

**Evaluation of a Hammer Mill and Planetary
Ball Mill for Hemp Fibre Decortication**

by

Meghan Lyndsay Baker

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfilment of the requirements of the degree of

Master of Science

Department of Biosystems Engineering
University of Manitoba
Winnipeg, Manitoba, Canada

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ABSTRACT

Hemp fibre is becoming an increasing interest to the biocomposite industry for its market potential. Hemp fibre is comparable to other synthetic fibres, such as glass, but its high tensile strength and durability make it a superior choice. For biocomposites to be equivalent to other synthetic products, hemp must be decorticated in such a manner to achieve optimal fibre yield. The objective of this study was to test different decortication machines, including a hammer mill and a planetary ball mill, and to study the final fibre state of the product and the effectiveness of each machine. For the hammer mill, three parameters, including feeding mass, screen scenario, and pre-cutting scenario, were used to determine the power requirement, energy requirement, fibre yield, core yield, and effectiveness of decortication of the mill. For the planetary ball mill, two parameters, grinding speed and grinding duration, were used to determine the fibre yield, core yield, chaff, detaching efficiency, and performance index of the mill. An analysis of variance was performed on the hammer mill and planetary ball mill test variables to determine significant effects of the different treatments.

For the hammer mill, large screen scenarios (25.7 mm round-holed openings) and a small feeding mass (75 g) allowed for a maximum fibre yield for Retted hemp (34.5%). Whereas, a 75g feeding mass and small screen scenario (19.3 mm round-holed openings) produced a maximum fibre yield (15.9%) for Green hemp. Power and energy requirements for both Retted and Green hemp decreased as the screen scenario size increased. The combination of the 19.3 mm screen scenario, a feeding mass of 75 g, and pre-cut feedstock for Retted hemp performed the best in terms of fibre yield and effectiveness of decortication.

Grinding speed and grinding duration parameters had an effect on the planetary ball mill performance. Low grinding speeds and short grinding durations resulted in poor detaching efficiencies (52.6%) and low fibre yields (39.1%). Whereas, high grinding speeds and long grinding durations produced all chaff (100%). Optimal fibre yield and detaching efficiency was observed when grinding speed and grinding duration were 200 rpm for 4 min and 250 rpm for 6 min, respectively.

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1. INTRODUCTION

1.1 General

Environmental issues and the availability and use of non-renewable resources are concerns of individuals as well as many industries. Industrialized hemp, which is environmentally friendly and respects the definition of a renewable resource, has been replacing many of the more traditional fibre sources. The international and domestic everyday use of hemp products is growing every year. Thus, the potential growth of the market is evident.

Commercial growth of hemp was legalized in Canada in 1998. Soon after, interests from international and local industries in hemp products, such as fibre, grew considerably. Machines were, and are, needed for the harvesting of all individual parts of the plant such as seeds, leaves, and fibre. Crops may be left in fields to ret, which allows for the degradation of pectin (the substance that holds the outer fibre layer to the inner core layer) by microorganisms. Following retting, hemp is baled and then transported to a processing plant. A process known as decortication has served well in separating the fibre of hemp stems from the woody core. Bales are then unrolled or cut and sent through a decorticating machine to obtain fibre which is expected to be free of core fragments. However, current decortication machinery produces product with low purity rates and is not very energy efficient. The availability, ease of use, ability to produce high-purity fibre, and energy efficiency of decortication machinery would be a great asset to the hemp industry.

Hemp cultivation is a growing industry that is gaining attention as a renewable and environmentally acceptable feedstock for natural fibre based products (Munder et al. 2003). However, the majority of research dealing with hemp has been concentrated on the plant itself

and little research on the decortication machinery has been done. Present machinery is expensive to use and must be supplemented with additional separators in order to attain the desired fibre purity. To comply with the increasing interest in hemp fibre products, changes need to be made to the processing machinery. By researching the decorticator, including its power requirement, and fibre output, improvements or alterations may be addressed in order to achieve high fibre product in an efficient manner.

1.2 Objectives

Primary objective: The primary objective of this study was to experimentally study two different fibre decorticating systems: hammer mill and planetary ball mill decorticators. The fibre yield and detaching efficiency of each type of the selected detachers will be examined using differing screen scenarios (hammer mill), varying feeding masses (hammer mill), different pre-cutting scenarios (hammer mill), varying grinding speeds (ball mill), and varying grinding durations (ball mill). In addition, the peak power and energy requirements of the hammer mill will be tested using two different retting conditions (Green and retted feedstock), recorded, and compared.

Secondary objective: The secondary objective of this study was to provide recommendations for improved fibre yield results using a decorticator including: power and energy efficient methods and greater fibre yields. This will be based on results obtained from the primary objective.

1.3 Thesis Structure

This thesis has been structured in paper formats. General Introduction and Literature Review are presented in Chapters 1 and 2, respectively. Chapters 3 and 4 are the parts of the

thesis written in paper formats and they address the two objectives of the study. General conclusions are outlined in Chapter 5.

2. LITERATURE REVIEW

2.1 Hemp plant

2.1.1 General Hemp (*Cannabis sativa*) is a temperate climate plant grown mostly in Russia, Eastern Europe, and Canada. Several cultivars of hemp exist, all of which vary in morphological and agronomic characteristics, which are described in the following sections. Hemp is either grown as a dual purpose crop (grown for both seed and fibre) or solely for fibre or seed. Final products obtained from hemp grown in Russia, Europe, and Canada is produced from seed and stalk, and has low concentrations of delta-9-tetrahydrocannabinol (THC), the major drug component in marijuana (Gratton 2002; de Meijer 1995).

2.1.2 History of hemp in Canada Hemp is one of the oldest cultivated plants in the world. In the 1920s, Agriculture Canada was involved in hemp research as part of a crops program. During that time a small commercial hemp crop was grown in Manitoba and the fibre was used to produce cordage (MAFRI 2008). However, due to the economic factors of the Great Depression, cultivation of hemp ceased to exist by the mid-1930s, and due to its similarity to marijuana, cultivation was banned in 1938 under Canada's federal narcotics regulations (MAFRI 2008). In the early 1990s, certain varieties of hemp were allowed as crops in the European Union (EU), and in 1998 the cultivation of industrial hemp was permitted in Canada. Thus, the 60-year ban was lifted and the licensed commercial production of hemp in Canada was re-established.

Since 1998, varieties approved for production in the EU have been grown on a commercial scale in Canada. The cultivation of hemp in Canada is a growing industry. In the year 2001, the number of licensed hectares in Canada was 1,315 and by 2007 this number

increased to 4,682 (MAFRI 2008). Manitoba industrial hemp hectares exhibited a similar growth trend for those years. In 2001, the number of licensed hectares in Manitoba was 529 and by 2007 the number of hectares increased to 1727 (MAFRI 2008).

2.1.3 Physiology In Canada, the varieties grown, such as USO 14 and USO 31, may reach a height of 1.5 to 2.5 m and have an average stem diameter of 7 to 16 mm (Gratton and Chen 2003; Gratton and Chen 2000). Height is dependent upon numerous factors, such as sun exposure, plant variety, soil, nutrient availability, water supply, and plant density (Bócsa and Karus 1997). Bócsa and Karus (1997) noted that in order to achieve an optimal height, a minimum of 250 mm of precipitation is required during the vegetative period. The stem of most hemp plants consists of an inner hollow core with an outer fibrous layer consisting of long bast fibres (Gratton and Chen 2003). Bast fibres are obtained from the stems of various dicotyledonous plants (*i.e.* plants with two seed leaves cotyledons) (Mwaikambo 2006). The bast fibres are composed of elongated thick-walled cells that are joined together both end-to-end and side-by-side, and arranged in bundles along the length of the stem (Mwaikambo 2006). The proportion of bast fibres in hemp stalks is known to vary between cultivars. Bast fibre mass proportions may range from 16 to 35% among different cultivars, while core fibre proportions may range from 52 to 68% (Gratton 2002; de Meijer 1995).

The anatomy of the hemp plant consists of wood and bast tissue (Bócsa and Karus 1997). The inner core consists mainly of parenchyma cells, which are composed of cellulose, hemi cellulose, and lignin (Gratton 2002). The amount of cellulose, hemi cellulose, and lignin within the parenchyma cells varies between varieties. Fibres found within the core are made of thin-walled cells and have a length of approximately 0.55 mm (Gratton 2002). Gratton (2002) noted that bast fibres, found in the outer fibrous layer, are generally much longer (540 mm). Bócsa and

Karus (1997) determined that hemp fibre consisted of approximately 65% cellulose, 15% hemicellulose, and 4% lignin, while hemp core consisted of 37% cellulose, 35% hemicellulose, and 21% lignin.

2.2 Hemp cultivation

Hemp may be grown successfully using conventional seeding equipment (MAFRI 2008). Hemp cultivation requires little herbicides and a limited amount of fertilizer (Struik et al. 2000; van de Werf 1994). Industrial hemp planted for fibre is usually sown in 150 to 180 mm row spacings, using every run of standard grain drills. Suggested seeding rates for hemp fibre crop should be approximately 45 kg ha⁻¹, while for seed or grain crop the seeding rate should be approximately 23 kg ha⁻¹ (MAFR 2000). Seeding depth should be shallow, which is typically 19 to 70 mm (MAFRI 2008). Seeding at greater depths is possible; however, it may delay emergence and the plant's competitiveness (Gratton 2002). Minimal fertilizer may be required for hemp if it is planted in a suitable rotation; however, good results have been found in Manitoba soils containing total amounts of 90 to 112, 50, 67, and 17 kg/ha of N, P, K, and S, respectively (MAFRI 2008).

Hemp is day-length sensitive, and thus the time it takes to mature varies with seeding date (Gratton 2002). As day-light decreases, 4 to 5 weeks after the summer solstice (June 21), vegetative growth slows and flower development is triggered (MAFR 2000). Recommended maturing times for most varieties are within 120 to 150 days (MAFRI 2008). Hemp grows well on various soil types, and responds well to drained loam soil with a pH above 6.0. Hemp is sensitive to saturated soils and prolonged exposure to wet soil conditions results in stunted growth, yellowing, and poor crop (MAFR 2000).

Fibre quantity and quality are greatly influenced by the harvest date. The determining factor for harvest date depends upon achieving the largest quantity and best quality of fibre (Bócsa and Karus 1997). Different plant sexes have different optimal harvest dates. For male plants, the best harvest date is during flowering; whereas with female plants, the best harvest date is at the first appearance of flowers (Bócsa and Karus 1997).

2.3 Uses of hemp fibre and core

2.3.1 Current uses Hemp is an extremely renewable resource, and since hemp is extremely self-tolerant, it can be planted year after year in the same field. The market opportunity for hemp fibre comes from products which can be made with both the fibre and core, or either of the two components separately. Properties of natural fibre plants, such as hemp, allow for the production of a wide range of products. Natural fibre plants can be used for the production of useful materials such as fibres, starch, oils, solvents, dyes, resins, proteins, specialty chemicals, and pharmaceuticals (van Wyk 2007). Many industries have incorporated hemp into their products. For example, the automotive industry has seen a steady growth in the use of natural fibre composites. The use of natural fibres, such as hemp, has been used in the automotive industry for moulded parts because of its light weight and ease of recyclability (Fortenbery and Bennett 2003). Fortenbery and Bennett (2003) noted that several BMW models have used hemp fibre for trunk liners and press-moulded airbag parts.

Currently, hemp has also established market niches using its fibre, core, seeds, and seed oils. Insulation is one of many products that are currently taking advantage of hemp fibre. Natural fibre insulation has a low negative environmental impact during manufacturing and installation. In addition, natural fibres can outperform competing materials in use and they are

generally less toxic (van Wyk 2007). In 2001, France and Germany were noted as being the largest producers of hemp insulation in Europe, and approximately 1500 ha of hemp were grown for insulation (Kymäläinen 2004).

Hemp fibre has also been used for wall and floor coverings. Coarse fibres can be used to make underlay materials or backing for carpets (Merfield 1999). Finer fibres can be used on their own or in mixtures with wool or synthetics to produce carpets with superior characteristics such as wear, non-pilling, and biodegradability (Merfield 1999). Hemp fibre offers a cost-competitive carpet in which following normal wear-and-tear, the carpet can be composted (Bócsa and Karus 1997). The use of natural fibres offers performance benefits in terms of toughness, thermal comfort, and indoor environmental quality.

Hemp also has many possibilities for fauna. Traditionally, hemp cores were solely noted as a by-product of fibre production with no worth. However, hemp cores are now a valuable by-product of fibre production. In England, France, and Germany hemp core is being sold for cat litter. Hemp core is favoured for its water absorbency, odour suppression, and is less allergenic (Fortenbery and Bennett 2003; Merfield 1999). Core has also been sold as source of animal bedding, more specifically horse bedding.

2.3.2 Potential uses Most of the interest in hemp fibre comes from its potential as a replacement or additive fibre source in products that already use other natural or synthetic fibres (PIHG 2003). This potential exists due to the fact that hemp fibre has many desirable properties that can be exploited to improve the products in which they are used.

Hemp can be processed into a diverse range of products including foods, cosmetics, textiles, and industrial materials. However, on the economics of hemp there is a large gap

between a potential product and its financial viability (Merfield 1999). Clothing is a high profile potential market for hemp, as well as other fabrics and textiles such as upholstery, rugs, fashion accessories, and carpets. Hemp fibre has a number of superior properties when compared to alternative products such as cotton and synthetic fibres. These include strength, durability, low UV light transmission, and warmth (Merfield 1999). However, high costs and the need for manufacturing machinery have placed a hold on textile hemp products.

In addition to hemp textiles, hemp paper is another potential product. Hemp paper is more resistant to decomposition, stronger (especially when wet), less prone to yellowing, and uses less chemicals in production compared to tree based paper (Merfield 1999). Hemp paper has a potential market in many non-writing paper industries, such as cigarette paper, tea bags, and filters where wood is too weak. However, the price of hemp fibre is too high and would need to decrease considerably to be a competitor of tree based paper (Merfield 1999). In addition, the transport and storage of raw hemp is also a problem, since hemp cannot be harvested year-round, considerable quantities of unprocessed or semi processed hemp would have to be stockpiled, which is expensive.

