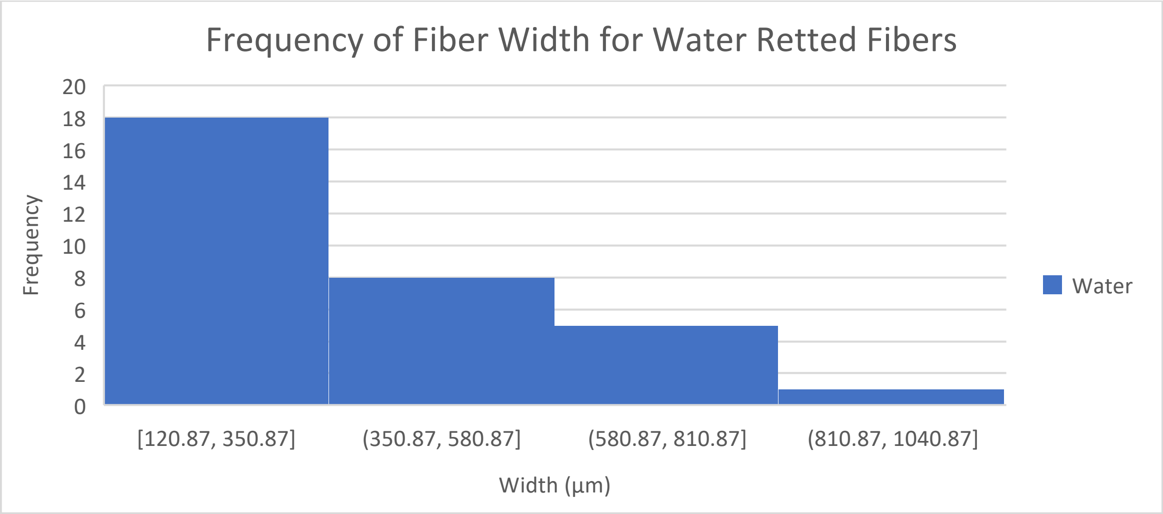

Figure 4.12 Fiber width histogram for water retted fibers.

Breaking to water retted fibers (Figure 4.13) had 10 fiber widths within the range of 174.73-474.73µm, 11 fiber widths between 474.73-774.73µm, nine fiber widths between 774.73-1074.73µm, and two fibers with a width between 1074.73-1374.73µm.

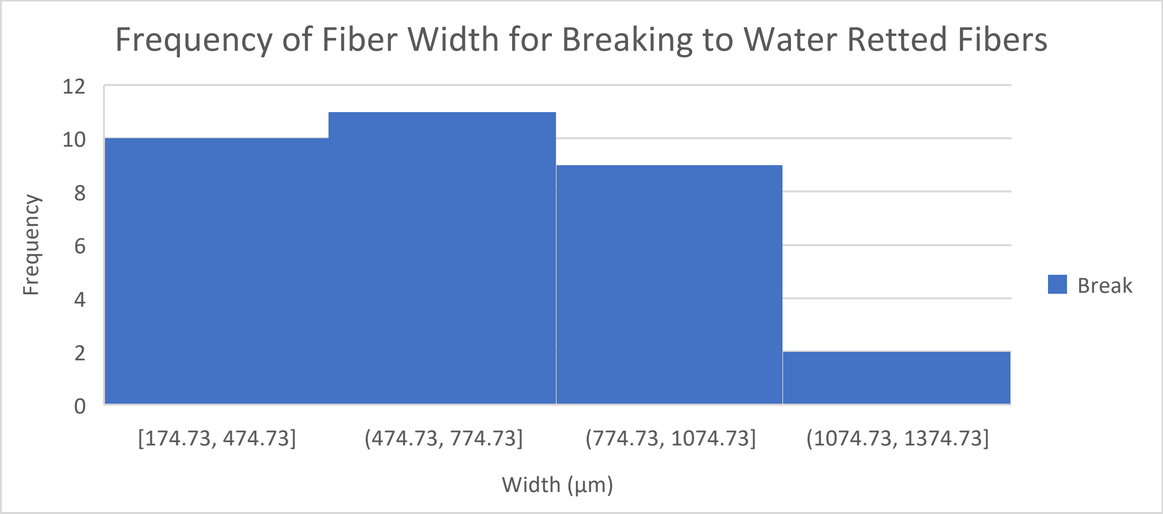

Figure 4.13 Fiber width histogram for breaking to water retted fibers.

The greatest frequency of dew retted fiber widths was within the range of 67.07-267.07µm with 15 fibers (Figure 4.14). Thirteen fibers had a width between 267.07-467.07µm, two fibers had a width between 467.07-667.07µm, one fiber width was between 667.07-867.07µm, and another fiber had a width between 867.07-1067.07µm.

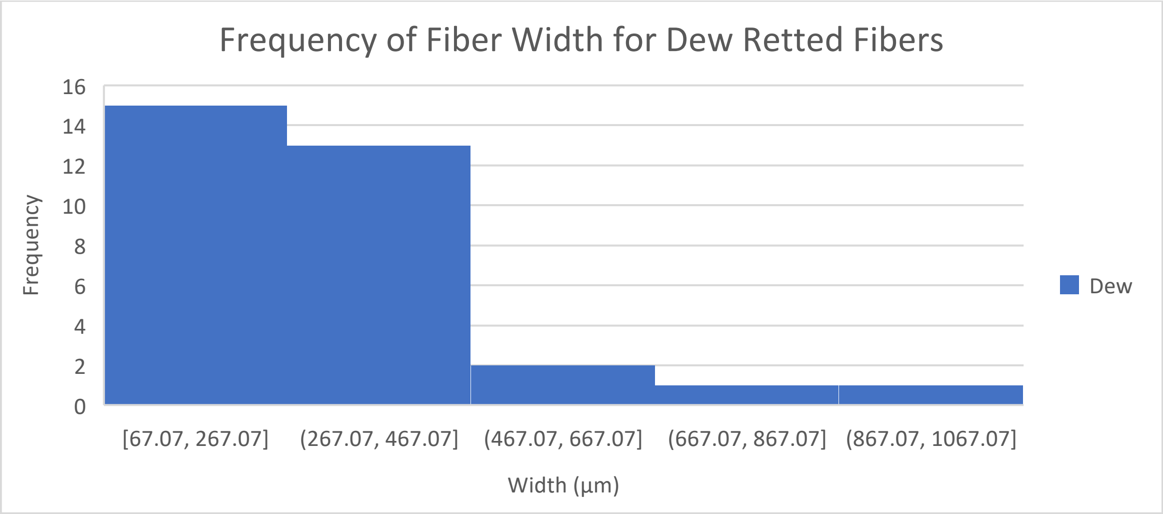

Figure 4.14 Fiber width histogram for dew retted fibers.

Images from SEM show that fibers from the green processing method (Figure 4.15) produced a smoother fiber compared to the fibers from the other methods. The water retting (Figure 4.16) and breaking to water retting methods (Figure 4.17) both produced fibers that showed breakage and rogue fiber fragmentation along the length of the fibers. The dew retting method (4.18) produced fibers that appear to have a rippled or crackled texture, almost like scales. This could indicate that some retting methods were not as effective at removing impurities from the fibers, or an indication of the ease of combing of the fibers. Furthermore, the fiber cracking seemed to only occur in the methods where bines were dried before retting as opposed to being freshly processed. This texture could be the result of manipulating the bines from a dry state to a waterlogged state.

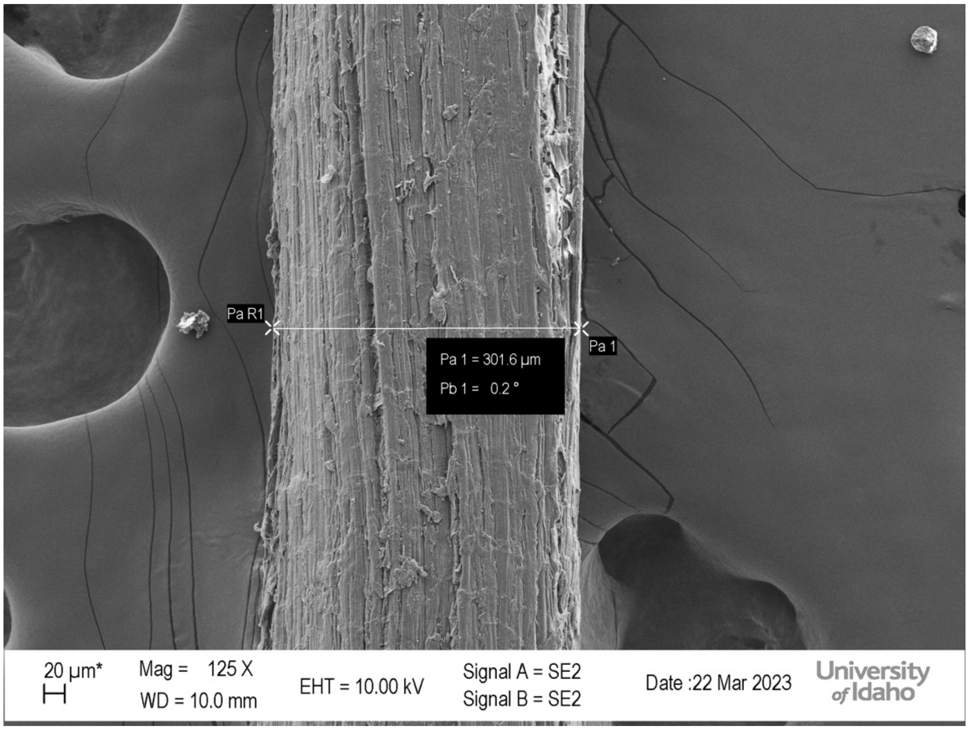

Figure 4.15 SEM of green processed fiber at 125x magnification.

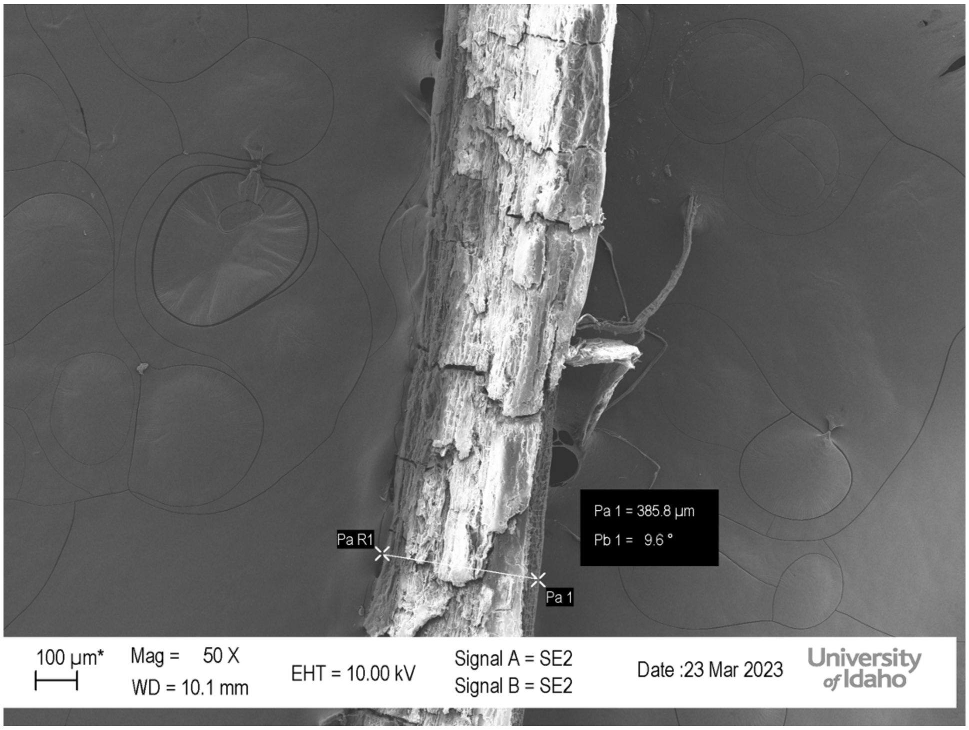

Figure 4.16 SEM of water retted fiber at 50x magnification.

