CHARACTERIZATION OF FLAX SHIVES AND FACTORS AFFECTING THE QUALITY OF FUEL PELLETS FROM FLAX SHIVES

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ABSTRACT

Flax shives are a source of abundant biomass from renewable sources. They are considered to be environmentally benign and have a high-energy content for heating and generation of electricity, but only after being processed into pellets. Pelleting of the shives was done by using the single-pelleter and pilot-scale mill. The effect of grinding with screens of 2.4, 3.2, and 6.4 mm on unit density and durability was conducted with a completely randomized design using shives from Biofibre Industries Inc.**,** Canora, SK. The central composite face-centered design with 3 levels of lower grade canola meal used as a binder (18, 21, and 24%), moisture content (8, 11, and 14% (w.b)), and hammer mill screen size (3.2, 4.8, and 6.4 mm) was used to determine the effects of these three factors on the properties of fuel pellets made from shives obtained from Biolin Research Inc., Saskatoon, SK.

The initial moisture content of coarse flax shives from both sources was about 10.5% wet basis (w.b.). The moisture content of flax shive grinds ranged from 9.6 to 10.5% (w.b.) after grinding, using the smaller screens for the Biofibre material, while the moisture content ranged from 7.9 to 8.6% (w.b.) for shives from Biolin. Also, smaller screen size reduced the geometric mean particle size for shives from both sources. The use of the smaller hammer mill screen resulted in an increase in both bulk and particle density of shives. There was a decrease in coefficient of the internal friction of shives from 0.20 to 0.14 and an increase in a cohesion of shives from 2.18 to 3.83 kPa when the screen size decreased from 6.4 to 3.2 mm. The flax shives contained cellulose (53.27%), hemicelluloses (13.62%), and lignin (20.53%) at a moisture content of 7.9% (w.b). Specific heat capacity of flax shives changed from 1.5 to 2.7 kJ/ (kg °C) when the moisture content was increased from 8 to14%

(w.b.) and temperature from 15 to 80°C. The shives had the combustion energy of 17.67 MJ/kg at a moisture content of 8.1% (w.b.).

The smallest screen size (2.4 mm) resulted in the highest unit density (1010 kg/m^3) and the highest durability (88%) in the pellets produced by the single-pelleting equipment. The change in length of pellets produced by the pilot-scale mill increased as canola meal increased from 18 to 24% at the highest moisture content (%). The pellets were more stable at the highest moisture content when the lowest canola meal used. The addition of 18% canola meal and grinds from a screen size of 6.4 mm produced the highest unit density in the pellets at all moisture levels. The highest bulk density (682 kg/m^3) was obtained from shive mixtures with 18% canola meal and a moisture content of 8%. The highest hardness and durability were found for the shive pellets that were produced with 18% canola meal at a moisture content of 14% (w.b). Pellets that were produced at a moisture content of 14% (w.b) resulted in the lowest percentage of moisture absorption.

The inclusion of the canola meal in the shive mixture resulted in an increase in the combustion energy of the pellets because of the fat content in the binder. The two levels of canola meal for shive pellets had essentially the same level of emissions. However, there were significant differences between shive pellets and commercial wood pellets in the level of the emissions. Lower amounts of methane (1.29 ppm) and oxygen (164.3 ppt) were found for flax shive pellets than of methane (1.63 ppm) and oxygen (176.6 ppt) in commercial wood pellets.

In short, pelleting of flax shives into fuel pellets improved the handling characteristics, increased bulk density and energy content. Fuel pellets made from flax shives had less emission of methane and oxygen from combustion when compared to commercial wood pellets.

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DEDICATION

This thesis is dedicated to my dear friend Grace Kathryn Sauder (June 5, 1934-October 21, 2009). Grace was encouraging and supporting me to continue my education.

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NOMENCLATURE

C_c= cohesion (kPa)

C_p = specific heat capacity (J/(kg°C))

d.b. = dry basis (%)

df = degree of freedom

d_{gw} = geometric mean particle size (mm)

dH/dt = heat flow rate (J/s)

e = correction for the heat of firing fuse wire (J)

H = energy content of the sample (J/kg).

H_g = energy content of standard benzoic acid (J/kg)

l/d = length-to-diameter ratio

m = mass (g)

m_a = mass of benzoic acid (g)

m_i = initial mass of the sample (g)

m_w = mass of water added to the sample (g)

M_{wf} = final desired moisture content (wet basis, w.b.) of the sample

M_{wi} = initial moisture content (w.b.) of the sample

MS = Mean square

n = number of replicates

PDI = pellet durability of index

P_1 = pressure reading after pressurizing the reference volume (kPa)

P_2 = pressure reading after including volume of the cell (kPa)

R^2 = coefficient of determination

S.E. = standard error

SEE = standard error of estimate

S_{gw} = geometric standard deviation of particle size (μm)

t = time (s)

t = corrected temperature rise (°C)

T = sample temperature (°C)

V = volume of compacted sample at pressure P (cm^3)

V_0 = volume of sample at zero pressure (cm^3)

V_C = volume of cylinder (cm^3)

V_{cell} = volume of the cell (cm^3)

V_R = reference volume for the large cell (cm^3)

V_s = volume of solid (cm^3)

W = weight of sample (g)

W = energy equivalent of calorimeter (J/K)

w.b. = wet basis (%)

W_d = moisture content (% d.b.)

W_w = moisture content (% w.b.)

α = distance of axial point from the center

ε = porosity (%)

μ = coefficient of friction

ρ_b = initial bulk density (kg/m^3)

σ = normal stress (Pa)

ρ_t = particle density (kg/m^3)

τ = shear stress (Pa)

φ_i = angle of internal friction (degree)

1. INTRODUCTION

In recent times, many of man's practices have resulted in negative effects to the environment. In addition, the burning of fossil fuels has enormous negative effects on human health. The fossil fuels energy source including coal, oil, and natural gas is used worldwide for heating and electricity generation. These sources of energy, which have been used for a long time, are non-renewable and eventually these will be depleted. With the cost increase to produce the energy from fossil fuels, there has been a corresponding increase in interest in alternate sources for heating, such as solid fuels. As a result, a global effort has been started to generate renewable sources of energy which can meet increasing energy needs.

In response to these factors, researchers and engineers are developing methods of using fuels from biomass. Biomass is any biological material originated from living organisms including wood waste, forest residues such as straw, saw dust, shavings, corn stover and switchgrass. According to Demirbas (2004), biomass contributes the balance of the atmospheric carbon dioxide in the air and does not add to the greenhouse effect to the same degree as the use of fossil fuels.

Various types of biomass have been studied extensively as a source of biofuel by densification. The first U.S. patent for densification was issued in 1880 (Reed and Bryant 1978), and the method was commonly used for producing animal feed. Densification can be done by extrusion, pelletizing, and briquetting (Li and Lui 2000; Pietsch 2002). Densification of biomass in the form of cubes, briquettes, and pellets is achieved by applying a mechanical force to particles causing them to bond together and is affected by both raw material properties and process variables. Raw material properties such as particle size, size distribution, bulk and particle density, and chemical components were studied on the densification. In the densification process, grinding creates inter-particle bonding, as well as, well-defined shapes and sizes of pellets, briquettes, and cubes (Kaliyan and Morey 2006).

It is important that densified products meet the quality criteria that included higher bulk density, higher hardness, higher durability, higher energy content and lower gase emissions. Therefore, the properties of the end products made from various biomass materials were also studied extensively. The solid fuel made from biomass in the form of pellets must have uniform shape and size; high bulk density; and high hardness and durability. Pellets must also have resistance to moisture adsorption and have high energy content, as well as low emissions.

Flax straw is one example of an abundant biomass that has potential as a biomass fuel. In Canada, many farmers grow oilseed flax for the production of the oil. After harvesting the seeds, the flax straw, composed of fiber and shive, is left in the field. Since flax straw biologically degrades slowly in the field, farmers often burn it in order to get rid of this residue. The fibers have been used commercially in the traditional textile sector, as filler in plastic composite materials, as insulation bats, and for other industrial purposes. However, only a small percentage of the flax straw produced in Canada is processed for the extraction of fiber. Schweitzer-Mauduit Canada is the only large processor of oilseed flax fiber in Canada producing between 27,000 and 40,000 tonnes of roughly cleaned fiber per year (Ulrich 2008). After the fibre has been removed from the straw, the residue is known as shives which are non-fibrous by-products consisting of a mixture of particles with various chemical and physical structures. Oilseed straw contains about 78% shives with an average price of approximately $2 per tonne (Ulrich 2008). Shives consist of both cellulose and hemicelluloses, and lignin (Shaw and Tabil 2005) that acts as a binding agent when processing. They also can be used for animal bedding, particle board, horticulture applications, filler in bio-composites, and biofuel markets. In addition, it was stated on the website of Irish Linen (2002) that 2 kg of shives have the same heating value as 1 litre of fuel oil.

The above statements indicate that flax shives have potential value and could be utilized as biofuels which add fewer pollutants to the environment, thereby reducing some of the problems of global warming brought about by greenhouse gas emissions. However, there are a number of problems related to using flax shives as a raw material in the production of biofuel pellets. One of the major problems of using shives as a solid biofuel is their low density. It is difficult to handle shives in their current form because they require large spaces to store and transport. Without further compression, storage and transportation costs would be too high to use this material economically for fuel. Furthermore, bulky and dusty shives can be a fire hazard during handling and storage.

The solution of the above problems is to densify them in the form of pellets. Pelleting brings particles together applying the mechanical forces to the particles during processing. Therefore, this improves the handling characteristics, reduces the storage requirement, increases the energy content, and decreases the emissions. Final quality of the pellets can be affected by both the raw material and processing factors. The densified products will contribute to value-added processing and to total utilization of flax crops giving additional environmental benefits.

1.1 Objectives

The overall objective of this research was to study the criteria for manufacturing biofuel pellets from flax shives, a residue or co-product of oilseed flax straw processing, using a single pelleting unit and a pilot-scale pellet mill. The specific objectives were:

1. to characterize flax shives in terms of physical, chemical, and thermal properties including particle size and distribution, densities, heat of combustion, specific heat capacity, and composition;

2. to investigate the effects of particle size, moisture content, and the addition of canola meal on the physical properties of flax shive pellets; and

3. to measure the heat of combustion of the pellets and to analyze the gas emissions during combustion of shive pellets.

1.2 Organization of the Thesis

This research work is presented in six chapters namely: Introduction, Literature Review, Materials and Experimental Methods, Results and Discussion, Conclusion and Recommendations. In the Literature Review, both the raw material properties and processing parameters affecting biomass densification are reviewed. In addition, the physical properties of the compacts (i.e. pellets and briquettes) along with the specific energy consumption required to grind feedstocks in the formation of fuel products are presented. The chapter ends with a discussion of emissions from biomass fuel pellets after combustion, and a summary of the literature review. In the Materials and Experimental Methods chapter, the equipment and methodology used for measuring the physical, chemical, and thermal properties of the materials and fuel pellets are described. The Results and Discussion section presents and discusses the experimental values obtained for the physical properties, chemical composition and thermal properties of the raw material. This chapter also presents the effects that the properties have on the dimensional stability, densities, hardness, durability, and moisture absorption of fuel pellets, a statistical analysis used to find differences and significance among the different treatments used to manufacture pellets. Finally, the Conclusion is presented followed by the Recommendations which enumerate the issues to be addressed in future studies.

2. LITERATURE REVIEW

This chapter reviews how material properties and processing parameters affect mechanical properties of pellets and briquettes made from a variety of raw materials. In addition, properties of densified products made from a variety of biomass feedstock are reviewed. The energy content of biomass fuel product and the specific energy required to grind the biomass and produce the products along with the emissions from combustion are also reviewed in this chapter.

2.1 Raw Material Properties Affecting Biomass Densification

Densification of material such as animal feed and biofuel from biomass including sawdust, straws, wood chip, shavings, corn stover, switchgrass, and many others has been studied extensively (Haussman 1975; Wamukonya and Jenkins 1995; Tabil 1996; Tabil and Sokhansanj 1996; Thomas et al. 1996; Mani et al. 2004a; Rhen et al. 2005, Mani et al. 2006b; Mozammel et al. 2006; Kaliyan and Morey 2006; Shaw 2008). However, no research work on densification of flax shives was found in the literature. Raw waste material such as the flax shives shown is a heterogeneous mixture with a range of particle sizes and a complex mixture of chemical components and physical structures. Raw material properties such as particle size, particle size distribution, unit density, particle density, bulk density, and moisture content affecting densification are of primary interest in this study, since the quality of final densified products depends on the raw material variables. Therefore, this section summarizes previous studies of how the raw material properties listed above along with the angle of internal friction affect the densification and properties of products made out of a variety of raw materials.

2.1.1 Particle size and particle size distribution

Raw materials must be reduced in particle size before they are processed into fuel pellets by densification. Size reduction, one of the main operations in biofuel pellet production, can be done using a variety of grinders. The grinds produced have a wide range of particle sizes which can be controlled by the screen size of the grinder. Mani et al. (2004a) stated that particle size and particle size distribution of biomass materials have a significant influence on the binding characteristics of densification and are also important considerations in the design of pneumatic conveyors and cyclones. Mechanical properties of the materials and final product properties are affected by the particle size and its distribution. Therefore, when reducing the particle size of raw materials using a hammer mill, it is important to ensure that the screen size used results in higher bulk and particle densities. The geometric mean particle size is a more realistic expression of the mean size of the particles since the size of the biomass particles has a logarithmic distribution. Mani and co-workers (2006b) reported that wheat and barley straw grinds had a geometric standard mean particle size of 0.64 and 0.69 mm respectively when ground using a hammer mill with a screen size of 3.2 mm. They also observed that reducing the geometric mean particle size from 0.64 to 0.28 mm of wheat straw grinds resulted in an increase of bulk density from 97 to 121 kg/m^3 and particle density from 1030 to 1340 kg/m^3. Shaw and Tabil (2006) found that the geometric average of the particle size of flax shives was 0.64 mm using a hammer screen of 6.4 mm. For corn stover, the geometric mean particle size was 0.68 mm when using a 6.4 mm screen size (Mani et al. 2004b). Mani et al. (2004b) also reported that the particle density of corn stover grind increased with a decrease in the geometric mean particle size of the grind. Decreasing the particle size of corn stover from 0.80 to 0.66 mm increased the relaxed density by 5 to 10%, and the briquette durability from 62 to 75% at 150 MPa pressure (Kaliyan and Morey 2006). This occurs since there is more particle surface area available for bonding at a smaller particle size than at a larger particle size.

The particle size distribution of raw materials is important since it affects raw material properties including moisture content, bulk and particle densities, which in turn affect the densification process, and final product properties such as density, hardness, and durability. Mani et al. (2004a) found that grinding wheat straw and barley straw using a hammer mill with a screen size of 3.2 mm gave a wide range for particle size distribution, and particles distributed in this range were suitable for compaction (pelleting or briquetting) process. Tabil and Sokhansanj (1997) emphasized that the alfalfa grind particles with a size below 0.4 mm are considered fine and are easily compressed into pellets.

2.1.2 Bulk and particle density

The bulk and particle densities of the raw materials and grinds are functions of the particle size and moisture content. Shaw and Tabil (2006) found that the bulk density of flax shives using a hammer mill with a 6.4 mm screen was 107.99 kg/m^3. Mani et al. (2004b) found that ground corn stover had a bulk density ranging from 42.25 kg/m^3 for coarse material (tub ground chop) to 130 kg/m^3 for finer material using a hammer mill screen size of 3.2 mm. These two sets of results indicate that flax shives and corn stover have similar bulk densities. Mozammel et al. (2006)

found that bulk density of small size wood chips increased from 180 to 314 kg/m^3 when the moisture content increased from 10.7 to 55.7% wet basis (w.b.). The length of the small size chips ranged from 10 to 25 mm. Also, they reported that the bulk density of barley straw ranged from 24 to 54 kg/m^3 as the average particle size decreased from 50 to 6 mm respectively at a moisture content of 8.45% (w.b.). Tabil and Sokhansanj (1997) reported that the bulk density of the low, medium, and high quality alfalfa grinds at a moisture content of 5.3, 5.4, and 6.2% (w.b.) was 238, 263, and 236 kg/m^3, respectively. Shaw (2008) studied the bulk and particle densities of selected feedstock, namely, poplar, pretreated poplar, and wheat straw at two moisture levels (9 and 15% w.b.) using screen sizes of 0.8 and 3.2 mm. Both bulk and particle densities of the feedstock decreased with an increase in moisture and screen size.

2.1.3 Moisture content

The knowledge of the effect of moisture content on the properties of the raw material is important for determining steps in the processing of raw materials. Moisture content can affect the specific energy required to compact biomass materials as well as properties such as densities, angle of friction, specific heat capacity, force-deformation characteristics, and thermal conductivity. The initial moisture content of the grinds also has a significant effect on the densification process and final product properties. Mani et al. (2004c) studied the compaction mechanism of four biomass grinds wheat and barley straws, corn stover, and switchgrass at different applied forces, moisture contents, and particle size. They concluded that at low moisture levels (5 and 10% w.b.) corn stover produced more stable and durable briquettes with high-density than at a higher moisture level (15%

w.b.). Orth and Lowe (1977) found that moisture content of hay below about 12% (w.b) did not form stable wafers in a continuous extrusion system without temperature control. However, increasing the moisture content from 12 to 16% (w.b.) resulted in higher durability of the wafers, while the maximum density of the wafers was reached at 14% (w.b.). They also reported that both density and durability decreased with a further increase in the moisture content. Moisture content has an effect on the specific energy for compacting ground materials. Mani et al. (2006a) found that the moisture content of corn stover greatly affects the magnitude of compression and extrusion energy required to produce briquettes. They found that by increasing the moisture content (10-15% w.b.) less total energy was consumed. Carre et al. (1987) stated that very low moisture content in wood residues made it difficult to produce briquettes due to improper heat transfer.

Sometimes biological materials do not compress easily unless water is added. The presence of water favours structure formation in the bonding of wheat straw (Koullas and Koukios 1987) because the water acts as a binder in processing. Faborode (1989) stated that an increase in moisture content of compacts produced from barley straw resulted in an increase in the axial expansions. Rehkugar and Buchele (1969) studied the compaction of wafering for moisture content in the range of 6 to 25% (w.b.) and reported that the relaxed density of pellet decreased with increasing moisture content. There were several studies reporting the effect of moisture content on the durability of compacted biomass (Mohsenin and Zaske 1976; Smith et al. 1977; Coates 2000). These studies reported that more durable compacts were made in the moisture content range of 15 to 20% (w.b.) for alfalfa, wheat straw, and cotton plant residues. Kubler (1987) reported that moisture content exceeding 20% dry basis (d.b.) may cause microbial growth in wood chips. Due to this, there is degradation and self-heating during storage. According to Haussmann (1975), briquettes made from sawdust, sander dust, shavings, peanut hulls, etc. with an existing moisture content of 15% (w.b.) were dense and stable. Briquetting switchgrass at a temperature of 25°C when moisture content increased from 10 to 15% (w.b.) resulted in relaxed densities that decreased from 40 to 30% (Kaliyan and Morey 2006). Also, it was found that an increase in moisture content from 10 to 15% (w.b.) resulted in increased durability of corn stover briquettes from 50 to 80% at an applied pressure of 100 MPa.