Hemp produces large amounts of biomass. Due to these large amounts, a number of claims have been made that hemp could be used as a fuel source, either burnt directly or converted into liquid fuels such as ethanol (Merfield 1999). The high potential of industrial hemp will not only benefit agriculture, but also consumers, all levels of governments, and value added companies.

2.4 Decortication

2.4.1 Methods of decortication Decortication and retting techniques are usually employed to separate fibre bundles from the leaf and core of plants (Mwaikambo 2006). Typically, fibrous

material is removed from the core of the plant by one of three decorticating processes; biological, physical, or mechanical. One example of biological processes is retting the stems of cut plants (*i.e.* exposing stems in a swath to dry and wet conditions) to undergo microbiological digestion of chemical bonds between fibre bundles (Bruce et al. 2001). This process is commonly known as dew retting, and is mostly seen in geographical regions with little precipitation (Hann 2005). Special care must be taken so that stalks are not over retted. Over-retting occurs when field conditions are too moist, and it may lead to destruction of the fibre.

Most physical methods are a combination of physical and biological processes. Traditional physical methods involved submerging the fibre stock in non-turbulent sources of water (*i.e.* dams, ditches, or slow running rivers and streams) (Hann 2005). Modern methods involve soaking the stems in (temperature controlled) water tanks for approximately 8 to 14 days, after which the fibrous layer will readily slip off when the stalks are broken by hand (Hann 2005). Stems are then removed from the tanks and dried. Small equipment can be used, and the fibre undergoes scutching and hackling; the separation of fibre from the core (Belsham 2000). In the final step, the hackling process, fibre is combed over pins to remove any remaining core (Belsham 2000).

2.4.2 Equipment used for decortication Mechanical methods involve machinery such as; hammer mills, crushing rollers, and cutterheads. Hammer mills can be described as a drum with pivoting hammers mounted on cross-shaped rotors (Feed Machinery 2008). Hammer mills may be used for unretted stalks when low fibre purity and high processing capacity are required (Chen et al. 2004). Hammer mills generate more chaff when compared to crushing rollers; thus, the output may contain loose fibre and fibre-bound-to-core (Chen et al. 2004). To run a hammer mill, material is introduced at the top of the machine, and the fibres are separated by the ganged

hammers (*i.e.* rectangular pieces of hardened steel) attached to a high speed rotating shaft inside the chamber (Feed Machinery 2008). Impact and shearing forces crush and shatter the material by continuous hammer impacts and collisions with the walls of the grinding chamber (Feed Machinery 2008). The hammer mill method does not allow for an entire separation of the fibre from the core (Gratton and Chen 2003; Fűrll and Hempel 2000) and outputs usually have lower fibre purity suitable for non-textile applications (Gratton and Chen 2003). However, this process has a higher efficiency for separation and does not require a long retting time, compared with the scutching process (Gratton and Chen 2003).

The crushing roller comprises of two or more adjacent rollers differing in diameter size and uniformity. Rollers are placed parallel to one another and rotate in opposite directions (Gupta and Yan 2006). Plant stems are fed lengthwise into the machine between rollers. Roller pairs may have a diameter of 0.2 to 0.3 m, and their length to diameter ratio may be as great as 4:1 (Feed Machinery 2008). Rollers may be flat, fluted, or pinned to allow for the stems to be compressed (*i.e.* woody core to be broken up), crimped, or combed free of any remaining core, respectively. To ensure optimal results, material must be fed between the rolls in a uniform and constant manner (Feed Machinery 2008). When rollers of equal diameter rotate at the same speed then compression is the primary force; if the rolls operate at different speeds then shearing and compression are the primary forces, which cause an unequal force for separation of the fibre; if the rolls are grooved a tearing or grinding force is applied (Feed Machinery 2008).

A modified cutterhead machine was used by Gratton and Chen (2003) for in-field hemp decortication. The prototype was constructed using a conventional forage harvester as a separating device, and was powered by a 115 hp tractor. The machine originally featured 12 knives, but was modified to be fitted with three cutting knives and nine scutching bars to

increase the cutting length (Gratton and Chen 2003). The cutterhead configuration with knives and scutching bars resulted in better fibre purity and removed more core as compared to the original cutterhead configuration with knives only (Gratton and Chen 2003). In addition, it was found that with a lower feeding rate and longer retting times, higher fibre purity may be obtained.

2.5 Performance of decortication process and equipment

The design and placement of hammers in a hammer mill is determined by operating parameters such as rotor speed, motor horsepower, and open area of the screen (Koch 2002). Different rotor speeds require a different size and number of hammers. Depending on the diameter of the mill chamber, the rotational velocity, tip speed, horsepower, and screen area will change. The greater the diameter, the slower the rotational velocity and the more power required. The following results were reported by Koch (2002). Mills in which rotor speed is approximately 1800 rpm, hammers should be approximately 250 mm long and 6.5 mm across. For a rotor speed of about 3600 rpm, hammers should be approximately 150 to 200 mm long, 50 mm across, and 6.5 mm thick (Koch 2002). The number of hammers used for 1800 rpm should be one for every 1864 to 2610 watts (2.5 to 3.5 hp) and for 3600 rpm, one for every 746 to 1491 watts (1 to 2 hp). The distance between hammers is critical for proper size reduction, and the tip speed is calculated by multiplying the rotational speed by the circumference of the hammer tip.

Leduc et al. (1998) patented a crushing roller for the decortication of plant material. They found that machines beat the straw to detach the shortened fibres separated from the core. The patented crushing roller had the capacity to process approximately 4500 kg h⁻¹, and the yielding fibre output from the final processing section was found to be in the range of 55 to 60%

of fibre purity. The machine was comprised of feeding, fluted, and smooth rollers. The feed rollers rotated at a rate of approximately 60 to 110 rpm, the intermediate speed rollers at a rate of approximately 1000 to 1750 rpm, and the high speed rollers at a rate of approximately 2000 to 3500 rpm.

Fang et al. (1997) studied varying components, such as roll speed differential and roll gap, and their impacts on decortication. Roll speed differential is defined as the ratio of the fast roller and slow roller speeds, and is known to greatly affect the grinding action between the two rollers (Fang et al. 1997). At slower speeds, a lower energy requirement is required to crush material into coarse particle sizes; whereas, at faster speeds, a shearing action is applied to the material resulting in a finer particle size and a greater energy requirement (Fang et al. 1997). The most critical component, roll gap, is the separation between a set of rollers. The set distance between a pair of rollers determines the final size of the material; a small roll gap results in material being decorticated into small pieces, whereas a larger roll gap results in a large final material size. Fang et al. (1997) observed that roll gap affected the particle size and particle size distribution of the ground material, capacity of the roller mill, and the energy requirement.

Ball mills may be used to grind hemp samples for decortication. Ball mills use grinding balls to crush and disintegrate material in a grinding bowl. Prasad et al. (2005) explain that ball milling is a mechanical process in which the energy used for grinding comes from a combination of the collision between balls and from the centrifugal action in the ball mill. Grinding bowls of various sizes, and various materials, are filled with a specific number of grinding balls. The number, size, and type of balls are dependent upon the size of the bowl, type of bowl, and product to be ground. Material to be ground is placed in the grinding bowl on top of the grinding balls and is then rotated about a horizontal axis (Prasad et al. 2005). The grinding balls and the

material in the grinding bowl are acted upon by centrifugal forces due to the rotation of the grinding bowl about its own axis and the rotating supporting disc (Fritsch 2005). When the mill rotates, the balls travel up the wall of the container until they reach the top, where they lose contact with the wall and then drop down (Prasad et al. 2005). Prasad et al. (2005) explain that while the grinding balls are in contact with the walls, some decortication takes place, but most takes place at the bottom of the bowl where the material is hit by the balls dropping down. The faster the mill rotates, the farther the balls are carried up inside the bowl and the higher the balls are carried up the greater the impact at the bottom (Prasad et al. 2005). However, if the mill rotates too fast, the balls inside the mill are carried over all along the walls and do not drop down (Prasad et al. 2005). In addition, the grinding duration, grinding speed, and number of grinding balls have an impact on the final product.

2.6 Characteristics of hemp from decortication

2.6.1 Fibre Practical fibre yield varies with the variety grown. Characteristics, such as shape, length, and mass, along with the target fibre purity and yield, all affect the design of a fibre cleaning device (Chen et al. 2004). In an experiment completed by Munder et al. (2003), using a hammer mill, they found that long fibres constituted 25% of the output fraction, followed by core with short fibres (21%) and solely core (21%). The fibre length of the long fibres varies in a wide range after processing; however, it can be adjusted by pre-cutting. Munder et al. (2003) found a mean fibre length of 118 mm after processing.

In an experiment conducted by Belsham (2000), results indicated that fibre properties were affected by plant density. It was found that plant density (plants m^{-2}) and specific stress had a direct relationship: a low density produced a lower specific stress (Belsham 2000).

Belsham (2000) used three seeding rates: 50, 100, and 350 plants m^{-2} . The hemp stalks from all

three seeding rates were field retted and harvested at the same time at the onset of flowering. The average specific stress (N tex^{-1}) for the seeding rates of 50, 100, and 350 plants m^{-2} were 0.1661, 0.2395, and 0.3785, respectively.

Gratton and Chen (2003) used a cutterhead method for hemp decortications. Their output fibre purity results ranged from 35 to 52%. Fibre purity is defined as the ratio of the fibre mass to the mass of the sample from the fibre outlet (Gratton and Chen 2003; Anthony 2002). On average, Gratton and Chen (2003) lost approximately 45% of fibre to the chaff outlet. Gratton and Chen (2003) found that fibre purity could be increased by collecting lost loose fibre which accounted for 11 to 35% of the total lost fibre.

Hobson et al. (2001) used a modified laboratory-scale flax decorticator for hemp decortication. They used two samples of 4 kg stems, retted and unretted (approximately 75 to 100 stems) to determine yield using a crushing roller. Results showed similar fibre and core yields for both retted and unretted hemp stems; also there was a greater core yield from the retted stems and more waste from the unretted stems. The unretted stems showed mean yield results of 30.5, 58.9, and 10.6% for fibre, core, and waste, respectively. For retted stems, the corresponding mean yield results were 30.8, 65.5, and 3.6%.

2.6.2 Core and fine particles Fine particles are a mixture of short fibres and cores with a wide range of particle size distribution. The particle size of the cores can be adjusted by the operating parameters of the decortication machine, for example, the mesh size of the screen in the case of a hammer mill (Munder et al. 2003).

Munder and Fűrll (2004) used a swing-hammer mill in their experiment for processing bast fibre plants. End results showed components of different qualities and quantities; long

fibres 25%, cores 20.7%, cores with short fibres 21.1%, short fibres with core 6.0%, short fibres from fibre separator 14.2%, short fibres from pre-filter 1.3%, and waste 0.9%. Munder and Füll (2004) also found that approximately 45% of cores arise at the decorticating machine and the other 55% arise at the feeding system of the fibre cleaning stage. Four fractions of cores are usually produced: short fibres, rough cores, medium size cores, and fine cores. The modified cutterhead used by Gratton and Chen (2003) showed the ratio of core mass and the outlet mass from the chaff outlet to be 55.5%. Core yield was defined as the ratio of the core mass and the outlet mass from the chaff outlet.

2.7 Measurement technology

2.7.1 Fibre properties In order to identify fibre characteristics and to assess the quality of the fibre, there are several properties that need to be measured. Ultimately, these properties influence the performance of the end products (Xu et al. 1993). These measurements include fibre length and fibre fineness. For the measurement of natural and synthetic fibre varieties, numerous experimental methods have been used.

The ASTM standard D 519-04 covers the measurement of the average length and length distribution of fibres in wool top (ASTM 2007). A comb sorting device is used to sort fibre samples by length. The device consists of a bed of evenly-spaced parallel combs mounted on a frame (Gratton 2002). The needles of the combs face upwards, and a sample of fibre is placed parallel over the combs so that the ends of the fibre are square with the outer comb (ASTM 2007). Fibres which are square with the outer comb are then secured by an additional comb, with needles pointing down, and placed on top (Gratton 2002). The fibre sample is then slowly pulled out straight to remove any fibres that are not secured by the outer comb. The other combs are then secured with their own corresponding top comb. Following this, the end comb at the

fixed end is removed and any fibres shorter than the next corresponding comb are removed. Gratton (2002) reported that “this procedure is repeated until all combs have been removed”. The fibres are then removed from each length and weighed.

Fibre fineness is a measure of the cross-sectional thickness of fibres obtained by counting the number of fibres in each length group and then dividing by the mean length of the weight group (Gratton 2002). Fibre fineness and cross-sectional shape have been found to have a direct influence on the physical properties of fibre (Xu et al. 1993). Fibre fineness is expressed in units of tex where 1 tex is equal to 1 g km^{-1} (Kymäläinen 2004). Traditional methods of hemp processing have a minimum fibre fineness length of 1000 mm and a maximum length of approximately 2000 to 3000 mm, and the average fineness is 2.2 tex (Gratton 2002; Doberczak et al. 1964).

2.7.2 Decortication equipment performance Power requirement is another important performance indicator of decortication equipment. In an experiment done by Yu et al. (2006), a torque sensor was connected to the engine shaft of a Schutte heavy-duty hammer mill to measure the transfer of torque and engine rotational speed. Labview software was used to analyze and record the collected data. The sensor used in this experiment was a PCB Rotating Transformer Shaft Torque Sensor (Model 4205-01A). The sensor was directly coupled to the engine shaft to measure the transfer of power, torque, and speed between them.

3. FIBRE YIELD AND ENERGY REQUIREMENTS OF HEMP DECORTICATION USING A HAMMER MILL

3.1 ABSTRACT

Hemp fibre is a renewable resource that provides industries with numerous possibilities for market development. A hemp decortication experiment was conducted using a hammer mill. Varying treatments, including three screening scenarios (19.3 and 25.7 mm round-holed screens and no screen), three feeding masses (75, 125, and 200g), and two pre-cutting scenarios (hemp feedstock cut into 40 mm segments and non-cut) were studied using Green and Retted hemp feedstock. Fibre yield, core yield, effectiveness of decortication, power, and energy requirement were determined following decortication. Results showed that screening scenario, feeding mass, and pre-cutting scenario all impacted the power requirement, energy requirement, and fibre yields. Large screen scenarios, such as no screen, required less power and energy for both Green (14.4 kW and 37.4 kNm) and Retted (5.8 kW and 4.1 kNm) feedstock, but gave low fibre yields (2.7 and 5.9%, respectively). Pre-cut hemp for Green and Retted feedstock increased fibre yields (7.6 and 16.8%, respectively), core yields (27.3 and 54.6%, respectively), and the effectiveness of decortication (37.9 and 93.8%, respectively). Given the results, the combination of 19.3 mm screen, pre-cut feedstock, and a 75 g feeding mass for Retted hemp performed the best, in terms of fibre yield and effectiveness of decortication suggest a best combination for Green hemp.