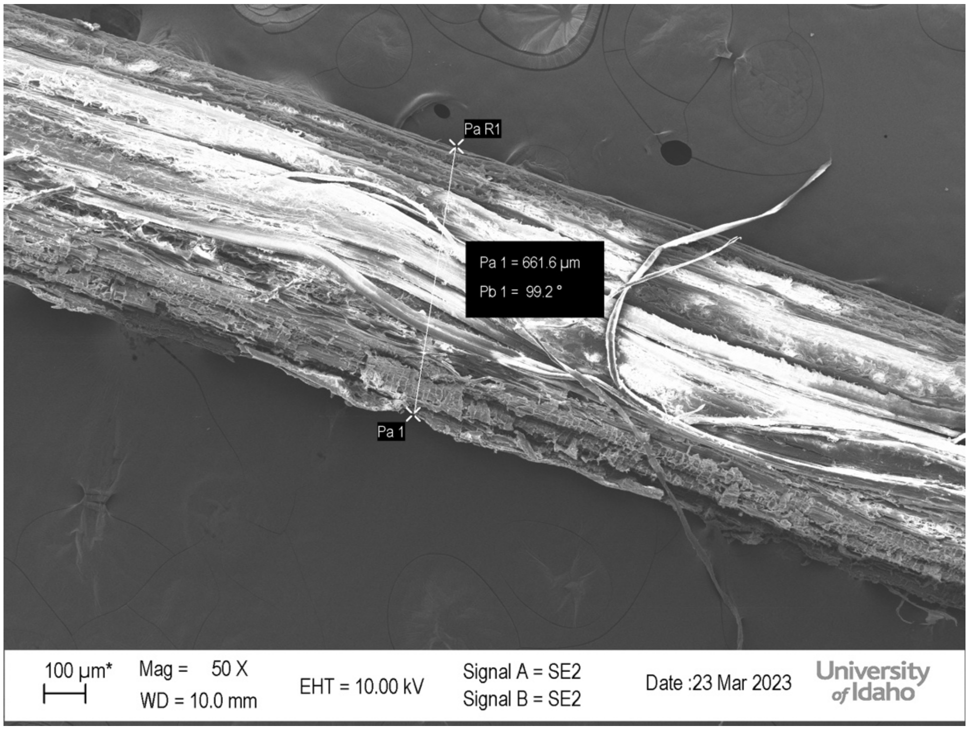

Figure 4.17 SEM of breaking to water retted fiber at 50x magnification.

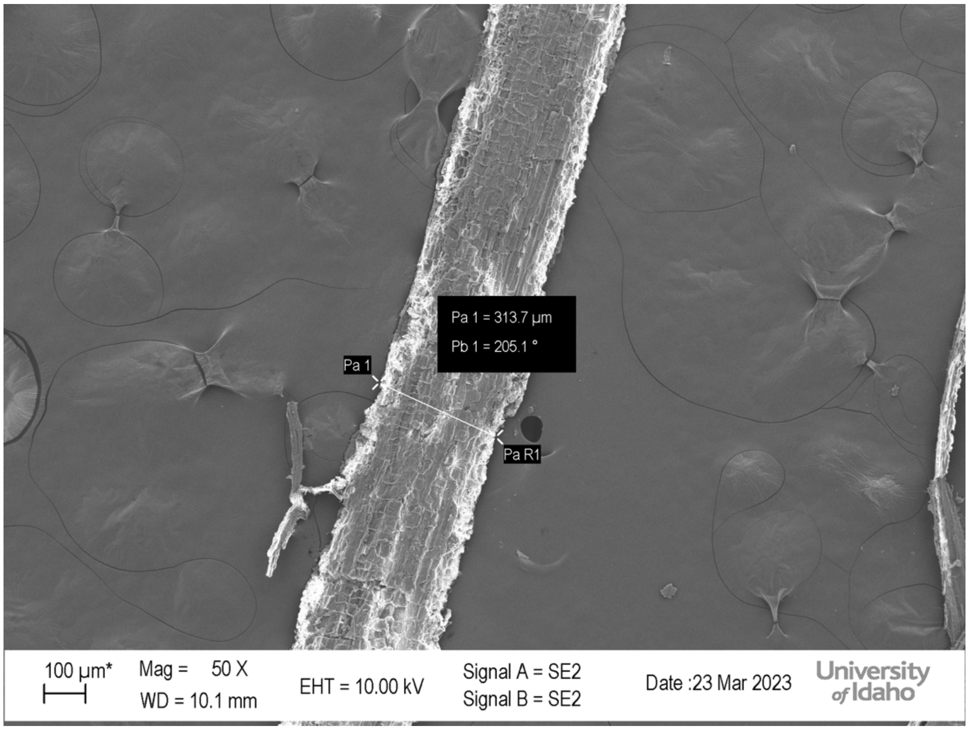

Figure 4.18 SEM of dew retted fiber at 50x magnification.

Linear Density

A boxplot comparing linear density (expressed as denier) for the four methods is shown below (Figure 4.19). Of all the retting methods tested, dew retting produced the finest fibers with a denier of 158.81D ± 88.33 and breaking to warm water retting produced the thickest fibers with a denier of 492.67D ± 376.77. Green processing method had an average denier of 282.84D ± 175.33, warm water retting method had an average denier of 420.99D ± 391.3, and dry decortication did not produce any fibers. Green processing had two outliers at denier 811.76D and 882.52D. Warm water retting had three outliers at 1369.91D, 1595.17D, and 2408.24D. Breaking to water retting had one outlier at 1800D, and dew retting had two outliers at 404.59D and 535.44D. These denier results are not comparable to the 48 ± 19 denier from (Reddy & Yang, 2009).

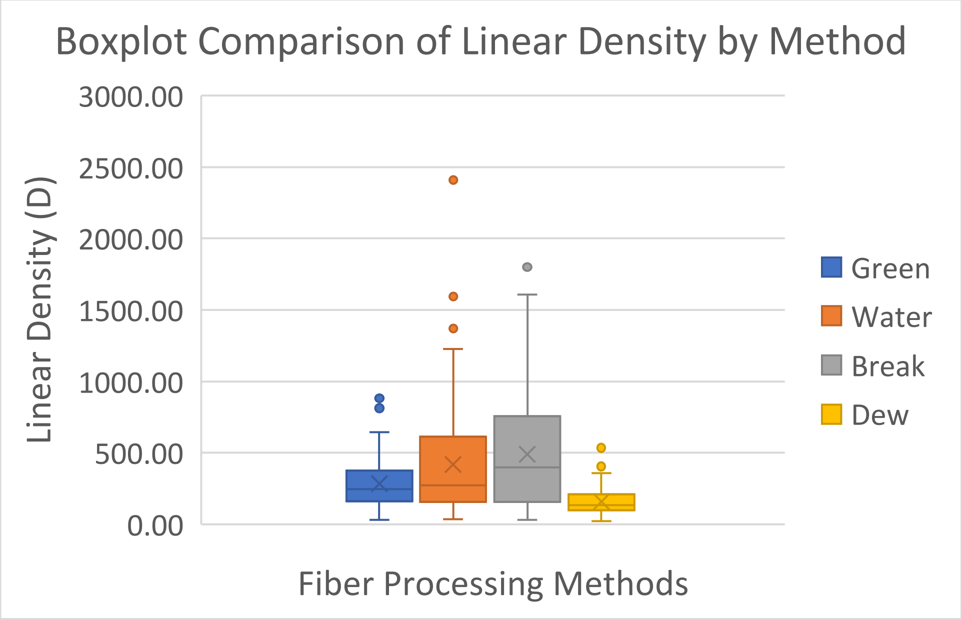

Figure 4.19 Boxplot of linear density by method.

The greatest linear density frequency for green processed fibers had 34 fibers between 163.33-293.33D (Figure 4.20). Twenty-five green processed fibers had a denier between 33.33-163.33D, 20 had denier between 293.33-423.33D, 10 were between 423.33-553.33D, and nine were between 553.33-683.33D. One was found between 683.33-813.33D, and another was found between 813.33-943.33D.

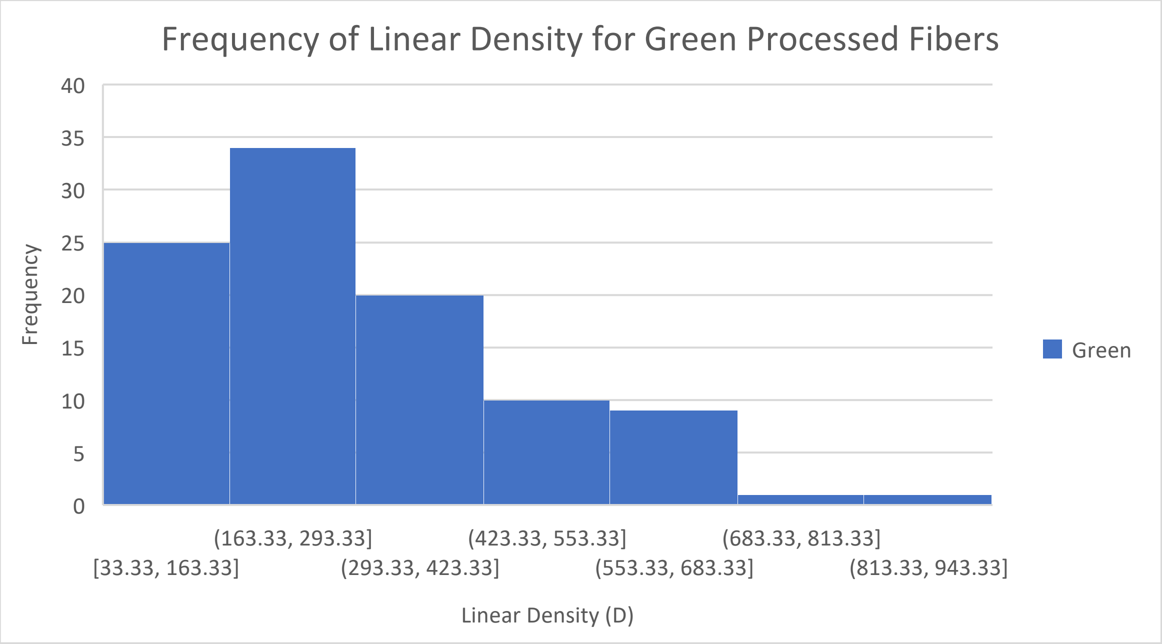

Figure 4.20 Linear density histogram of green processed fibers.

There were 59 water retted fibers with a linear density between 36.99-336.99D (Figure 4.21). There were 18 water retted fibers found to have a denier between 336.99-636.99D, 14 between 636.99-936.99D, and six between 936.99-1236.99D. Single fibers were found between 1236.99-1536.99D, 1536.99-1836.99D, and 2136.99-2436.99D.

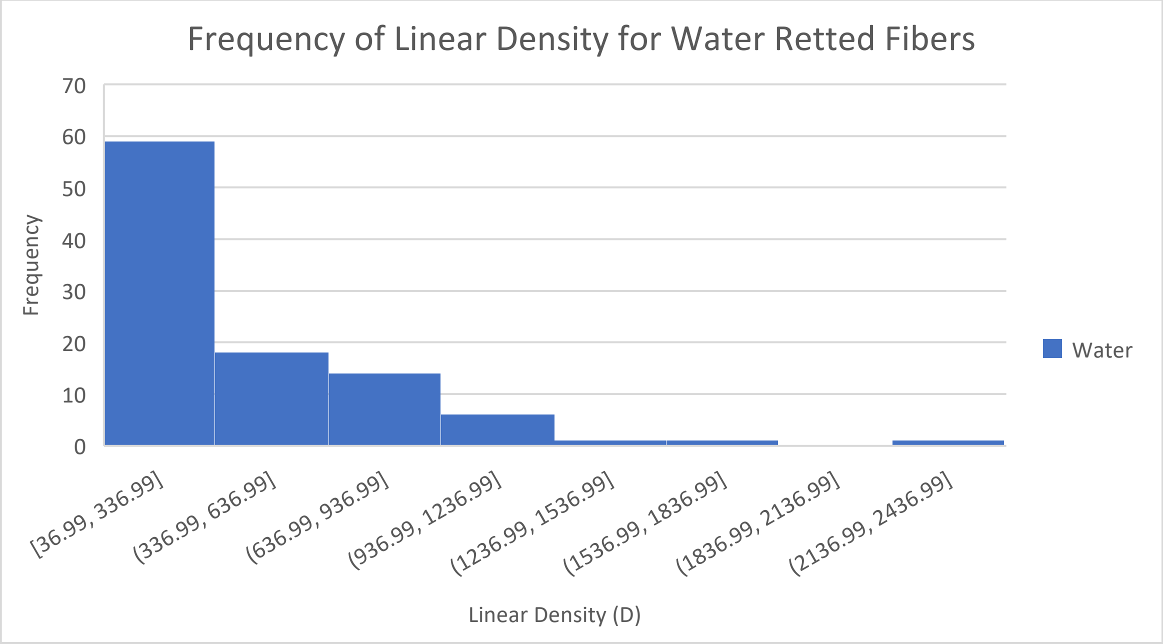

Figure 4.21 Linear density histogram of water ret fibers.

The breaking to water retted fibers had the most frequent linear density between 30-310D with 43 fibers (Figure 4.22). Eighteen fibers were found between 310-590D, 20 between 590-870D, 13 between 870-1150D, four between 1150-1430D, one between 1430-1710D, and one between 1710-1990D.