In summary, it is clearly understood that the optimum moisture content for densification is variable depending upon the type of raw material and pelleting conditions.

2.1.4 Chemical composition

Biomass is composed of mainly cellulose, hemicelluloses, and lignin. The chemical composition affects the ability to density of biomass material. Mani et al. (2006b) determined the chemical composition of wheat straw, barley straw, corn stover and switchgrass and found out the effects of the amount of protein and lignin on the pelleting properties of all four biomass species. At high temperature all natural binders such as protein, lignin, and starch become soft and may melt. Shaw and Tabil (2006) reported the chemical composition of the different biomass samples including peat moss, wheat straw, oat hulls, and flax shives. It was found that flax shives contained protein (3.1%), ash (2.7%), fat (1%), crude fiber (56.9%), neutral detergent fiber (82.3%), acid detergent fiber (67.6%), and lignin (17.0%). The percentage of the components is expressed in a dry basis (d.b.). They found that peat moss had the highest lignin content of 28.6% while flax shives had the lowest ash content of 2.7%.

2.1.5 Angle of internal friction and cohesion

It is important to have an accurate knowledge of the frictional behavior of biomass grinds before designing the handling and storage equipment as well as predicting flow behavior. The angle of internal friction and cohesion is one of the mechanical properties of powdery materials and biomass grinds that need to be considered when designing handling equipment. Seville et al. (1997) stated that the coefficient of internal friction is related to the stress distribution within particles under strain, while the coefficient of wall friction is related to the magnitude of the stresses between the particle and the walls of its container. Another expression of the angle of internal friction, the friction coefficient, of a variety of agricultural materials has been reported by a number of researchers (Richter 1954; Snyder et al. 1967; Thompson and Ross 1983; Chung and Verma 1989; Puchalski and Brusewitz 1996; Molenda et al. 2000). According to Knowlton et al. (1994), flowability can be described by cohesive strength, wall friction and compressibility.

There are a number of factors including moisture content, particle size and shape, temperature, storage time, etc. that affect the wall friction of the biomass grinds. Mani et al. (2004b) studied the effect of moisture content on the coefficient of wall friction of corn stover grinds from a grinder with different screen sizes. They found that the coefficient of wall friction increased significantly from 0.18 to 0.26 as the moisture content increased from 7 to 15% (w.b.). This is partly explained by an increase in adhesion between the grind and the steel surface with increased moisture content. An increase in the coefficient of wall friction with an increase in the moisture content of chopped hay and straw, grains and beans was similarly reported (Wieneke 1956; Brubaker and Pos 1965; Snyder et al. 1967; Thompson and Ross 1983; Chung and Verma 1989).

2.2 Process Variables Influencing Biomass Densification

In addition to the raw material properties, pelleting process parameters such as pressure, temperature, amount of binder used to form pellets and steam conditioning have an effect on the mechanisms of compression and the quality of the compacted materials. Also, die size and die speed have a significant influence on pellet properties during and after densification.

2.2.1 Pressure

In commercial pellet mills, typical pressures applied to ground materials are in the range of 50 to 150 MPa (Sitkei 1986). Due to high pressure, the biomass components can change their properties and may act as binders and stabilizing agents (Pickard et al.1961; Reece 1966; Rehkugler and Buchele 1969).

Mani et al. (2004c) studied the effect of compressive pressures between 31.08 and 136.77 MPa on the density of biomass pellets made from wheat and barley straws, corn stover, and switchgrass using a single pelleter. It was found, for all materials except the corn stover, that an increase in the compressive force resulted in an increase in the compacted density of the pellets different screen sizes (0.8, 1.6, and 3.2 mm). For corn stover grinds there was no significant effect on the pellet density. They also reported that the maximum compact density was attained easily for corn stover and less pressure was required for densification. Rhen et al. (2005) investigated the effect of the pressure on the density and moisture absorption for pellets produced from Norway spruce sawdust. It was concluded that for pressures within the range of 46 to 114 MPa, there was very little effect on density and moisture absorption. They also observed that the pressure in the die does not need to exceed 50 MPa during the pelletizing process.

The density of straw briquettes has been found to increase almost linearly with an increase in applied pressure (Reed et al. 1980; Singh and Singh 1982; O'Dogherty and Wheeler 1984; Bhattacharya and Yeasmin 1984). Kaliyan and Morey (2006) studied the effect of pressure on briquettes made from corn stover and switchgrass using a piston cylinder apparatus. They concluded that increasing the applied pressure within a range of 100 and 150 MPa at a temperature of 25°C and moisture content of 10% (w.b.) increased the unit density and specific energy and reduced the porosity of the briquettes. It was also reported that the durability of corn stover briquettes, densified in the same condition, increased from 50 to 60%.

The optimum pressure for satisfactory pellets depends upon the physical and chemical properties of the feedstocks.

2.2.2 Preheating temperature

Optimum preheating temperature of biomass is of importance for production of acceptable physical quality of pellets in terms of hardness, moisture absorption, tensile strength, and durability. It also affects the specific energy consumption in the grinding and pelleting processes. Compacted products made at higher temperatures result in lower force requirements (Hall and Hall 1968). Rhen et al. (2005) studied the effect of temperature, ranging from 26 to 144°C, on pellets made from Norway spruce sawdust. They reported that the dry density of pellets increased with higher temperatures and lower moisture contents. In a temperature controlled extrusion process using closed-ended die equipment, when the temperature was increased from 40 to 50°C at a moisture content of 14% (w.b), the power required to produce wafers with the highest density was reduced (Orth and Lowe 1977). Smith et al. (1977) investigated the effect of temperature on the stability and density of briquettes made from wheat straw using a closed die unit. They found that when the temperature increased from 80 to 110°C, both the stability and density of briquettes increased. Reed et al. (1980) found that densified biomass (wood materials, agro-industrial residues and agricultural residues) produced at temperatures around 220°C had higher strength, density, and energy content than those produced at lower temperatures. They also found that preheating the raw materials reduced the compressive pressure. Kaliyan and Morey (2006) reported that increasing the preheating temperature of corn stover and switchgrass from 75 to 100°C had the potential to activate the natural binding components and resulted in briquettes that were more dense and durable. They also found preheating temperatures in this range resulted in less volume expansion for briquettes.

2.2.3 Binding of particles

Lignocellulose biomasses are mainly composed of lignin, cellulose, and hemicelluloses that play an important role in the binding particles together in the processing materials into pellets and briquettes. They also consist of natural binding agents such as wax and protein that interact to help bond particles during densification.

In lignocellulosic biomass, the amounts of lignin and glass transition temperature of lignin will affect efficiency of densification. At the glass transition temperature, the amorphous components of lignocellulosic material, lignin and hemicelluloses, are activated, softened and act as a binder for the particles. Irvine (1984) reported that the glass transition temperature of lignin was in the range of 60 to 90°C. Kaliyan and Morey (2006) found that the glass transition temperature of lignin ranged from 62 to 101°C, while that of corn stover and switchgrass ranged from 50 to 115°C. Several researchers (Gray 1968; Rumpf 1962; Tabil 1996; Thomas and van der Poel 1996; Pietsch 2002; Shaw 2008) studied the binding of particles of biomass feedstocks to produce densified products in the form of briquettes and pellets. Knowledge of the binding mechanism and fundamental compaction properties of biomass species is important for understanding the densification process and to design the appropriate compaction equipment.

The binding mechanism between individual particles in densified products consists of five different forces: solid bridges, attraction forces, mechanical interlocking, adhesion and cohesion forces, and interfacial forces (Rumpf 1962; Pietsch 2002). Solid bridges can be formed among molecular structures as well as between particles because of high pressures and temperatures. Many attraction forces, such as van der Waals' forces, valence forces, and magnetic forces, are created during compression and act to adhere particles. Flat-shaped and bulky particles of raw material develop mechanical bonds by interlocking and creasing of fibers during densification. Highly viscous binders such as molasses and tar adhere to the surfaces of solid particles either by smoothing out surface roughness or by allowing the intermolecular attractive forces to take in part in the binding mechanism. Existence of moisture between particles can bond particles and cause cohesive forces which are a result of interfacial forces and capillary pressure at the liquid-gas interface.

According to Thomas and van der Poel (1996), the binding mechanism consists of solid-solid interactions between particles, capillary forces among water, air and solid material, adhesive and cohesive forces between particulates and binders, and interactions between particles.

Mani et al. (2006b) reported that the binding mechanism for compaction (pelletization) is comprised of particle rearrangement, elastic and plastic deformation, and interlocking of particles. During particle rearrangement, a closely packed mass is created without changing the original properties of the particles, although, they are affected by wall friction. In the elastic and plastic deformation stages, the particles are forced against each other as the applied pressure is increased. As a result of this, there is an increase in the inter-particle contact area. Gray (1968) stated that brittle particles add to mechanical interlocking and increase the overall strength of the pellet. In these stages, bonding forces like van der Waal's forces take effect (Pietsch 1997).

Binders or stabilizing agents may be needed to bond particles when the natural binding agents in the biomass, protein, lignin, and cellulose, are insufficient. Therefore, with the addition of binders, a better quality of densified products can be achieved, in terms of density, hardness, durability, and moisture absorption during handling, transportation, and storage. Binders can be introduced to reduce the springiness of raw material, to maintain maximum bulk density and to increase the durability of the densified pellets (Sokhansanj et al. 2005). Tabil and Sokhansanj (1996) and Pfost (1964) reported the most commonly used binders for pelleting of animal feeds are calcium lignosulfonate, colloids, bentonite, starches, proteins, and calcium hydroxide.

Increasing the amount of binders may result in an increase of relaxed density, durability and shear strength of briquettes (Chin and Siddiqui 2000). The durability of rice straw briquettes increased to 80% when they were produced with the addition of molasses, sodium, and silicate in the range of 10 to 25% (by weight).

Clarke and Marsh (1989) added 5 to 20% (by weight) petroleum pitches to increase the compressive strength of coal briquettes. The addition of 25% ground almond hulls to rice straw produced cubes with 75% durability (Waelti and Dobie 1973).

2.2.4 Steam conditioning

In the pelleting process, steam conditioning is an important process parameter which affects the density, hardness, and durability of pellets. Robinson (1984) stated that steam conditioning contributes to the activation of natural and artificial binders, gelatinization and natural lubricants of animal feeds during pellet manufacture. There was also an increase in moisture and an improvement in feed conversion due to steam conditioning.

During conditioning, dry or saturated steam can be added to ground materials as a heat and moisture source. Steam conditioning may involve both vapor diffusion and condensation. Vapor diffusion from the pressurized steam causes inter-particular voids in the mash, while condensation of vapor on the surface of the mash changes the thermal properties of the mash.

The effect of steam conditioning parameters on the quality of pellets has been reported by a number of researchers (Dobie 1959; Smith 1959; Skoch et al. 1981; Winowiski 1985; Hill and Pulkinen 1988; Tabil, 1996). Steam conditioning temperature is an important parameter which affects the densification process and quality of the final products.

Winowiski (1985) studied the conditioning temperature for a variety of feed rations and suggested how to optimize the feed temperature during the conditioning process prior to pelleting. According to Tabil (1996), the conditioning of alfalfa grinds at temperatures of 92°C and above resulted in better quality pellets. It was also found that increasing the conditioning temperature resulted in an increase in durability and a decrease in energy consumption in the pelleting process. Using steam conditioning, raising the temperature of alfalfa mash from 60 to 104°C resulted in a 30 to 35% increase in alfalfa pellet durability (Hill and Pulkinen 1988).

Another important parameter that affects the densification of feedstock when using the steam conditioning is moisture content. Hill and Pulkinen (1988) reported that the moisture content of alfalfa from 3.5% to 8% (w.b.) did not affect pellet durability. However, the power consumption of the pelleter was decreased by half with an increase in moisture content due to a lubrication effect. In alfalfa grinds, the moisture content of 8.5 to 10% (w.b.) was suitable for making pellets (Tabil 1996).

Steam conditioning time is also affects the physical quality of the densified feedstocks, as well as, the energy consumption of the pellet mill. Tabil (1996) reported that a steam conditioning time of 17 to 20 seconds was sufficient to achieve the desired level of moisture and temperature for processing alfalfa pellets. In pelleting animal feeds, increasing the residence time of the mash in the steam conditioning chamber above 30 seconds slightly reduced pellet durability (Vest 1983).

2.2.5 Die geometry and die speed

In the pelleting process, die geometry and die speed significantly affect the pellet densities, hardness, and durability and the specific energy required to form pellets. Heffner and Prost (1973) studied the effect of die geometry on pellet durability. They concluded that the die size with a higher length-to-diameter (l/d) ratio resulted in an increase in durability of pellets. Tabil (1996) also studied the effect of die geometry on alfalfa pellet durability. Length-to-diameter (l/d) ratios of 4.1 and 7.31 produced pellets with mean durabilities of 49.8 and 65.8%, respectively. From the results, it was clearly seen that higher l/d ratios resulted in more durable pellets. It was concluded that an increase in alfalfa pellet durability was a function of the increased pressure and frictional heating of the ground particles in the die during the pelleting process.

Die speed also influences pellet densification and the quality of pellets produced using a pellet mill. Leaver (1985) stated that die speeds between 250 and 300 rpm are suitable for the production of small diameter pellets. Alfalfa pellets produced at two die speeds (250 and 316 rpm) and a die with a hole diameter of 6.1 mm were considered by Tabil (1996). He observed that there is an increase in the durability of the pellets created at the lower die speed. Pelleting using high die speeds (501 and 565 rpm) was found to require high specific energy for the pellet mill motor to complete densification. It was determined that the high rotational speeds created more centrifugal force which affected the ability of the particles to flow through the die.

2.3 Physical Quality of Densified Products

This section presents the important physical properties, including dimensional stability, density, tensile strength (compression strength), hardness, durability, and moisture absorption of densified products. Also, it discusses how these properties are influenced by variation in the raw biomass material and in the parameters of the processing equipment.

2.3.1 Dimensional stability and densities

In general, a change in the length and diameter of pellets is caused by absorption of water and the breakage of bonds that were developed during the compaction process. Many studies have been conducted with regard to the effect of factors such as die temperature, particle size, and moisture content on the dimensional stability of pellets produced from a variety of biomass feedstocks.

Shaw (2008) reported that the pellets formed from raw poplar and wheat straw expanded in both the diametrical and longitudinal directions. In addition, pellet expansion in both axes was decreased with an increase in the die temperature and a decrease in the feedstock moisture content and particle size. Pellets produced from peat moss, wheat straw, oat hulls, and flax shives had longitudinal expansions of 0.52, 2.59, 1.80, and 1.27% and diametrical expansions of 0.02, 0.61, 0.31 and 0.33%, respectively (Shaw and Tabil 2005).

Studies have shown that the preset load (compressive pressure), temperature, moisture content and particle size affect the pellet density. Shaw (2008) reported that the initial density of pellets formed at different conditions increased as the preset load and temperature were increased and the particle size was decreased. It was also found that the initial density of pellets formed from wheat straw increased as the moisture content decreased from 15 to 9% (w.b.).

Using a laboratory-scale pellet mill with a die size of 4.76 mm, Colley et al. (2006) found that the particle and bulk densities of pellets made from switchgrass decreased from 16 to 24 % as the moisture content was increased from 6.3 to 17 %

(w.b.). There was a slight initial decrease in the porosity of the pellets reaching a minimum of 51.61% at a moisture content of 8.62% (w.b.). A further increase in moisture resulted in an increase in the porosity of the pellets.

2.3.2 Tensile strength

Due to static and dynamic forces during handling, transportation, and storage, pellet attrition can be substantial. According to Thomas and van der Poel (1996), attrition of pellets represents the gradual reduction of the pellet strength and consists of fragmentation and abrasion. Particle size distribution of pellets has an impact on both fragmentation and abrasion. Fragmentation involves cracks in pellets and fines at the fracture area while abrasion involves cracks on the edge or surface-unevenness of particles. Since the fines are produced due to abrasion, the bulk density of pellets may increase. In other words, small particles fill the space in the large voids in the middle of pellets, and therefore, the bulk density increases.

Tensile strength is one indicator of pellet quality and can be determined by a diametrical compression test. Tensile strength is affected by the processing temperature of equipment, moisture content and particle size of the feedstock. Higher tensile strength indicates higher quality pellets.

According to Shaw (2008) increasing both processing temperature (70-100°C) and moisture content (9-15% w.b.) resulted in an increase in the tensile strength of untreated poplar and wheat straw pellets. When formed using hammer-mill screen sizes of 0.8, 1.6 and 3.2 mm, the tensile strength of the pellets increased from 0.45 to 1.28 MPa for the poplar and from 0.47 to 1.33 MPa for the wheat straw. Decreasing the particle size (i.e. screen) showed a significant increase in the tensile strength of the untreated feedstock pellets.

An increase from 0.44 to 2.47 MPa in the tensile strength of alfalfa pellets was reported by Tabil and Sokhansanj (1997) when preset compressive loads of 500-4400 N were used. The alfalfa grinds were classified into three groups, namely high, medium, and low quality grinds in accordance with leaf-to-stem ratio and weed content. High quality alfalfa grinds had high leaf-to-stem ratios and low weed content, while low quality alfalfa grinds had low leaf-to-stem ratios and high weed content. Pellets produced from the high quality alfalfa grinds had the highest tensile strength (2.47 MPa) using preset loads of 3000 N, whereas pellets formed from medium quality grinds had the lowest tensile strength (0.44 MPa) using preset loads of 500 N.

2.3.3 Hardness

Hardness represents the amount of force that is needed to fragment pellets. A number of test devices for hardness have been developed, such as the Kahl device, Schleuniger test apparatus, Pendulum pellet hardness test device and the Universal compression test device. These were reviewed by Thomas and van der Poel (1996).

An increase in moisture content from 6.3 to 17% (w.b.) resulted in a decrease in hardness from 30.21 to 21.6 N for switchgrass pellets (Colley et al. 2006). The reason for this is probably due to moisture disrupting particular bonds formed during the compaction process. Alfalfa pellets produced without binders from intermediate and high quality chops had the higher hardness compared to pellets from low quality alfalfa (Tabil 1996).

2.3.4 Durability

Durability is the most important property for evaluating the quality of biomass compacts (pellets, briquettes, cubes). The durability of pellets describes their ability to resist the effects of impact force and vibration generated during handling and transportation (Mani et al. 2006a). Thus, it is a good indicator how well the material resists forces that cause the material to be dusty and crumbly during handling and storage.