Keywords: Hemp, decortication; hammer mill; fibre; power; energy

3.2 INTRODUCTION

Commercial growth of hemp (*Cannabis sativa*) was legalized in Canada in April 1998. Soon after, interest in hemp products, such as fibre, arose from international and local industries. Most of the interest in hemp fibre comes from its potential as a replacement or additive fibre source in products such as specialty textiles, paper, and composites. This potential exists due to

the fact that hemp has many advantages over other fibre crops, such as flax. The advantages of hemp include high biomass yield and high fibre content in stems (Sankari 2000), which may be exploited to improve the products in which they are used. Hemp, in combination with various resins, can be used to make composite boards, and hemp fibres also have the potential to replace fibreglass in certain applications (Fortenbery and Bennett 2004).

Fibre (the outer layer of hemp plants) and core (the inner woody layer of hemp plants) are two products generated from a decortication process. Fibre is the end-product of decortication, and core is the by-product. Decortication of hemp can be achieved by material processing machines, such as hammer mills, crushing rollers, and cutterheads. Hammer mills can be described as a drum with pivoting hammers mounted on cross-shaped rotors (Feed Machinery 2008). Hammer mills generate high impact forces and may be used for unretted hemp stalks when low fibre purity and high processing capacity are required (Chen et al. 2004). Hammer mills generate more chaff when compared to crushing rollers (Chen et al. 2004). A crushing roller comprises of rolls differing in size and uniformity. If the rolls rotate at the same speed compression is the primary force; if the rolls operate at different speeds shearing and compression are the primary forces which cause an unequal force for separation of the fibre; if the rolls are grooved a tearing or grinding force is applied (Feed Machinery 2008). A cutterhead machine adopted from a forage harvester was used by Gratton and Chen (2003) for in-field hemp decortication. The machine originally featured 12 knives, but was modified to be fitted with three cutting knives and nine scutching bars. The modified cutterhead resulted in better fibre purity, longer fibre, and more core removal compared to the cutterhead configuration with knives only.

Among all decortication machines, hammer mills are the most efficient, in terms of processing capacity (tones per hour). Because of this advantage, hammer mills have a wide range of applications. In the Australian coal industry, swing hammer mills have been used to grind coke oven feed to a size of less than 3 mm (Shi et al. 2003). Hammer mills have also been used as a pre-treatment of biomass for energy conversion. Feedstock for fuel pellets and briquettes have to be ground prior to being made into a denser product (Mani et al. 2004). A hammer mill was used in studies comparing some of the handling-related physical properties of biomass, with respect to grinding performance and final particle size of switchgrass, corn stover, and wheat and barley straws. Hammer mills are also widely used in the forage industry for grinding alfalfa chops to produce pellets (Shi et al. 2003). With the increased interest in fibre applications, hammer mills have been re-developed to accommodate this interest. Munder and Fürll (2004) reported that a hammer mill was included in a complete new machine line for processing natural fibres, including all stages from pick-up and cutting of straw bales to the cleaning of the final products, fibres and cores.

However, hammer mills are energy intensive machines. Thus, energy requirement is an important performance criterion of a hammer mill. Many factors such as screen size, feedstock particle size, moisture content, and feed rate all affect the energy requirement of the machines (Yu et al. 2006; Lopo 2002; Shi et al. 2003). Mani et al. (2004) observed that moisture content was directly related to energy consumption by hammer mills during processing of switchgrass, barley and wheat straws: the higher the moisture content, the higher the energy consumption. Desired final particle size is also known to impact the energy requirement of a hammer mill. Another factor affecting energy requirement is screen size. The smaller the screen opening, the more energy is required in order to grind the material to a small enough size to pass through the

screen (Yu et al. 2006; Savoie et al. 1989). Hammer mill grinding speed was also noted as having a significant effect on the energy requirement. Vigneault et al. (1992) studied the energy requirement for increasing hammer tip speed of a 6.4 mm thick hammer. They observed that energy requirements increased as the hammer tip speed increased.

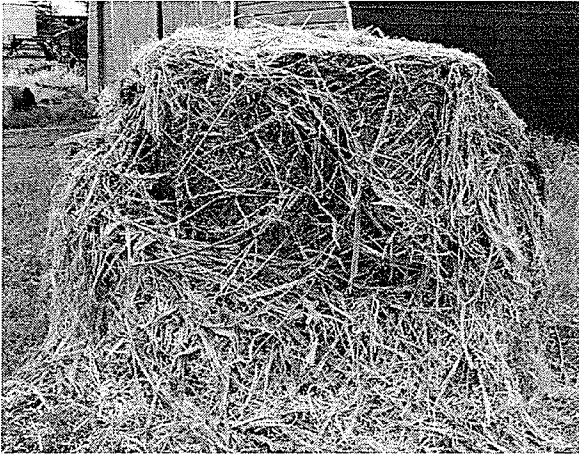
Other performance indicators of a hammer mill are the characteristics of the outputs, i.e. the characteristics of decorticated material. Gratton and Chen (2003) characterised the decorticated material as different fractions, such as fibre only, core only, and fibre-bound-to-core (core remains attached to fibre). Similar parameters were used by Munder et al. (2003) who observed that fibre accounted for 25% of the processing output, while core accounted for 21%, and 27% of product was fibre-bound-to-core. These fractions can be used to determine fibre yield and the effectiveness of the decortication process.

In summary, little or no research has been done on the fibre characteristics and energy requirement of hammer mill decortication of retted and green hemp. Lack of data on these aspects is the major obstacle for the further development of decortication machines. The objective of this study was to study fibre yield, power requirement, and energy requirement of a hammer mill for decortication of retted and green hemp under different initial pre-cutting scenarios, feeding masses, and screen scenarios.

3.3 MATERIALS AND METHODS

3.3.1 Description of feedstock

Two types of hemp feedstock, Retted hemp and Green hemp, were used in the decortication experiment. The hemp plants were harvested according to common farming practices in Manitoba. Retted hemp (USO 31 variety) was harvested in the previous year and left to ret in the field for approximately six weeks prior to being baled. Bales were stacked and stored outdoors. Samples for the decortication experiment were handpicked from a randomly selected bale (Fig 3.1a). Green hemp plants (Alyssa variety) were taken from the field (Fig. 3.1b) prior to seed harvest, and they were cut approximately 250 mm above soil level and the leaves were stripped from the stalks. The moisture content of the retted and green feedstock was 9.7% and 68.2%, respectively, and was measured by the oven-dry method at 60 °C for 72 hr (ASABE 2006). Retted and green hemp feedstock samples were then bagged in poly-woven grain bags and transported to the lab for decortication experiments.



(a)

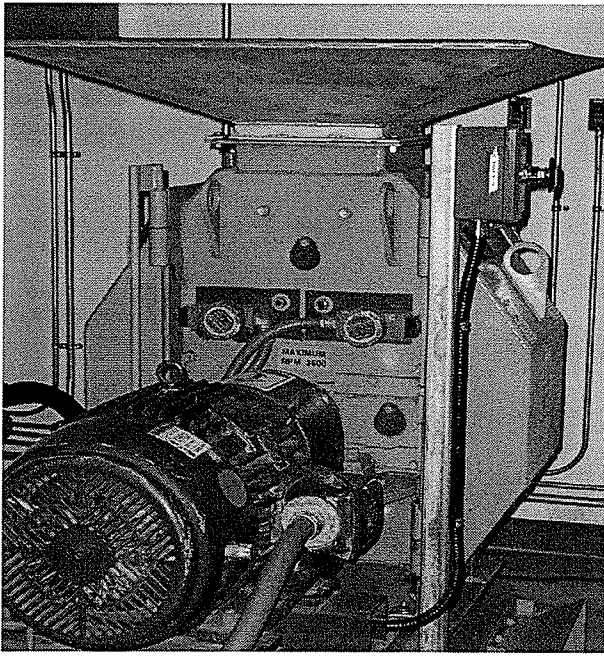


(b)

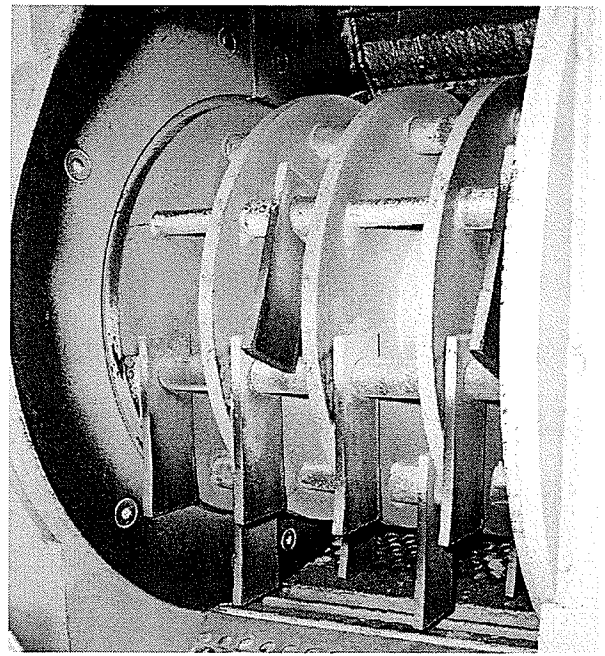
Fig. 3.1. Experimental feedstock for (a) Retted; and (b) Green hemp.

3.3.2 Decortication machine

The decortication machine used for the experiments was a swing hammer mill (Model E221.5-TFA, Bliss Eliminator, Oklahoma, U.S.A) available in the laboratory of Composites Innovation Centre (CIC), Manitoba. The hammer mill (Fig. 3.2a) consisted of a drive motor, a feeding hopper, and a cyclone (Model RC-24, Alanco) for collecting dust generated during decortication. The inner casing of the hammer mill, which housed the rotating shaft and hammers, had a diameter of 560 mm. There were 24 swinging hammers, and each was 175 mm long, 50 mm wide, and 7 mm thick. They were attached to shafts (Fig. 3.2b) powered by a 22 kW (30 hp) electric motor. The shafts rotated at a speed of 3600 rpm. The concave screen under the hammers could be removed and reinstalled through extra-heavy carriage locks.



(a)



(b)

Fig. 3.2. Decortication equipment; (a) hammer mill; and (b) swing hammers.

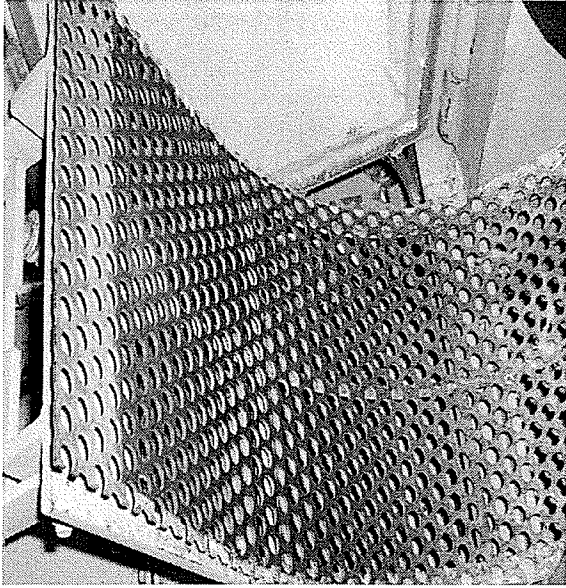
3.3.3 Experimental design

For the hemp decortication experiment, a randomized complete block design (RCB) was used under each type of feedstock; Retted and Green hemp. Blocks were represented by three screen scenarios: 19.3 mm opening, 25.7 mm opening, and no screen. Within each block, treatments included two pre-cutting scenarios: hemp feedstock cut into 40 mm and no pre-cutting, and three feeding masses: 75, 125, and 200 g. Treatments are summarised in Table 3.1.

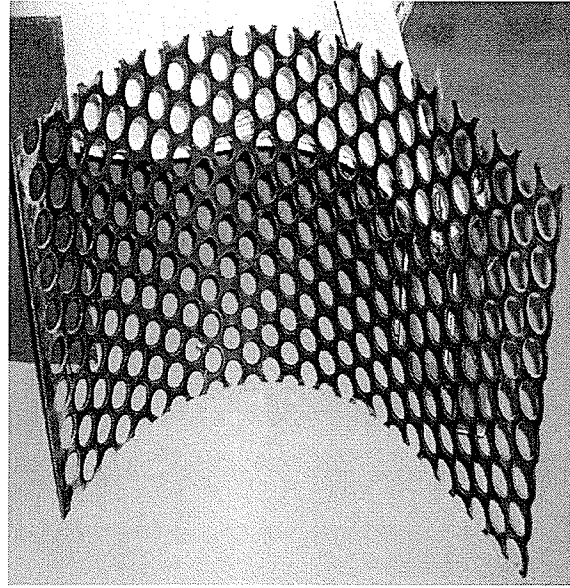
Table 3.1. Summary of treatments and symbols.

Treatment	Symbol
Type of feedstock	
Field retted and baled hemp	Retted hemp
Green and unbaled hemp	Green hemp
Screen scenario	
19.3 mm round screen opening	S1
25.7 mm round screen opening	S2
No screen	S3
Feeding mass	
75 g	F1
125 g	F2
200 g	F3
Pre-cutting scenarios	
Pre-cutting to 40 mm length	C1
Non-cut	C2

The screen sizes selected were the largest possible with the hammer mill. Both screens were staggered perforated screens with round screen openings (Fig 3.3a and 3.3b). The cut length of 40 mm was chosen based on ideal lengths for different end-products specified by the CIC lab. The selected masses were chosen based on the decortication capability of the hammer mill according to the results from preliminary trials using different masses. A total of four replications were performed for each treatment. Thus, a total of 72 tests (3 screen scenarios x 2 pre-cutting scenarios x 3 feeding masses x 4 replications) were performed.