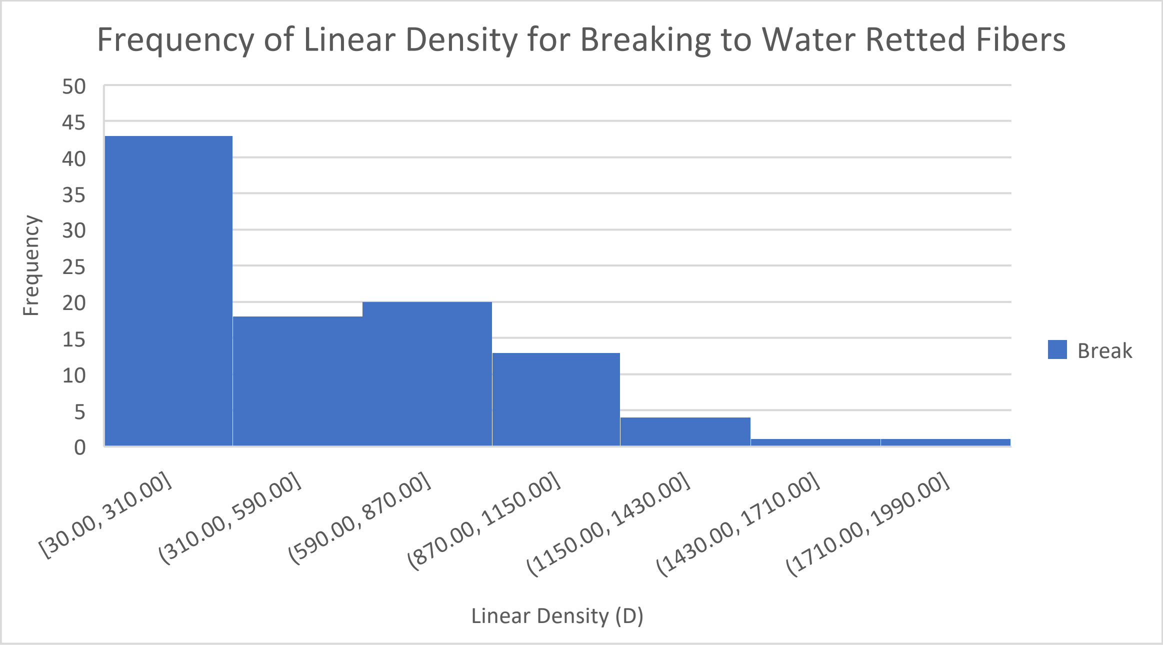

Figure 4.22 Linear density histogram of breaking to water retting fibers.

Forty was the most frequent linear density for dew retted fibers within the range of 21.43-88.43D (Figure 4.23). Twenty-one dew retted fibers had a denier between 88.43-155.43D, 17 were between 155.43-222.43D, 14 were between 222.43-289.43D. There were four fibers with denier between 289.43-356.43D, three between 356.436-423.43D, and one between 490.43-557.43D.

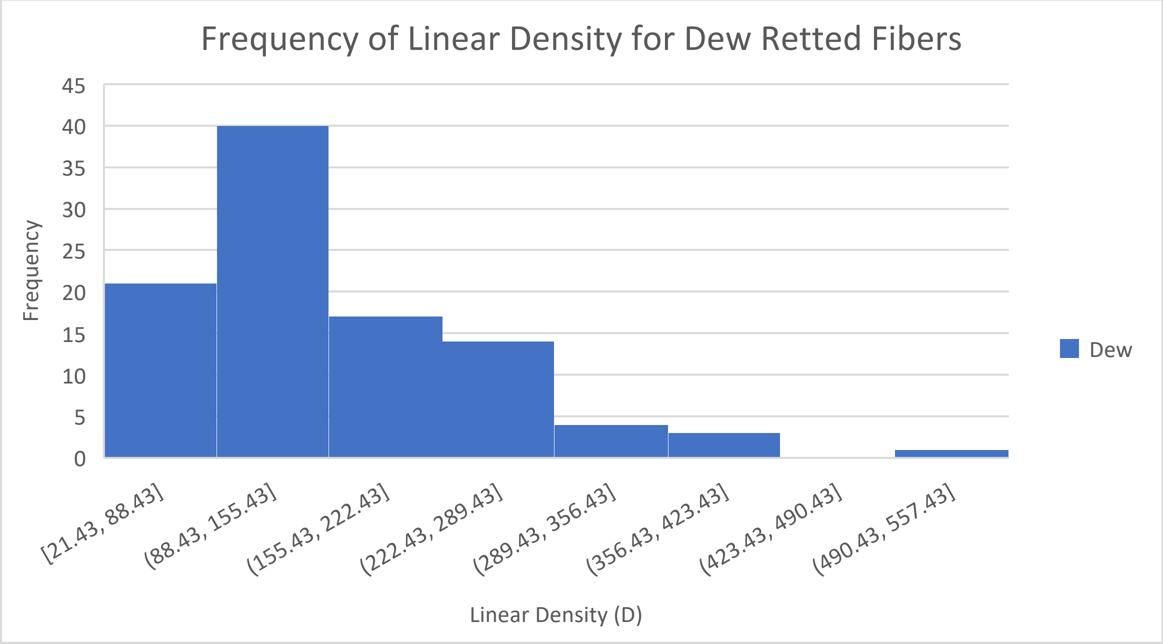

Figure 4.23 Linear density histogram of dew ret fibers.

To fully understand the influence of fiber length to fiber mass, a correlation between length and mass was conducted for all fiber methods (Figure 4.24). Dew retting had the least variation in mass to fiber length increase, with fibers weighing below 10mg and fiber lengths ranging from 41-185mm. Most green processed fibers weighed 10mg or less with fiber lengths between 45-200mm. Water retted fibers experienced greater mass to length ratio with fiber lengths roughly between 100-160mm and a mass between 10-20mg. Water retted fibers also experienced longer length to weight ratios with fibers weighing 10mg or less in the 150-200mm range. Breaking to water retted fibers exhibited more typical mass to length ratios as increases in mass denoted increases in length.

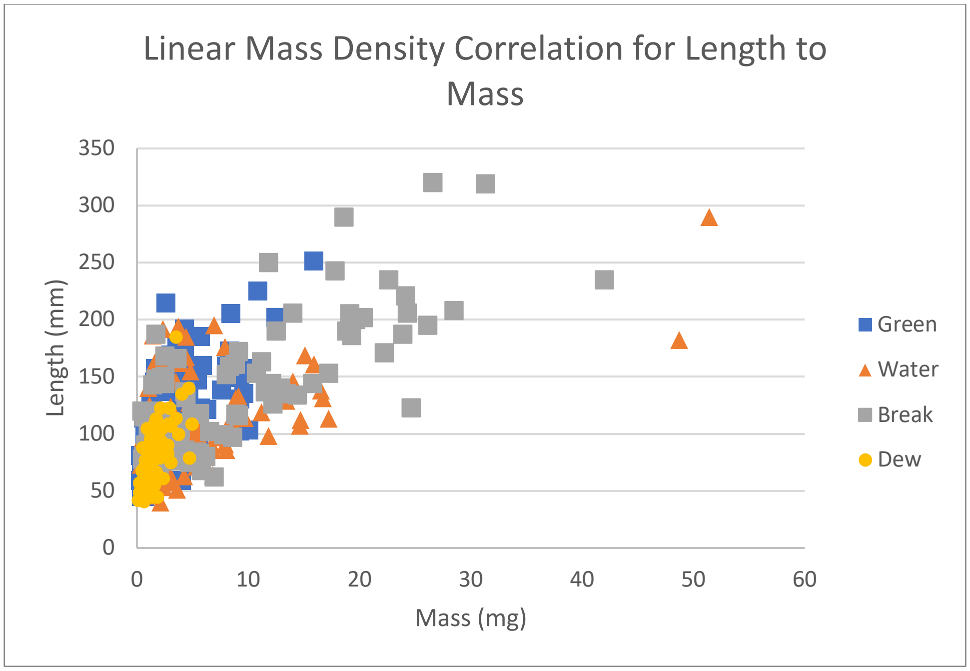

Figure 4.24 Length to mass correlation overlay of all fiber methods.

Tensile Test

Unfortunately, there were only two processing methods tested for tensile on the DMA instrument, the green processed fibers and the water retted fibers. Breaking to water retted and dew retted fibers were tested using an Instron 5565 after the DMA instrument got damaged and became inoperable. The average breaking tenacity (stress) for green processed fibers was 12.78 cN/tex ± 10.79, with an average elongation at break (strain) of 4.59% ± 4.08, and modulus of 379.93 cN/tex ± 365.47. The average breaking tenacity for water retted fibers was 13.92 cN/tex ± 8.18, with an average elongation at break of 4.92% ± 5.61, and modulus of 490.95 cN/tex ± 410.83. The average breaking tenacity for breaking to water retted fibers was 14.75 cN/tex ± 8.97, with an average elongation at break of 4.18% ± 1.94, and modulus of 657.05 cN/tex ± 323.39. The average breaking tenacity for dew retted fibers was 19.65 cN/tex ± 15.19, with an average elongation at break of 4.00% ± 1.98, and modulus of 1084.24 cN/tex ± 512.58. The dew retted fibers had on average a higher modulus compared to the other fibers suggesting that it has a higher stiffness. The dew retted fibers also had a high breaking tenacity suggesting that it is also stronger than the other fibers.

Comparing these breaking tenacity, elongation %, and modulus measurements to Reddy & Yang (2009), the above measurements were less than what they had measured. Since their tenacity was recorded in grams/denier, the following conversion was calculated to represent their measurements in cN/tex (Textile School, 2018).

$$\mathrm{cN} \,/\, \mathrm{tex} = (\mathrm{g/den})/0.113$$

Equation 4.1 Conversion of g/den to cN/tex.

Reddy & Yang’s converted tenacity equaled 36.3 cN/tex ± 16.8, with an elongation was 3.3 % ± 1.2, and modulus of 14.2 ± 5 N/tex, or 1420 ± 500 cN/tex. This could suggest that stronger fibers can be obtained by chemical processing rather than mechanical or biological processing. Typical values for elongation for textile fibers are 5-70%, the typical tenacities for textile and industrial fibers are within the 10-300+ cN/tex range, and typical moduli for textile fibers are 50-1000 cN/tex (Schultze-Gebhardt & Herlinger, 2008).

Moreover, the kurtosis, a measure of skewness, for the stress and strain values were especially high for green processed fibers (16.97 and 13.5, respectively), strain for water retted fibers (54.31), and stress for dew retted fibers (15.61). Normal range of kurtosis is ± 7 (Watson, 2018). Breaking to water retted fibers did not exhibit values over the normal kurtosis range. Outliers greater than three standard deviations were removed from the green, dew, and water retted stress and strain results, which helped bring down the kurtosis values. Green processed fiber kurtosis after the removal of stress outliers was 0.31, and 1.24 for strain. Water retted fiber kurtosis after the removal of strain outliers was 5.7, and dew retted kurtosis was -0.03 after stress outliers were removed. The corrected breaking tenacity for green processed fibers once outliers were removed was 11.16 cN/tex ± 6.5, and 17.89 cN/tex ± 10.41 for dew retted fibers. The corrected elongation at break once outliers were removed was 3.99% ± 2.29 for green processed fibers and 4.41% ± 2.73 for water retted fibers.

An analysis of variance was conducted for stress, strain, and modulus to compare statistical significance between the four methods with outliers excluded. There was significance found for the stress results, $F(3, 381) = 9.8$, $p = < .001$, $\eta_p^2 = .072$. A post-hoc test using Bonferroni correction showed that there was statistical significance found between green processing and breaking to water retting, $p = .025$, green processing to dew retting $p < .001$, and water retting to dew retting, $p = .01$. No statistical significance was found between the green processing to water retting method, $p = .178$, the water retting to breaking to water retting, $p = 1$, and the breaking to water retting to dew retting, $p = .068$. There was no significance found for breaking tenacity, $F(3, 385) = 0.7$, $p = .534$, $\eta_p^2 = .006$. There was significance found for modulus, $F(3, 383) = 60.7$, $p < .001$, $\eta_p^2 = .322$. Green processing to breaking to water retting, green processing to dew retting, water retting to dew retting, and breaking to water retting to dew retting all had $p < .001$. Water retting to breaking to water retting was also significant with $p = .018$. Green processing to water retting did not have a statistical significance $p = .704$.

Fiber Yield

Of the retting methods tested (Figure 4.26), the dew retting method produced the lowest fiber yield with 4.58g ± 4.42 and the breaking to water retting method produced the highest fiber yield with 46.34g ± 20.32. Green processing method had 15.42g ± 7.88, water retting method had 20.59g ± 8.02, and dry mechanical processing did not produce any fibers.