Several devices are available for the evaluation of the durability of pellets. Studies of Thomas and van der Poel (1996) discussed different instruments including the Pfost tumbling can, Holmen tester, and sieving device. The tumbling can method can be used with variations in the speed of tumbling, length of tumbling time, sieve size and the amount of samples tumbled (Richards 1990; Raghavan and Conkle 1991). For determining the durability of very hard pellets such as dairy feed pellets, the tumbling can method can be modified by adding steel nuts, bolts, or ball bearings along with the pellets before tumbling (Winowiski 1998).

McKee (1990) studied the durability range and testing time for both the Pfost tumbling can and Holmen tester. The results of his research showed that for the Pfost tumbling can, there was a curvilinear decrease in durability ranging from nearly 98 to 91% with testing times up to 20 min, while for the Holmen tester, durability was in a range from 95 to 60% with times up to 5 min. Therefore, it was clearly shown that the Holmen tester gives durability in a wider ranger with a shorter testing time compared to the Pfost tumbling can.

Tabil (1996) studied the durability of alfalfa pellets at three different qualities of chops using both Dural and Stein breakage testers and found pellets made from high quality chops were the most durable. Rhen et al. (2005) used compressive strength as a measure of durability. They found that the durability of Norway spruce pellets increased with an increase in temperature and a decrease in moisture content.

Durability of switchgrass pellets was studied in a moisture range of 6.3 to 17 % (w.b.) (Colley et al. 2006). Initially, there was an increase in durability as the moisture increased, since the binding force of the water molecules strengthened the bond between individual particles in the pellets. Maximum durability (96.65%) was found to occur at a moisture content of 8.62% (w.b.). Beyond a moisture content of 8.62% (w.b.) particle bonds were disrupted and the durability of the pellets decreased to 78.44%. The maximum durability of straw wafer was obtained at moisture contents ranging from 13 to 17% (w.b.) (O'Dogherty and Wheeler 1984).

2.3.5 Moisture absorption

Generally, an increase in air temperature and relative humidity will cause an increase in the moisture absorption of pellets during storage and handling. It was stated by Kalliyan and Morey (2006) that transportation and storage in rainy or high humidity conditions may affect the quality of densified products.

Colley et al. (2006) reported that moisture absorption of the pellets decreased with a decrease in relative humidity. It was found that the minimum moisture absorption occurred at a temperature of about 90˚C (Rhen et al., 2005). For Norway spruce pellets, they found that low initial moisture content resulted in maximum moisture absorption and concluded that a period of 25 h is enough for the conditioning of pellets.

Tabil (1996) studied the effect of absorbed moisture on pellets made from different qualities of alfalfa chops. An environmental chamber with a relative humidity of 90% and temperature of 28°C was used. In this study, pellet quality was described in terms of durability, hardness, and volume expansion. Pellets produced from intermediate quality chops took longer to absorb moisture among the pellets from other quality chops. There was a significant decrease in pellet durability when pellet moisture content was above 10% (w.b.). It was also observed that pellet hardness was sensitive to moisture changes and decreased significantly as the moisture increased above 8% (w.b). For the volume expansion of pellets made from low and intermediate chops, moisture contents of 8 or 10% (w.b.) and above resulted in a significant increase in the volume.

2.4 Specific Energy Requirement and Economics

In the densification process, the total specific energy consists of both the energy required to grind the raw material and the energy needed to form pellets from the ground materials. Therefore, this section presents research regarding the specific energy of biomass grinding using a hammer mill and the energy required to form pellets from biomass using a single-pelleter. In addition, the economics of pelleting flax shives is reviewed.

2.4.1 Specific energy required to grind biomass

The specific energy required to grind biomass is affected by the particle size, and moisture content of the raw materials, as well as type of grinder used. Schell and Hardwood (1994) found that grinding lignocellulosic biomass using a hammer mill requires less specific energy than disc milling. Mani et al. (2004a) evaluated the specific energy required for the grinding of four biomass, namely wheat straw, corn stover, switchgrass and barley straw using a hammer mill with three different screen sizes (0.8, 1.6, and 3.2 mm). The specific energy required to grind all feedstocks was significantly increased with a decrease in the particle size. According to Datta (1981), coarse grinding (0.2-0.6 mm) of hardwood chips required 72 to 144 MJ/t, whereas fine grinding (0.15-0.3 mm) of hardwood chips demanded 360 to 720 MJ/t of specific energy. However, it was not reported what type of mill was used. Shaw (2008) determined the specific energy required to grind feedstocks, raw poplar and wheat straw, using a hammer mill with screens of 3.2 and 0.8 mm. The specific energy required to grind wheat straw was in a range from 41 to 284 MJ/t. From this result, it is clearly seen that more specific energy is required when the particle size of wheat straw is reduced. The initial moisture content of the grinds was 11.7 % (w.b.).

The specific energy required for grinding of all four biomass increased with an increase in moisture content (Mani et al. 2004). Grinding of switchgrass with the use of a hammer mill with a screen size of 3.2 mm at a moisture content from 8 to 12% (w.b.) required the highest specific energy from 86 to 99 MJ/t, whereas grinding of corn stover using the same screen size at a moisture content from 6.2 to 12% (w.b) consumed the lowest specific energy from 25 to 40 MJ/t. This may be explained by an increase in the shear strength of the biomass as the moisture content of the feedstock is increased.

However, Jannasch et al. (2001) reported that grinding switchgrass at moisture contents of 10 to 12% (w.b.) using a commercial hammer mill with screen sizes of 5.6 and 2.8 mm both required the same energy of 201 MJ/t when throughput was about 2 t/h.

2.4.2 Specific energy required to form pellets

In general, total specific energy depends upon a variety of parameters including the pre-set load (i.e., compression pressure), processing temperature, moisture content, and particle size of the grinds. The total specific energy consists of the specific energy required for compression and the specific energy required to extrude the grinds during densification using single pelleting equipment.

Shaw (2008) found that only a small amount of the total specific energy is required to extrude the grinds, while a large percentage of the total specific energy is used for compression of the feedstocks. It was found that the specific compression energy was 7.2 and 39.1MJ/t at pre-set loads of 1000 N (31.6 MPa) and 4000 N (126.3 MPa) for pretreated wheat straw and untreated wheat straw, respectively. This supports the assertion that an increase in the pre-set load results in an increase in the specific energy required for compression.

In general, increasing the preheating temperature of biomass results a decrease in the specific energy consumption. According to Sokhansanj et al. (2005), increasing the process temperature caused a significant decrease in the specific energy required to compress the grinds. In this study, grinds at processing temperatures of 70 and 100°C and moisture content levels of 9 and 15% (w.b.) were used to form pellets. There was not a significant effect on the specific compression energy of the feedstocks. It was also found that an increase in the moisture content of the feedstocks resulted in a decrease in the specific energy required for compression. For extrusion, the mean value of specific energy required to extrude wheat straw pellets was in a range from 0.25 to 0.78 MJ/t.

Mani et al. (2006a) reported that the total specific energy for pelleting corn stover ranged from 12 to 30 MJ/t including both the compression and extrusion energies. Compacting corn stover into the form of briquettes was performed at moisture contents of 5, 10, and 15% (w.b.) and compression pressures of 5, 10, and 15 MPa. Specific compression energies of 8.1 to 7.3 MJ/t were reported using a pre-set pressure of 5 MPa at the high moisture content levels of 10 and 15% (w.b.), respectively.

2.4.3 Economics of pelleting

A number of issues are considered regard to the economic value of pellets produced from flax shives. The total amount of flax produced yearly in Saskatchewan or in Western Canada is of importance. Ulrich (2008) stated that there are about 639,000 tonnes of salvageable oilseed flax straw produced annually in Canada. Schweitzer-Mauduit, Canada purchases from 80,000 to 120,000 tonnes of straw annually for the processing tow fiber used in cigarette papers. Shive content is estimated to be about 78% of flax straw and the average price of shives is assumed to be $2/tonne, based on a 10 year average of oilseed flax straw. These statistics show that there would be abundant source of heat produced if waste flax shives were converted into biofuel. The cost of this solid fuel is relatively low when compared with other sources of energy such as crude oil, coal, and natural gas.

2.5 Emissions

The environmental issues related to biomass fuels must be considered. Biofuels are more carbon-friendly than fossil fuels as the carbon released has been recently removed from the air. The burnig of fossil fuels may cause more adverse health effects than the use of biofuels. When biofuels are burned, inorganic ash and particulate matter remain, and gases, such as carbon monoxide, are released. When compared to coal, biomass fuels have lower levels of carbon, mineral ash, higher alkali levels and higher levels of volatile products (Demirbas 2004). The important chemical properties, such as the proximate and ultimate chemical analysis and the heating value of the volatiles, were reviewed for different biomass fuels (Demirbas 2004). Several studies reported that softwood pellets are an environmentally friendly fuel with low emissions (i.e., no serious effect on the environment). Therefore; they could be used in places where the population is large (Boman et al. 2003; Olsson et al. 2003; Johansson et al. 2004; Olsson and Kjallstrand 2004). Olsson (2006) studied the emissions for fuel pellets made of wheat straw and peat and compared the amount released to those from the combustion of softwood pellets. It was found that pellets made from wheat straw and peat/wood had low emissions during combustion. Boman et al. (1998) performed a study of the products of combustion of six biofuels that were derived from products of the logging industry. From the results of this study, it would appear that biofuels would be less harmful to health than coal or petroleum products.

2.6 Summary

Biomass materials including straw saw dust, shavings, corn stover, switchgrass, and many others have been studied extensively as a source of biofuel. There is a need for densification of these materials to reduce the difficulties of handling and the costs for storage and transportation. However, no research work on the densification of flax shives is found in the literature. Densification of various types of biomass is affected by both raw material properties and process variables. Important raw material properties such as particle size, particle size distribution, bulk and particle density, moisture content constituents, and chemical components were studied on various biomass materials. The quality of densified products made from a variety of biomass feedstocks was also studied extensively, considering parameters such as bulk and particle density, hardness, durability, and moisture absorption.

Particle size reduction of biomass materials is needed before processing them into pellets by densification. Particle size and particle size distribution affect the material properties and binding characteristics of particles during densification. Decreasing the particle size and moisture content resulted in higher bulk and particle density and more particle surface area availabe for binding particles. A wide particle size distribution is more suitable for the compaction process. At high temperatures, natural binders, including proteins and lignins, become soft and help to bond the particles together.

Process variables including pressure (load), preheating temperature, bonding agents, steam conditioning, die geometry, and die speed affect biomass densification. At high pressure, the biomass components change their properties and act as a binding agent for particles. An increase in an applied pressure resulted in an increase in density of corn stover pellets. Increasing the applied pressure above 150 MPa resulted in an increase in unit density and durability of corn stover briquettes. The preheating temperature, when increased from 80 to 110° C, resulted in an increase in both stability and density of wheat straw briquettes.

Natural binding components were activated when the preheating temperature increased from 75 to 100° C for corn stover and switchgrass and resulted in higher density and durability and less volume expansion for the briquettes. If natural binding agents are not sufficiently present, additional binders are needed to bond particles together when processing them into pellets and briquettes. Binders including calcium lignosulfonate, colloids, bentonite, starches, proteins, and calcium hydroxide are used to maintain maximum bulk density and to increase the durability of pellets for animal feeds.

Steam conditioning contributes to the activation of natural and artificial binders by causing gelatinization at an increased conditioning temperature. Alfalfa grinds at a temperature of 92° C and above resulted in better quality pellets. In addition, steam conditioning resulted in increasing the moisture content by about 2%.

Reduction of particle size of the biomass increased the specific energy required for grinding. However, increasing the preheating temperature and moisture content of the feedstocks to form pellets resulted in a decrease in the specific energy required for compression. Biomass fuels had lower levels of mineral ash, higher levels of alkali and volatile products when compared to coal. Softwood, wheat straw, and peat pellets are environmentally more friendly fuels due to their low emissions during combustion.

3. MATERIALS AND EXPERIMENTAL METHODS

The coarse flax shives and ground shives used in this research were obtained from two flax straw processing companies. This chapter presents the physical and chemical properties of the shives and of the waste canola meal used as a binding agent. In addition, the methodology and equipment used to determine the raw material properties, the methods followed for determination of the properties of the solid fuel pellets and, the experimental designs used for characterization of the flax shive material and production of the fuel pellets are described.

3.1 Materials and Characterization

Flax shive material was obtained from two flax straw processing companies, Biofibre Industries Inc. and Biolin Research Inc. First, the physical and chemical properties and the heat of combustion of the coarse raw material and prepared ground material were determined. Then, the ground material was processed into biofuel pellets using the single pelleter and a pilot-scale pellet mill. For the fuel pellets that were produced using the pilot-scale pellet mill, canola meal used as a binder obtained from the University of Saskatchewan, was added to improve the quality of the pellets. The physical properties and chemical composition of the canola meal were also determined in the course of this research. The coarse flax shives and canola meal are shown in Figure 3.1.


(a) (b)

Figure 3. 1 Materials: (a) coarse flax shives, (b) canola meal used as a binder.

A representation of the overall material characterization for the ground flax shives is given in Figure 3.2.

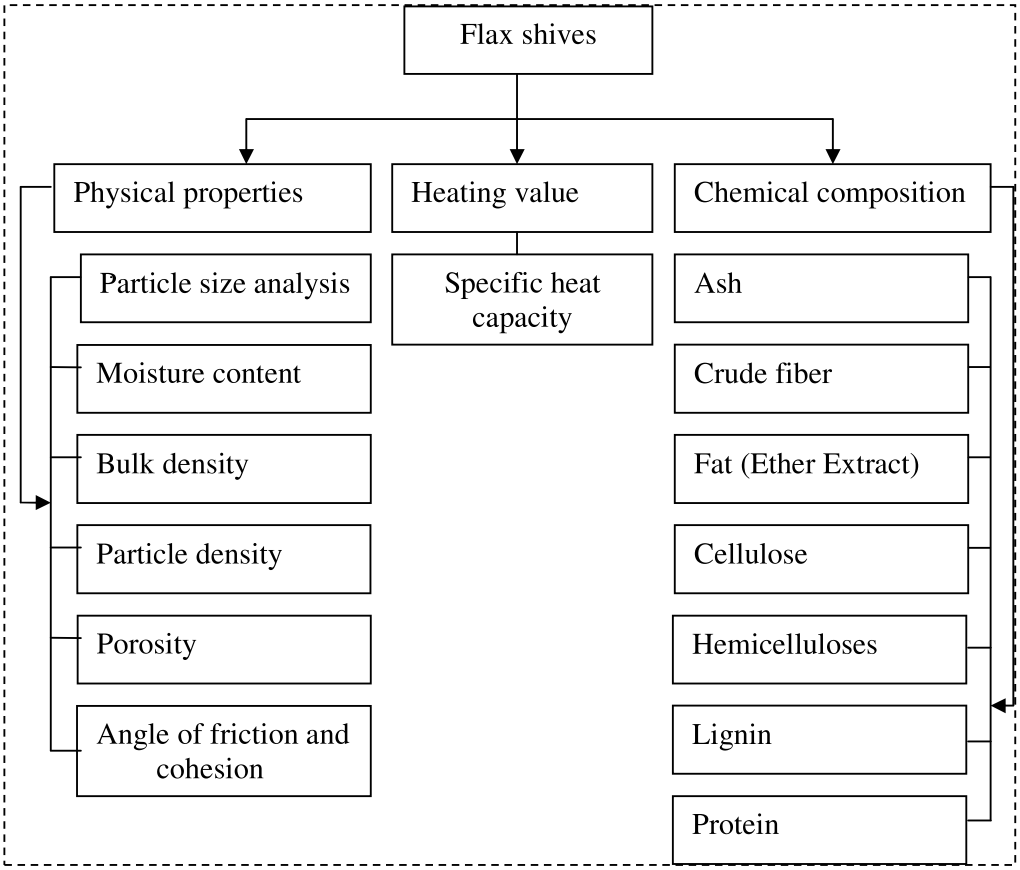


Figure 3. 2 Material characterization of flax shives.

The flax shives from Biofibre Industries Inc. were characterized in terms of particle size and distribution, moisture content, particle density, and bulk density.

The goal of the experiments on these was to evaluate the effect of grinding (i.e., particle size of the flax shives) on the density and durability of the pellets. The pellets were produced using single-pellet equipment. The raw material contained some large pieces of straw that had not been broken into fiber and shives. Therefore, it was necessary to remove these large particles before processing. For the preparation of the material, the flax shives were cleaned to separate fine linen fiber from coarse material before grinding. To perform this operation, a forage separator analyzer was used. This piece of equipment has a screen with 3.8 mm square openings. The particles which passed through the screen were then ground using a Buhler hammer mill (Buhler Manufacturing, Winnipeg, Morden, MB) with screen sizes of 2.4, 3.2 and 4.8 mm. Finally, for this set of experiments, the flax shive grinds were characterized and then densified using a single pelleter.

The flax shives from Biolin Research Inc. were characterized in terms of physical and chemical properties, as well as, heating value. The flax shives were already quite clean in a raw form. Therefore, cleaning and separating the fiber from the raw form was unnecessary. The goal of the experiments on these shives was to determine the effects of moisture content, particle size and the addition of canola meal on the pellet quality. The flax shives were ground in the same hammer mill as above, however, with screen sizes of 3.2, 4.8 and 6.4 mm. They were then pelletized using a laboratory-scale pellet mill. To determine the specific heat capacity, the flax shives were ground using a Thomas Wiley Laboratory Mill (Model 4, Thomas Scientific, Swedesboro, NJ) with a screen size of 1.0 mm.

The canola meal, which was only added to the shives from Biolin Research Inc., was ground using the Buhler hammer mill with a screen size of 3.2 mm. Some physical and chemical properties of the canola meal were determined prior to mixing with the flax shive grinds.