(a)



(b)

Fig. 3.3. Hammer mill round-holed screens for; (a) the treatment S1 (opening size: 19.3 mm); and (b) the treatment S2 (25.7 mm).

3.3.4 Test procedure

For both Retted and Green hemp, 40 mm cut hemp feedstock was obtained using a heavy-duty paper cutter. For a test run, the hammer mill was started, and after the rotational speed was increased to a constant speed of 3600 rpm, feedstock with the desired mass was loaded into the hopper in a single motion by hand. The material fell through the screen and went to the chaff stream and that remained on the top of the screen went to the product stream. The chaff stream was disposed and the decorticated material in the product stream was re-bagged for later analysis. The hammer mill was cleaned out after each run.

3.3.5 Measurements

Decorticated material was separated manually into three fractions: fibre (free of core), core (free of fibre), and fibre-bound-to-core (core remained attached to fibre). Each fraction was weighed using a digital scale (Model MS200, Mars, North York, Canada). The mass of each fraction was recorded to determine the fibre yield, core yield, and effectiveness of decortication of the hammer mill as described below.

3.3.5.1 Fibre yield Fibre yield was defined as the mass of fibre divided by the mass of feed.

Fibre yield was determined using the following equation:

$$Y_f = \frac{m_F}{M} 100 \quad (1)$$

where:

Y_f = fibre yield (%);

m_f = mass of fibre fraction (g), and;

M = mass of feedstock (g).

3.3.5.2 Core yield Core yield was defined as the mass of core fraction divided by the mass of feedstock. Core yield was determined by the following equation:

$$Y_C = \frac{m_C}{M} 100 \quad (2)$$

where:

Y_C = core yield (%);

m_C = mass of core fraction (g), and;

M = mass of feedstock (g).

3.3.5.3 Effectiveness of decortication To assess the effectiveness of the hammer mill in separating fibre from its core, the reduction in the amount of fibre-bound-to-core was determined. More fibre-bound-to-core implied less effectiveness of the hammer mill. The effectiveness of decortication was determined by:

$$\eta = \frac{M - m_{f/c} - m_{ch}}{M} 100 \quad (3)$$

where:

η = effectiveness of decortication (%);

$m_{f/c}$ = mass of fibre-bound-to-core fraction (g),

m_{ch} = mass of chaff fraction (g), and;

M = mass of feedstock (g).

3.3.5.4 Power requirement Motor power was measured using 9000XDrive Software, which was directly linked from a laptop computer to the hammer mill via an adjustable frequency drive (Model SVX9000, Eaton, Ohio, USA). This setup recorded the motor torque, speed, power, current, and voltage every 0.1 second. Only the power data was discussed in this study. Figure 3.4 shows a typical bell-shaped power-time curve. The output values of the power were the

percentage of the motor rated maximum power (22 kW). The initial high increase in power was due to material being decorticated. The highest point in the curve is referred to as its peak power value. The slow decrease from peak power was due to the material being displaced from the screen and the completion of decortication. To examine the power requirement as affected by the experimental factors, the peak power was taken from each power-time curve. Power required for decortication was determined based on an assumed 15% loss of power between the motor and the hammer mill.

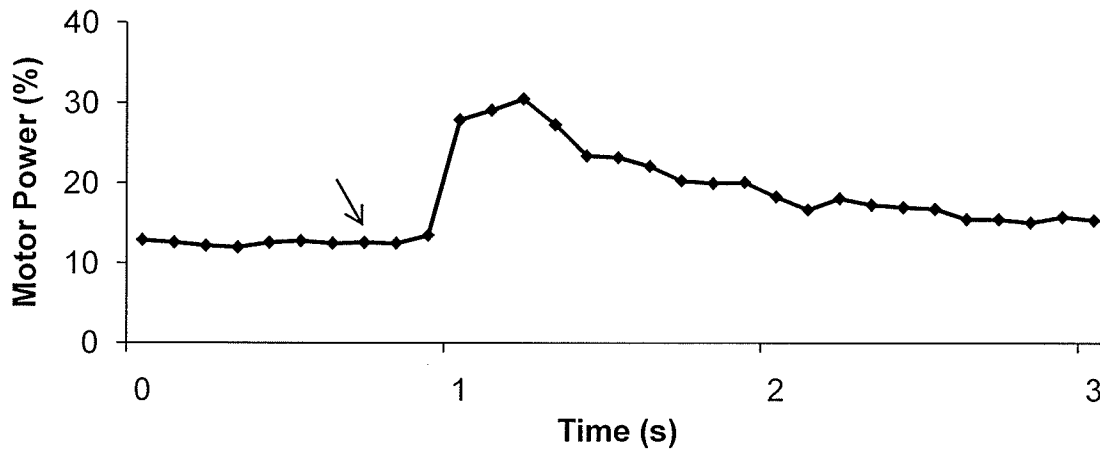


Fig. 3.4. Motor power measurement recorded using 9000XDrive software. Values are a percentage of the motor power. The arrow indicates the point in time which the sample was fed into the machine.

3.3.5.5 Energy requirement The recorded power-time curve was used to estimate the energy. The total energy is represented by the area underneath the power-time curve. The calculation is demonstrated by the following equation:

$$E = \left[\left(\frac{y_2 + y_1}{2} \right) * \Delta t + \left(\frac{y_3 + y_2}{2} \right) * \Delta t + \dots + \left(\frac{y_n + y_{n-1}}{2} \right) * \Delta t \right] \quad (4)$$

where:

E = Energy (kNm);

y_1 = the first data point (kW);

y_2 = the second data point (kW);

y_n = the n^{th} data point (kW), and;

Δt = time interval (s).

3.3.5.6 Data analysis Analysis of variance (ANOVA) was performed on the data for different treatments within each of Retted and Green hemp using Statistical Analysis Software (SAS/STAT V9.1.3). The macro procedure “pdmix800.sas”, in combination with the Fisher’s Least Significant Difference (LSD) test, was used to detect the differences among treatment means at a significance level of 0.05.

3.4 RESULTS AND DISCUSSION

The results of the ANOVA analysis are summarised in Tables 3.2a and 3.2b. Results were seen to be variable; however, significant effects of the experimental factors (feeding mass, screen scenario, and pre-cutting scenario) were detected for most cases. The interactions of the experimental factors were also significant in many cases. When the interaction effects of experimental factors were not significant, the main effects of the experimental factors are presented. Otherwise, the simple effects are presented.

Table 3.2a. Analysis of variance (ANOVA) results of Green and Retted hemp on power and energy requirements.

Source**	Power (kW)		Energy (kNm)	
	F Value	Pr>F	F Value	Pr>F
<i>Green hemp</i>				
S	3.91	0.0264*	20.26	<0.0001*
C	0.39	0.5364	15.39	0.0003*
F	2.14	0.1287	37.63	<0.0001*
C*F	1.53	0.2272	2.09	0.1340
S*C	1.29	0.2841	3.75	0.0302*
S*F	0.98	0.4279	1.06	0.3874
S*C*F	0.79	0.5359	2.48	0.0560
<i>Retted hemp</i>				
S	890.02	<0.0001*	110.37	<0.0001*
C	27.13	<0.0001*	7.53	0.0084*
F	4.43	0.0169*	40.13	<0.0001*
C*F	3.91	0.0265*	1.73	0.1881
S*C	19.33	<0.0001*	2.59	0.0847
S*F	5.77	0.0007*	7.27	0.0001*
S*C*F	1.70	0.1658	0.98	0.4262

* Statistically significant (P < 0.05).

** S – Screen scenario; C – Pre-cutting scenario; F – Feeding mass.

Table 3.2b. Analysis of variance (ANOVA) for Green and Retted hemp on fibre yield, core yield, and effectiveness of decortication.

Source **	Fibre yield		Core yield		Effectiveness of decortication	
	F Value	Pr>F	F Value	Pr>F	F Value	Pr>F
<i>Green hemp</i>						
S	184.25	<0.0001*	3.26	0.1097	1.10	0.3396
C	7.36	0.0095*	12.73	0.0009*	15.57	0.0003*
F	299.19	<0.0001*	281.26	<0.0001*	388.95	<0.0001*
C*F	2.73	0.0765	0.17	0.8466	0.59	0.5563
S*C	34.52	<0.0001*	3.25	0.0486*	7.75	0.0012
S*F	22.51	<0.0001*	4.80	0.0027*	1.96	0.1147
S*C*F	31.46	<0.0001*	2.38	0.0665	7.03	0.0001*
<i>Retted hemp</i>						
S	15.18	0.0043*	17.42	0.0031*	59.30	<0.0001*
C	0.62	0.4359	4.82	0.0335*	0.95	0.3342
F	0.23	0.7950	0.62	0.5413	16.63	<0.0001*
C*F	0.86	0.4318	2.10	0.1346	21.77	<0.0001*
S*C	0.42	0.6629	6.31	0.0039*	17.46	<0.0001*
S*F	0.41	0.7984	1.20	0.3245	14.97	<0.0001*
S*C*F	3.28	0.0202*	3.12	0.0240*	31.09	<0.0001*

* Statistically significant ($P < 0.05$).

** S – Screen scenario; C – Pre-cutting scenario; F – Feeding mass.

3.4.1 Peak power and energy

3.4.1.1 Effects of pre-cutting scenario For decorticating Green hemp, cut (C1) and non-cut hemp stalk (C2) scenarios resulted in similar peak power under all screen scenarios: S1, S2, and S3 (Table 3.3). The average peak power over the three screen scenarios was 14.2 kW. However, C2 had a greater energy requirement than C1, and the difference was significant under S1 and S2. This means that more energy was required to decorticate non-cut hemp stalk than cut stalk of the same amount. Values of energy for Green hemp varied from 36.9 to 79.7 kNm. The highest energy value for Green hemp was observed for the combination of S1 and C2, meaning that decorticating the non-cut Green hemp with the smallest screen opening size required the greatest energy.

For Retted hemp, pre-cutting scenario affected the peak power and energy only when the 25.74 mm screen (S2) was used (Table 3.3). In this case, peak power increased from 13.8 kW for the pre-cutting scenario C1 to 14.1 kW for the non-cut scenario (C2). Results of energy requirements for Retted hemp showed a similar trend to the power results, in terms of the treatment effects. Only under S2, pre-cutting scenario made a difference in energy requirement, and an increase in energy from 16.9 kNm for C1 to 22.5 kNm for C2 was observed. Mani et al. (2004) observed similar results in which energy consumption increased with larger mean chop sizes.

The results of the lower energy requirement for the non-screen scenario may be explained by the following facts. When there was no screen under the hammers, the hemp feedstock would drop straight through the hammers, resulting in a very short decortication duration. Thus, the material could be only slightly decorticated by the hammers, regardless of the feedstock being cut or not.

Table 3.3. Means of peak power and energy for different pre-cutting scenarios.

Treatment**	Green hemp				Retted hemp			
	Power (kW)		Energy (kNm)		Power (kW)		Energy (kNm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
S1								
C1	14.22 a*	0.09	53.33 b	12.59	14.28 a	0.05	19.04 a	6.33
C2	14.24 a	0.06	79.73 a	35.31	14.28 a	0.04	19.44 a	8.23
S2								
C1	13.72 a	0.16	44.75 b	10.56	13.83 b	0.51	16.94 b	0.38
C2	14.28 a	0.06	60.91 a	23.56	14.13 a	0.29	22.52 a	9.87
S3								
C1	14.36 a	0.14	36.89 a	23.99	4.46 a	0.60	2.95 a	1.08
C2	14.36 a	0.12	37.99 a	15.32	7.03 a	1.69	5.19 a	0.80

* Means with the same letter are not significantly different within each screen scenario at $P < 0.05$.

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; C1 – 40 mm cut length feedstock; C2 – non-cut feedstock.

3.4.1.2 Effects of feeding mass Peak power of decorticating Green hemp differed between feeding masses only for S2, where the lowest feeding mass, F1 treatment, had a higher peak power than F2 and F3 (Table 3.4). The higher peak power for a lower feeding mass was unexpected. The reason could be that the feed was not evenly distributed in the hammer mill housing, and went through the housing as a lump, which caused an unexpected power jump. In this case, energy data may better reflect the effects of feeding mass. In fact, the energy data showed a very consistent increasing trend with the increasing feeding mass, regardless of the screen scenario.

Similar to Green hemp, peak powers of Retted hemp were at the same levels under S1 and S3 (Table 3.4). Under S2, peak power was different among the three feeding masses. However, the highest peak power of F2 was unexpected. This could also be the result of uneven feed mass distribution on the mill housing. Again, the energy requirement under S1 and S2 significantly increased with the increase of feeding mass. A similar trend under S3 was also observed, although it was not statistically significant.

Table 3.4. Means of peak power and energy for different feeding masses.

Treatment**	Green hemp				Retted hemp			
	Power (kW)		Energy (kNm)		Power (kW)		Energy (kNm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
S1								
F1	14.20 a*	0.05	51.06 b	6.16	14.28 a	0.04	13.09 c	2.15
F2	14.25 a	0.08	54.50 b	12.81	14.25 a	0.01	17.51 b	1.80
F3	14.25 a	0.11	94.04 a	37.04	14.30 a	0.05	27.14 a	1.22
S2								
F1	21.25 a	22.33	36.10 c	1.15	13.96 b	0.22	12.48 c	1.41
F2	14.27 b	0.00	52.30 b	13.43	14.18 a	0.09	18.98 b	2.92
F3	14.28 b	0.17	70.07 a	19.71	13.79 c	0.78	27.73 a	7.50
S3								
F1	14.28 a	0.03	19.92 b	11.25	4.74 a	0.79	3.06 a	1.88
F2	14.51 a	0.03	34.68 b	5.94	5.62 a	2.24	4.30 a	1.28
F3	14.30 a	0.06	57.71 a	2.98	6.89 a	2.49	4.86 a	1.60

* Means with the same letter are not significantly different at $P < 0.05$.

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; F1 – Feeding mass 75 g; F2 – Feeding mass 125 g; F3 – Feeding mass 200 g.