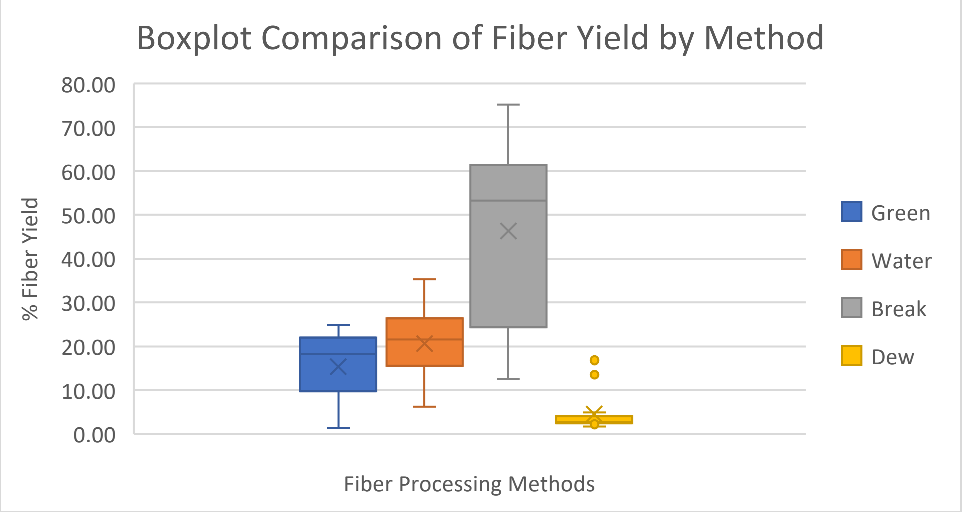

Figure 4.25 Boxplot comparing methods for fiber yield.

Using a 100% stacked column graph, green processing method produced a 14.37% fiber yield from the 13 sample batches processed (Figure 4.27). Of the 76.32g of fibers processed, only a total of 10.97g of combed out fibers were usable.

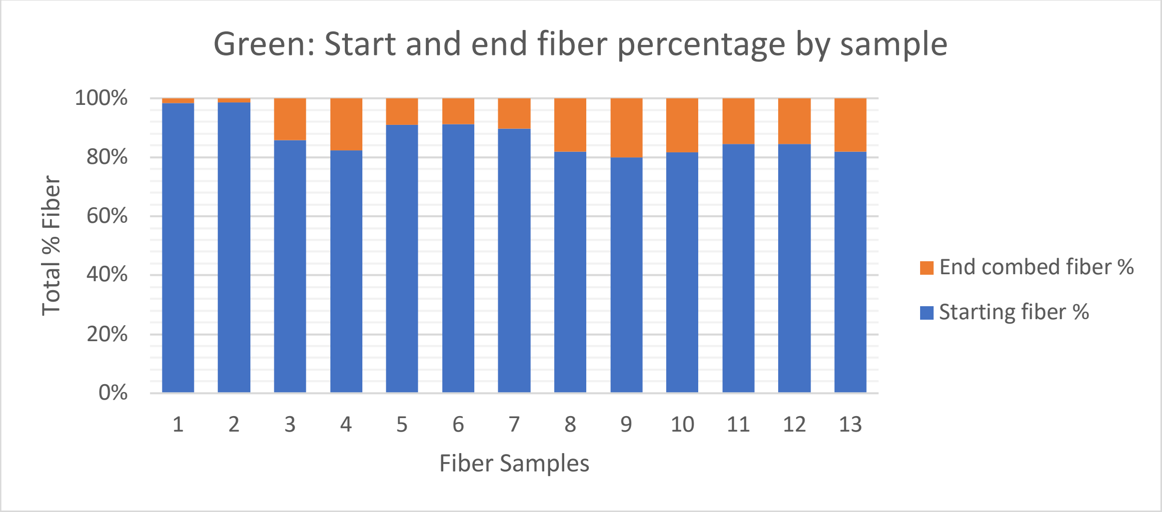

Figure 4.26 100% stacked column totals for green processed fibers.

The water retting method produced a 20.67% fiber yield from the 15 sample batches processed (Figure 4.28). Of the 88.1g of fibers processed, only a total of 18.21g of combed out fibers were usable.

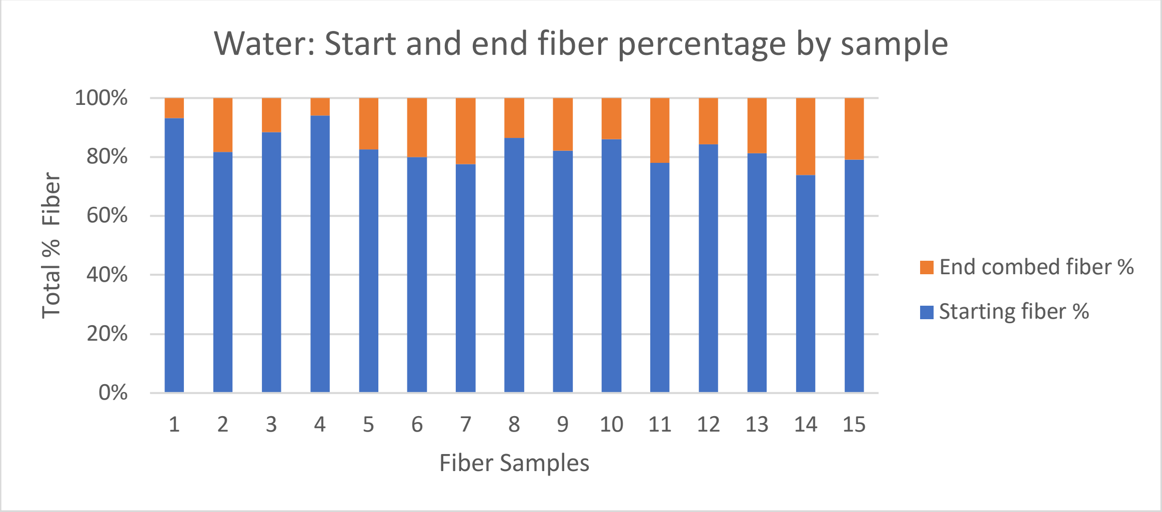

Figure 4.27 100% stacked column totals for water retted fibers.

The breaking to water retting method produced a 42.7% fiber yield from the 15 sample batches processed (Figure 4.29). Of the total 75.22g of fibers processed, a total of 32.12g were combed out and declared as usable fibers.

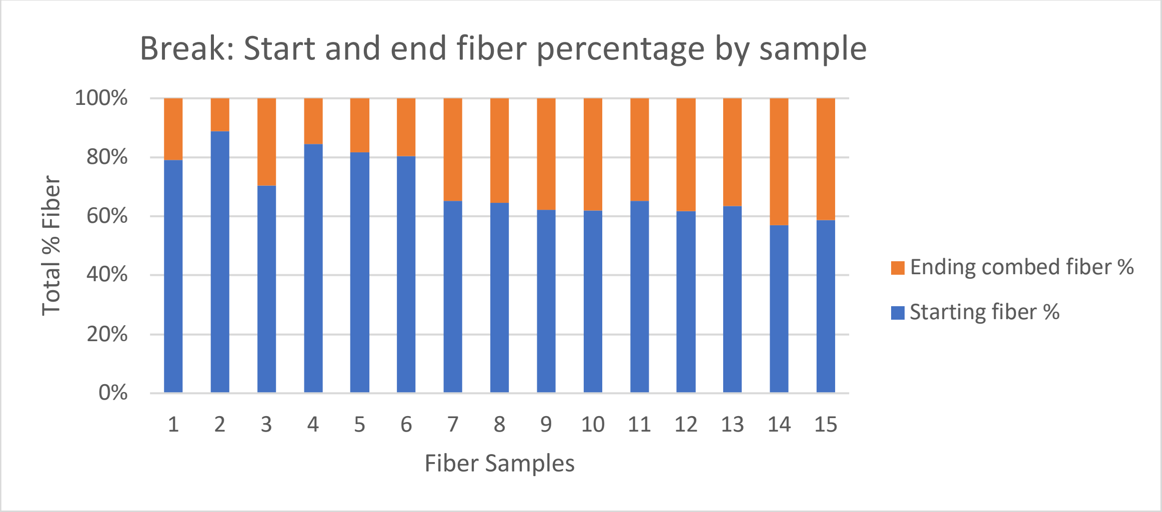

Figure 4.28 100% stacked column totals for breaking to water retted fibers.

The dew retting method produced a 3.15% fiber yield from the 15 sample batches processed (Figure 4.30). Of the 897.9g of fibers processed, only a total of 28.3g of combed out fibers were usable.

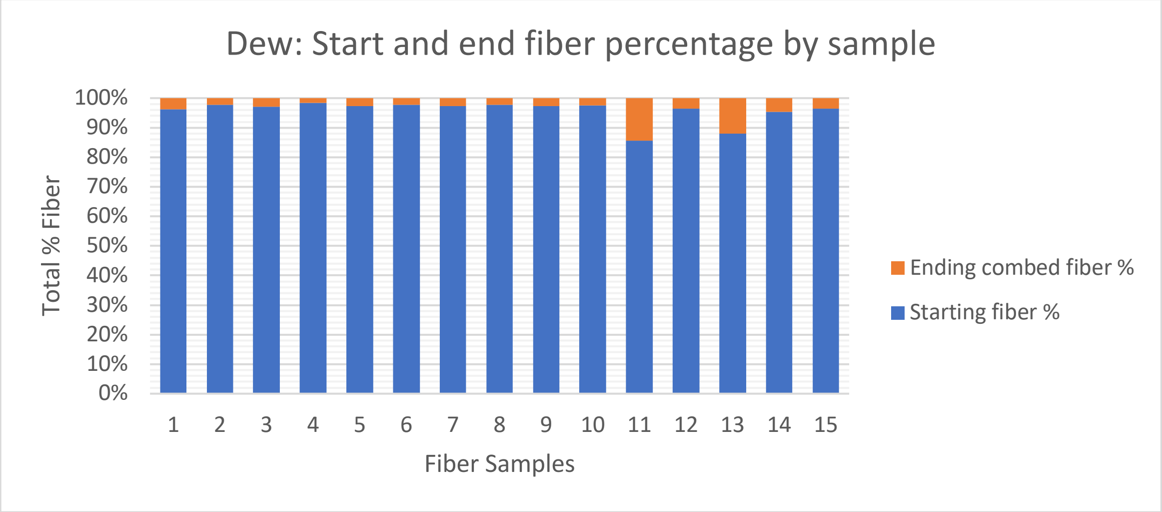

Figure 4.29 100% stacked column totals for dew retted fibers.

An analysis of variance test was conducted for each method combination, $F(3, 54) = 32.8$, $p = < .001$, $\eta_p^2 = .646$. A post-hoc test using Bonferroni correction showed that there was no statistical significance between the green processing to water retting method, $p = 1$, and the green processing to dew retting, $p = .121$. Statistical significance, however, was found between green processing and breaking to water retting, $p < .001$, water retting to breaking to water retting $p < .001$, water retting to dew retting, $p = .003$, and breaking to water retting to dew retting, $p < .001$.

Qualitative Results

Spinning

Fibers were wet spun, meaning they were spritzed with water before spinning. This was to ensure less breakage during the spinning process. The spinner spent about an hour spinning each fiber type into a woolen spun yarn. A woolen spun yarn differs from a worsted spun yarn in that the fibers are not in alignment before being spun. Rather, the fibers curled on themselves instead of overlapping which weakens the yarn strength. The woolen yarn texture is also "fuzzier" and produces an inconsistent yarn diameter, also known as slubby or thick and thin yarn.

Figure 4.30 Spun yarn of green processed fibers.

Of the four fiber types, the green processed fibers were the most enjoyable for the spinner to spin and dew retted fibers were the least enjoyable to spin. The spinner felt it was easy to pull or draft the green processed fibers into the spinning wheel, almost comparable to wool, and the fibers spun consistently, avoiding being overspun (Figure 4.31). The fibers also had a nice hand feel and produced a strong smooth yarn. The only negative feedback for spinning these fibers was that there was still dirt on them, and they produced a strong odor when wetted for spinning. However, despite these negatives, the spinner felt like they had market potential.

Figure 4.31 Spun yarn of water retted fibers.

Another fiber the spinner felt had market potential was the water retted fibers because they held together while spinning, were draftable, produced a strong yarn with a medium hand feel, and had low odor (Figure 4.32). The water retted fibers, however, were fairly hairy and would get caught on the hooks of the flyer, causing some difficulties for the yarn to be smoothly drawn onto the bobbin. This caused the spinner to have to manually wind the yarn onto the bobbin, slowing down the spinning process. Although the yarn was “fussy” to spin, the spinner said they would spin these fibers again and saw this fiber as a potential marketable fiber.

Figure 4.32 Spun yarn of breaking to water retted fibers.

The breaking to water retted fibers held together for drafting, but the fibers did not draft consistently (Figure 4.33). The fibers would stick to themselves and either cause the yarn to overspin or they would catch on the hooks of the flyer, making the yarn difficult to draw onto the bobbin well. A few times, the spinner had to manually wind the yarn onto the bobbin. The spinner also noted that the fibers had a rough hand feel because there were more guard hairs than soft fibers. Guard hairs are coarse fibers that protect the soft inner fibers against the elements. The spinner suggested the breaking to water retted fibers might work best on a drop spindle where smaller amounts of fibers can be spun at a time. The spinner did not comment on this fiber's marketability.

Figure 4.33 Spun yarn of dew retted fibers.

The dew retted fibers were the spinner’s least favorite fibers to work with because the short staple length and fiber smoothness made it difficult to spin (Figure 4.34). The spinner noted that it was challenging to find the right balance of twist to hold the fibers together without breaking the yarn. Even though the hand feel of the fibers were soft, their short length and lack of “stickiness” made the resulting yarn very rough and hairy. It also created a mess for the spinner because the fibers were hard to hold in hand for drafting. The spinner did not recommend this fiber for market.