3.1.1 Particle size and size distribution

Initial particle length of flax shives in the raw form from both sources was determined by ASABE Standard, ANSI/ASAE S424.1 MAR1992 (R2007). The flax shives from both sources were ground to give a size distribution more suitable for manufacturing the pellets as a biofuel. To determine the geometric average particle size of the grinds, a Ro-Tap sieve shaker (W.S. Tyler Inc., Mentor, OH) was used. The particle size distribution of the flax shives was determined according to ASAE Standard S319.3 (ASAE, 2005) and the experiment was replicated three times, once for each of the three hammer mill screen sizes. For the grinds from Biofibre Industries Inc., a stack of sieves arranged from the largest to the smallest openings was placed in the shaker. The sieves had Canadian series sieve numbers of 16, 20, 30, 40, 50, 70 and 100 with nominal openings of 1.188, 0.841, 0.595, 0.420, 0.297, 0.210 and 0.149 mm, respectively. For the shives from Biolin Research Inc., the particle size and distribution of the grinds was determined using the Canadian series sieve numbers of 4, 6, 8, 12, 16, 20, 30, 50, 70, 100, 140, 200 and 240 with nominal openings of 4.760, 3.366, 2.376, 1.612, 1.188, 0.841, 0.595, 0.297, 0.210, 0.149, 0.105, 0.074 and 0.052 mm, respectively. Approximately 100g of ground material were used and the shaker was run for 10 minutes. After sieving, the particles obtained on each sieve were weighed. The geometric mean particle size (d_{gw}) and geometric standard deviation (S_{gw}) for the log-normal distribution on a weight basis were calculated as follows:

$$d_{gw} = \log^{-1}\left[\frac{\sum_{i=1}^{n}(W_i \log \bar{d}_i)}{\sum_{i=1}^{n} W_i}\right] \tag{3.1}$$

$$S_{\log} = \left[\frac{\sum_{i=1}^{n} W_i (\log \bar{d}_i - \log d_{gw})}{\sum_{i=1}^{n} W_i}\right]^{\frac{1}{2}} \tag{3.2}$$

$$S_{gw} \approx \frac{1}{2} d_{gw} [\log^{-1} S_{\log} - (\log^{-1} S_{\log})^{-1}] \tag{3.3}$$

where d_i = nominal sieve aperture size of the i^{th} sieve (mm),

d_{i+1} = nominal sieve aperture size in next larger than i^{th} sieve (mm),

d_{gw} = geometric mean particle size or median size of particles by mass (mm),

$S_{\log}$ = geometric standard deviation of log-normal distribution by mass in ten-based logarithm, dimensionless,

S_{gw} = geometric standard deviation of particle size by mass (mm),

W_i = mass on i^{th} sieve (g), and

n = number of sieves +1 (pan).

3.1.2 Bulk and particle density

The bulk densities of the coarse and ground shives from both sources and the ground canola meal were determined using the grain bulk density apparatus. A standard 0.5 L (500g) steel cup (SWA951, Superior Scale Co. Ltd., Winnipeg, MB) was filled using a funnel. To maintain a continuous flow, a thin steel rod was used. The cup was then gently levelled, with a rubber-coated steel rod, and weighed. The measurements were repeated three times for all samples. The bulk density was calculated as

$$\rho_b = \frac{m}{Vc} \tag{3.4}$$

where ρ_b = bulk density (kg/m^3),

m = mass of sample in the cylinder (kg), and

V_c = volume of cylinder (m^3).

To measure the particle density of the ground flax shives and ground canola meal, a gas pycnometer (Quantachrome Corp., Boynton Beach, Fla.) was used. The particle densities of the three grinds produced from both sources were determined. Prior to the particle density measurements, the pycnometer was calibrated using a large spherical ball of known volume. To determine the particle densities of the samples, first, a reference volume of nitrogen gas was pressurized to about 117.2 kPa (P_1). The gas was then allowed to flow into the sample cell until a constant pressure P_2 was reached. By measuring the pressures, P_1 and P_2, the volume of solid V_s may be calculated by

$$V_{\mathrm{s}} = V_{\mathrm{cell}} - V_{\mathrm{R}}\left(\frac{P_1}{P_2 - 1}\right) \tag{3.5}$$

where V_s = volume of solid (cm^3),

V_{cell} = volume of the cell (cm^3),

V_{R} = reference volume for the large cell (cm^3),

P_1= pressure reading after pressurizing the reference volume (kPa) and

P_2= pressure reading after including volume of the cell (kPa).

After the volumes for all of the samples were determined, their masses were then determined. The particle densities of the ground flax shives and canola meal were calculated using

$$\rho_{\mathrm{t}} = \frac{m}{V_{\mathrm{s}}} \tag{3.6}$$

where ρ_t = particle density (kg/m^3),

m = mass of sample in the cylinder (kg), and

V_s = volume of solid (m^3).

An average particle density was obtained from three trials. Porosity of the shive samples was calculated using

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100 \tag{3.7}$$

where ε = porosity (%),

ρ_b = bulk density (kg/m^3) and

ρ_t = particle density (kg/m^3).

3.1.3 Moisture content and conditioning

The moisture contents of the coarse and ground flax shives, the canola meal, the final mixture of shives and canola meal, and the pellets produced from the shives were determined according to ASAE Standard S358.2 (ASAE, 2005), as this is the standard method for forages. This method involves determining the reduction in weight of samples, after oven drying for 24 h at 103°C. A forced convective electric oven (Blue M Thermal Products Solutions, Williamsport, PA) was used and three replicates were performed for each sample. The flax shive samples were first conditioned to various moisture levels as required for different measurements. For example, to measure the specific heat capacity of the shives, samples were conditioned to 8, 11, and 14% (w.b.). The mixtures of shives and canola meal prior to producing pellets were conditioned to 8, 11, and 14% (w.b.). The following equation was used to determine the amount of water that was required to achieve the desired moisture content of samples.

$$m_w = m_i \frac{M_{wf} - M_{wi}}{1 - M_{wf}} \tag{3.8}$$

where m_w = mass of water added to sample (g),

m_i = initial mass of sample (g),

M_{wf} = final desired moisture content of sample (w.b.), and
M_{wi} = initial moisture content of sample (w.b.).

After adjusting the moisture content, the samples were stored in sealed bags and allowed to equilibrate for 24 hours at room temperature before being subjected to measurement and processing.

3.1.4 Chemical components

The chemical compositions of the flax shives from Biolin Research Inc. and the canola meal were determined in this research. Protein, ash, fat and crude fiber contents of the samples were determined at Sun West Food Laboratory, Saskatoon. Determination of ash content, crude fiber content and protein content was performed according to AOAC methods of 942.05 (AOAC, 2005), 992.23 (AOAC, 2005) and 962.09 (AOAC, 2005), respectively. The standard method of AOCS Am 2-93 (2000) was used to determine the fat content of samples. The amounts of acid detergent fiber (ADF), neutral detergent fiber (NDF) and acid detergent lignin (ADL) were determined in the Plant Sciences Department at the University of Saskatchewan using the ANKOM 200/220 Fiber Analyser (ANKOM Technology, Fairport, NY). In addition, cellulose and hemicelluloses of the samples were calculated by

$$\text{Cellulose} = \text{ADF} - \text{ADL} \tag{3.9}$$

$$\text{Hemicelluloses} = \text{NDF} - \text{ADF} \tag{3.10}$$

The values chemical components are expressed by weight in percentage dry basis (d.b.).

3.1.5 Angle of internal friction and cohesion

Since there is no information on the frictional properties of grinds from flax shives, the frictional characteristics of shives on a steel surface were determined in this study. Friction and cohesion are important as they have an effect on the power needed to handle the raw material and this affects the design of equipment. A Wykeham Farrance shear box apparatus (Wykeham Farrance International Ltd., Slough, UK) shown in Figure 3.3 equipped with a 100 mm square shear box and motor assembly was used to determine the angle of internal friction and cohesion of the flax shives obtained from Biolin Research Inc. Both the top and bottom boxes of the apparatus were filled with a sample. The bottom box was then pulled horizontally at a constant speed of 0.4 mm/min. Shear stress at four different normal loads of 100, 200, 300, and 400 N was applied to the shives via a load hunger and was measured in three replicates. The method and calculation of the coefficient of internal friction and cohesion of the flax shive sample were conducted, as explained by Peleg (1977) and Tabil and Sokhansanj (1997).

$$\tau = C_c + \tan \varphi_i \, \sigma \tag{3.11}$$

where τ = shear stress (kPa),

C_c= cohesion (kPa),

φ_i= angle of internal friction; and

σ= normal stress (kPa).

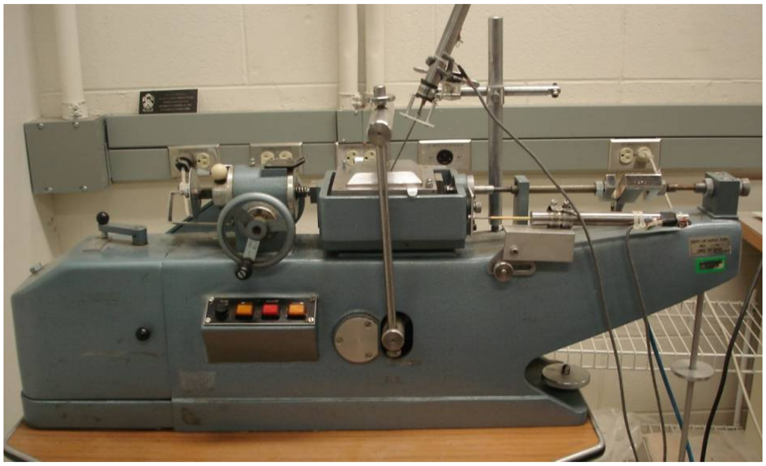


Figure 3. 3 Wykeham Farrance shear box apparatus.

3.1.6 Specific heat capacity

Specific heat capacity is a function of temperature and moisture content, and is an important parameter for characterizing the flax shives obtained from Biolin Research Inc. For the measurement of specific heat capacity of flax shives, Differential Scanning Calorimetry, DSC 111 (Setaram Scientific & Industrial Equipment, Caluire, France) was used and is shown in Figure 3.4.

Figure 3. 4 Differential Scanning Calorimetry, DCS 111 for specific heat capacity measurement of samples.

Yang et al. (2002) and Izadifar and Baik (2007) reported that DSC is an accurate and rapid method for measuring specific heat capacity.

Flax shives were ground using a laboratory grinder (Laboratory Mill Model 4, Thomas Scientific Co., USA) with a screen size of 1 mm. The specific heat capacities of flax shives with three different levels of moisture content, i.e., 8, 11, and 14% (w.b), were determined. About 10 mg of flax shives were placed in the DSC machine and sealed in an aluminum pan along with a blank reference pan. During the measurement, the temperature was increased from 25 to 80°C at a heating rate of 5°C/min and three replicates were performed. The specific heat capacity was calculated using

$$C_p = \frac{dH}{dt} \Big/ \left(\frac{dT}{dt} M\right) \tag{3.12}$$

where dH/dt = heat flow rate (J/s),

M = sample mass (kg),

Cp = specific heat capacity (J/(kg°C)),

t = time (s) and

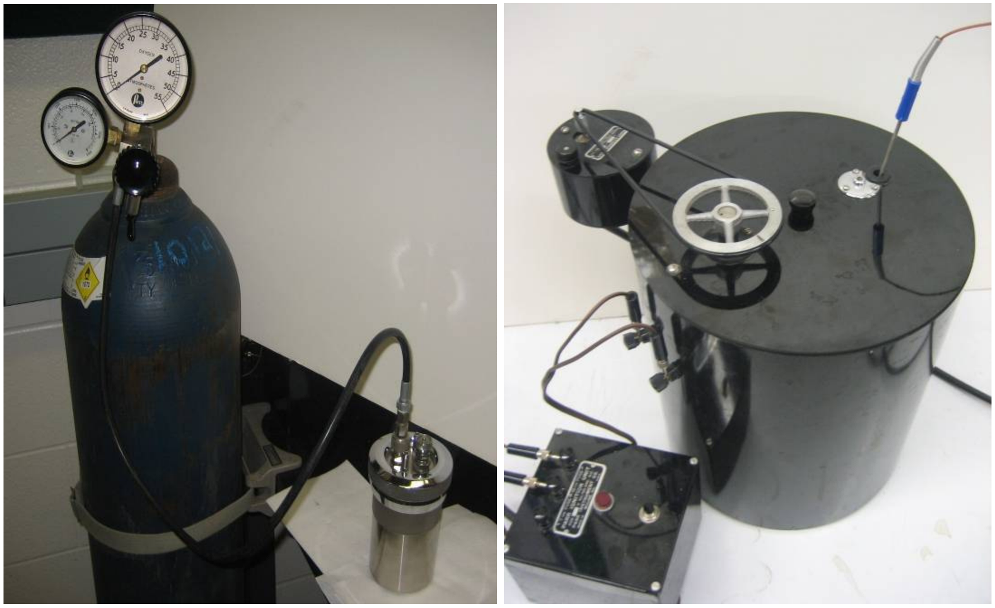
T = sample temperature (°C).

3.1.7 Combustion energy

The combustion energy of the flax shives obtained from Biolin Research Inc. was measured by a bomb calorimeter (Series 1300 Plain Calorimeter, Parr Instrument Company, Moline, IL) which is shown in Figure 3.5. The bomb calorimeter consists of an oxygen combustion bomb, water container, ignition switch and gas cylinder (Figure 3.6). The thick steel bomb contains a sample pan and ignition wire.

Calibration of the bomb calorimeter used benzoic acid. First, the water container was filled with about 2 liters of distilled water. Then, a 1g pellet of benzoic acid, with a known caloric value of 26.5 MJ/kg, was placed into the stainless steel sample pan. A 10 cm long fuse wire touched the pellet and ignited the benzoic acid in the bomb calorimeter. A thermometer was connected to a Campbell data logger (Model CR10X, Campbell Science, Inc. Logon, UT) to record the water temperature.

Figure 3. 5 Bomb calorimeter set up.



(a) (b)

Figure 3. 6 Bomb calorimeter; (a) Gas cylinder and oxygen bomb, (b) Bomb calorimeter in water container with ignition switch, and thermometer.

Prior to measurement, the water was allowed to reach an equilibrium condition. After completion of the measurements, the unburned fuse wire was removed and the length was measured. The change in the temperature of water indicates the energy that was released by combustion, and 2.3 cal/cm of wire burned needs to be subtracted from the calorie reading as this is the amount of energy.

The energy content of the shives in pellet form was evaluated according to ASTM Standard E 711 (ASTM, 2003), the accepted test method for the combustion energy of coal and coke. The energy content for the samples was calculated using

$$H = \frac{(t\,W - e)}{m_a} \tag{3.13}$$

$$H_g = \frac{(t\,W - e)}{m} \tag{3.14}$$

where W = energy equivalent of calorimeter (J/°C),

H_g = energy content of standard benzoic acid (J/kg),

m_a = mass of benzoic acid (kg),

t = corrected temperature rise (°C),
e = correction for heat of firing fuse wire (J),
m = mass of sample in combustion cap (kg) and
H = energy content of sample (J/kg).

3.2 Material Processing Equipment and Procedures

Once the experiments on the flax shives were complete, the pelleting process was performed using a closed-end die and plunger unit for the shives from Biofibre Industries Inc. and a pilot-scale pellet mill for the shives from Biolin Research Inc.

3.2.1 Pelleting with the single pelleter

The single pelleting equipment is shown in Figure 3.7. The single pelleter consists of a die and plunger assembly and stainless steel base (supporter) along with a heating element.

Figure 3. 7 Single pellet equipment.

The plunger and die both had diameters of 6.35 mm. The die was 135.24 mm long and had a heating element wound around it. To control the temperature, two type-T thermocouples were installed in the die wall and attached to a temperature controller. A stainless steel base was used to support the entire assembly and provide a rigid surface upon which to compress the sample.

The single-pelleter was constructed for use in the Instron® model 1011 testing machine (Instron Corp., Canton, MA) as shown in Figure 3.8. The Instron testing machine was used to control pressure, and the cross-head speed of the plunger during pelleting. The preheating temperature of the biomass was controlled by the heating element. To produce the pellets, constant pressure of 139 MPa, temperature of 100˚C and moisture content of 10% (w.b.) were used. The preset load was 4400N. Approximately 0.5g of shives was placed in the single pelleter die chamber prior to loading and the die was heated to 100˚C. The ground flax shives were then compressed by the plunger with a crosshead speed of 50 mm/min. When the preset load was reached, the crosshead on the plunger was stopped.

Figure 3. 8 Instron® model 1011 testing machine with attached single pelleter.

The pellet was removed from the chamber by application of a gentle force. Grinds from three different screen sizes (i.e., 2.4, 3.2 and 4.8 mm) were formed into pellets using the single-pelleter and nine pellets from each particle size were produced. These pellets were produced to study the effect that the particle size has on the unit density and durability of individual pellets.

3.3.2 Pelleting with the pilot-scale pellet mill

After grinding and combining with set amounts of canola meal, the flax shives were processed into pellets, using a California Pellet Mill (CPM-Laboratory Model CL-5, California Pellet Mill Co., Crawfordsville, IN) without steam conditioning, as shown in Figure 3.9. A chart of the complete process for producing fuel pellets from the raw flax shives, as supplied, is given in Figure 3.10. Prior to the pelleting process, the required amount of canola meal was calculated and mixed with ground shives using a cement mixer. After mixing, the moisture content was determined and moisture conditioning was performed using distilled water.

Figure 3. 9 California Pellet Mill.

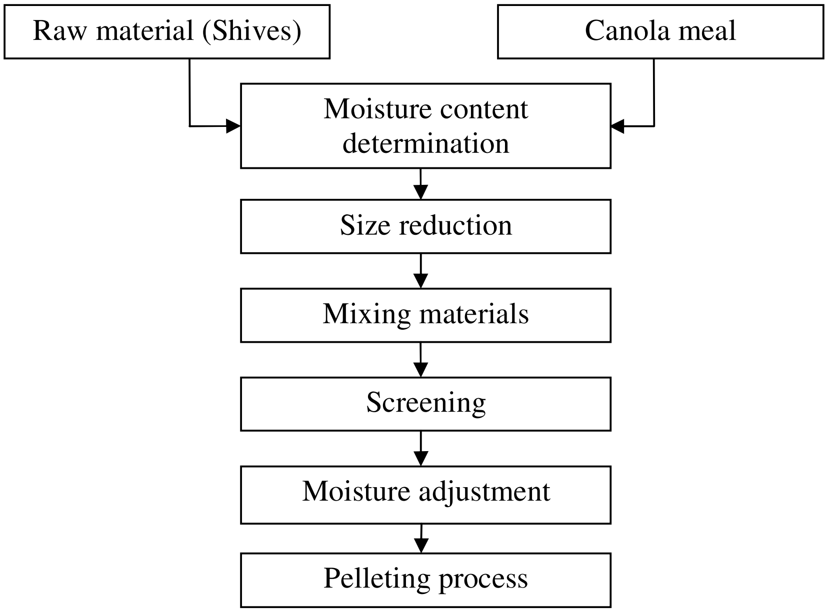
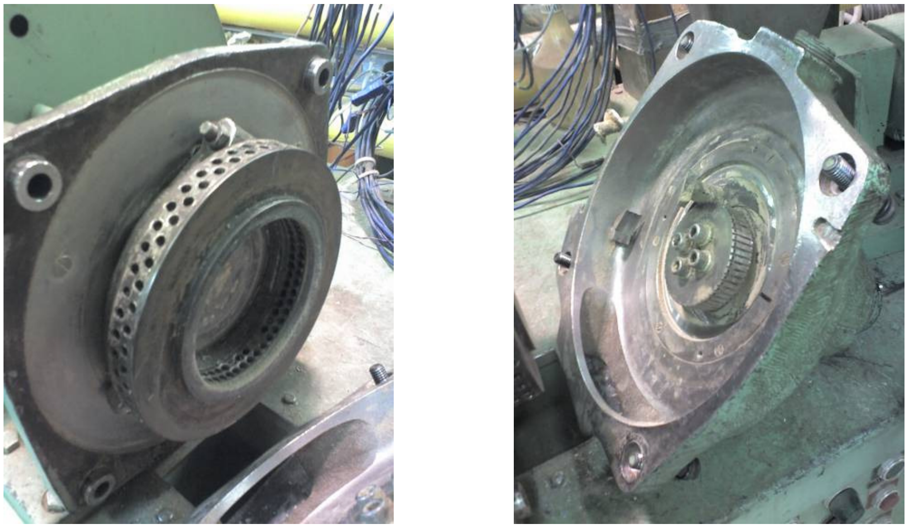


Figure 3. 10 Processing scheme of flax shives for fuel pellets.