3.4.1.3 Effects of screen scenario and type of hemp feedstock For Green hemp, power results were not statistically different between screen scenarios, indicating that the screen scenarios had no impact on the peak power for decortication of Green hemp (Fig. 3.5). For Retted hemp, peak powers were similar for tests when screens were present. However, in the absence of a screen, the power requirement dropped significantly. These results are in agreement with Mani et al. (2004) who observed that with a constant increase in screen size the power requirement drops. When Green hemp was compared to Retted hemp, a slightly higher peak power was observed for Green hemp. Yu et al. (2003) determined that power requirement, in part, is related to moisture content. The high moisture content of the Green hemp accounted for the majority of the total feeding mass, and therefore, required a more vigorous processing for extracting fibre. This may be attributable to the greater peak power of Green hemp.

Green hemp results showed no significant difference in energy requirement between screen scenarios (Fig. 3.6). Retted hemp under S3 required lower energy than under S2 and S1. Yu et al. (2006) observed that energy requirements increased as the final particle size decreased when screens were present. This may explain the result of higher energy requirements of S1 and S2. The presence of the screen in these two treatments would result in the hemp feedstock being processed into smaller particles. Whereas in the case of no screen, material simply passed by the hammers before being processed. When Green hemp was compared to Retted hemp, much higher energy was required for the decortication of Green hemp. Again, the higher moisture content of Green hemp may be the major contributing factor, as reported by Mani et al. (2004) who observed a direct relationship between moisture content and energy requirement.

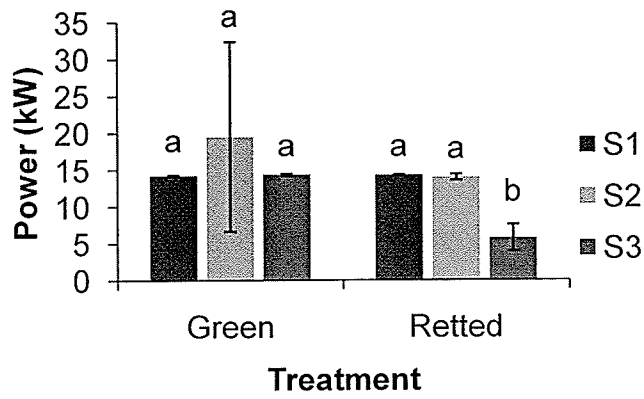


Fig. 3.5. Peak power for decorticating Green and Retted hemp using three different screen scenarios: 19.3 mm (S1), 25.7 mm (S2), and no screen (S3).

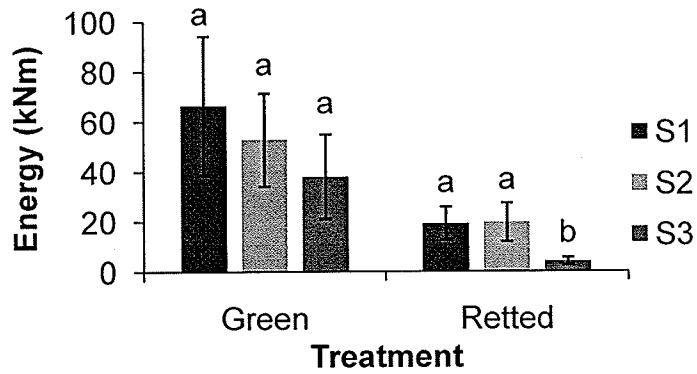


Fig. 3.6. Energy for decorticating Green and Retted hemp using three different screen scenarios: 19.3 mm (S1), 25.7 mm (S2), and no screen (S3).

3.4.2 Fibre yield, core yield, and effectiveness of decortication

3.4.2.1 Effects of pre-cutting scenario Values of fibre yield (Y_f) varied from 2.8 to 11.1% (Table 3.5). Effects of the pre-cutting scenario on Y_f showed mixed trends among S1, S2, and S3 for Green hemp. As compared with C2, under S1, C1 produced a lower Y_f , under S2, C1 produced a higher Y_f , and under S3, C1 produced a similar Y_f . The highest Y_f was observed for the combination of C1 and S2, which demonstrated that using the 25.7 mm screen scenario to decorticate pre-cut hemp resulted in the most fibre. Fibre yields were generally low for Green hemp. A lack of retting and a late harvest date may have contributed to the low fibre yields. Mediavilla et al. (2001) observed that fibre yield is dependent upon the growth stage of the plant, and maximal fibre yield is reached at male flowering (summer solstice).

For core yield (Y_C) of Green hemp, Y_C of C1 was greater than that of C2 for all under S2 and S3, meaning that pre-cutting favoured higher core yield. Effects of pre-cutting scenario on effectiveness of decortication (η) were significant for S2 and S3 for Green hemp, where cut feedstock was more effective, in terms of detaching fibre from the core. A partial decortication action which took place during the preparation of the C1 samples may have contributed to the effectiveness of decortication.

Table 3.5. Green hemp – means of fibre yield, core yield, and effectiveness of decortication for different pre-cutting scenarios.

Treatment **	Fibre yield (%)		Core yield (%)		Effectiveness of decortication (%)	
	Mean	SD	Mean	SD	Mean	SD
S1						
C1	8.70 b*	5.32	23.34 a	12.50	32.04 a	13.59
C2	9.91 a	8.09	23.32 a	14.75	33.23 a	18.82
S2						
C1	11.12 a	6.95	26.79 a	12.47	37.91 a	14.28
C2	6.81 b	3.79	21.79 b	13.16	28.60 b	13.69
S3						
C1	2.82 a	3.25	31.81 a	20.04	34.63 a	20.30
C2	3.47 a	2.03	26.06 b	16.63	29.53 b	16.75

* Means with the same letter are not significantly different at $P < 0.05$.

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; C1 – 40 mm cut length feedstock; C2- non-cut feedstock.

For Retted hemp, treatment effects on output products were generally similar to those for Green hemp. For example, cutting hemp feedstock helped increase the fibre and core yields and the effectiveness of decortication (Table 3.6). For Retted hemp, the S1-C1 combination resulted in the greatest Y_f (23.3%) for this range of study. This may be due to a partial decortication process which took place in the preparation of the pre-cutting scenario C1. For both S2 and S1, C1 had a greater Y_C than C2. Values increased from 57.9 to 73.7% and 39.1 to 55.8% for S2 and S1, respectively. For Retted hemp, effects of pre-cutting scenario on η were mixed under different screen scenarios. The greatest η was found for C1 using S2 (93.8%), whereas the C2 for S3 was the least effective (40.6%) due to the limited decortication action.

Table 3.6. Retted hemp – means of fibre yield, core yield, and effectiveness of decortication for different pre-cutting scenarios.

Treatment**	Fibre yield (%)		Core yield (%)		Effectiveness of decortication (%)	
	Mean	SD	Mean	SD	Mean	SD
S1						
C1	23.30 a*	13.54	55.78 a	23.03	79.08 a	26.72
C2	13.43 b	4.66	39.08 b	7.92	52.51 b	9.20
S2						
C1	20.06 a	16.70	73.71 a	64.52	93.77 a	66.65
C2	21.23 a	12.11	57.86 b	23.65	79.09 b	26.57
S3						
C1	7.07 a	6.35	34.44 a	8.04	41.51 a	10.25
C2	6.72 a	4.58	33.85 a	9.83	40.57 a	10.84

* Means with the same letter are not significantly different at $P < 0.05$

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; C1 – 40 mm cut length feedstock; C2- non-cut feedstock

3.4.2.2 Effects of feeding mass For Green hemp, the greatest Y_f for each screen was found for F1, followed by F2 and F3, respectively (Table 3.7). Thus, the F1 for S1 performed the best for Green hemp, since it resulted in the highest Y_f (15.9%). Feeding mass F1 gave a greater Y_C than F2 and F3 for all screen scenarios. More fibre was detached from the core for smaller feeding masses, as shown by the effectiveness of decortication with feeding mass. These results suggest that larger feeding masses need to be decorticated a second time or undergo a longer milling duration.

Table 3.7. Green hemp – means of fibre yield, core yield, and effectiveness of decortication for different feeding masses.

Treatment**	Fibre yield (%)		Core yield (%)		Effectiveness of decortication (%)	
	Mean	SD	Mean	SD	Mean	SD
S1						
F1	15.93 a *	4.41	38.27 a	2.41	54.20 a	5.03
F2	8.81 b	2.53	19.91 b	2.55	28.73 b	3.59
F3	3.18 c	0.68	11.80 c	0.11	14.98 c	0.69
S2						
F1	14.61 a	6.29	38.13 a	2.94	52.74 a	6.94
F2	5.27 b	0.49	21.88 b	3.81	27.15 b	3.84
F3	2.92 c	2.39	12.84 c	3.86	15.77 c	4.54
S3						
F1	5.31 a	1.78	49.96 a	7.05	55.27 a	7.27
F2	3.16 b	2.80	20.10 b	0.95	23.26 b	2.96
F3	0.97 c	0.36	16.74 c	4.21	17.71 c	4.23

* Means with the same letter are not significantly different at $P < 0.05$.

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; F1 – Feeding mass 75 g; F2 – Feeding mass 125 g; F3 – Feeding mass 200 g.

For S2 and S1 of Retted hemp, the smallest feeding mass resulted in a greater Y_f and Y_C , possibly due to a limited degree of decortication (Table 3.8). The greatest Y_f was observed at S2 for F1 (34.6%). Values of Y_C for Retted hemp increased from 26.9 to 63.8% and 35.0 to 57.3% for S2 and S1, respectively, when the feeding mass decreased from F3 to F1. The maximum Y_C was observed for F1 at S2 (63.8%). Again, greater effectiveness of decortication was observed for smaller feeding masses.

Table 3.8. Retted hemp – means of fibre yield, core yield, and effectiveness of decortication for different feeding masses.

Treatment**	Fibre yield (%)		Core yield (%)		Effectiveness of decortication (%)	
	Mean	SD	Mean	SD	Mean	SD
S1						
F1	24.07 a*	10.36	57.26 a	9.30	81.33 a	13.92
F2	18.95 b	9.45	50.01 b	6.10	68.96 b	11.25
F3	12.07 c	2.00	35.02 c	4.54	47.09 c	4.96
S2						
F1	34.59 a	11.15	63.76 a	14.78	98.38 a	18.51
F2	20.28 b	13.23	49.66 b	6.03	69.94 b	14.54
F3	7.96 c	1.81	26.93 c	5.57	34.89 c	5.86
S3						
F1	8.33 a	5.37	36.86 a	3.34	45.18 a	6.32
F2	8.46 a	5.89	39.66 a	3.31	48.12 a	6.77
F3	3.90 b	2.42	25.92 b	2.66	29.82 b	3.60

* Means with the same letter are not significantly different at $P < 0.05$.

** S1 – 19.3 mm screen; S2 – 25.7 mm screen; S3 – no screen; F1 – Feeding mass 75 g; F2 – Feeding mass 125 g; F3 – Feeding mass 200 g.

3.4.2.3 Effects of screen scenario and type of hemp feedstock For both Green and Retted hemp, Y_f from S1 was similar to that from S2, and a significant decrease in Y_f was observed when no screen (S3) was used (Fig. 3.7). The lower Y_f of S3 was due to the insufficient decortication action, resulting in the majority of the fibre being still attached to the core in the output product. Overall, Y_f of Retted hemp was greater than Green hemp. Retting made decortication easier (Gratton and Chen 2003). Kymäläinen (2004) observed that very little pectin remains with well retted plants to hold the fibre to the core.

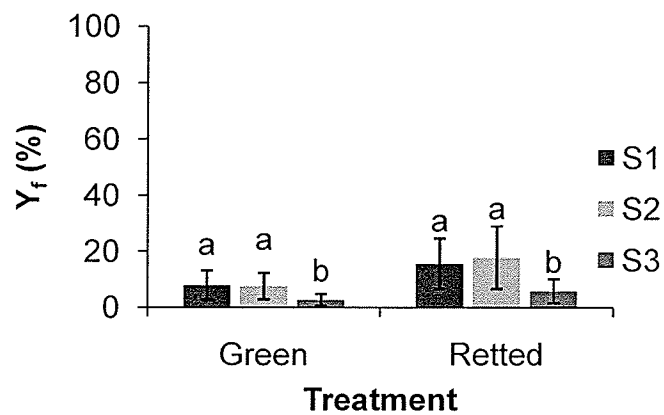


Fig. 3.7. Green and Retted hemp fibre yield (Y_f) and standard deviations for 19.3 mm (S1), 25.7 mm (S2), and no screen (S3).

For Green hemp, screen scenario did not make a difference in Y_C (Fig. 3.8). For Retted hemp, Y_C was different among three screen scenarios with the S2 having the greatest Y_C (55.9%). More cores were produced from Retted hemp than from Green hemp. These results agree well with Hobson et al. (2001) who observed that core fragments remained within the fibre of non-retted hemp following decortication, whereas with Retted hemp, core fragments are easily separated from the fibre.

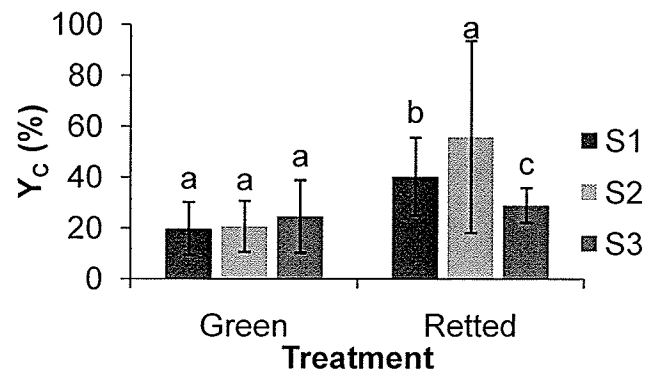


Fig. 3.8. Green and Retted hemp core yield (Y_C) and standard deviations for 19.3 mm (S1), 25.7 mm (S2), and no screen (S3).

For Green hemp, effectiveness of decortication did not significantly differ between screen scenarios (Fig. 3.9). Effects of screen scenario on η showed that S3 significantly differed from S1 and S2 for Retted hemp. In the presence of screens, 65.8 and 68.9% of fibre was detached from the core using S1 and S2, respectively. This value decreased to 41.0% when S3 scenario was used.