Weaving

All the yarns were still moist from spinning which is not the typical condition yarns are in when being woven. The texture of the woven fabrics all felt fairly coarse. Some weft shots, or side to side passes of yarn across the warp, had more hairs sticking out than others which affected the hand feel of the final fabric. Some yarns were able to weave easier than others due to them having a tighter spun yarn. All the yarns were utilized to weave each fabric swatch and a tail of yarn was left unwoven for observation.

Figure 4.34 Woven fabric of green processed yarn.

The green processed yarn was the easiest to weave of all the yarns (Figure 4.35). The yarn was spun more evenly, and it did not have as many fiber hairs sticking out that would catch on the warp yarns when it was being woven. The yarn also didn’t require a heavy beat to keep the woven yarn in place. The final woven fabric is scratchy, stiff, and has a green tinge to it. Since this yarn was woven moist, the yarn tail felt strong to pull on, however, once dried, the yarn tail snapped in a tug test. This yarn had greater strength when wet as opposed to dry. This could have an impact on its weaving abilities if not properly conditioned beforehand.

Figure 4.35 Woven fabric of water retted yarn.

Chunks of the water retted yarn broke off during the weaving process. There were also a lot of fibers that caught on the warp yarns or come loose during weaving. It created a mess at the end and produced a rough and hairy feeling fabric with a greenish-brown tinge (Figure 4.36). However, the more the fabric was handled, the softer it became. The dried yarn tail for this method held together in a tug test, meaning that the yarn is stronger dry than wet.

Figure 4.36 Woven fabric of breaking to water retted yarn.

Weaving the breaking to water retted yarn was the most physically demanding of the four methods because it required multiple hard beats for every weft shot to keep the yarn in place (Figure 4.37). The yarn would shed and curl on itself when weaving and the yarn was very inconsistent in size. The hand feel of the fabric was also very coarse and scratchy with many fiber hairs sticking out, but the fabric also felt the most durable of the woven fabrics. The color of the woven fabric is brown. The dried yarn tail for this method held together in the tug test. This indicates that the yarn is strong wet or dry.

Figure 4.37 Woven fabric of dew retted yarn.

The dew retted yarn shed a lot of fibers during the weaving process, and it curled and caught on itself with every weft shot (Figure 4.38). The yarn was thick and thin and did not break when weaving. Although the yarn felt scratchy to the touch, the woven fabric had a springy texture to it when pinched between fingers and was more pliable than the breaking to water retted and water retted fabrics. Despite the spinner's difficulty with this yarn, the dried yarn tail did not break during the tug test. The color of the woven piece was also a very light brown, which could be due to sun bleaching during the dew retting process.

Discussion

<u>Dry Decortication</u>

The dried bines set aside for mechanical retting were too brittle to be used for this process. When put through the fluted rollers, the bines would break off into smaller pieces. The pith was still attached to the outer bark, making it difficult to run through with the combs or hand peel to obtain fibers. The pieces of bark that were able to be peeled would strip into small ribbons and the fibers could not be separated with the combs. Other modifications to this method were tested. One method tried was spritzing the dried bines with water before and after being decorticated, and then hand peeling the bark and combing through with the hackling combs. This process was tedious and did not produce fibers that could be individualized; there was still too much shive attached. Therefore, no length, width, tensile test, or fiber yield were provided for this method.

The different fiber qualities and quantities of the four methods that were able to produce fibers are detailed in Table 4.1 below. Despite these characteristic differences, these fibers all produced a thick coarse woven fabric that would not be recommended as a clothing textile without further chemical processing or industrial equipment.

Fiber Characteristics	**Green**	**Water**	**Break**	**Dew**
Length	Medium-long	Short-medium	Long	Short
Width	Thin-medium	Medium	Thick	Thin
Density	Fine-medium	Medium-large	Large	Fine
Yield	Medium	Medium	High	Low
Spin	Easiest	Medium	Medium	Hardest
Weave	Medium beat	Medium beat	Hard beat	Medium beat

Table 4.1 Comparison of final fiber characteristics between the four processing methods.

Green Processed Fibers

Since the bines were cut on site, they contained high moisture content as opposed to the other retting methods whose bines were dried. The bines were sent through the decortication machine and juicer to see which machine produced the best results. The decortication machine appeared to split the bark and bast fibers from the inner core while the juicer flattened and split the bine in half, still leaving the core intact along with the fibers and bark. The decortication machine seemed the most effective method for the fresh bines because the fibers could be isolated from the core, thus making it more efficient to process.

The fibers produced from this method show promise for indoor carpeting, rugs, or mats. It would not be recommended for twine or rope since the yarn snapped when dry.

Water Retted Fibers

There were two batches of water retted bines due to uncertainty with finished bine retting. Bines from the first bin were pulled after 12 days to stay consistent with literature for hemp water retting, but it was not long enough to ret the hops bines. The second batch was left in for 35 days which seemed to be the appropriate amount for water retting. The bines were then stripped of the bark and draped over a bar and hung to dry. Once dry, the peeled bark was very rigid and took the shape in which it was dried. The dried bark was hackled with some difficulty due to the stiffness of the bark. This created a lot of fiber breakage and tow with each hackling comb. It was also difficult to get singular fibers, indicating that the fibers might not have been fully retted. Although this is a common method that has been used for many bast fiber plants, it did not produce fibers without impurities as well as it does for flax or hemp.

Before hackling, the texture of the bark fiber strips seemed like good material for basket weaving due to their rigidity and long length. As a textile, the yarn from this fiber could be used for rope or cordage if it were double-plied. The structure and stiffness of the woven fabric could be used for mats or heavy rugs.

Breaking to Water Retted Fibers

Compared to the water retting method, the retting time for this method was reduced because the bines were decorticated before water retting. However, fibers from this method were the densest of all the methods. This was either due to the handler's combing style or because the bines were not fully retted at the time they were pulled from the water, making it difficult to obtain singular fibers.

The yarn produced from this method was strong when dry, suggesting that rope or cordage could be made from this process. Furthermore, the durable feel of the woven fabric produced from this method could be used for heavy-use applications such as indoor/outdoor rugs and mats.

Dew Retted Fibers

Bines and pith began splitting after four days and continued to throughout the entire dew retting process. Where the bines split, black mold started to grow. This was an indicator that the process was effective in breaking down the lignin holding the fibers to the core. Fibers were also visibly separating in places where the bines had split. Changes in weather necessitated an end to the dew retting process. Bines were collected and brought to the lab for combing. Once in the lab, the bines that previously had been flexible in the outdoor environment were now hard and brittle. Though the rigidity made fiber extraction difficult, we were successful in combing out fibers. However, the fiber yield was less than expected given that this is a common method highly used for other bast fiber plants.

The fibers produced from this method were short and soft, making it difficult to hand spin. However, the woven fabric produced from this method shows promise for heavier applications such as indoor or outdoor rugs or mats, or as rope or twine. The fabric also became softer the more it was handled.

Limitations

The list of limitations was long and extensive. Primarily, the main limitations were time and equipment. First, the green processed bines were not sourced from the same location as the dried bines gathered from Carpenter Ranches. This is because the bines were collected and driven back to

Moscow for processing instead of bringing equipment to the ranch to process bines on site. The bines used for green processing were sourced from local hops growers. The species of hops were unknown, which could have played a role in the different fiber characteristics. Another limitation was that not all 50 retted bines from each dried bine method were processed. This was due to a lack of time and resources. Even though there were 15 batches of bines processed from each of the dried methods, it was only a fraction of the total bines that were retted. Processing bines is a lengthy and tedious process and requires long hours of labor. Luckily, I had an assistant helping me, however, we had different combing styles. This limitation affected the consistencies of fiber quality, which could have had an overall effect on the length, width, denier, yield, and tensile strength. Another limitation was due to equipment failure. Although this was out of my control, the best I could do to remedy this was use the tensile testing instrument from the neighboring university to complete the breaking to water retted and dew retted fibers. The final limitation was that the spinner was not the most experienced at spinning bast fibers. Though they have spun hops yarn for me in the past, the fibers might have been better handled by a spinner who can manage the intricacies of untamable bast fibers. This might have led to a more consistent yarn with better fiber alignment.

Chapter 5: Conclusion

It is feasible to make a textile material out of hops fibers extracted from adopted bast fiber hand-processing techniques! Additionally, the resulting hops fiber quality and quantity did indeed differ between each method and should be taken into consideration to match the end goal of the final product. For the small-scale fiber producer, this regionally sourced raw material is overabundant and usable. It should be noted that the retting and fiber extracting process for hops is more difficult than flax, nettle, or hemp (Lukešová et al., 2019) and will require equipment for processing. Nevertheless, with the right equipment, this fiber can be processed on a small scale or at home. What the user does with it is up to them, however this research provides the foundational and comparative information the user can reference to process hops bines for fiber.

If equipment is available to process hops bines on site, then the green processing method would be ideal because it produced nice, thin, medium-long length fibers that were easy to spin and weave. If the hops bines obtained are dry, then consider using water retting for a “middle of the road” kind of fiber quality. The water retting method produced fibers that had a medium yield, short-medium length and medium width fibers that were good for spinning and weaving. Even though the fiber yield was low, the dew retting method produced short, soft, and fine fibers that were hard to spin but made a compressible weave. The breaking to water retting method produced the greatest yield of fibers, but also the longest and thickest fibers. This method was also hard to weave because it had to be repeatedly beaten with a hard beat to keep the weft in place. As a woven textile, hops fibers are hairy and scratchy. As an unfinished raw material, it would not be ideal for apparel but could have uses in other applications such as rugs, mats, twine, or cordage. As a nonwoven textile, the fibers could be matted together to form insulation, revegetation mats, or paper. This fiber could also be used for making composites or fiberboard.

Although this fiber source has a long way to go in terms of reputation and use in different applications, it shows great potential to be in the market as a regional textile source. This is a win for the fibersheds in the Pacific Northwest, the textile industry, and the planet. As Rebecca Burgess had stated from her 150-mile wardrobe challenge, “the wardrobe was a living expression of where I live, what values I have, and what sort of community I belong to” (Burgess & White, 2019, p. 61). Leveraging what has been discovered about hops fiber thus far, there is hope for a more sustainable textile future that involves place-based fibers.

Future Work

Since one of my limitations was using two different hops fiber sources, it would be interesting to compare the different characteristics from processing methods to the different hops fiber sources. For example, does hops grown in Idaho share the same characteristics as hops grown in Washington or Oregon? Another idea for future work would be to see if blending hops fiber with other natural fibers would enhance overall fiber quality. Exploring new applications for hops fiber could be beneficial, as well as seeing how the woven hops would feel when finished with a chemical or mechanical softening treatment. The last future work suggestion might be a long shot, but it would be remarkable to see hops bines being processed with industrial equipment such as that for flax and hemp. If this happened, it would mean that hops fibers could be of commercial importance and worth investing in for textiles.

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Appendix A: Green Fiber Data Sheet

Hops fiber data sheet

Method: Green Processed Fibers

Sample ID	Length (mm)	Mass (mg)	Linear Density (D)	Stress (cN/tex)	Strain (%)	Modulus (cN/tex)
F1	85	3.6	381.18	4.96	3.545	210.6
F2	119	2.1	158.82	4.98	2.154	244.7
F3	115	4.1	320.87	3.58	4.533	97.59
F4	103	10.1	882.52	7.97	3.021	379.2
F5	142	3.2	202.82	11.79	2.164	829.6
F6	168	3.9	208.93	20.62	4.403	751.5
F7	225	10.9	436.00	11.95	3.52	211.1
F8	102	2.9	255.88	14.30	5.121	358.7
F9	134	4.7	315.67	9.71	2.971	174.6
F10	99	5.1	463.64	2.87	5.966	62.83
F11	177	3.6	183.05	5.77	2.447	323.4
F12	83	2.5	271.08	12.90	2.455	639.7
F13	125	1.3	93.60	28.51	2.128	1416
F14	155	5.2	301.94	15.16	6.954	405.9
F15	135	9.6	640.00	7.26	1.379	228.7
F16	88	3.4	347.73	6.25	2.336	216
F17	117	2.7	207.69	11.95	11.155	206.6
F18	107	4.1	344.86	7.59	7.453	292.4
F19	102	9.2	811.76	2.17	2.716	115.9
F20	90	2.2	220.00	12.26	3.222	270.6
F21	130	9.3	643.85	9.79	5.293	100.7
F22	160	5.9	331.88	16.19	7.155	212.8
F23	169	3.1	165.09	13.01	2.36	792.3
F24	157	10.5	601.91	4.91	2.817	94.15
F25	80	5.2	585.00	4.36	4.757	41.64
F26	122	5.8	427.87	3.09	2.959	53.6
F27	98	0.7	64.29	4.55	0.510	1189
F28	59	4	610.17	2.33	2.35	43.96
F29	205	8.5	373.17	13.07	3.073	159.1
F30	100	4.3	387.00	1.73	2.994	49.33
F31	172	8.3	434.30	18.10	7.272	233.1
F32	97	5.6	519.59	1.07	7.469	5.794
F33	98	5.4	495.92	14.85	4.751	122.2
F34	145	3.9	242.07	4.18	2.034	145.1
F35	214	2.6	109.35	2.29	9.753	5.243
F36	192	4.3	201.56	6.51	10.69	211.5
F37	82	0.8	87.80	7.54	7.01	78.89
F38	64	0.9	126.56	10.07	5.961	207.9
F39	99	2.8	254.55	14.56	3.919	256.2
F40	159	3.6	203.77	22.23	3.219	571