In this experiment, the pilot-scale CPM had a motor power 1.5 kW (2.0-hp) and a die and roller assembly consisting of two main parts: a die, with 6.4 mm holes and a length of 46.8 mm, and a roller. These are shown in Figure 3.11.



(a) (b)

Figure 3. 11 Die and roller assembly; (a) Die, (b) Roller.

To produce the pellets, about 0.9 kg of ground flax shive sample was placed in the vibratory feeder and the flow rate was controlled by the feeder chute located on the control panel. In the pelleter, the die and roller rotated in opposite directions which created frictional heating by high pressure and force. The ground raw materials (i.e., the mixture of flax shive grinds and canola meal) were densified through the open-ended cylindrical die from the inside of the ring towards the outside of the ring and compacted particles were formed which were compressed against each other. The feedstock was then cut off with a knife at lengths of less than 30 mm. After pelletizing, the pellets were cooled to room temperature.

The purpose of the experiments performed on these pellets was to investigate the effects of the moisture, particle size of flax shives and the addition of three levels of canola meal on the properties of pellets produced using the pilot scale pellet mill. Therefore, the quality of the pellets, in terms of bulk and particle densities, dimensional stability, hardness, durability, and moisture absorption were studied using a Central Composite Face-Centered Design (CCFD). This type of design helps to optimize the estimation of the effects of the independent variables with a minimum number of experimental points and consists of a 3^k factorial, where k is the number of levels in each of 3 factors. Some of the 3^k combinations of runs were left out. Analysis of variance and regressions were used to find estimates of the effects of independent variables on the dependent variables and to test hypotheses about the significance of these effects. The assumptions for least squares methods are that 1.) the treatment and environmental effects are additive, and that 2.) the experimental errors are randomly distributed, independent and normally distributed and with a common variance.

For the pellets produced using the CPM, the three factors that were varied were screen size for the grinds, moisture content and amount of canola meal added. To grind the flax shives, the hammer mill used screen sizes of 3.2, 4.8 and 6.4 mm. The samples had moisture contents of 8, 11 and 14% (w.b.) and canola meal amounts of 18, 21 and 24% by weight of the total mixture. The CCFD specified the 20 experimental runs as given in Table 3.1.

Table 3.1 Central Composite Face-Centered Design (CCFD).

Run	Screen size (mm)	Moisture content (% w.b.)	Canola meal (%)
1	3.2	8	18
2	3.2	14	18
14	3.2	11	21
3	3.2	8	24
4	3.2	14	24
12	4.8	11	18
10	4.8	8	21
9	4.8	11	21
11	4.8	14	21
13	4.8	11	24
16	4.8	11	21
17	4.8	11	21
18	4.8	11	21
19	4.8	11	21
20	4.8	11	21
5	6.4	8	18
6	6.4	14	18
15	6.4	11	21
7	6.4	8	24
8	6.4	14	24

3.3 Quality Properties of Pellets

Several experimental tests were used to evaluate the physical and fuel properties for the fuel pellets made from flax shives. These tests are listed in Table 3.2 along with the equipment that was used to perform the tests. For emission measurements of the flax shive pellets, emissions from commercial wood pellets were also measured for comparison of combustion gases.

Table 3. 2 Evaluation tests performed and equipment used.

Property tests	Equipment
Dimensional stability and unit density	Digital caliper
Bulk density	Grain bulk density apparatus
Particle density	Gas multipycnometer
Hardness	Instron testing machine
Durability	Dural tester
Moisture absorption	Humidity chamber
Combustion energy	Bomb calorimeter
Emissions	Grain burning stove

3.3.1 Dimensional stability

The dimensional stability test was performed only on the flax shive pellets produced using the CPM. Ten randomly selected pellets from each run were subjected to the dimensional stability test. The length and diameter of the individual pellets were measured after the pellets cooled and the length/diameter ratio of the pellets was calculated. Pellets from all 20 runs were sealed in bags and stored at room temperature for 21 days. Then, the length and diameter measurements were taken again and the changes in the length, diameter and length/diameter ratio of individual pellets were calculated in terms of percentage.

3.3.2 Densities of pellets

The length and diameter of the pellets produced by the single pellet equipment were measured just after removal from the die chamber. The unit density of these pellets (total of 27 single pellets) was calculated based upon the volume and the mass.

For the pellets formed using the CPM, the dimensions (i.e., length and diameter) of 10 randomly selected pellets from all 20 runs, total 200 pellets, were measured to determine the average unit density. Bulk and particle densities and porosity were also determined using the same equipment and methods as described previously for the raw material. The bulk density of pellets from all 20 runs was performed in triplicate, whereas the particle density of pellets (about 10g pellets samples) was determined without replication. In addition, the porosity of the pellets was calculated.

3.3.3 Hardness

The hardness of pellets made from the shives from Biolin Research Inc. was determined by a compression test (ASAE standard S368.2) using the Instron testing machine. The hardness test assembly is shown in Figure 3.12. Two parallel horizontal flat plates with a diameter of 57.2 mm were used with a crosshead speed of 10 mm/min. This is identical to the method which was used by Tabil (1996). The measurements were performed on ten randomly selected pellets from each of the 20 runs. The maximum force in Newtons (N) needed to break the pellets was determined and was used as a measure of its hardness.

Figure 3. 12 Hardness test assembly.

3.3.4 Durability

Durability of the flax shive pellets from the single pelleter was determined by a drop resistance test similar to the method used by Sah et al (1980), Khanhari et al (1989), Shirivastava et al (1989) and Al-Widyan and Al-Jalil (2001). Prior to the test, the pellets were stored in a refrigerator to ensure that they had the similar moisture content. They were dropped from a height of 1.85 m onto a steel metal plate surface three times per each sample. A total of 27 pellets were subjected to the drop resistance test. The durability of single pellets for each sample was calculated as the percentage of pellet mass retained. The pellet durability index (PDI) or durability was calculated using

$$\text{Durability}\left(\%\right)=\frac{\text{Mass of pellets after dropping}}{\text{Mass of pellets before dropping}}\text{ x100} \tag{3.15}$$

The durability of the pellets produced by the CPM was evaluated by a different method. In this experiment, the durability of the pellets was determined using the DURAL tester which was developed at the University of Saskatchewan for testing alfalfa cubes (Sokhansanj and Crerar, 1999). Before the durability test, the pellets were sieved using a 5.56 mm round hole sieve to remove any dust. A 100g sample of pellets was randomly selected, weighed and placed in the tester. The tester was run for 30 s at a speed of 1600 rpm to tumble the pellets. The sample was then sieved using the same screen as before the test. The durability of the sample was expressed as the ratio of the remaining mass of the pellets to the initial mass. Three replicates of this test were done on pellets from all 20 runs. The pellet durability index (PDI) or durability was calculated using

$$\text{Durability}\,(\%) = \frac{\text{Mass of pellets after tumbling}}{\text{Mass of pellets before tumbling}} \text{ x } 100 \qquad (3.16)$$

3.3.5 Moisture absorption

A sample of about 150g of the pellets produced by the CPM for each of the 20 runs were subjected to a moisture absorption test using a temperature and humidity conditioner oven (Model AH-213, BRYANT Manufacturing Associates, Ayer, MA). The moisture content of the pellets was measured and they were then sealed in plastic bags and kept in the fridge for about a week. The reason to store the samples in the fridge was that the time between making the pellets and taking the measurement could vary among treatments. The moisture content of the samples was determined again after removing them from the fridge. The pellets were placed in the oven for three days at a temperature of 25 ˚C and humidity of 90%. The mass of pellets from each sample was measured for every 24 h for three days to determine the percentage change in moisture content of the samples.

3.3.6 Combustion energy

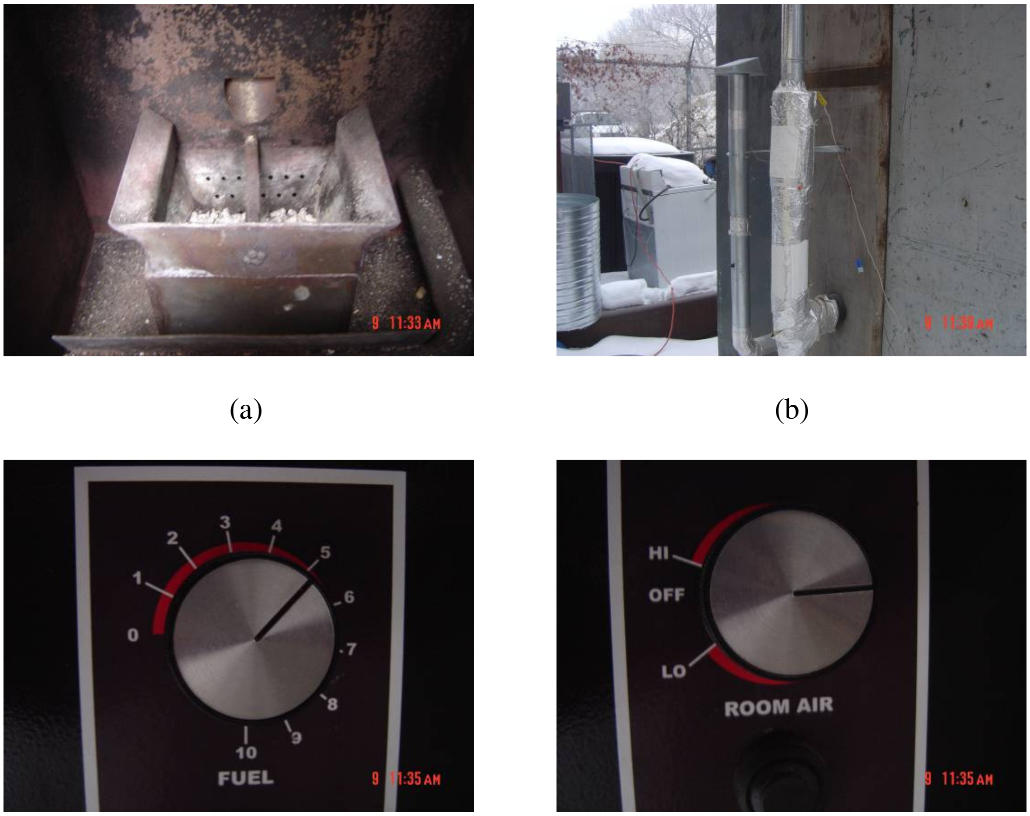
The combustion energy of the individual biomass pellets produced using the single pelleter and the CPM was measured using the bomb calorimeter discussed previously. However, for the pellets produced by the CPM, only the pellets made from flax shives ground with a hammer mill screen size of 4.8 mm were used for energy content determination. These pellets were made with 18% by weight canola meal and had a moisture content of around 10% (w.b). The experiment was performed three times on samples whose mass ranged from 0.5 to 1.0g.

3.4 Emission Measurement

Emission tests of the fuel pellets were performed using the Prairie Fire Multi Fuel Stove (Prairie Fire Grain Energy, Bruno, SK) shown in Figure 3.13. Approximately 3kg of pellets containing 22% and 30% by weight canola meal were used for the emission measurements. For comparison purposes, wood pellets were also tested.

A small quantity of pellets was also placed in the firebox (Figure 3.14a) to start the fire. For the burning of the fuel pellets, the feeding rate of fuel pellets was controlled by setting the fuel control knob at the middle level and room temperature by setting the temperature control knob at position between low and high level, as shown in Figure 3.14c and 3.14d. In the beginning, it was necessary to press the prime button continually for about few minutes to start the feeding auger. Once the temperature inside the stove rose, the automatic fuel feeder started working normally. After 15-20 minutes of burning pellets, the combustion process was assumed to be in a steady state and the first gas sample was taken using a needle and syringe at the outlet shown in Figure 3.14(b). Four samples were taken every 2 min to evaluate the emissions. This evaluation was conducted using a gas chromatography (GC) analysis in the Department of Soil Science at the University of Saskatchewan. Nitrogen (N), oxygen (O_2), methane (CH_4), nitrogen oxide (NO_2), and carbon dioxide (CO_2) were measured and analyzed.

Figure 3. 13 Grain burning stove used to measure emissions.



(a) (b)

(c) (d)

Figure 3. 14 Some components of the grain burning stove; (a) Firebox, (b) Outlet where gas samples were collected, (c) Fuel control knob, (d) Room temperature control knob.

3.5 Statistical Analysis

SAS statistical software (SAS Institute, Cary, NC) was used for the analysis of some of the data that was collected. For the specific heat capacity of the flax shives, temperature and moisture content were taken as the main independent variables. Using SAS, the significance of differences among moisture content and temperature, as well as, the interaction of moisture content and temperature at different levels was analyzed using a linear regression model.

The effect of grinding on single pellet density and durability was determined using a completely randomized design. The experimental data analysis was carried out using an analysis of variance (ANOVA) to find differences and significance among the treatments.

For the pelleting of shives using the CPM, the effects of three variables; moisture content, particle size of shive particles, and addition of canola meal; and their interactions with dependant variables (i.e., density, hardness, durability, etc.) of the densified pellets were analyzed using a SAS General Linear Model (GLM) and multiple regression models. GLM includes estimation procedures for parameters in models for a wide range of error distributions. Further investigation to find any unknown effects that were missed with ANOVA was investigated using a linear regression with the various methods. For normal distribution of errors ANOVA and regression methods are used which are based on least squares estimation procedures. The least square means are estimates of the means from parameters in a least squares model. They are weighted for the number of replicates in the various treatments. If all treatments have equal replications, errors are normally distributed and the least square means are equal to arithmetic means.

4. RESULTS AND DISCUSSION

This chapter presents the experimental results of the study in five parts. First, the physical properties, such as moisture content, particle size and size distribution, bulk and particle densities and angle of friction of flax shives and canola meal are presented and discussed. Second, the chemical composition, specific heat capacity and combustion energy of flax shives are presented. Third, the effect of particle size (i.e., screen size) on density and durability of the single pellets is presented. Fourth, the effects of particle size, moisture content and canola meal levels on the various properties of fuel pellets made from the flax shives obtained from Biolin Research Inc. are presented and discussed. Lastly, the combustion energy and emission of flax shive pellets and commercial wood pellets are compared and discussed.

4.1 Physical Properties of Flax Shives and Canola Meal

Table 4.1 indicates which physical properties were determined for the flax shives from the two sources and the canola meal.

Table 4. 1 Measured physical properties of flax shives and canola meal.

Properties	Source of coarse flax shives		Source of ground shives		Canola meal
	Biofibre Inc.	Biolin Inc.	Biofibre Inc.	Biolin Inc.	
Moisture content	yes	yes	yes	yes	yes
Particle size	yes	yes	yes	yes	no
Size distribution	yes	yes	yes	yes	no
Bulk density	yes	yes	yes	yes	yes
Particle density	no	no	yes	yes	yes
Angle of friction	no	no	no	yes	no

4.1.1 Moisture content

The initial moisture content of the coarse flax shives from both sources was about 10.5% (w.b.). The average moisture content of flax shives after the three grinding treatments is given in Table 4.2.

Table 4. 2 Moisture content of flax shives.

Screen size (mm)	Moisture content (% w.b.)*	
	Biofibre Inc	Biolin Inc
Unground	10.5 (0.09)	10.6 (0.02)
6.4	10.4 (0.52)	8.6 (0.08)
4.8	N/A[a]	8.2 (0.05)
3.2	10.0 (0.06)	7.9 (0.03)
2.4	9.6 (0.03)	N/A[a]

*Numbers in parenthesis are standard deviations (n=3).
[a] Data not available.

The results show that grinding with a smaller screen size caused a decrease in the moisture content of the shives. This is due to extra heat generation during grinding with a smaller screen. Grinds with a large screen had more variations than those ground with a small screen. The canola meal used as a binding agent in pelleting of shives had an initial moisture content of 6.63% (w.b.).

4.1.2 Particle size

The initial particle size of the biomass has an effect on the energy consumption required for grinding (Mani et al. 2004a). Therefore, particles sizes of the flax shives were determined in this research. For the raw flax shives from Biofibre Industries Inc., the initial geometric mean chop size was 2.42 mm, while the geometric mean chop size was 8.46 mm for flax shives from Biolin Inc. Geometric standard deviations of the chopped shives were 3.31 mm and 2.63 mm for Biofibre and Biolin shives, respectively. The geometric mean particle size (d_{gw}) for ground shives from both sources, along with the geometric standard deviation (S_{gw}), is given in Table 4.3.

Table 4. 3 Geometric mean particle size (d_{gw}) and standard deviation (S_{gw}) of shives.

Screen size (mm)	Geometric mean particle size (d_{gw}) (mm)*	
	Biofibre Inc	Biolin Inc.
6.4	0.438 (0.012)	0.636 (0.025)
4.8	N/A[a]	0.547 (0.020)
3.2	0.408 (0.014)	0.454 (0.009)
2.4	0.367 (0.009)	N/A[a]

*Numbers in parenthesis are geometric standard deviations of particle size, S_{gw} (n=3).

[a]Data not available.

Grinding of Biofibre shives with a Buhler hammer mill using screen sizes from 6.4 to 2.4 mm reduced the geometric mean particle size from 0.438 to 0.367 mm, respectively. Grinds from the screen size of 2.4 mm had the lowest standard deviation of 0.009 mm. For grinding with other screen sizes, differences in the average particle size were varied slightly. For Biolin shives, the use of hammer mill screens of 6.4, 4.8, and 3.2 mm resulted in the geometric mean particle size with values of 0.636, 0.547, and 0.454 mm, respectively. Again, grinding with a hammer mill with screen sizes from 6.4 to 3.2 mm reduced the geometric mean particle size from 0.636 to 0.454 mm. The lower standard deviation at a screen size of 3.2 mm indicates that the material became more uniform in size. The effects of grinding shives with various screen sizes on particle size and particle size distribution were analyzed using one-way ANOVA within the SAS statistical software. The ANOVA of particle size of flax shive grinds from the two sources at the three screen sizes (Table B.1) found that the differences mentioned above were significantly different ($p<0.01$). The reduction in the geometric mean particle sizes due to grinding was slightly different for the shives, even when the same screen size was used. However, the results are comparable to other studies. Mani et al. (2004a) reported that the geometric mean particle sizes of corn stover and switchgrass were 0.41 mm at a moisture content of 6.22% (w.b.), and 0.46 mm at a moisture content of 8.00% (w.b.), respectively. Both biomass grinds resulted from a hammer mill screen size of 3.2 mm. Shaw and Tabil (2006) reported that the geometric average of particle size of flax shives was 0.64 mm using a hammer screen of 6.4 mm. Using 6.4 and 3.2 mm screen sizes, Mani et al. (2004b) determined the geometric mean particle sizes of corn stover grinds at a moisture content of 7% (w.b), were 0.682 and 0.407 mm, respectively.