Fig. 3.9. Green and Retted hemp effectiveness of decortication (η) and standard deviations for 19.3 mm (S1), 25.7 mm (S2), and no screen (S3).

3.5 CONCLUSION

Screen scenario, feeding mass, and pre-cutting scenario had an effect on peak power requirement, energy requirement, fibre yield, core yield, and the effectiveness of decortication. Non-cut hemp feedstock, in combination with the smallest screen scenario, required more power and energy for Green (14.2 kW and 79.7 kNm) than Retted (14.3 kW and 19.4 kNm) hemp decortication. In general, the larger the feeding masses the more power and energy required for Green and Retted hemp decortication. When the feeding mass increased from 75 to 200 g, the energy required for both Green and Retted hemp approximately doubled for all screen scenarios. Overall, Retted hemp required significantly more power and energy than Green hemp.

Retted hemp produced higher fibre and core yields than Green hemp (23.3 and 73.7%, and 11.1 and 31.8%, respectively). The greatest fibre yield (34.6%) was observed for the smallest feeding mass and screen scenario for Retted hemp. As screen scenario increased the fibre yield decreased. The highest core yield (63.8%) was observed for the smallest feeding mass using the 25.7 mm screen for Retted hemp. With an increase in feeding mass, and a decrease in screen scenario and feedstock cut length, the core yield increased.

Effectiveness of decortication showed to have an impact of the final product, and favoured smaller feeding masses. The greatest effectiveness of decortication (93.4%) was observed for the smallest feeding mass using the smallest screen for Retted hemp. Green feedstock with high moisture contents are not suitable for hammer mill decortication, and must be decorticated with an alternate machine or allowed to ret prior to decortication. These conclusions are limited on account that the study was carried out with small feeding masses, and

machinery more suitable for grain and flax processing. Further research is required to confirm the above conclusions.

3.6 ACKNOWLEDGMENTS

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4. HEMP FIBRE DECORTICATION USING A PLANETARY BALL MILL

4.1 ABSTRACT

The hemp industry is an expanding sector of the Canadian economy that presents a positive change for the environment. Hemp fibre is a renewable resource which has the market potential for producing new, and replacing existing fibre products. A hemp decortication experiment was conducted using a planetary ball mill. Varying treatments, including three grinding durations (2, 4, and 6 min) and seven grinding speeds (100, 150, 200, 250, 300, 350, and 400 rpm) were studied using retted hemp feedstock. Under these treatments, fibre yield, core yield, and amount of chaff were determined following decortication. The detaching efficiency (defined as the reduction in the amount of fibre-bound-to-core), along with the performance index, were also determined to evaluate the performance of the ball mill for hemp decortication. Results showed that grinding duration and speed impacted all the measured variables. Low grinding speeds, such as 100 rpm, resulted in a poor detaching efficiency (52.6%). Higher grinding speeds, such as 350 rpm, allowed for a greater detaching efficiency (99.7%), but reduced fibre yields (27.8% for 6 min grinding duration). The combination of the greatest grinding speed and duration resulted in high levels of chaff production (up to 100.0%). Given all these facts, the combination of 200 rpm grinding speed and 4 min grinding duration, or 250 rpm grinding speed and 6 min grinding duration, performed the best, in terms of fibre yield and detaching efficiency. **Keywords:** hemp, decortication, planetary ball mill, fibre yield, grinding speed, grinding duration.

4.2 INTRODUCTION

Hemp (*Cannabis sativa*) is a temperate climate plant grown mostly in Europe, Russia, and Canada. In April of 1998, hemp was legalized for industrial cultivation in Canada. The legalization of hemp allowed for its use as a natural fibre. High quality hemp fibre may be cottonized and used in the textile industry, composite industry, or other fibre industries (Kostuik et al. 2007). Natural fibre composites (biocomposites) have been used to replace glass mostly in non-structural applications, such as automobile components (Wambua et al. 2003) as well as building materials. Biocomposites offer numerous advantages compared to traditional composites, such as light weight and high tensile strength.

Increasing interest in hemp fibre has been occurring due to desired properties such as low density, acceptable strength, good thermal insulation, reduced dermal and respiratory irritation, recyclability, and biodegradability (Park et al. 2006; Li et al. 2000; Wong et al. 2004; van de Weyenberg et al. 2003; Gassan 2002; Baiardo 2004). Hemp fibre is comparable to glass fibre in high volume applications in regards to its tensile and modulus strength, and durability (Williams and Wool 2000). In a study conducted by Wambua et al. (2003), hemp fibre showed a tensile strength of approximately 52 MPa. The high tensile strength makes hemp fibre an acceptable choice for biocomposite material.

To obtain fibre, hemp needs to go through a decortication process. Decortication removes the outer fibrous layer (fibre) from the inner layer (core). This is also referred to as the detaching process in which the bonds between the outer fibres and the inner core break by forces applied by the machine. Decortication can be achieved with several mechanisms, such as hammer mills, crushing rollers, and cutterheads. Their working principle is to produce shear

force, compressive force, impact force, or a combination of forces to break the bonds between fibre and core. The detached material is a mixture of bast fibre, core, and fines. The mixture needs to go through a cleaning system where cores and fines are separated from fibre to obtain clean fibres.

Hammer mills are energy-intensive machines that use impact and shear forces to separate fibre from core. Gratton and Chen (2004) used a modified cutterhead with three knives and angle steel scutching bars to decorticate hemp stalk. Cutting and impact forces were involved for separating fibre and core. A maximum fibre yield of 61% with a purity of 52% was observed, and approximately 45% of the fibre was lost into the chaff outlet. Another method of decortication involves crushing rollers which were widely used to grind wheat into flour (Fang et al. 1997). They were adopted for hemp decortication. Crushing rollers utilize fluted, pinned, and flat rollers to crush and separate hemp fibre. The major separation force is compressive force. In general, hammer mill and cutterhead methods generate low fibre purity and do not allow for an entire separation of fibre from core (Fürll and Hempel 2000; Gratton and Chen 2004). Crushing rollers may produce cleaner fibre when they are used for retted hemp. However, the processing capacity of crushing rollers is low.

Decortication may also be achieved through the use of a ball mill. Ball mills have a wide range of research applications. Fukazawa et al. (1982) used a ball mill to investigate the efficiency of enzyme digestion of ball milled aspen wood. Ball mills were utilized for medical research to prepare a dry powder vaccine which contained whole inactive influenza virus, and a mucoadhesive compound for nasal delivery (Garmise et al. 2006). Ball mills have also been used in the materials research industry. Périgo et al. (2007) used a planetary ball mill to produce sintered PrFeB magnets. The milling process is a mechanical process in which energy is

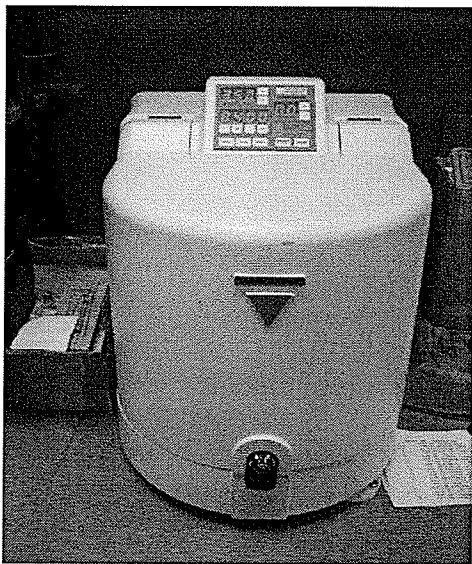
released at the point of collision between grinding balls (Prasad et al. 2005). Material is placed into a specific size and type of grinding bowl along with an appropriate size, type, and number of grinding balls. The ball mill operates in a circular motion, and when the mill rotates centrifugal forces cause the balls to travel upward along the wall of the grinding bowl. The faster the mill rotates, the farther the balls are carried up inside the mill (Prasad et al. 2005). The falling balls produce impact force upon the material. This kind of process could be potentially used for hemp decortication.

In summary, some research has been performed on the decortication of hemp using a hammer mill, crushing roller, and cutterhead, but no research has been done on the decortication of hemp using a ball mill. The objective of this study was to investigate the performance of a ball mill for hemp decortication under different grinding durations and grinding speeds. The major performance indicators measured included fibre yield and detaching efficiency of grinding.

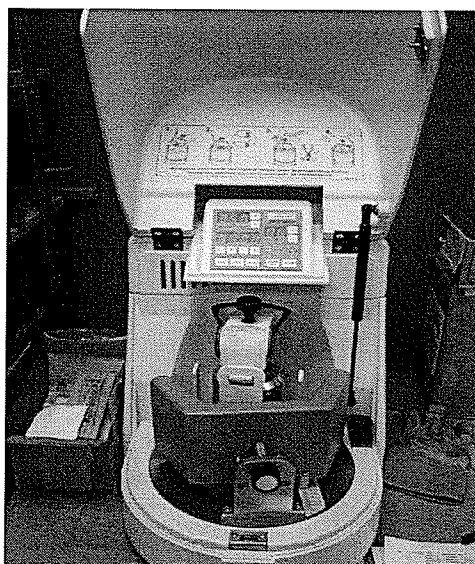
4.3 MATERIALS AND METHODS

4.3.1 Ball mill machine

A lab-scale Planetary Mono Ball Mill (Fig. 4.1a) (Model Pulverisette 6, Fritsch, Idar-Oberstein, Germany) was used to decorticate hemp stock. The mill was securely fastened to a level surface during decortication. Inside the mill housing, there was a grinding bowl holder and disc which supported the grinding bowl (Fig. 4.1b). The grinding bowl (Fig. 4.1c) had an agate-liner inside and the net volume of the bowl was 250 mL. The grinding media were fifteen 20 mm diameter agate balls (Fig. 4.1d). In a grinding operation, the grinding bowl, filled with the grinding balls, was clamped onto the bowl holder. The grinding bowl rotates about its own axis and at the same time rotates with the support disc in the opposite direction (Fig. 4.2a). Thus, the centrifugal forces alternately act in the same and opposite directions (Fritsch 2005). This results in the grinding balls running along the inner wall of the grinding bowl (Fig. 4.2b) causing frictional and impact effects on the material being ground. The control panel of the mill allowed for the selection of rotational speeds in the range of 100 to 650 rpm in 10 rpm intervals, and grinding durations from 1 min to 99 h.



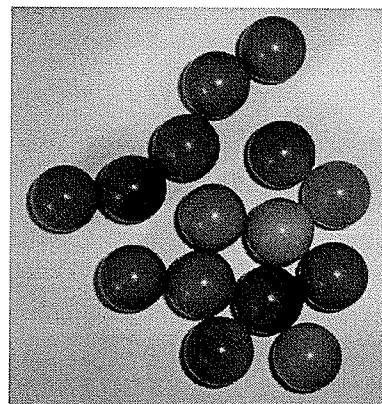
(a)



(b)

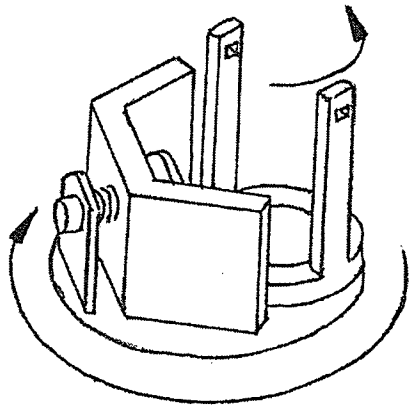


(c)

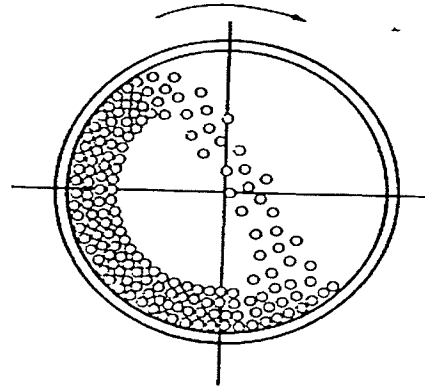


(d)

Fig. 4.1. Decortication equipment; (a) the planetary mono ball mill; (b) inside the mill; (c) grinding bowl; and (d) agate grinding balls.



(a)



(b)

Fig. 4.2. Diagram showing the working principle of the planetary mono ball mill; (a) opposite rotational directions of grinding bowl holder and support disc; and (b) top view of balls running along inner wall of grinding bowl (Fritsch 2005; Prasad 2005).

4.3.2 Description of hemp feedstock

The milling process of a ball mill is a relatively slow process when compared with a hammer mill, due to a relatively lower impact force of the ball mill. Kymäläinen et al. (2001) observed that retting makes decortication easier. Thus, field retted and baled (USO 31 variety) hemp feedstock (Fig. 4.3) was used for grinding tests. Samples were collected at Baker Farms, located in Dauphin, MB. The moisture content of the feedstock was 9.7%, as measured by the oven-dry method at 60 °C for 72 h (ASABE 2006). Plants were harvested according to common farming practices in Manitoba. The hemp crop was swathed using a mower-conditioner in the second week of August 2007, and left to ret in the field for approximately six weeks prior to being baled. Bales were stacked and stored outside. Samples for grinding tests were handpicked from a randomly selected bale (Fig. 4.3) in July 2008, and bagged in poly-woven grain bags to be transported to the laboratory at the University of Manitoba.

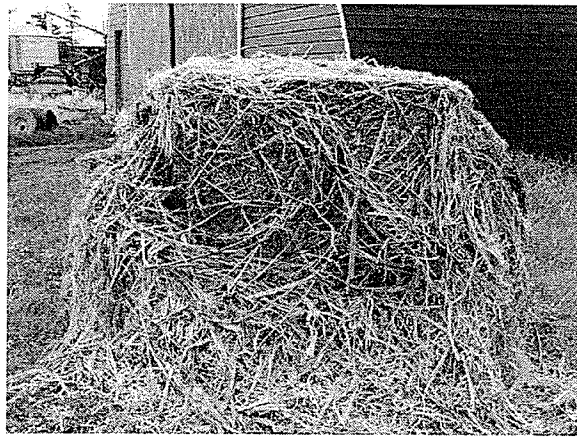


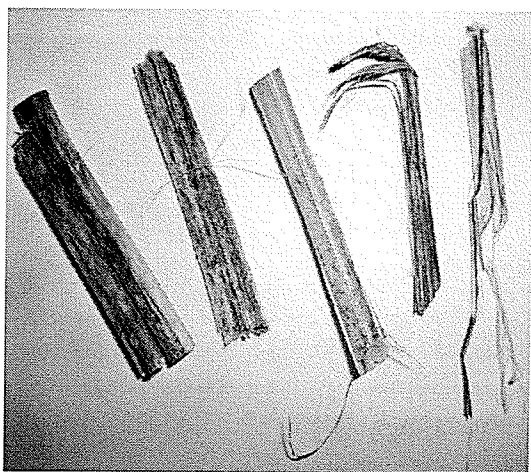
Fig. 4.3. Retted USO 31 hemp feedstock.