F41	106	3.6	305.66	11.56	3.201	55.93
F42	165	3.4	185.45	15.74	3.631	95.81
F43	70	0.4	51.43	43.86	5.077	392.3
F44	115	3.5	273.91	5.81	5.745	171.6
F45	130	3.9	270.00	11.79	6.554	27.09
F46	105	2.6	222.86	9.70	3.336	161.1
F47	65	1.3	180.00	7.22	2.84	103.7
F48	81	0.4	44.44	81.55	8.993	1117
F49	84	3.5	375.00	9.57	6.502	34.37
F50	81	0.3	33.33	21.78	5.659	220.1
F51	45	0.4	80.00	7.43	3.619	196.5
F52	55	0.8	130.91	14.15	3.407	351.9
F53	67	0.7	94.03	29.95	4.135	957.4
F54	100	1.6	144.00	2.28	1.407	313.2
F55	59	0.3	45.76	35.93	2.817	1715
F56	87	0.8	82.76	9.34	1.999	255.6
F57	145	1.6	99.31	15.87	1.63	992.9
F58	117	3.7	284.62	23.02	4.577	374.4
F59	111	3.7	300.00	20.85	3.56	1179
F60	170	4.3	227.65	21.07	3.943	425.4
F61	98	1.8	165.31	13.09	5.742	100.9
F62	82	3.2	351.22	6.11	5.719	16.44
F63	95	2	189.47	15.11	3.443	344.1
F64	55	1	163.64	21.31	22.17	105.5
F65	117	2.7	207.69	8.21	4.362	28.18
F66	95	1.5	142.11	14.12	5.469	215.6
F67	74	1.6	194.59	13.62	4.622	75.33
F68	55	1.1	180.00	8.32	3.48	343.2
F69	155	9.7	563.23	0.18	0.306	66.35
F70	114	0.6	47.37	42.18	8.719	79.58
F71	94	2.1	201.06	12.85	4.636	118.7
F72	164	3.8	208.54	14.97	6.067	478.4
F73	105	2.1	180.00	18.53	3.424	1056
F74	113	4.5	358.41	14.48	4.752	253.7
F75	159	8.1	458.49			
F76	62	0.7	101.61	12.49	2.559	540.1
F77	251	15.9	570.12	12.37	25.87	528.5
F78	185	5.7	277.30			
F79	106	4.1	348.11	6.16	1.192	423.6
F80	121	6.3	468.60	0.67	22.91	18.86
F81	147	5.4	330.61	8.36	2.915	341.6
F82	157	1.7	97.45	11.47	1.172	1247
F83	102	2.5	220.59	13.78	3.014	679.4
F84	138	7.6	495.65	7.72	1.89	438.7
F85	149	9.3	561.74	11.60	2.901	319.8

F86	77	2	233.77	10.67	2.473	328.4
F87	89	4.6	465.17	5.88	2.317	144.7
F88	202	12.5	556.93	11.94	2.405	623.2
F89	131	1.4	96.18	19.93	2.242	934.4
F90	149	4.9	295.97	10.06	3.22	300.4
F91	119	3.5	264.71	11.03	2.017	761.6
F92	107	4.3	361.68	7.60	1.3	401.7
F93	102	4.4	388.24	12.45	3.127	230.3
F94	78	0.6	69.23	26.48	3.076	1242
F95	137	2.3	151.09	13.51	2.335	507.3
F96	91	1.7	168.13	12.07	4.721	105.4
F97	133	4.5	304.51	26.74	4.238	1096
F98	89	2.6	262.92	2.03	10.4	268.6
F99	45	0.7	140.00	3.93	0.848	430.7
F100	110	1.2	98.18	15.22	3.249	889.5

Appendix B: Water Fiber Data Sheet

Hops fiber data sheet

Method: Water Retted Fibers

Sample ID	Length (mm)	Mass (mg)	Linear Density (D)	Stress (cN/tex)	Strain (%)	Modulus (cN/tex)
W1	51	1.4	247.06	12.54	3.816	381.6
W2	89	4	404.49	11.23	3.307	330.7
W3	100	4.1	369.00	6.46	2.344	234.4
W4	97	7.1	658.76	7.49	2.627	262.7
W5	131	16.7	1147.33			
W6	290	51.4	1595.17	7.34	52.051	5205.1
W7	146	14	863.01	3.39	4.568	456.8
W8	130	12.6	872.31	3.91	2.869	286.9
W9	138	16.5	1076.09	14.15	6.019	601.9
W10	51	3.6	635.29	6.78	3.366	336.6
W11	129	13.4	934.88	2.85	3.022	302.2
W12	161	15.9	888.82	8.04	4.103	410.3
W13	86	8	837.21	4.51	1.717	171.7
W14	64	6.8	956.25	2.46	2.278	227.8
W15	40	2.1	472.50	6.14	3.548	354.8
W16	112	14.7	1181.25	7.75	2.899	289.9
W17	119	11.2	847.06	11.19	4.585	458.5
W18	63	1.1	157.14	15.39	2.313	231.3
W19	182	48.7	2408.24	6.67	4.242	424.2
W20	113	17.2	1369.91	11.75	4.497	449.7
W21	112	8.4	675.00	10.24	4.311	431.1
W22	90	6.7	670.00	4.18	3.354	335.4
W23	46	0.9	176.09	11.02	2.141	214.1
W24	58	3.1	481.03	17.61	10.09	1009
W25	124	3	217.74	14.81	3.773	377.3
W26	155	4.8	278.71	19.34	4.502	450.2
W27	86	1.9	198.84	6.95	1.938	193.8
W28	97	4.9	454.64	7.40	2.724	272.4
W29	58	2.1	325.86	15.95	3.267	326.7
W30	83	1.2	130.12	11.30	2.238	223.8
W31	107	14.6	1228.04	5.12	3.185	318.5
W32	73	1.5	184.93	8.69	1.769	176.9
W33	61	2.4	354.10	15.40	4.448	444.8
W34	107	5.6	471.03	7.24	5.637	563.7
W35	65	2.9	401.54	19.36	6.22	622
W36	84	1.5	160.71	10.34	3.479	347.9
W37	74	0.9	109.46	12.92	2.454	245.4
W38	62	1.6	232.26	18.91	5.083	508.3
W39	192	2.3	107.81	35.11	2.676	267.6
W40	166	1.8	97.59	16.38	1.356	135.6

W41	145	2.1	130.34	16.95	12.371	1237.1
W42	85	1.3	137.65	13.63	4.939	493.9
W43	118	2.3	175.42	17.96	3.725	372.5
W44	185	4.4	214.05	20.03	5.1	510
W45	62	2.3	333.87	12.96	3.312	331.2
W46	86	6.8	711.63	9.14	3.242	324.2
W47	167	4.4	237.13	13.19	4.103	410.3
W48	96	0.5	46.88	37.12	3.013	301.3
W49	64	1.2	168.75	11.23	16.074	1607.4
W50	63	4.2	600.00	3.10	3.526	352.6
W51	133	9.1	615.79			
W52	73	0.3	36.99	32.04	4.842	484.2
W53	131	8.9	611.45	7.23	2.459	245.9
W54	107	6	504.67	11.29	2.678	267.8
W55	59	1.2	183.05	9.45	3.49	349
W56	162	3.8	211.11	16.02	3.85	385
W57	78	0.4	46.15	33.64	5.975	597.5
W58	140	1	64.29	27.69	10.25	1025
W59	195	6.9	318.46	15.69	12.926	1292.6
W60	194	3.7	171.65	44.17	4.296	429.6
W61	147	2.6	159.18	8.46	1.725	172.5
W62	163	2.9	160.12	18.34	1.218	121.8
W63	163	3.3	182.21	19.38	3.1	310
W64	76	2.1	248.68	9.95	2.719	271.9
W65	94	1.1	105.32	11.69	1.622	162.2
W66	162	1.6	88.89			
W67	146	3.5	215.75	12.03	3.569	356.9
W68	125	1.1	79.20	34.50	2.887	288.7
W69	186	1.4	67.74	25.09	2.931	293.1
W70	75	0.8	96.00	20.91	3.068	306.8
W71	121	2	148.76	15.36	3.411	341.1
W72	78	2.7	311.54	21.46	5.188	518.8
W73	114	2.7	213.16	22.74	5.504	550.4
W74	71	5.3	671.83	11.99	4.597	459.7
W75	114	9.7	765.79	5.69	4.251	425.1
W76	98	11.8	1083.67	10.38	4.247	424.7
W77	73	2.2	271.23	13.06	5.358	535.8
W78	87	2.7	279.31	9.58	4.448	444.8
W79	100	5.5	495.00	12.72	12.09	1209
W80	91	7.9	781.32	11.85	6.678	667.8
W81	127	4.7	333.07	8.99	2.921	292.1
W82	94	1.8	172.34	9.45	3.263	326.3
W83	176	7.9	403.98	9.96	4.065	406.5
W84	106	1.5	127.36	30.55	4.428	442.8
W85	100	2.6	234.00	10.87	3.675	367.5

W86	107	6.2	521.50	11.58	4.416	441.6
W87	67	1	134.33	14.54	3.937	393.7
W88	51	0.5	88.24	10.43	2.989	298.9
W89	57	0.8	126.32			
W90	93	1.8	174.19	11.18	3.109	310.9
W91	85	2.9	307.06	13.11	4.845	484.5
W92	53	2.4	407.55	7.25	12.739	1273.9
W93	82	3.6	395.12	22.34	11.834	1183.4
W94	63	0.8	114.29			
W95	72	0.7	87.50			
W96	61	1	147.54	21.24	5.704	570.4
W97	169	15.1	804.14	8.29	3.675	367.5
W98	105	3.5	300.00	12.98	4.706	470.6
W99	55	0.9	147.27	26.38	4.789	478.9
W100	68	1.9	251.47	12.94	3.578	357.8

Appendix C: Break Fiber Data Sheet

Hops fiber data sheet

Method: Breaking to Water Retted Fibers

Sample ID	Length (mm)	Mass (mg)	Linear Density (D)	Stress (cN/tex)	Strain (%)	Modulus (cN/tex)
R1	190	18.8	890.53	25.26	1.68	
R2	84	5.3	567.86	37.04	3.64	
R3	195	26.1	1204.62	15.17	3.58	559.29
R4	76	3.1	367.11	28.54	6.85	1029.03
R5	68	1.8	238.24	19.30	5.18	583.84
R6	83	5.6	607.23	2.02	10.4	352.90
R7	99	7.8	709.09	8.67	2.28	674.47
R8	62	6.9	1001.61	4.55	1.93	415.10
R9	144	2.5	156.25	33.04	3.8	1727.85
R10	117	8.9	684.62	10.95	4.73	393.97
R11	320	26.6	748.13	19.54	4.64	650.32
R12	137	11.5	755.47	6.01	1.73	540.96
R13	190	12.5	592.11	7.00	3.97	390.68
R14	163	11.2	618.40	18.15	3.9	851.43
R15	235	42	1608.51	8.05	4.55	525.47
R16	140	12.9	829.29	9.37	3.22	421.97
R17	144	12.1	756.25	13.41	3.37	468.67
R18	243	17.8	659.26	23.24	6.26	992.94
R19	135	13.4	893.33	11.46	3.55	432.97
R20	116	9.1	706.03	7.22	3.26	382.41
R21	235	22.6	865.53	5.35	1.91	624.35
R22	206	24.3	1061.65	11.02	2.58	655.36
R23	171	22.2	1168.42	11.48	2.92	531.60
R24	134	14.4	967.16	15.52	2.96	721.97
R25	123	24.6	1800.00	13.46	4.07	452.44
R26	152	8	473.68	10.05	2.05	585.74
R27	112	2.3	184.82	15.89	4.87	470.20
R28	187	23.9	1150.27	6.04	2.03	523.19
R29	86	4.3	450.00	10.61	5.48	187.03
R30	208	28.5	1233.17	8.26	1.91	566.92
R31	75	4.7	564.00	12.60	6.22	476.94
R32	172	9.1	476.16	8.41	4	293.41
R33	137	4.3	282.48	16.11	3.45	622.91
R34	206	14	611.65	6.35	2.02	450.65
R35	75	1.5	180.00	15.60	4.46	567.24
R36	149	2.2	132.89	29.46	3.56	1065.83
R37	186	19.3	933.87	12.05	4.05	570.88
R38	319	31.3	883.07	26.74	4.85	823.91
R39	106	2	169.81	13.06	2.92	913.62
R40	159	8.3	469.81	4.70	1.37	377.96