4.1.3 Particle size distribution

Figure 4.1 compares the particle size distribution after grinding of the flax shives from Biofibre Industries Inc. The most material were retained on the sieve with an opening of 0.595 mm for all grinding treatments. However, there is a large difference between the treatments for the sieve with an opening of 1.190 mm. Overall, the grinds from the various screens had a large size distribution. The reason for only a small shift in the size distribution was attributed to the removal of large pieces of flax straw from the raw material before grinding.

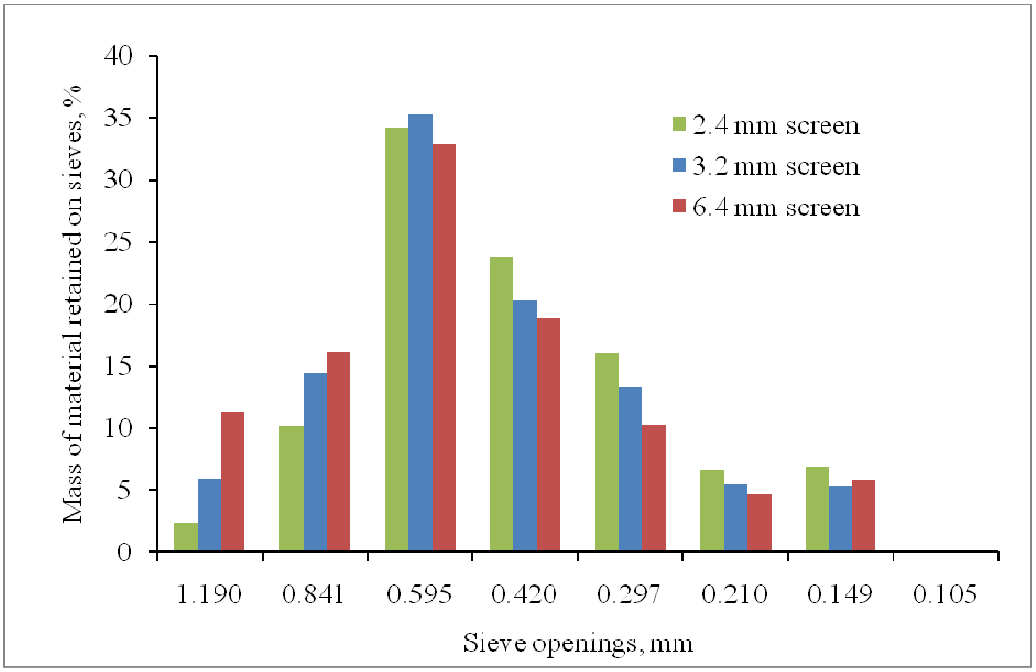


Figure 4. 1 Particle size distribution of shives from Biofibre Industries Inc. at various screen sizes.

A chart of the particle size distribution of the grinds from the flax shives from Biolin Research Inc. is shown in Figure 4.2. The use of more sieves resulted in a better separation of particles. The majority of the particles were retained on the sieves with openings from 1.190 to 0.595 mm. This may have been due to the fact that the material was not subjected to an initial screening before grinding. Mani et al. (2004a) used sieve sizes with openings ranging from 0.09 to 2.00 mm to determine the particles size distribution of various biomass grinds at various screen sizes. They found that the grinds from screen size of 3.2 mm had the largest size distribution.

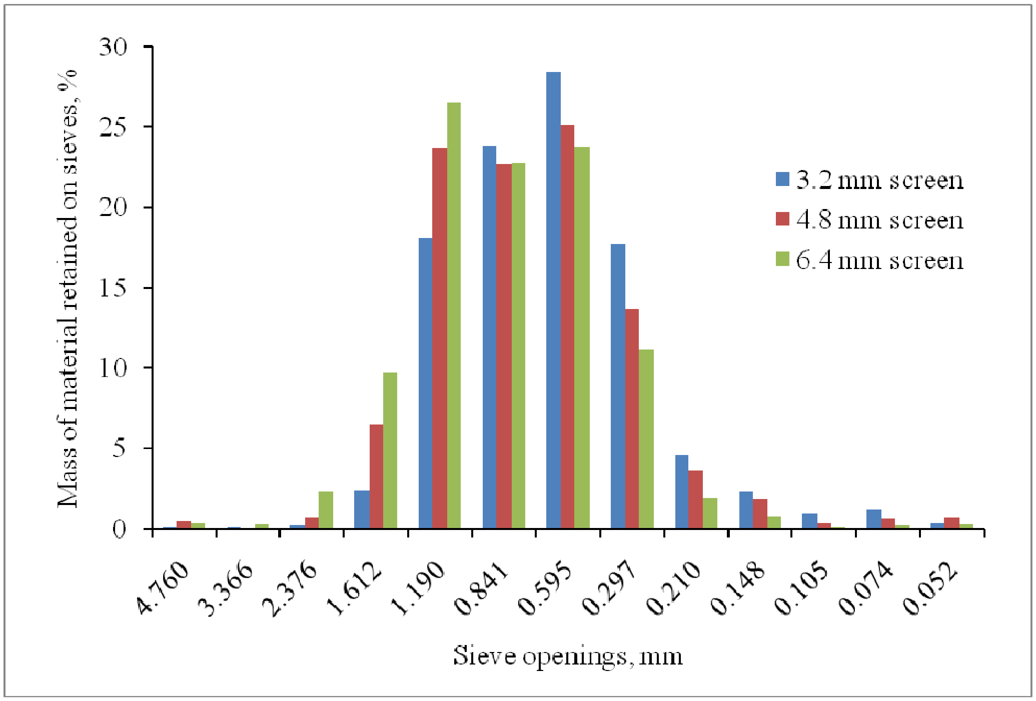


Figure 4. 2 Particle size distribution of shives from Biolin Research Inc. at various screen sizes.

4.1.4 Bulk and particle density

The results of the bulk and particle density testing on the ground shives, including the porosity, are given in Table 4.4. The initial bulk density of shives (i.e., raw material) from Biofibre Industries Inc., was determined to be, on average, 133.1 kg/m^3.

Table 4. 4 Means of bulk and particle density and porosity of ground flax shives from Biofibre Industries Inc.

Screen size (mm)	Bulk density (kg/m^3)*	Particle density (kg/m^3)*	Porosity (%)
6.4	156.6 (2.92)	1175 (19.74)	86.67
3.2	162.7 (2.57)	1228 (6.17)	86.75
2.4	166.4 (2.73)	1285 (10.38)	87.50

*Numbers in parenthesis are standard deviations of densities of shives (n=3).

Both the bulk and particle densities of ground flax shives increased as the screen sizes decreased. The porosity of the ground flax shives was essentially the same amongst the grinding treatments. Therefore, the screen size did not affect the porosity. When the bulk density of shives ground with the 3.2 mm screen was compared to other studies, it was found to be higher. This may be due to the care that was taken to remove the larger pieces of straw, which contain fiber, from the raw material.

Table B.2 shows that the statistical effects of different screen sizes on the bulk and particle density of shives from Biofibre Industries Inc. determined using ANOVA. Use of a smaller screen caused a statistically significant increase in the both bulk and particle densities of shives. For corn stover grinds, Mani et al. (2004b) noticed that the particle density of corn stover grinds at a moisture content of 7% (w.b.) increased from 1085 kg/m^3 to 1210 kg/m^3 when the hammer mill screen size decreased from 6.4 to 3.2 mm. Unground shives from Biolin Research Inc. had an initial bulk density of 71.2 kg/m^3. The average bulk and particle densities and the porosity of the ground flax shives are given in Table 4.5. There were large variations with the used of screen sizes of 6.4 and 3.2 mm for the particle density of shives. The bulk and particle densities of the canola meal ground with a screen size of 3.2 mm were 396.3 kg/m^3 and 1368.92 kg/m^3, respectively.

Table 4. 5 Means of bulk and particle density and porosity of ground flax shives from Biolin Research Inc.

Screen size (mm)	Bulk density (kg/m^3)**	Particle density (kg/m^3)**	Porosity (%)
6.4	113.3 (6.03)	1312 (28.86)	91.36
4.8	133.7 (6.52)	1314 (9.91)	89.82
3.2	151.3 (5.59)	1338 (42.33)	88.69

*Numbers in parenthesis are standard deviations of ground shives (n=3).

ANOVA Table B.3 shows how the different screen sizes used for grinding shives from Biolin affected the particle and bulk densities. Using ANOVA, it is shown that use of a smaller screen has a significant effect on the bulk density, but not on the particle density.

4.1.5 Frictional behaviour of biomass grinds

The results from the determination of the friction and cohesion of flax shives from Biolin Research Inc. are given in Table 4.6. Regression equations were estimated for data from the three hammer mill screen sizes at four levels of normal loads (100, 200, 300, 400N) for the angle/coefficient of internal friction and cohesion. From Table 4.6, cohesion increased when smaller screen sizes (and consequently smaller particle size) were used. The use of a small screen resulted in a decrease in the angle of the internal friction of shives. The coefficient of determination (R^2) was higher. Figure A.1 also shows that there is a linear relationship between shear stress and normal stress of ground shives.

Table 4. 6 Angle of internal friction and cohesion of shives.

Screen sizes (mm)	μ_i	φ_i (Degree)	*Cohesion C_c		
			Estimate (kPa)	R^2	SEE
Small (3.2)	0.14	8.01	3.83	0.91	0.54
Medium (4.8)	0.15	8.69	3.81	0.95	0.42
Large (6.4)	0.20	11.23	2.18	0.92	0.69

*Values are averages of three replicates.
μ_i: coefficient of internal friction.
φ_i: angle of internal friction.
SEE: standard error of estimate of cohesion.

Mani and co-workers (2004b) found that the adhesion of corn stover grind increased from 1.85 to 2.79 kPa at a moisture content of 11% (w.b.) as the hammer mill screen size decreased from 6.4 to 3.2 mm. It was also stated that the coefficient of wall friction decreased from 0.19 to 0.18 as the hammer mill screen size increased from 3.2 to 6.4 mm on a polished steel surface.

4.2 Chemical and Thermal Properties

In this section, chemical composition of both flax shives and canola meal is presented. Also, the specific heat capacity of the shives and combustion energy of flax shives are presented.

4.2.1 Chemical composition

The chemical compositions of the flax shives and the canola meal used as a binder are presented in Table 4.7. For comparison, results from other studies are included in the table.

Table 4. 7 Chemical composition of flax shives and canola meal (percent dry matter basis).

Biomass	Protein (%)	Crude fiber (%)	Fat (ether extract) (%)	Ash (%)	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)
Flax shives	3.01	65.59	3.11	3.53	53.27	13.62	20.53
Canola meal	30.51	11.40	30.57	6.09	10.40	5.43	6.47

The flax shives, in this research, had a moisture content of 7.9% (w.b.), while the canola meal had a moisture content of 6.6% (w.b.). The flax shives had a relatively large amount of crude fiber, cellulose and hemicelluloses that made up the most significant portion in their chemical composition. Some of the components include a mixture of the other components in the table. Also, they contained a relatively high amount of lignin that can support the particles during densification. However, canola meal has a large percentage of protein that helps to bind particles of shives during the densification process. This also can support densification as a lubricating agent for the pelleting equipment.

4.2.2 Specific heat capacity of flax shives

The average heat capacity of flax shives ranged from 1.5 to 2.7 kJ/(kg°C) depending on the temperature and moisture content (Table 4.8). To analyze the results, a multiple regression analysis with stepwise selection method at a 95% confidence level was conducted. The variables in this analysis were the first and second orders of temperature T and T^2, moisture content X, and the interaction of moisture content and temperature XT. The first order of moisture, and interaction between the first orders of moisture and temperature had the significant effect on the heat capacity of flax shives. As a result of the analysis, the specific heat capacity (C_p) was estimated using the regression equation below.

$$Cp=460.188+120.532X+0.871XT-0.073TX^2+0.008XT^2 \tag{4.1}$$

The coefficient of determination (R^2) was equal to 0.9575. Figure 4.3 illustrates the variation of the estimated specific heat capacity of the flax shive particles as a function of temperature and moisture content. The specific heat capacity of shive particles increased when both the temperature and moisture content increases.

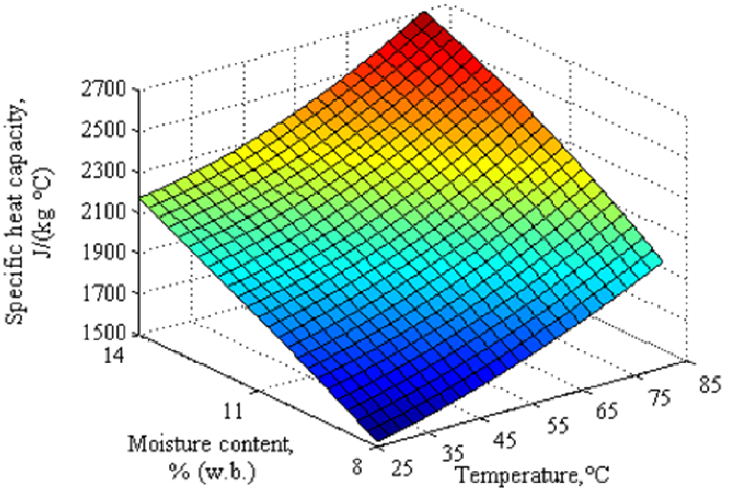


Figure 4. 3 Graph of estimated specific heat capacity of flax shives with respect to moisture content and temperature.

Table 4. 8 Specific heat capacity of flax shives at six levels of temperature and three levels of moisture content.

Temperature (°C)	Specific heat capacity J /(kg °C)		Difference (%)
	Measured	Estimated*	
Moisture content at 8 % (w.b.)			
25	1507	1520	0.9
35	1586	1548	0.4
45	1645	1651	0.4
55	1714	1735	1.2
65	1814	1831	1.0
80	1990	1998	0.4
Moisture content at 11 % (w.b.)			
25	1884	1857	1.4
35	1942	1915	1.4
45	2008	1989	0.9
55	2091	2080	0.5
65	2197	2188	0.4
80	2389	2382	0.3
Moisture content at 14 % (w.b.)			
25	2132	2161	1.3
35	2190	2204	0.6
45	2259	2268	0.4
55	2350	2354	0.2
65	2459	2460	0.0
80	2665	2660	0.2

Table 4.8 compares the measured and estimated specific heat capacity values of the flax shive particles for six levels of temperature and three levels of moisture content. The difference between the measured and estimated values of the specific heat capacity was calculated using the following equation.

$$\text{Difference \%} = 100 \times [C_{p\ \text{measured}} - C_{p\ \text{estimated}}]/C_{p\ \text{measured}} \qquad (4.2)$$

There is a good agreement between the measured and estimated values, i.e., the maximum differences between the two did not exceed 1.4%.

4.2.3 Combustion energy

The temperature change of water during the combustion of flax shives is shown in Figure A.2. The average combustion energy of the flax shives was 17.67 MJ/kg at a moisture content of 8.1% (w.b.). This is comparable to the combustion values of other lignocellulosic materials. Shaw (2008) found that the combustion values of poplar and wheat straw were 17.76 MJ/kg at the moisture content of 8.2% (w.b.) and 17.04 MJ/kg at a moisture content of 8.0% (w.b.), respectively. These give differences of 0.5% and 4.1% from the poplar and wheat straw, respectively.

4.3 Effect of Flax Shive Particle Size on Pellet Density and Durability

The pellets that were made from the flax shives are shown in Figure 4.4. A single-pelleter was used to manufacture the pellets. One-way ANOVA was used to analyze to determine the significance of particle size on pellet properties.

Figure 4. 4 Flax shive pellets produced by a single-pelleter.

4.3.1 Unit density of pellets made with single-pelleter

Mean unit density of pellets is shown in Table 4.9. The unit density from 6.4, 3.2, and 2.4 mm screen sizes was 1010, 1004, and 1000 kg/m^3, respectively. The variation for unit density was small among replicates within treatments.

Table 4. 9 Unit density and durability of pellets at three levels of grinding.

Screen sizes (mm)	Moisture content (%, w.b.)	Unit density* (kg/m^3)	Durability* (%)
2.4	9.6	1010 (3.16)	88.0 (1.13)
3.2	10.0	1004 (2.06)	80.8 (0.56)
6.4	10.4	1000 (1.96)	63.1 (0.56)

*Value in parenthesis is standard error; n = 9.

One-way ANOVA was used to determine the significance of particle size on the unit density. The ANOVA of unit density of pellets (Table B.4) showed that there was a significant difference due to the different grinding treatments. A small screen size resulted in pellets with a higher unit density than those produced with a large screen.

4.3.2 Pellet durability

The mean durability values for the pellets produced using the single-pelleter are given in Table 4.9. The durability of the pellets increased as the size of the screen used for grinding decreased. This is likely due to smaller particles filling voids in the pellets and rearrangement during pelleting.

Once again, one-way ANOVA was used to determine the significance of particle size. These results are given in Table B.4. The reduction in size and variation in particle size resulted in pellets that were statistically significant differences in durability.

4.4 Effect of Particle Size, Moisture Content, and Canola Meal Levels on the Physical Properties of Flax Shive Pellets Produced in the Pilot-scale Pellet Mill

ANOVA and multiple regression analysis were used to determine the effects of particle size, moisture content, and canola meal on dimensional stability, unit density, bulk and particle density, porosity, hardness, durability, and moisture absorption of the flax shive pellets. Pellets that were produced using the CPM CL-5 pilot-scale pellet mill are shown in Figure 4.5.

Figure 4. 5 Flax shive pellets produced using a pilot-scale pellet mill.

4.4.1 Dimensional stability

The dimensional stability of the pellets was determined in terms of the change in length (percentage), diameter, and ratio of length to diameter (Table 4.10). Table B.5 contains the ANOVA results that show how the length, diameter, and ratio of length to diameter are affected by various factors. The change in length was greater for a moisture content of 8% than for 14% (w.b.). Pellets formed at higher moisture content did not absorb much more moisture, and therefore, the pellet length was not increased as much. However, the pellets formed at a moisture content of 11% (w.b.) had the smallest change in length. The smallest changes in the length of pellets were those from a treatment containing 18% canola meal using the screen size of 6.4 mm, while the largest change observed in the length of the pellets from a treatment containing 21% canola meal using 4.8 mm screen, respectively.