4.3.3 Experimental design

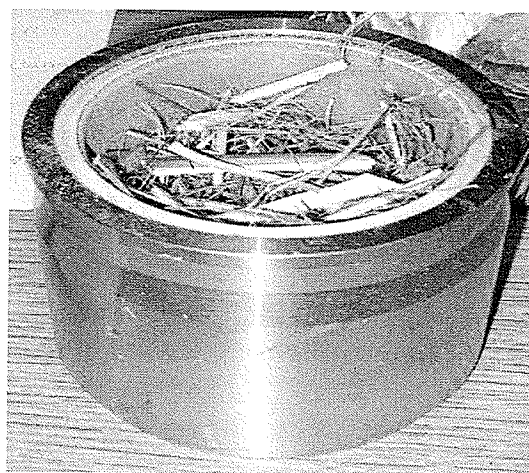
A randomized complete block design was used for the hemp decortication experiment using the ball mill. Two experimental factors were used: seven rotational grinding speeds (100, 150, 200, 250, 300, 350, and 400 rpm) and three grinding durations (2, 4, and 6 min). Factorial combinations of grinding speed with grinding duration gave 21 treatments. These speeds and durations were selected based on preliminary trials to observe the impact of different speeds and grinding durations on fibre. Results from the preliminary trials showed that grinding durations greater than 6 min, in combination with the grinding speed greater than 400 rpm, produced entirely chaff (fine particulate matter) which was not desired. Four replications were performed, totalling 84 tests (7 rpm grinding speeds x 3 grinding durations x 4 replications).

4.3.4 Test procedure

Hemp feedstock was cut to a length of approximately 40 mm (Fig. 4.4a) using a heavy-duty paper cutter. A length of 40 mm was chosen as it was the most appropriate length for the production of biocomposites. Three-gram hemp feedstock was selected based on the ball mill feeding capacity. Sample masses were weighed using an electronic scale (Mars, Model MS200, North York, Canada). The 3 g sample was placed on top of the grinding balls in the bowl (Fig. 4.4b), and the bowl was clamped into the bowl holder. The bowl was securely fastened and the lid was closed, milling commenced for the appropriate grinding duration and grinding speed. Once milling stopped, the ground sample was collected and placed in small plastic bags. The grinding bowl and grinding balls were cleaned between milling tests.



(a)



(b)

Fig. 4.4. Hemp feedstock; (a) 40 mm cut lengths; and (b) loaded in grinding bowl prior to milling.

4.3.5 Measurements

Ground samples were separated using a stainless steel sieve shaker (Retsch AS200, Hann, Germany) (Fig. 4.5). The two screen opening sizes used were: 20 and 5 mm. Thus, the ground sample was separated into three length categories: Long (≥ 20 mm); Short (5-20 mm); and Chaff (< 5 mm). Following sieving, samples from each length category were separated into three products: fibre, fibre-bound-to-core (fibre remained attached to the core), and core. Each fraction was weighed using a digital scale (Mars, Model MS200, North York, Canada). The mass of each fraction was recorded. The designations of the mass fractions measured are summarized in Table 4.1.



Fig. 4.5. Retsch sieve shaker: screens and collecting pan used for sizing.

Table 4.1. Symbols of mass fractions of hemp products after milling.

Product	Length category		
	Long (>20 mm)	Short (5-20 mm)	Chaff (<5 mm)
Fibre	m_{Lf}	m_{Sf}	
Fibre-bound-to-core	$m_{Lf/c}$	$m_{Sf/c}$	
Core	m_{Lc}	m_{Sc}	
Total	m_{Lt}	m_{St}	m_{ch}

Fibre was the desired end-product of the decortication process while core was the by-product. Fibre-bound-to-core was the undesired product. In practice, fibre-bound-to-core in the fibre stream will decrease the purity of the fibre; while fibre-bound-to-core go in the core stream will decrease the fibre yield or increase the fibre loss. The following parameters were derived from those fractions listed in Table 4.1 to evaluate the performance of the decortication using the ball mill.

4.3.5.1 Fibre yield Fibre yield was defined as the mass of fibre after milling divided by the mass of feedstock. Long fibres were expected to have more applications than Short fibres. Thus, yields for Long and Short fibres were determined separately, using the following equations:

$$Y_{Lf} = \frac{m_{Lf}}{M} 100 \quad (1a)$$

$$Y_{Sf} = \frac{m_{Sf}}{M} 100 \quad (1b)$$

$$Y_f = \frac{m_{Lf} + m_{Sf}}{M} 100 \quad (1c)$$

where:

Y_f , Y_{Lf} , and Y_{Sf} = yield for total, long, and short fibre (%), respectively, and

M = mass of feedstock sample (3g).

4.3.5.2 Core yield Core yield was defined as the mass of core after milling divided by the mass of feedstock. Long cores and Short cores were expected to have similar market values. Thus, yields for Long and Short cores were combined to the total core yield (Y_C):

$$Y_C = \frac{m_{Lc} + m_{Sc}}{M} 100 \quad (2)$$

where:

Y_C = yield for core (%).

4.3.5.3 Chaff Percentage of chaff was determined using the following equation:

$$Y_{ch} = \frac{m_{ch}}{M} 100 \quad (3)$$

where:

Y_{ch} = percentage of chaff (%).

4.3.5.4 Detaching efficiency To assess the effectiveness of the decortication process, the reduction in the amount of fibre-bound-to-core was used to determine the detaching efficiency. This parameter shows how much fibre was detached from the core for a given grinding speed and duration. The detaching efficiency was defined as:

$$\eta = \frac{M - m_{Lf/c} - m_{Sf/c}}{M} 100 \quad (4)$$

Where:

η = detaching efficiency (%).

4.3.5.5 Performance index Detaching efficiency represents the amount of fibre being detached from the core. It does not represent the final state of the fibre, such as the length of the fibre and amount of chaff produced. When the mill works at higher detaching efficiencies, the output could be shorter fibres or more chaff. Thus, detaching efficiency alone cannot be used to completely assess the performance of the mill. Fibre yield or amount of chaff should also be taken into consideration to evaluate the performance of the mill. Therefore, a performance index was introduced and it was defined as:

$$I = \eta Y_f \quad (5)$$

where:

I = performance index (dimensionless).

4.3.5.6 Data analysis Analysis of variance (ANOVA) was performed on data under each length category with Statistical Analysis Software (SAS/STAT V9.13) to detect any significant differences among treatments. Statistical Analysis Software macro procedure “pdmix800.sas” was used in combination with LSD test to detect differences among treatment means at a significance level of 0.05.

4.4 RESULTS AND DISCUSSION

The results of the ANOVA analysis are summarized in Table 4.2. Although the data were highly variable, significant effects of the experimental factors (grinding speed and duration) were observed in most cases. For fibre yield, core yield, chaff data, and performance index effects of the experimental factors and their interactions were significant in 13 out of 18 cases. For detaching efficiency data, effects of grinding speed were significant. When interactions were significant, simple effects of the experimental factors were presented. Otherwise, main effects were presented.

Table 4.2. Results of analysis of variance (ANOVA).

Variables	Symbol	Source					
		Duration		Speed		Duration*Speed	
		F	Pr>F	F	Pr>F	F	Pr>F
<i>Fibre yield</i>							
Long fibre	Y _{Lf}	5.17	0.0085*	10.58	<0.0001*	10.85	<0.0001*
Short fibre	Y _{Sf}	4.28	0.0183*	2.97	0.0131*	0.90	0.5506
Total fibre	Y _f	7.70	0.0011*	12.93	<0.0001*	3.41	0.0230*
<i>Core yield</i>	Y _C	2.29	0.1100	7.24	<0.0001*	1.27	0.2602
<i>Chaff</i>	Y _{ch}	11.45	<0.0001*	55.73	<0.0001*	3.85	0.0002*
<i>Detaching efficiency</i>	η	0.35	0.7073	63.59	<0.0001*	1.20	0.3013
<i>Performance Index</i>	I	6.23	0.0035*	12.01	<0.0001*	2.40	0.0129*

* Statistically significant (P < 0.05).

4.4.1 Fibre yield

4.4.1.1 Long fibre Simple effects of grinding speed and duration on the Long fibre yields are presented (Fig. 4.6) due to the significance of the interaction between these two experimental factors (Table 4.2). The 2 min grinding duration showed no significant differences in the long fibre yield (Y_{Lf}) among the seven grinding speeds, and the average Long fibre yield over all speeds was 36.0%. However, the Y_{Lf} for 4 and 6 min durations showed an increasing and then decreasing trend among the grinding speed range of 100 to 400 rpm. The peak Y_{Lf} was observed at the 200 rpm for the 4 min grinding duration and at 250 rpm for the 6 min grinding duration. Beyond the peak value, Y_{Lf} rapidly decreased to 10.8% for the 4 min duration and to 0% for the 6 min grinding duration when grinding at the highest speed (400 rpm). The increasing trends before the peak yields were possibly due to an increase in grinding intensity as the grinding speed increased, and therefore more fibre was separated from the core. The decreasing trends after the peak yields may be explained by the fact that the hemp feedstock was subjected to an excessive grinding action at high grinding speeds. The excessive grinding resulted in the fibres being ground into shorter lengths, and lost to the short fibre or chaff stream. These results are in agreement with Prasad et al. (2005) who observed that with intense milling some fibre bundles are opened up and develop into powder.

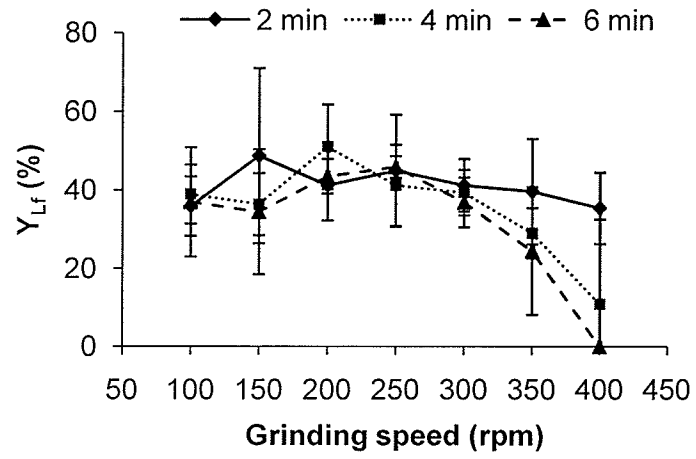
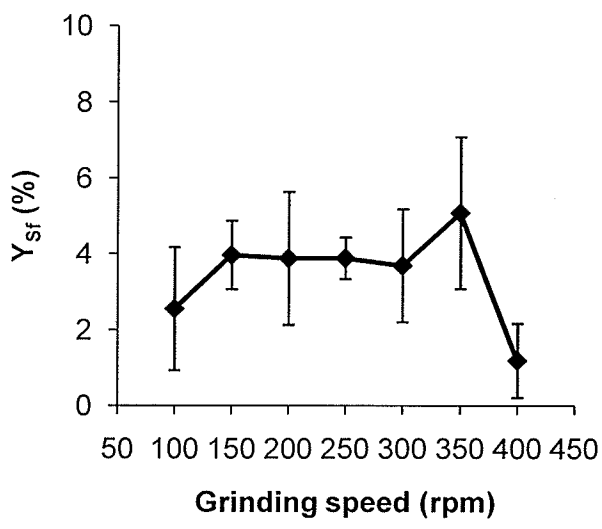
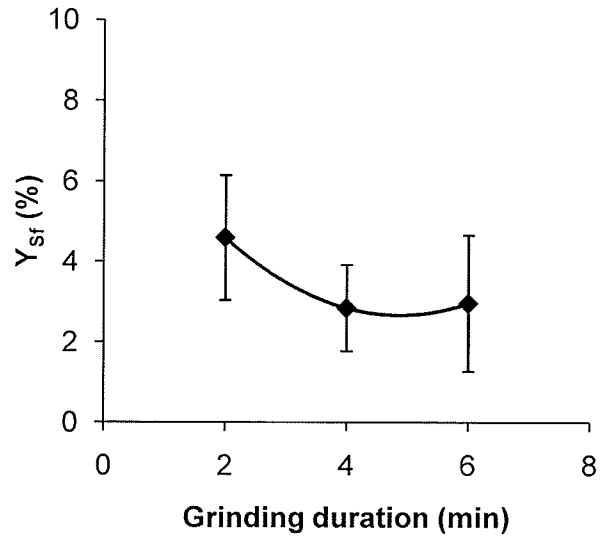


Fig. 4.6. Long fibre yield (Y_{Lf}) and standard deviation bars versus different grinding speeds for different grinding durations.

4.4.1.2 Short fibre According to the ANOVA results (Table 4.2), interactions between the experimental factors were not significant. Thus, the main effects of the experimental factors are presented (Figs 4.7a, b). The grinding process generated little short fibre, as demonstrated by the Short fibre yields (Y_{sf}) which were 10 times lower than those of Long fibre, Y_{Lf} . The value of Y_{sf} increased from 100 to 150 rpm, remained fairly constant between 150 and 350 rpm, and then significantly decreased at 400 rpm (Fig. 4.7a). The effect of grinding duration resulted in a slight decrease of Y_{sf} after being ground for 4 and 6 min, when compared to 2 min (Fig. 4.7b).



(a)



(b)

Fig. 4.7. Short fibre yield (Y_{sf}) and standard deviation bars for; (a) different grinding speeds; and (b) different grinding durations.