R41	168	2.5	133.93	31.81	10.6	782.52
R42	80	0.6	67.50	8.54	3.91	827.77
R43	250	11.8	424.80	19.22	9.21	1457.14
R44	150	2.5	150.00	19.28	4.82	779.64
R45	187	1.7	81.82	4.39	8.21	882.61
R46	110	3.4	278.18	11.43	2.6	717.52
R47	161	8.8	491.93	17.86	2.63	1158.53
R48	153	17.2	1011.76	14.05	4.06	520.22
R49	110	1.6	130.91	17.00	4.05	594.74
R50	104	3.9	337.50	7.12	5.05	396.23
R51	144	15.8	987.50	13.50	2.81	732.03
R52	78	1.3	150.00	6.94	5.09	429.88
R53	86	2.7	282.56	7.35	2.28	412.80
R54	105	3.2	274.29	12.00	2.45	643.50
R55	90	0.8	80.00	9.33	4.35	669.18
R56	95	1.8	170.53	15.78	5.92	539.41
R57	117	4.9	376.92	5.51	4.21	526.99
R58	114	1	78.95	23.75	5.09	857.29
R59	120	1.4	105.00	26.91	4.75	751.13
R60	126	12.2	871.43	10.62	3.94	321.78
R61	115	1.9	148.70	12.83	3.57	554.52
R62	76	0.7	82.89	32.95	6.85	634.93
R63	104	1.7	147.12	15.95	7.16	325.65
R64	74	1.2	145.95	12.71	4.03	420.74
R65	76	2.8	331.58	3.20	1.52	300.48
R66	98	3.8	348.98	8.94	2.7	415.98
R67	90	3.4	340.00	13.73	7.06	420.42
R68	120	0.4	30.00	38.40	5.05	1291.35
R69	290	18.6	577.24	11.19	4.68	368.32
R70	143	1.4	88.11	18.44	3.63	679.57
R71	202	20.3	904.46	8.23	2.25	501.14
R72	118	1	76.27	39.87	5.86	1045.31
R73	166	3.6	195.18	15.55	4.35	647.54
R74	68	5.8	767.65	6.18	1.95	471.83
R75	115	1.4	109.57	22.50	9.35	658.22
R76	115	0.6	46.96	12.64	6.67	2198.36
R77	97	8.6	797.94	7.73	3.41	454.70
R78	143	11.8	742.66	19.92	2.92	965.47
R79	68	2	264.71	5.54	2.87	446.09
R80	221	24.1	981.45	6.11	1.68	508.63
R81	102	6.5	573.53	11.81	4.63	622.54
R82	78	0.5	57.69	48.99	4.42	1528.20
R83	118	5.6	427.12	6.43	3.18	378.60
R84	132	4.4	300.00	20.89	2.97	995.07
R85	95	3.8	360.00	10.93	6.22	530.07

R86	101	1	89.11	3.71	7.14	1043.94
R87	82	1	109.76	16.75	7.85	1284.28
R88	78	1.7	196.15	13.97	3.25	569.86
R89	103	2.2	192.23	21.77	3.84	681.63
R90	80	6.2	697.50	5.79	1.93	381.22
R91	99	1.4	127.27	14.66	4.08	459.37
R92	200	19.6	882.00	22.92	3.61	1086.10
R93	64	1.3	182.81	10.66	2.93	562.58
R94	205	19.1	838.54	8.65	2.85	491.47
R95	117	8.9	684.62	10.68	4.17	360.31
R96	153	10.7	629.41	12.02	2.3	826.50
R97	148	1.7	103.38	31.36	5.32	932.69
R98	80	1.4	157.50	17.85	4.2	540.09
R99	91	1.8	178.02	9.06	2.22	533.86
R100	109	2.6	214.68	20.53	7.28	395.75

Appendix D: Dew Fiber Data Sheet

Hops fiber data sheet

Method: Dew Retted Fibers

Sample ID	Length (mm)	Mass (mg)	Linear Density (D)	Stress (cN/tex)	Strain (%)	Modulus (cN/tex)
D1	45	0.3	60.00	37.08	3.1	1936.00
D2	105	1.1	94.29	17.67	3.02	1067.76
D3	101	1.5	133.66	9.17	1.58	908.20
D4	60	0.7	105.00	4.64	2.58	509.89
D5	80	2	225.00	11.78	3.2	501.27
D6	105	2.2	188.57	4.12	7.71	900.98
D7	42	0.1	21.43	115.57	10.5	2332.75
D8	55	0.9	147.27	10.74	2.4	695.17
D9	84	1.4	150.00	7.48	2.29	1275.29
D10	100	3.7	333.00	9.68	1.7	868.08
D11	91	2.2	217.58	20.80	2.43	944.28
D12	105	0.9	77.14	32.30	6.95	1358.16
D13	91	1.4	138.46	27.03	2.83	1195.59
D14	86	2.4	251.16	36.32	3.73	1549.84
D15	72	1.3	162.50	12.37	2.18	776.70
D16	81	1.1	122.22	26.34	3.04	1590.98
D17	41	0.6	131.71	14.61	2.57	861.63
D18	86	1.2	125.58	16.89	1.67	2239.06
D19	88	0.8	81.82	28.04	4.33	1200.99
D20	96	1.2	112.50	19.41	2.84	1184.64
D21	70	0.6	77.14	12.74	1.85	1207.31
D22	83	2.7	292.77	5.39	5.98	612.73
D23	74	1.1	133.78	25.89	2.82	1281.90
D24	70	1.1	141.43	10.27	5.97	707.73
D25	87	1.9	196.55	20.50	6.16	789.58
D26	185	3.5	170.27	28.19	2.11	1672.15
D27	88	0.5	51.14	41.04	5.87	2472.93
D28	50	0.4	72.00	16.08	2.58	955.18
D29	123	2.1	153.66	13.39	1.93	859.03
D30	68	0.4	52.94	30.35	3.24	1765.35
D31	114	3.5	276.32	12.59	1.81	1052.01
D32	90	2.7	270.00	13.52	5.37	900.93
D33	87	1.2	124.14	24.72	3.48	840.68
D34	109	2.8	231.19	25.65	4.72	927.24
D35	107	3	252.34	14.12	5.59	673.01
D36	113	1.7	135.40	20.59	4.8	704.83
D37	68	0.4	52.94	47.88	4.1	1791.57
D38	66	1	136.36	5.14	2.42	428.68
D39	45	1.4	280.00	6.60	2.9	477.36
D40	78	1.1	126.92	44.03	4.22	1595.07

D41	55	0.9	147.27	11.95	3.05	557.95
D42	82	1.6	175.61	0.02	11.8	284.26
D43	61	1	147.54	3.10	5.52	119.02
D44	94	2.1	201.06	14.11	2.42	984.35
D45	49	1.3	238.78	9.21	3.57	557.93
D46	80	1.6	180.00	11.68	5.84	532.99
D47	123	2.9	212.20	16.48	3.88	1156.23
D48	79	4.7	535.44	8.74	3.73	377.20
D49	69	1.2	156.52	29.63	4.53	1284.30
D50	95	1.3	123.16	9.66	1.98	933.35
D51	55	0.3	49.09	30.27	2.78	1714.24
D52	75	0.8	96.00	20.86	1.88	1369.85
D53	75	3	360.00	9.49	7.25	310.60
D54	113	1.7	135.40	17.57	2.21	1136.16
D55	108	2	166.67	19.70	4.58	807.91
D56	109	4.9	404.59	34.32	6.21	1651.76
D57	55	1.5	245.45	9.71	2.68	610.54
D58	59	0.4	61.02	11.55	3.33	831.24
D59	61	1	147.54	12.70	7.23	842.29
D60	67	1.7	228.36	22.17	4	1986.02
D61	59	1.3	198.31	24.22	3.04	1145.91
D62	64	1.2	168.75	19.77	2.15	1087.48
D63	92	1.2	117.39	26.69	6.74	1413.61
D64	110	1.6	130.91	22.87	5.58	1449.66
D65	87	1.2	124.14	41.62	5.07	2191.30
D66	57	0.2	31.58	65.87	4	2246.72
D67	65	0.6	83.08	14.79	5.58	777.38
D68	76	1	118.42	40.22	4.06	1597.14
D69	61	2.3	339.34	16.71	2.43	1126.29
D70	49	0.7	128.57	9.37	3.77	489.30
D71	79	2	227.85	8.99	1.42	849.42
D72	140	4.6	295.71	16.09	4.23	434.75
D73	83	2.1	227.71	8.57	2.1	955.31
D74	78	1.1	126.92	-0.06	5.88	483.23
D75	80	1.3	146.25	20.29	8.86	1221.51
D76	57	1.1	173.68	8.99	1.55	940.46
D77	86	1	104.65	14.55	2.08	954.54
D78	52	0.6	103.85	14.97	3.15	1207.66
D79	45	1.8	360.00	6.27	3.77	514.28
D80	87	2.5	258.62	6.67	2.53	442.79
D81	54	0.5	83.33	8.00	3.44	814.18
D82	43	0.2	41.86	22.48	2.65	2023.94
D83	43	0.3	62.79	18.43	1.71	1601.81
D84	61	1.2	177.05	14.07	2.35	947.73
D85	57	1.1	173.68	3.78	5.2	620.35

D86	135	4	266.67	3.32	4.98	435.57
D87	49	0.2	36.73	10.65	8.12	113.18
D88	86	0.8	83.72	20.34	3.4	1597.82
D89	73	0.8	98.63	15.95	5.97	1540.66
D90	80	1.1	123.75	19.34	7.21	1176.66
D91	77	0.7	81.82	14.86	5.85	832.15
D92	87	1	103.45	40.74	3.26	1782.86
D93	66	0.6	81.82	16.54	3.17	1060.90
D94	65	1.1	152.31	10.38	1.83	877.37
D95	85	0.9	95.29	43.19	3.93	1210.27
D96	105	1.3	111.43	20.46	5.26	1443.63
D97	83	1.1	119.28	19.41	4.58	1135.47
D98	65	0.6	83.08	29.72	3.6	1342.83
D99	85	2	211.76	24.98	4.08	958.32
D100	83	1	108.43	36.75	4.52	1719.03

Appendix E: Green Fiber Width

Fiber width data sheet

Method: Green Proccessed Fibers

Sample	Mag x	Width (µm)	Width (µm)	Width (µm)	Average Width (µm)
1	300	186.4	172.3	163.9	174.20
2	300	153.9	146.3	152	150.73
3	125	431.7	356.6	393.2	393.83
4	200	293.3	264.1	142.1	233.17
5	200	441.1	350.6	435.4	409.03
6	300	221.5	246.8	219.8	229.37
7	300	226.9	171.9	178.1	192.30
8	200	403.9	336.2	401.6	380.57
9	200	268.9	263.8	305.5	279.40
10	200	163.1	195.3	182	180.13
11	200	143.3	149.1	117.9	136.77
12	200	179.7	142.6	186	169.43
13	125	581.4	607.9	599.8	596.37
14	200	279.9	350.1	358.7	329.57
15	200	482.2	482.3	416.2	460.23
16	200	166.9	213.7	245.2	208.60
17	125	483.2	405.9	397.5	428.87
18	125	404.9	268.7	283.5	319.03
19	125	428.7	404.1	456.7	429.83
20	200	169.6	246.5	277.8	231.30
21	125	610.7	705.8	301.6	539.37
22	125	490.4	415.5	353	419.63
23	125	479.7	491.8	407.9	459.80
24	125	538.3	353.8	300.2	397.43
25	200	339.3	297.5	267.6	301.47
26	100	662.5	649	601.7	637.73
27	200	154.9	181.9	296.8	211.20
28	35	1043	1012	1019	1024.67
29	200	211.2	217	215.1	214.43
30	200	258	205.9	247.3	237.07
31	200	123.9	192.9	116.2	144.33
32	200	106.7	117.9	96.63	107.08

Appendix F: Water Fiber Width

Fiber width data sheet

Method: Water Retted Fibers

Sample	Mag x	Width (µm)	Width (µm)	Width (µm)	Average Width (µm)
1	200	132.2	128.3	166.4	142.30
2	50	582.9	665.2	394.6	547.57
3	50	324	331.3	329	328.10
4	50	385.8	387	515.3	429.37
5	200	170.8	155.6	206.4	177.60
6	200	126.4	123.1	113.1	120.87
7	200	112.8	157.6	167.9	146.10
8	100	347	308.2	295.8	317.00
9	100	364.8	306.4	358	343.07
10	50	373.8	373.4	360.9	369.37
11	50	545.9	650	593.1	596.33
12	200	247.4	262.4	225.8	245.20
13	200	260.1	240.5	199.2	233.27
14	200	279.2	263.1	269.2	270.50
15	50	351.9	344.1	325.9	340.63
16	50	770	739.5	820.4	776.63
17	200	202.9	222.2	212.6	212.57
18	200	95.73	141.3	141.4	126.14
19	50	773.2	650	629.4	684.20
20	50	551.9	561.3	492.8	535.33
21	200	187.2	173.4	182.5	181.03
22	50	324.6	228.3	242.9	265.27
23	200	195.4	197.9	194.7	196.00
24	100	284.6	458.1	387	376.57
25	35	833.4	773.8	884.2	830.47
26	50	777.3	718	530.5	675.27
27	50	347.4	383.3	344.6	358.43
28	100	385.7	330.9	414	376.87
29	50	691.5	706	841.9	746.47
30	200	164.7	109.5	104.5	126.23
31	50	578.4	487.3	673.2	579.63
32	200	166.7	159.7	160.7	162.37