Table 4. 10 Percent change in length, diameter, and ratio of length/diameter of pellets during storage with standard error in parentheses.

Parameters	Level	n	Length (%)	Diameter (%)	Length/Diameter (%)
Canola meal, %	18	5	0.71(0.10)	0.56(0.10)	0.14(0.10)
	21	10	1.61(0.09)	0.58(0.9)	1.04(0.09)
	24	5	1.30(0.10)	0.66(0.10)	0.65(0.10)
Moisture content, % (w.b.)	8	5	1.39(0.10)	0.46(0.10)	0.93(0.10)
	11	10	0.94(0.09)	0.60(0.09)	0.34(0.09)
	14	5	1.30(0.10)	0.75(0.10)	0.55(0.10)
Screen size, mm	3.2	5	1.08(0.10)	0.60(0.10)	0.49(0.10)
	4.8	10	1.43(0.09)	0.60(0.09)	0.83(0.09)
	6.4	5	1.12(0.10)	0.60(0.10)	0.51(0.10)

Once the factors that were determined to be significantly significant from the ANOVA analysis multiple regression analyses were performed to illustrate the important two way interactions on change in length (Δl) of pellets. The model for the effects of screen size (X_1) and canola meal content (X_2), and their interaction (X_1X_2) is given below.

$$\Delta l\ (\%) = -2.165+0.237X_1+0.151X_2-0.011X_1X_2 \tag{4.3}$$

Figure 4.6 shows a plot of how interaction of screen size and canola meal content affects the change in length of the pellets. The graph shows that while the screen size has a small effect, the canola meal content affected the change in pellet length the most.

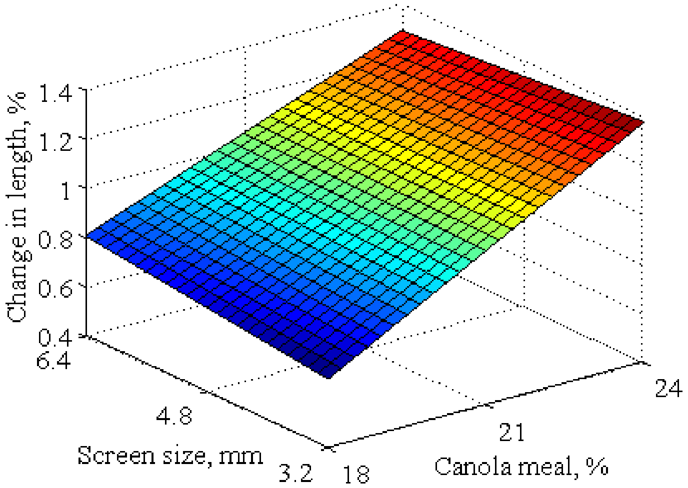


Figure 4. 6 Change in pellet length at various levels of screen size and canola meal content.

The results of the multiple regression analysis for the interaction of screen size (X_1) and moisture content (X_3) are shown in Figure 4.7. The equation for the model is shown below.

$$\Delta l\ (\%) = -2.089+0.692X_1+0.281X_3-0.062X_1X_3 \tag{4.4}$$

The graph shows that essentially two maximum and two minimum length changes exist for the factors considered. The largest screen size combined with the lowest moisture content and the smallest screen size combined with the highest moisture content resulted in the largest changes in pellet length. The opposite of these, i.e., smallest screen size with highest moisture content and largest screen size with lowest moisture content resulted in the smallest changes in pellet length.

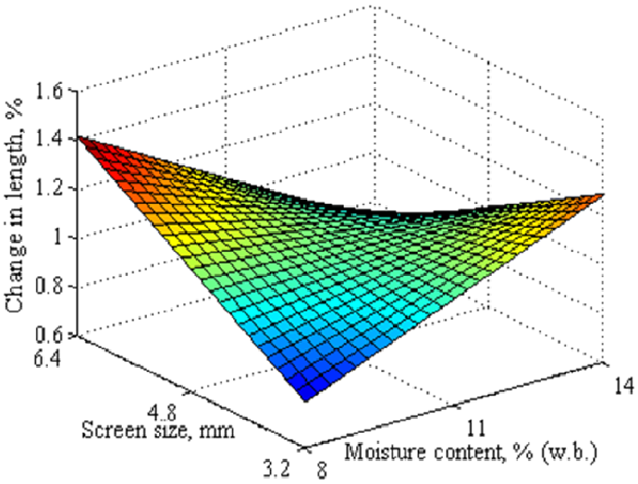


Figure 4. 7 Change in pellet length at various screen sizes and moisture contents.

The results of the regression analysis for the third two-way interaction, i.e., change in length of the pellets at various levels of canola meal (X_2) and moisture content (X_3), is shown below.

$$\Delta l\ (\%) = 8.283 - 0.336X_2 - 0.846X_3 + 0.04X_2X_3 \qquad (4.5)$$

The results of the interaction of moisture content and canola meal are shown in Figure 4.8. At the lowest moisture content, the change in pellet length was not affected by canola meal content. However, both the maximum and minimum length changes occurred at the highest canola meal content.

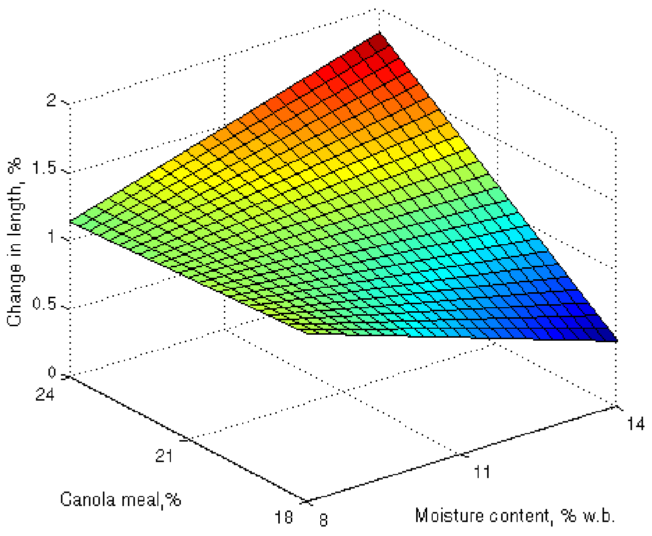


Figure 4. 8 Change in pellet length at various canola meal and moisture content.

The statistical analysis (ANOVA) of the data regarding change in diameter for the pellets showed that there was a significant effect only for the interaction of moisture content and canola meal (as shown in Table B.5). However, backward selection of parameters in linear regression models showed that levels of moisture content (X_3) and canola meal (X_2), and the interaction between these factors (X_3X_2) were all statistically significant.

$$\Delta d\ (\%) = 6.893-0.325X_2-0.602X_3+0.031X_2X_3 \tag{4.6}$$

Figure 4.9 shows the results of the regression analysis of the interaction between moisture and canola meal contents. The most significant change in diameter occurred at the highest moisture content when the highest canola meal used. This estimate agrees with the experimental results in which the largest change in diameter was 1.11% at a moisture content of 14% (w.b.) and canola meal content of 24%. Similar trends were found by Mani et al. (2006a) in terms of changes in length and diameter of briquettes produced from corn stover related to the moisture content. Shaw (2008) found that a decrease in the raw feedstock particle size resulted in a decrease in the lateral expansion.

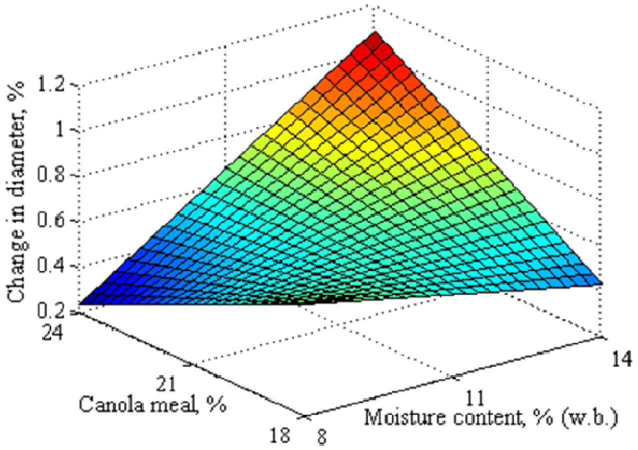


Figure 4. 9 Lateral expansions of pellets containing three level canola meal produced at three level moisture content.

The effect of the canola meal content on the ratio of length/diameter (Δl/d) of pellets appeared to be quadratic. Therefore, a second-order parameter for canola meal content $(X_2)^2$ with the first-order parameters, the screen size (X_1) parameter, canola meal content (X_2), and a parameter for their interaction (X_1X_2) was included in the model.

$$\Delta l/d\ (\%) = -12.212+0.539X_1+1.008X_2-0.019(X_2)^2-0.025X_1X_2 \qquad (4.7)$$

In Figure 4.10, the change of the length to diameter ratio of the pellets increased with increasing the canola meal content. However, the screen size did not significantly affect the change of this ratio.

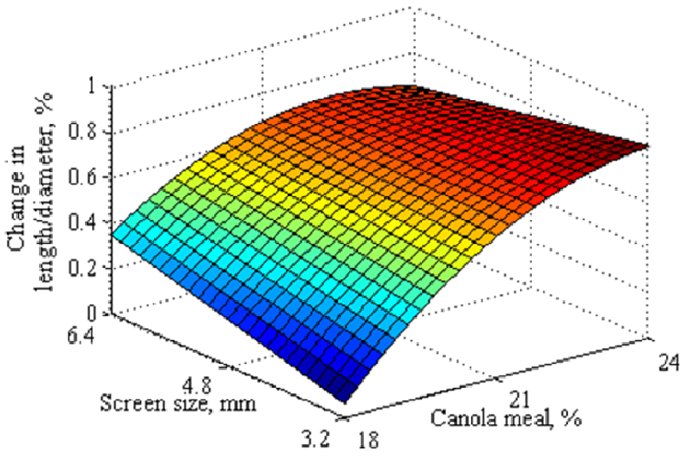


Figure 4. 10 Length to diameter of the flax shive pellets at various screen size and canola meal content.

First order parameters for screen size (X_1) and moisture content (X_3), their interaction (X_1X_3) were used to produce a multiple regression equation 4.8.

$$\Delta l/d\ (\%) = -2.091+0.682X_1+0.23X_3-0.061X_1X_3 \qquad (4.8)$$

Figure 4.11 illustrates the interaction between screen size and moisture content.

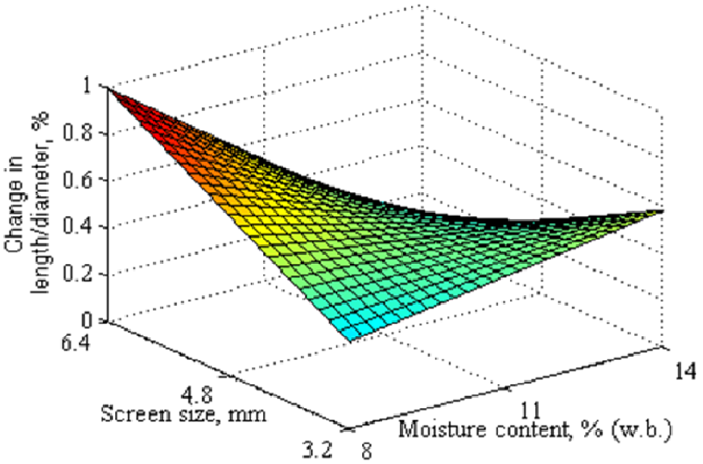


Figure 4. 11 Change in length to diameter ratio of the flax shives pellets at various screen sizes and moisture contents.

The trend shown in Figure 4.11 is similar to that of Figure 4.7 which illustrates the effect of screen size and moisture content on the change in pellet length. This is as expected since the change in diameter was not significantly affected by either of these factors. This leaves the change in the ratio dependent only on the length change.

4.4.2 Unit density of pellets

Table B.6 shows the results of an ANOVA of unit density of pellets with regard to screen size, canola meal content and moisture content. This shows that there are no significant effects from any of the factors considered or their interactions on the unit density. Least squares means of unit density values of the pellets that were formed using the parameters listed are given in Table 4.11.

Table 4. 11 Least squares means of unit density of shive pellets.

Parameters	Level	n	Unit density (kg/m^3)	Standard error
Screen size, mm	3.2	5	1134	28.2
	4.8	10	1160	25.7
	6.4	5	1140	28.2
Moisture content, % (w.b.)	8	5	1186	28.2
	11	10	1140	25.7
	14	5	1109	28.2
Canola meal, %	18	5	1188	28.2
	21	10	1151	25.7
	24	5	1095	28.2

After the ANOVA failed to identify factors that may have effects on unit density, a linear regression was performed and the following model was selected.

$$\text{Unit density} = 986.408+14.225X_2+44.108X_2-2.708X_2X_3 \qquad (4.9)$$

Figure 4.12 shows the effect of the interaction between canola meal (X_2) and moisture contents (X_3) with regard to the unit density of the pellets. There appeared to be a difference in the unit density between high and low moisture content when high levels of canola meal were used. This illustrates that the advantage of high levels of canola meal is reduced for making pellets with high unit density when the flax shive mixture had high enough moisture. However, moisture content did not have a large effect on the unit density at low canola meal.

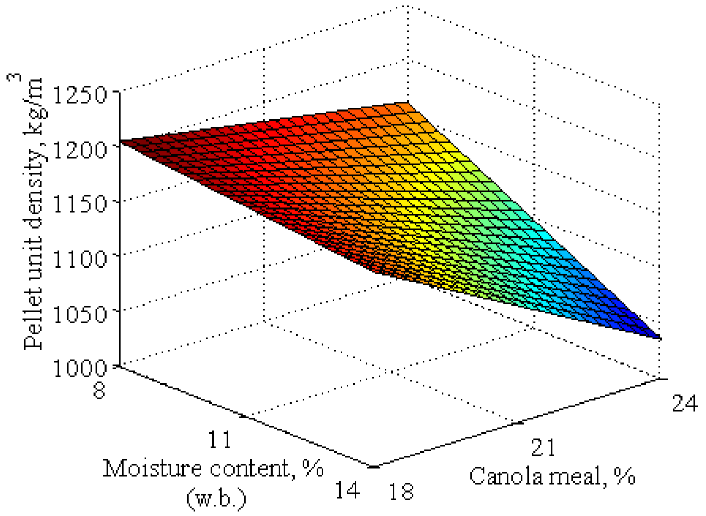


Figure 4. 12 Unit density of the pellets produced at various levels of moisture and canola meal contents.

This result is in agreement with other studies. Mani et al. (2006a) found that the density of corn stover briquettes produced with 5 to 10% (w.b.) moisture content was higher than those produced at a moisture content of 15% (w.b). In addition, Wamukonya and Jenkins (1995) reported that high quality briquettes were made from sawdust and wheat straw when produced at a moisture content ranging from 12 to 20% (w.b.).

4.4.3 Bulk and particle density

Table B.7 lists the results of an ANOVA performed on the data for the bulk and particle densities and porosity. For the bulk density, the analysis did not indicate any statistically significant effects with regard to screen size, canola meal content, moisture content or interactions among these factors. Table 4.12 shows the least squares means of bulk density, particle density, and porosity along with the standard errors.

Table 4. 12 Bulk and particle density and porosity of flax shive pellets.

Parameters	Level	Bulk density* (kg/m^3)	Particle density* (kg/m^3)	Porosity* (%)
Screen size, mm	3.2	653.7±23.7	1192±9.9	43.4±1.7
	4.8	667.9±21.7	1144±9.0	39.5±1.6
	6.4	662.3±23.7	1118±9.9	38.5±1.7
Moisture content, % (w.b.)	8	682.3±23.7	930±9.9	25.9±1.7
	11	652.8±21.7	1314±9.0	50.4±1.6
	14	648.8±23.7	1210±9.9	45.1±1.7
Canola meal, %	18	686.6±23.7	1147±9.9	37.5±1.7
	21	665.2±21.7	1152±9.0	40.0±1.6
	24	632.0±23.7	1155±9.9	43.9±1.7

*Mean±Standard error.

To further investigate the effects of the factors on the pellet bulk density, a linear regression analysis with backward selection method was performed. The regression model including parameters for moisture (X_3) and canola meal contents (X_2), and their interaction (X_2X_3) is shown below.

$$\text{Bulk density} = 901.181+2.976X_2-29.057X_3-2.114(X_3)^2-1.096X_2X_3 \qquad (4.10)$$

The second order of moisture content $(X_3)^2$ was also considered in the model. Figure 4.13 shows that the highest bulk density resulted from the smallest amount of canola meal and lowest moisture content.

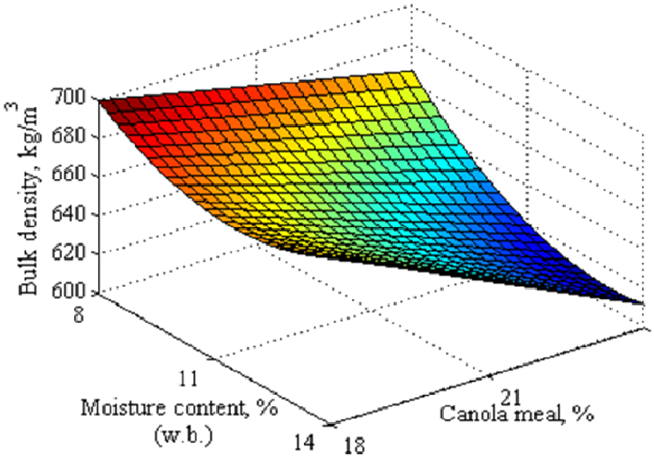


Figure 4. 13 Bulk density of flax shive pellets at various moisture and canola meal content.

The regression model using screen size (X_1), canola meal content (X_2), and their interaction (X_1X_2) as parameters is shown below.

$$\text{Bulk density} = 1006.14-33.195X_1-17.287X_2+1.709X_1X_2 \qquad (4.11)$$

Figure 4.14 shows the results of these factors have on the bulk density of pellets. The bulk density increased as the canola meal content decreased. However, the effect of the canola meal content was more significant for the 3.2 mm screen.

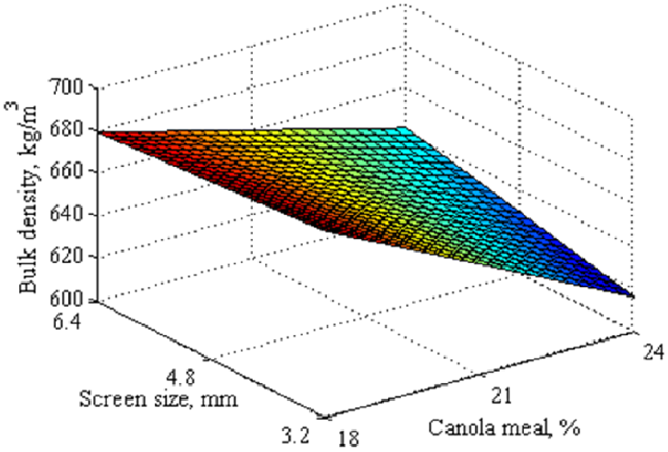


Figure 4. 14 Bulk density of flax shive pellets at various levels of screen size and canola meal.