4.4.1.3 Total fibre The total fibre yields (Y_f), that correspond to the sum of the Long and Short fibre yields, are presented in Fig. 4.8. As the short fibre yields were very low relative to the Long fibre yields, the data of Y_f followed the same trends as the data of Long fibre yields, in terms of effects of grinding speed and duration. In summary, when grinding for the short duration (2 min), the total fibre yields were similar among the seven grinding speeds. When grinding for the longer durations (4 or 6 min), the Y_f followed an increasing and then decreasing trend over the seven grinding speeds. When the 4 min grinding time was used, the 200 rpm grinding speed gave the highest Y_f . Similarly, when the 6 min grinding duration was used, the 250 rpm produced the highest Y_f . The higher range of grinding speeds, 300 to 400 rpm, may not be used in combination with the grinding durations of 4 and 6 min, due to the significantly decreased Y_f at these combinations.

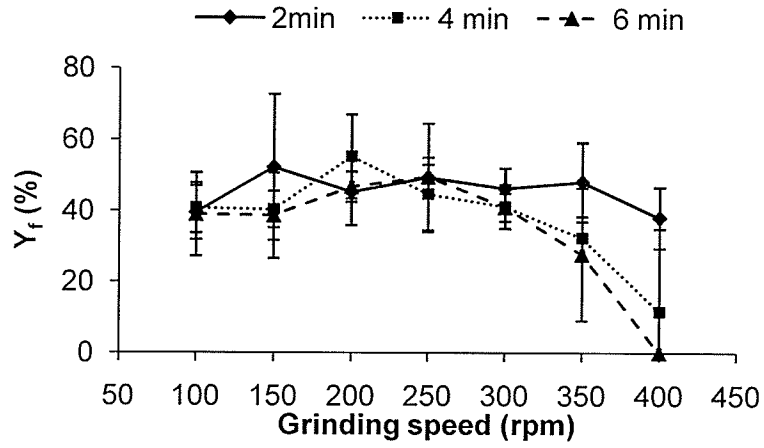


Fig. 4.8. Total fibre yield (Y_f) and standard deviation bars versus grinding speed for different grinding durations.

4.4.2 Core yield

As effects of grinding speed on core yields (Y_C) did not significantly interact with those of grinding duration (Table 4.2), the main effects are presented for the core yield data. Grinding speed had a significant effect on the Y_C (Fig. 4.9). Values of Y_C increased from 12.5 to 20.3% when the grinding speed was increased from 100 to 200 rpm, implying more cores were being separated from the fibre as the speed was increased. The maximum Y_C was observed at 200 and 250 rpm speeds. Beyond these speeds, more and more cores were further ground into chaff, resulting in decreased Y_C down to 1.8% at 400 rpm. Results agree well with a study done by Hobson et al. (2001), who observed that with vigorous processing, core was reduced in size and ultimately lost to the chaff fraction. Values of Y_C slightly decreased at the longer grinding duration. However, this effect was not significant (Table 4.2), and the data are not shown.

As core is a by-product from the decortication process, core yield data alone cannot justify which grinding speed is desirable. However, core yield data demonstrated effects of experimental factors on the outputs of a decortication process, and those data, together with the fibre yield data, are useful to identify the optimal grinding speed or duration for the most efficient and effective decortication process.

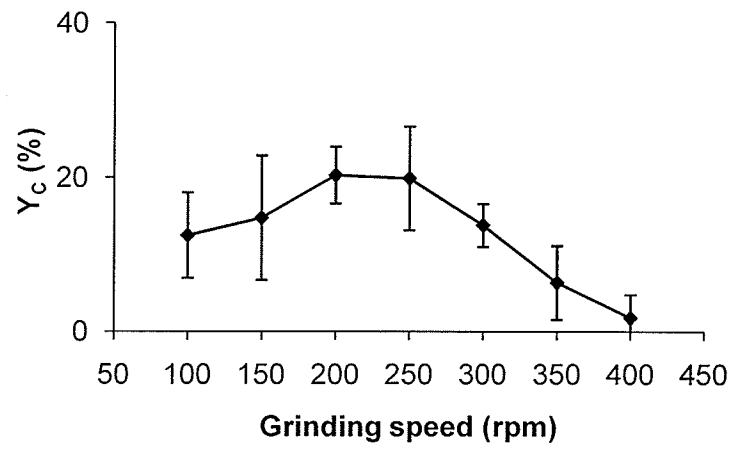


Fig. 4.9. Core yield (Y_C) and standard deviation bars for different grinding speeds.

4.4.3 Chaff

Interactions of grinding speed and grinding duration on chaff yield were significant (Table 4.2), and their simple effects are demonstrated in Fig. 4.10. Little chaff was produced at 100 and 150 rpm, regardless of grinding duration. The chaff accounted for as much as 81 and 100% when the hemp was ground at 400 rpm for the 4 and 6 min durations, respectively. These results implied that grinding at these conditions would result in fibre or core yields as low as 0%. These high percentages of chaff were due to the brittleness of the hemp feedstock with low moisture content (9.7%). These results are in agreement with Schwanninger et al. (2004) who observed that intensive ball milling resulted in a greater percentage of fine material in the sample.

The general trend was that with increasing grinding speed and grinding duration, the amount of chaff produced increased, as expected. However, there were no significant differences in chaff production among the grinding speeds for the 2 min grinding duration. For the 4 and 6 min grinding durations, significant differences appeared at grinding speeds equal to and greater than 300 rpm. The chaff data further explained the fibre yield data shown in Fig. 4.8 in that the fibre yields were inversely proportional to the amount of the chaff.

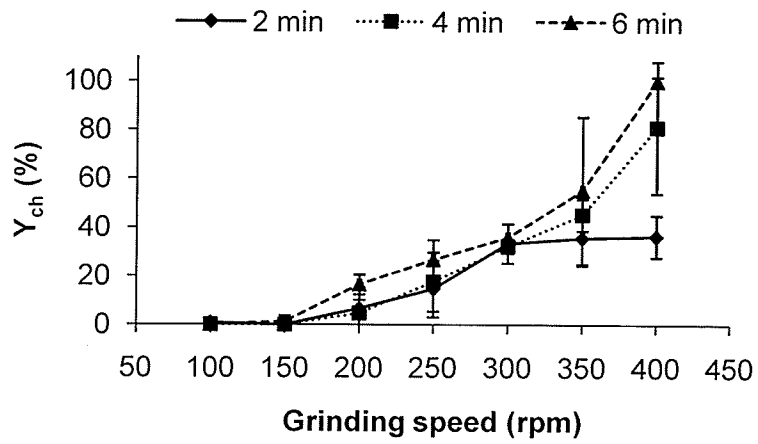


Fig. 4.10. Chaff (Y_{ch}) and standard deviation bars versus grinding speed for 2, 4, and 6 min grinding durations.

4.4.4 Detaching efficiency

Effects of grinding duration on detaching efficiency (η) were not significant (Table 4.2). Only the effects of grinding speed are presented (Fig. 4.11). The general trend was that with increasing grinding speed the efficiency increased. With faster grinding speeds, greater forces were generated to break apart the bonds between fibre and core, resulting in a greater separation of fibre from core. At low speeds, 100 and 150 rpm, approximately 52.6 to 57.1% of fibre was detached from the core. This value increased to 80.8% when the speed was increased to 200 rpm, and nearly reached 100% detaching efficiency at the speed range of 300 and 400 rpm.

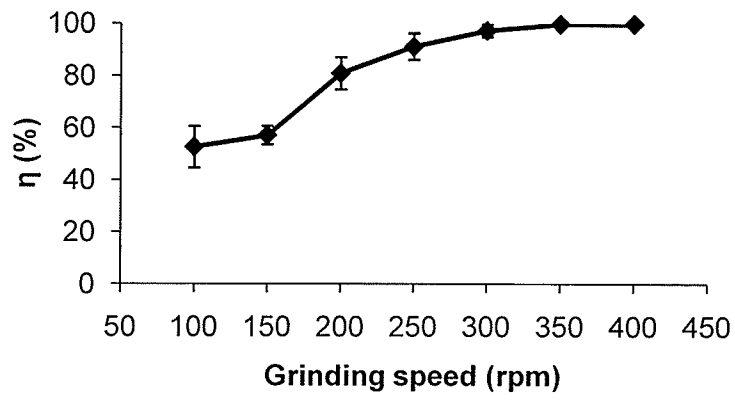


Fig. 4.11. Detaching efficiency (η) and standard deviation bars for different grinding speeds.

4.4.5 Performance index

Interactions of grinding speed and grinding duration on the performance index were significant (Table 4.2), and the simple effects are presented (Fig. 4.12). The performance index (I) along with the detaching efficiency assessed the performance of the mill with respect to the final state of the fibre. The index for the 2 min grinding duration increased from 100 to 400 rpm. For the 4 and 6 min grinding durations, the peak values of I were 45.1 and 47.6, which occurred at 200 and 250 rpm, respectively. Thus, the optimal grinding speed was between 200 and 250 rpm when the 4 or 6 min grinding duration was used. The lower grinding speeds resulted in lower I due to the low detaching efficiency. The higher grinding speeds resulted in a decrease in I due to the fibres being ground into chaff.

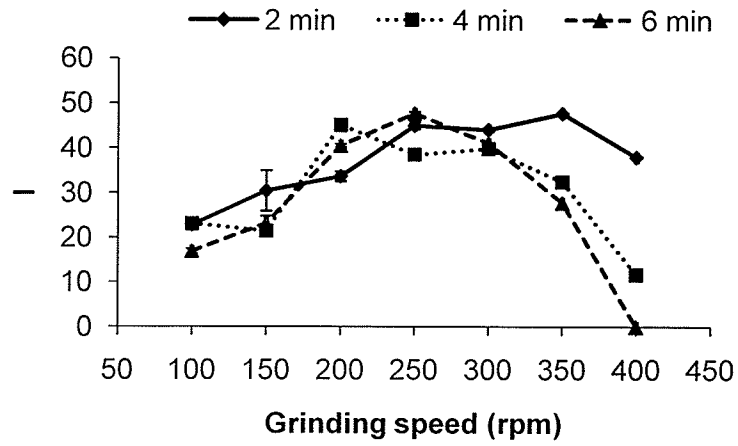


Fig. 4.12. Performance index (I) and standard deviation bars versus grinding speed for 2, 4, and 6 minute grinding durations.

4.5 CONCLUSIONS

Grinding speed and duration have an effect on fibre yield, core yield, chaff, and the detaching efficiency. The 2 minute grinding duration produced reasonably good Long and total fibre yield (43.3% on average), regardless of grinding speed. Similar fibre yields were observed for the longer grinding durations (4 and 6 min) when grinding speeds were lower than 250 rpm; higher grinding speeds resulted in a decrease in fibre yields. The highest core yield (20.1%) was observed around the grinding speed of 200 and 250 rpm. For the highest grinding speed of 400 rpm, fibre and core were ultimately lost to the chaff stream. Results indicated that with an increase in grinding speed and duration, chaff production also increased.

Grinding speed and detaching efficiency showed a direct relationship; as speed increased so did the detaching efficiency. However, higher detaching efficiency at higher grinding speeds may mean a greater loss of fibre. Considering all the performance indicators, grinding at 200 rpm for 4 min or grinding at 250 for 6 min were considered the best combinations of the operational parameters of the planetary ball mill for decortication of retted hemp. It should be pointed out that the hemp feedstock used was well retted and some fibre had already detached from the core before being decorticated with the ball mill. For other hemp stock, a longer grinding duration may be required. Further research is required to investigate feedstock with different retting conditions.

4.6 ACKNOWLEDGMENTS

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5. SUMMARY

The hemp industry is an ever growing sector that presents a positive change for the environment. Hemp fibre is a renewable resource that provides individuals and industries with numerous possibilities for market development. Since 1998, when hemp was declared legal for commercial growth in Canada, numerous Canadian companies have taken advantage of the market opportunity presented by hemp fibre. With the increasing awareness in the hemp industry, the equipment needed for processing is in need of a review. Current machinery, such as hammer mills, are expensive to run due to their high energy requirement and do not produce an acceptable fibre purity; whereas ball mills can only use a limited quantity of feedstock at a time. Research on the plant itself has been heavily researched. The physiology and agronomic characteristics are well known, but knowing the best fibre processing method is another question needing to be answered. Machinery used in the hemp industry has been based on flax decortication. Although present machinery works well for flax fibre, it is not always the case with hemp. Hemp is a much taller and stronger crop than flax. Thick stem diameter and height have presented hurdles in its harvest as well as decortication. There is a need for a better method of separating core from fibre through a more energy efficient manner.

Screen scenario, feeding mass, and pre-cutting scenario impacted the power requirement, energy requirement, fibre yield, core yield, and effectiveness of decortication for the hammer mill. Non-cut feedstock and small screen scenarios required more power and energy for both Green and Retted hemp decortication. Energy requirement also increased as the feeding mass increased for Green and Retted hemp. Results showed that Retted hemp is a better choice for hammer mill decortication than compared to Green hemp, as it produced higher fibre and

core yields (23.3 and 73.7%, and 11.1 and 31.8%, respectively). A maximum fibre yield (34.6%) was observed for Retted hemp using the smallest feeding mass and screen scenario.

Grinding speed and grinding duration of a ball mill had an effect on the fibre yield, core yield, chaff, and detaching efficiency. The 2 min grinding duration, regardless of speed, produced good Long and total fibre yield of 43.3%. For the 4 and 6 min durations, grinding speeds greater than 250 rpm resulted in low fibre yields. The greatest core yield (20.1%) was observed between the grinding speed of 200 and 250 rpm. Results showed that with an increase in grinding speed and duration, the amount of chaff also increased. Grinding speed had an effect on the detaching efficiency; as the speed increased so did the detaching efficiency. The high detaching efficiency was, in part, due to feedstock being well retted. Overall, the most optimal combination was a grinding speed of 200 rpm for 4 min or 250 rpm for 6 min.

Knowing the energy requirements, fibre yields, and effectiveness obtained from a hammer mill and ball mill allows for a better understanding of the machine's mechanics. Testing different operating parameters allows for an inside look of the power and energy requirements as well as the fibre yield and efficiencies of the machines. With results obtained through this research on hemp decorticators, the appropriate steps for the continuation of this industry can be obtained. The availability of better machinery will allow for many more manufacturing opportunities, profit, and jobs: it would be an asset all around.

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