Appendix G: Break Fiber Width

Fiber width data sheet

Method: Breaking to Water Retted Fibers

Sample	Mag x	Width (µm)	Width (µm)	Width (µm)	Average Width (µm)
1	125	518.9	448.6	435.8	467.77
2	50	446.3	476.3	470.8	464.47
3	35	1005	1111	808.9	974.97
4	200	179.9	184.8	159.5	174.73
5	35	838.8	717.6	1015	857.13
6	50	543.5	529.8	403.6	492.30
7	50	248.3	277.9	272.1	266.10
8	50	678.3	635.1	645.7	653.03
9	200	384.8	354.3	334.6	357.90
10	125	655.7	788.2	952.6	798.83
11	200	427.3	251.4	318.6	332.43
12	200	270	267.2	296.9	278.03
13	125	486.9	680.6	601.4	589.63
14	50	540	454.4	492.6	495.67
15	50	851.7	867.5	843.2	854.13
16	50	862.9	721.6	763.5	782.67
17	50	662.3	617.3	681.6	653.73
18	35	848.8	914.4	923.9	895.70
19	35	778.7	812.2	971.3	854.07
20	100	389.1	451.3	508.6	449.67
21	50	583.6	569.2	646.5	599.77
22	50	697.3	676.5	726.6	700.13
23	50	1132	1178	1055	1121.67
24	50	1234	1208	1234	1225.33
25	100	369	247.2	404.6	340.27
26	50	813.4	829	934.4	858.93
27	50	966.1	1027	1020	1004.37
28	50	663.3	664.6	645.6	657.83
29	200	193.4	190.9	179.3	187.87
30	50	661.6	665.7	727.6	684.97
31	50	644.3	644.7	601.4	630.13
32	50	602.3	630.6	548.4	593.77

Appendix G: Dew Fiber Width

Fiber width data sheet

Method: Dew Retted Fibers

Sample	Mag x	Width (µm)	Width (µm)	Width (µm)	Average Width (µm)
1	200	87.67	79.71	76.91	81.43
2	50	220	204	190.9	204.97
3	100	220.3	273.8	356.4	283.50
4	100	337.6	308.1	292.8	312.83
5	35	744.4	803.6	539.4	695.80
6	200	254.4	244.1	222	240.17
7	50	313.7	328.6	293.7	312.00
8	50	265.8	284.4	214	254.73
9	200	178.1	220.3	201	199.80
10	50	401.5	268.6	263.9	311.33
11	200	85.4	111.2	113.5	103.37
12	50	917.9	996.9	909.9	941.57
13	50	577.1	500.7	543.7	540.50
14	200	136.5	146.6	142.3	141.80
15	200	248.3	284.6	205.4	246.10
16	200	323.4	356.5	302.4	327.43
17	50	275.2	215.4	160.7	217.10
18	200	70.47	73.35	57.39	67.07
19	125	234.5	282.8	359.4	292.23
20	50	503.4	464.7	520.8	496.30
21	50	323.9	265.7	301.4	297.00
22	100	253.6	150.4	254.1	219.37
23	50	459.6	510.9	417.9	462.80
24	200	195.9	203.6	187.8	195.77
25	50	280.3	287.1	255.2	274.20
26	50	310.5	269.6	262.4	280.83
27	50	382.7	232.7	219.4	278.27
28	200	125.2	145.9	195.6	155.57
29	100	353.6	268.5	302.6	308.23
30	100	312.5	315.7	331.8	320.00
31	100	227.2	202.8	350.8	260.27
32	200	86.83	87.11	88.99	87.64

Appendix H: ANOVA for Stress with Outliers Removed

Results

ANOVA

ANOVA - Stress (cN/tex)

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Extraction (1=green, 2=water, 3=break, 4=dew)	2199.237	3	733.079	9.784	< .001	0.072
Residuals	28546.834	381	74.926			

Note. Type III Sum of Squares

Descriptives

Descriptives - Stress (cN/tex)

Extraction (1=green, 2=water, 3=break, 4=dew)	N	Mean	SD	SE	Coefficient of variation
1	94	11.161	6.523	0.673	0.584
2	94	13.916	8.177	0.843	0.588
3	100	14.752	8.969	0.897	0.608
4	97	17.888	10.412	1.057	0.582

Post Hoc Tests

Standard

Post Hoc Comparisons - Extraction (1=green, 2=water, 3=break, 4=dew)

		Mean Difference	SE	t	Cohen's d	p_{bonf}
1	2	−2.755	1.263	−2.182	−0.318	0.178
	3	−3.590	1.244	−2.887	−0.415	0.025
	4	−6.727	1.253	−5.370	−0.777	< .001
2	3	−0.836	1.244	−0.672	−0.097	1.000
	4	−3.972	1.253	−3.171	−0.459	0.010
3	4	−3.137	1.234	−2.543	−0.362	0.068

Note. P-value adjusted for comparing a family of 4

Appendix I: ANOVA for Strain with Outliers Removed

Copy of ANOVA

ANOVA - Strain (%)

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Extraction (1=green, 2=water, 3=break, 4=dew)	11.063	3	3.688	0.731	0.534	0.006
Residuals	1942.514	385	5.045			

Note. Type III Sum of Squares

Descriptives

Descriptives - Strain (%)

Extraction (1=green, 2=water, 3=break, 4=dew)	N	Mean	SD	SE	Coefficient of variation
1	96	3.991	2.286	0.233	0.573
2	93	4.411	2.729	0.283	0.619
3	100	4.182	1.941	0.194	0.464
4	100	4.001	1.980	0.198	0.495

Post Hoc Tests

Standard

Post Hoc Comparisons - Extraction (1=green, 2=water, 3=break, 4=dew)

		Mean Difference	SE	t	Cohen's d	p_{bonf}
1	2	−0.420	0.327	−1.286	−0.187	1.000
	3	−0.191	0.321	−0.596	−0.085	1.000
	4	−0.011	0.321	−0.034	−0.005	1.000
2	3	0.229	0.324	0.708	0.102	1.000
	4	0.410	0.324	1.266	0.182	1.000
3	4	0.180	0.318	0.568	0.080	1.000

Note. P-value adjusted for comparing a family of 4

Appendix J: ANOVA for Modulus

Copy of Copy of ANOVA

ANOVA - Modulus (cN/tex)

Cases	Sum of Squares	df	Mean Square	F	p	η^2_p
Extraction (1=green, 2=water, 3=break, 4=dew)	$2.695\times10^{+7}$	3	$8.982\times10^{+6}$	60.710	< .001	0.322
Residuals	$5.666\times10^{+7}$	383	147943.938			

Note. Type III Sum of Squares

Descriptives

Descriptives - Modulus (cN/tex)

Extraction (1=green, 2=water, 3=break, 4=dew)	N	Mean	SD	SE	Coefficient of variation
1	95	403.129	226.212	23.209	0.561
2	94	490.946	410.830	42.374	0.837
3	98	657.048	323.389	32.667	0.492
4	100	1084.242	512.583	51.258	0.473

Post Hoc Tests

Standard

Post Hoc Comparisons - Extraction (1=green, 2=water, 3=break, 4=dew)

		Mean Difference	SE	t	Cohen's d	p_{bonf}
1	2	−87.816	55.957	−1.569	−0.228	0.704
	3	−253.919	55.380	−4.585	−0.660	< .001
	4	−681.112	55.107	−12.360	−1.771	< .001
2	3	−166.102	55.529	−2.991	−0.432	0.018
	4	−593.296	55.257	−10.737	−1.542	< .001
3	4	−427.194	54.672	−7.814	−1.111	< .001

Note. P-value adjusted for comparing a family of 4

Appendix K: Green Fiber Yield

Fiber yield data sheet

Method: Green Processed Fibers

Sample	Start wt (g)	End wt (g)	% Yield
1	3.8	0.0642	1.69
2	8.2	0.121	1.48
3	9	1.5	16.67
4	5.1	1.1	21.57
5	6	0.6	10.00
6	10.5	1	9.52
7	5.2	0.6	11.54
8	4.1	0.9	21.95
9	4.12	1.03	25.00
10	4.69	1.05	22.39
11	6.1	1.11	18.20
12	5.62	1.03	18.33
13	3.89	0.86	22.11

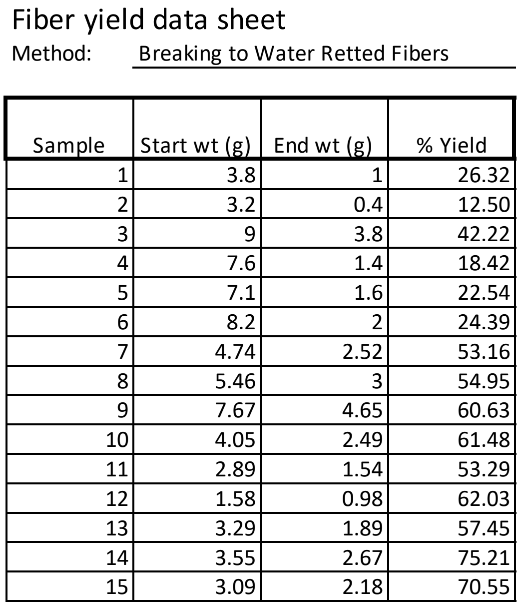
Appendix L: Water Fiber Yield

Fiber yield data sheet

Method: Water Retted Fibers

Sample	Start wt (g)	End wt (g)	% Yield
1	9.6	0.7	7.29
2	3.6	0.81	22.50
3	5.4	0.7	12.96
4	3.2	0.2	6.25
5	10.5	2.2	20.95
6	5.6	1.4	25.00
7	6.2	1.8	29.03
8	3.2	0.5	15.63
9	3.7	0.8	21.62
10	5.6	0.9	16.07
11	3.9	1.1	28.21
12	5.4	1	18.52
13	6.5	1.5	23.08
14	5.1	1.8	35.29
15	10.6	2.8	26.42

Appendix M: Break Fiber Yield



Fiber yield data sheet

Method: Breaking to Water Retted Fibers

Sample	Start wt (g)	End wt (g)	% Yield
1	3.8	1	26.32
2	3.2	0.4	12.50
3	9	3.8	42.22
4	7.6	1.4	18.42
5	7.1	1.6	22.54
6	8.2	2	24.39
7	4.74	2.52	53.16
8	5.46	3	54.95
9	7.67	4.65	60.63
10	4.05	2.49	61.48
11	2.89	1.54	53.29
12	1.58	0.98	62.03
13	3.29	1.89	57.45
14	3.55	2.67	75.21
15	3.09	2.18	70.55

Appendix N: Dew Fiber Yield

Fiber yield data sheet

Method: Dew Retted Fibers

Sample	Start wt (g)	End wt (g)	% Yield
1	112.4	4.5	4.00
2	113.2	2.7	2.39
3	117.9	3.5	2.97
4	77	1.3	1.69
5	81.2	2.2	2.71
6	76	1.7	2.24
7	108.7	3	2.76
8	72.2	1.6	2.22
9	62.4	1.7	2.72
10	12.4	0.3	2.42
11	13.1	2.2	16.79
12	8.4	0.3	3.57
13	15.5	2.1	13.55
14	14.1	0.7	4.96
15	13.4	0.5	3.73

Appendix O: ANOVA for Fiber Yield

Results

ANOVA

ANOVA - yield

Cases	Sum of Squares	df	Mean Square	F	p	η²
extraction (1=green,2=water,3=breaking,4=dew)	14032.379	3	4677.460	32.798	< .001	0.646
Residuals	7701.214	54	142.615			

Note. Type III Sum of Squares

Descriptives

Descriptives - yield

extraction (1=green,2=water,3=breaking,4=dew)	N	Mean	SD	SE	Coefficient of variation
1	13	15.419	7.881	2.186	0.511
2	15	20.588	8.017	2.070	0.389
3	15	46.343	20.323	5.247	0.439
4	15	4.581	4.421	1.141	0.965

Post Hoc Tests

Standard

Post Hoc Comparisons - extraction (1=green,2=water,3=breaking,4=dew)

		Mean Difference	SE	t	Cohen's d	p_{bonf}
1	2	-5.169	4.525	-1.142	-0.433	1.000
	3	-30.923	4.525	-6.834	-2.589	< .001
	4	10.838	4.525	2.395	0.908	0.121
2	3	-25.755	4.361	-5.906	-2.157	< .001
	4	16.007	4.361	3.671	1.340	0.003
3	4	41.761	4.361	9.577	3.497	< .001

Note. P-value adjusted for comparing a family of 4