The final regression model created for the bulk density considered screen size (X_1), moisture content (X_3), and their interaction (X_1X_3). It included a second order term of moisture content $(X_3)^2$.

$$\text{Bulk density} = 957.629+1.259X_1-52.707X_3+0.13X_1X_3+2.114(X_3)^2 \qquad (4.12)$$

Figure 4.15 shows the effect of screen size and moisture content on bulk density. There was a significant effect of the moisture content on the bulk density of the pellets. The maximum bulk density occurs at a moisture content of 8% (w.b.) and the minimum is between 11 and 14% (w.b.) moisture. The effect of screen size was insignificant.

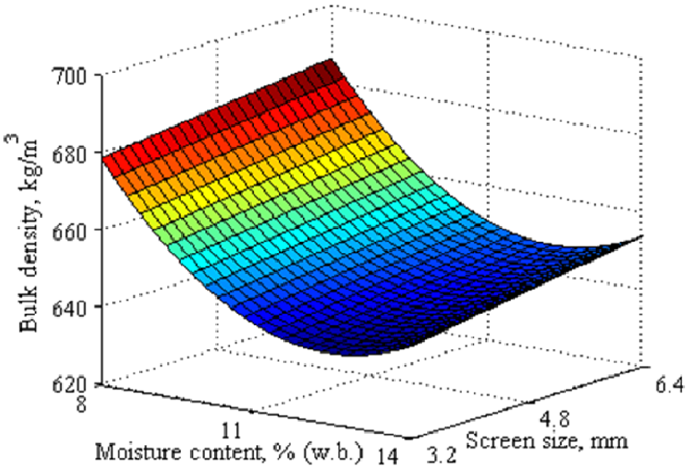


Figure 4. 15 Effect of screen size and moisture content of bulk density of pellets.

The ANOVA results for particle density, shown in Table B7, indicate that all the main effects and interactions that were considered are statistically significant. The least squares means of the particle density were calculated for each variation of screen size, moisture content and canola meal content. The results are shown in Table 4.12. The moisture content values suggest that this effect is quadratic as the middle levels gave the most compact pellets. The regression models for the three two-way interactions were used. The model for the effects of screen size (X_1), canola meal content (X_2), and their interaction (X_1X_2) as parameters on the particle density is given below.

$$\text{Particle density} = 657.603+104.478X_1+30.571X_2-6.073X_1X_2 \quad (4.13)$$

Figures 4.16, 4.17, and 4.18 illustrate the results three two way interactions. Figure 4.16 shows that the particle density of the pellets was higher for larger canola content and smaller screen size. This is, likely, a result of the higher particle density for the canola meal. However, the lowest particle density was obtained with the use of larger screen at higher canola meal content.

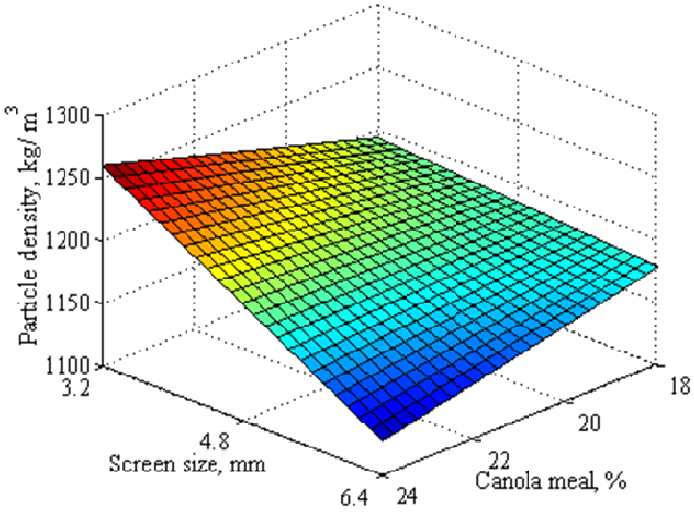


Figure 4. 16 Particle density of pellets at levels of screen size and canola meal.

The regression model created for the particle density considered the first orders of screen size (X_1), moisture content (X_3), their interaction (X_1X_3), and the second order of moisture contents $(X_3)^2$.

$$\text{Particle density} = -2166.458-47.641X_1+615.848X_3+2.236X_1X_3-26.361(X_3)^2 \quad (4.14)$$

The quadratic nature of the regression model with respect to moisture content is evident in Figure 4.17. The screen size did not have a significant effect on the particle density at each level of moisture. However, the moisture content had a large effect on the particle density.

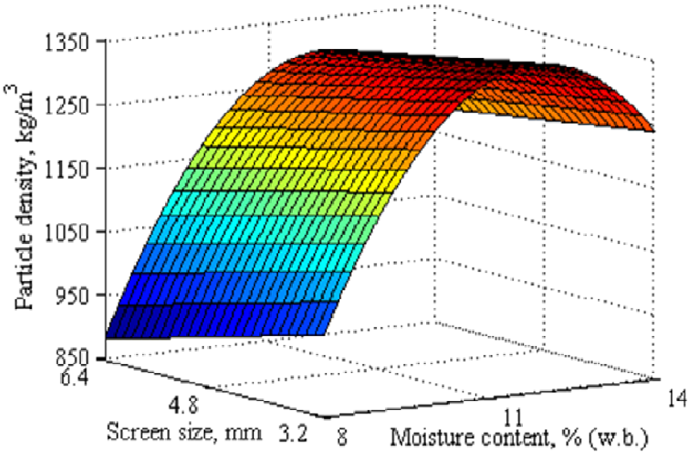


Figure 4. 17 Particle density of pellets at three levels of screen size and moisture content.

The regression model was created including parameters for canola meal content (X_2) and moisture content (X_3), and their interaction (X_2X_3) along with the second order of moisture content $(X_3)^2$.

$$\text{Particle density} = -3756.227+64.814X_2-5.763X_2X_3+747.601X_3-26.361(X_3)^2 \quad (4.15)$$

Once again, the quadratic nature is evident in Figure 4.18. While there are small differences in the particle density at different canola contents at each moisture level, the largest change is seen as the moisture level varies.

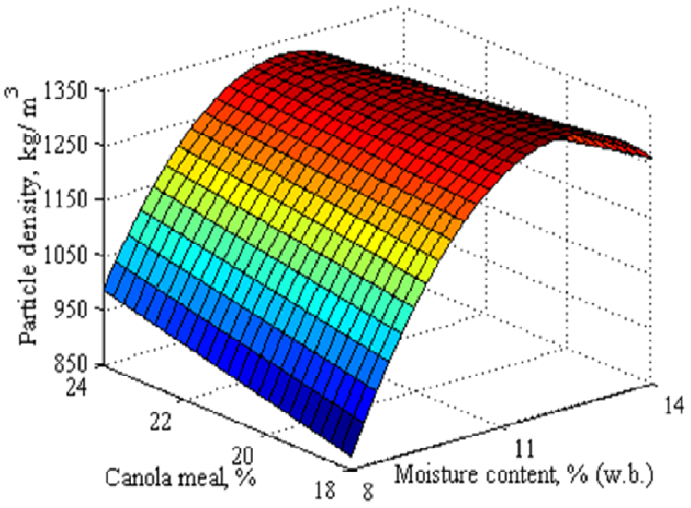


Figure 4. 18 Particle density of pellets at three levels of canola meal and moisture content.

The results of the ANOVA of the porosity data, shown in Table B.7, indicate that the moisture content had the only significant effect. The least squares means of porosity given in Table 4.12 also confirm this. Porosity decreased slightly as larger screen was used and as canola content increased, but their effects were not significant. Once again, the moisture content showed that the effect on porosity has a quadratic distribution (Table 4.12).

4.4.4 Hardness

Hardness is another measure of quality of the fuel pellets. This essentially measures the maximum crushing load of pellets to resist the forces generated during pelleting, cooling, handling, storage, and transportation. Colley et al. (2006) measured the hardness of switchgrass pellets as a measure of quality of fuel pellets. In addition, switchgrass pellet hardness was similar to alfalfa and wood pellets and increasing the fuel pellet hardness resulted in a reduction of the dust and fines generated during their transportation (Jannasch et al. 2001). As for the other properties, the hardness data was analyzed using ANOVA. This is shown in Table B.8. The results indicate there is only a significant effect on pellet hardness due to the level of canola meal. The least squares means given in Table 4.13 are in agreement with this result.

Table 4. 13 Least squares means and standard error of hardness of shive pellets.

Parameters	Level	n	Hardness (N)	Standard error
Screen size, mm	3.2	5	511.3	37.9
	4.8	10	482.8	34.6
	6.4	5	470.4	37.9
Moisture content, % (w.b.)	8	5	489.6	37.9
	11	10	445.2	34.6
	14	5	529.7	37.9
Canola meal, %	18	5	616.1	37.9
	21	10	448.3	34.6
	24	5	400.1	37.9

The result of the regression analysis for the effect of the first order of canola meal (X_2) moisture content (X_3), and the second order of moisture content $(X_3)^2$ on the hardness is shown below.

$$\text{Hardness} = 1879.226-35.986X_2-128.325X_3+6.136(X_3)^2 \tag{4.16}$$

Figure 4.19 shows the effect of canola meal and moisture content. The canola meal content affects the hardness more than the moisture level.

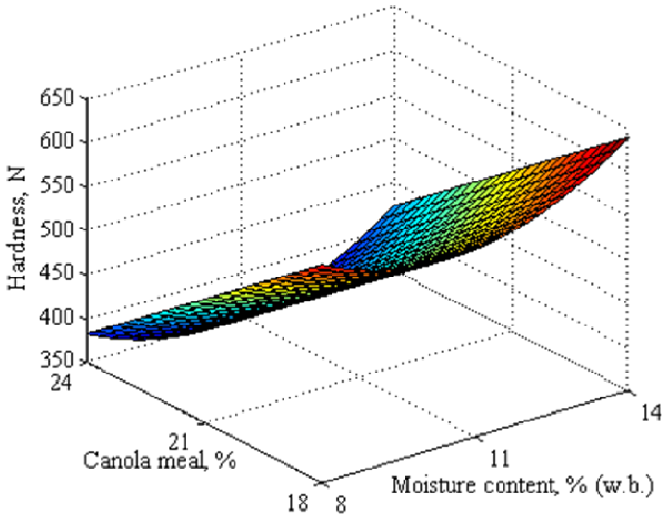


Figure 4. 19 Effect of canola meal and moisture content on pellet hardness.

4.4.5 Durability

In general, pellets with higher durability are more able to resist forces during transportation and storage. The results of analyzing the durability of the pellets using ANOVA are shown in Table B.9. This shows that there is a significant effect due to moisture content only. The least squares means presented in Table 4.14 show that there may also be a significant effect due to canola meal content.

Table 4. 14 Least squares means and standard error of durability of shive pellets.

Parameters	Level	n	Durability (%)	Standard error
Screen size, mm	3.2	5	70.2	5.5
	4.8	10	65.8	5.0
	6.4	5	73.7	5.5
Moisture content, % (w.b.)	8	5	62.2	5.5
	11	10	65.5	5.0
	14	5	82.1	5.5
Canola meal, %	18	5	81.5	5.5
	21	10	64.6	5.0
	24	5	63.7	5.5

To more conclusively determine what affected the durability most significantly, a backward elimination regression was performed. This model suggests that there is a second-order effect of canola meal content $(X_2)^2$ and possibly an interaction between levels of canola meal and moisture (X_2X_3).

$$\text{Durability} = 719.280-61.582X_2-1.353(X_2)^2+0.163X_2X_3 \qquad (4.17)$$

The results are shown in Figure 4.20. The highest durability occurred for the lowest canola meal content and highest moisture content. The durability was lowest at the middle canola meal content and least moisture content.

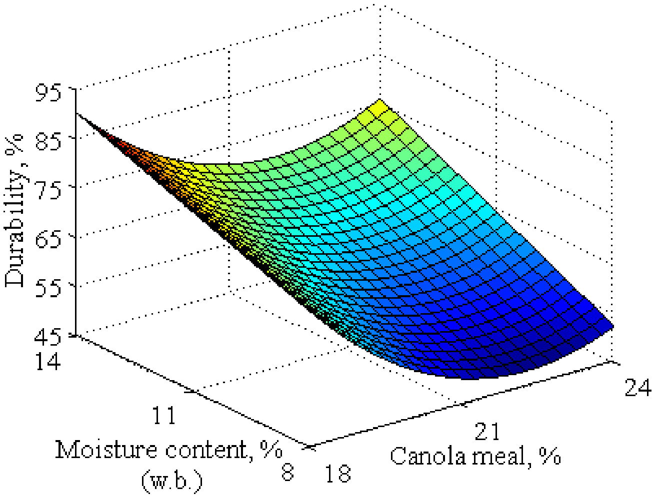


Figure 4. 20 Effect of moisture and canola meal content on pellet durability.

4.4.6 Moisture absorption

All pellets had volume changes due to moisture absorption. The results of the ANOVA of moisture absorption, shown in Table B.10, and determination of least squares means, shown in Table 4.15, indicate that the moisture content was the only factor that had a significant effect.

Table 4. 15 Least squares means and standard error of moisture absorption of shive pellets.

Parameters	Level	n	Moisture absorption (% d.b.)	Standard error
Screen size, mm	3.2	5	76.7	5.2
	4.8	10	70.2	4.8
	6.4	5	73.9	5.2
Moisture content, % (w.b.)	8	5	122.1	5.2
	11	10	73.8	4.8
	14	5	24.9	5.2
Canola meal, %	18	5	71.3	5.2
	21	10	79.8	4.8
	24	5	69.7	5.2

The model for the effect of screen size (X_1) and moisture content (X_2) on moisture absorption of flax shive pellets is shown the following equation.

$$\text{Moisture absorption} = 254.277-0.864X_1-16.207X_3 \tag{4.18}$$

Figure 4.21 shows that the lowest moisture absorption subjected to the pellets that produced at moisture content of 8% (w.b).

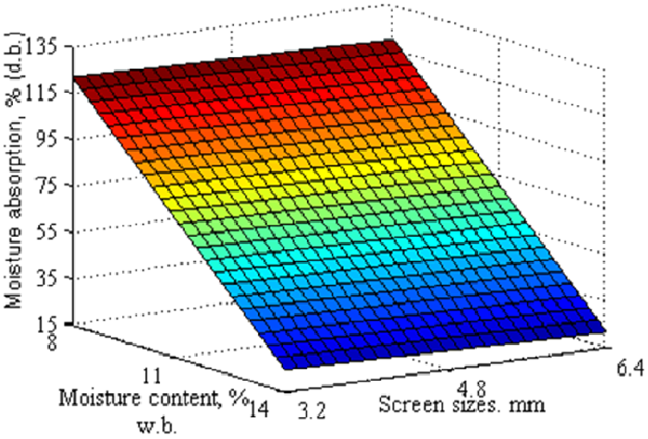


Figure 4. 21 Effect of screen size and moisture content on moisture absorption of flax shive pellets.

4.5 Combustion Energy and Emissions

4.5.1 Combustion energy

The combustion energy was measured in triplicate for flax shive pellets that were produced by both the single-pelleter and pilot-scale pellet mill. Pellets produced by the single-pelleter had combustion energy of 19.17 MJ/kg while the pellets formed by the pilot-scale pellet mill had combustion energy 20.47 MJ/kg. Pellets formed using the pilot-scale pellet mill had a higher combustion energy value than pellets formed in the single pelleter. The reason for that is due to the extra energy contained in the canola meal fat in the pellets produced using the pilot-scale pellet mill. The energy contents of the fuel pellets made from shives were identical to energy values of the biomass materials. The combustion energy contents were found for alfalfa stems (18.67 MJ/kg), wheat straw (17.97 MJ/kg), rice straw (15.09 MJ/kg), switchgrass (18.06 MJ/kg), and sugarcane (18.99 MJ/kg) (Jenkins et al. 1998). They also reported that coal had the combustion energy values greater than those for biomass materials due to their lower degree of oxidation.

4.5.2 Emissions

Emission measurements were performed on flax shive pellets, containing 22 and 30% canola meal, and commercial wood pellets. The flax shives were ground with the hammer mill screen and the initial moisture content of the mixture was 11% (w.b.). ANOVA (Table B.11) of emissions of wood pellets and flax shives pellets with an inclusion of canola meal shows that there is a significant difference. Table 4.16 shows the effects of the two levels of canola meal at the final moisture content of 6.9 and 8.3% (w.b.) on various emissions including carbon dioxide, nitrogen, methane, nitrogen dioxide, and oxygen. Also, the emissions of the commercial pellets are presented. Olsson and Kjallstrand (2004) reported that emissions of methane (8 ppm) from burning of softwood pellets in a stove. This value was higher than the emissions from methane from combustion of shive pellets. Therefore, it can be concluded that the emissions from burning of fuel pellets from shives will be negligible.

Table 4. 16 Emissions from flax shive pellets and wood pellets.

Product	Canola meal (%)	Emissions*				
		Nitrogen (ppt)	Oxygen (ppt)	Methane (ppm)	Nitrogen oxide (ppm)	Carbon dioxide (ppt)
Shive pellets	22	797.1(0.59)	163.6(2.0)	1.26(0.07)	1.14(0.13)	46.3(1.8)
Shive pellets	30	794.1(0.59)	164.3(2.0)	1.29(0.07)	1.45(0.13)	45.3(1.8)
Wood pellets	0	788.9(0.59)	176.6(2.0)	1.63(0.07)	0.34(0.13)	36.9(1.8)

*Value in parenthesis is standard error, n=4.
ppm = parts per million.
ppt = parts per thousand.

Pellets made from the two levels of canola meal were not different for any of the emission measurements. However, they were all different from the emission measurements taken on the wood pellets.

4.6 Summary

Grinding of flax shives from both sources with use of different hammer mill screen sizes gave a significant difference in moisture content and particle size. The moisture content ranged from 10.50% (w.b.) for unground shives to 9.55% (w.b.) for finely ground shives (Biofibre), while the moisture content of the Biolin shives ranged from 10.59% (w.b.) for unground material to 7.89% (w.b.) for shives ground with a screen size of 3.2 mm. A small hammer mill screen size of 2.4 mm reduced the geometric mean particle size up to 0.367 mm for Biofibre shives, while the screen size of 3.2 mm reduced the geometric mean particle size up to 0.454 mm for the Biolin shives. Also, the use of small screen sizes resulted in a slight shift in the particle size distribution for ground shives from both sources. The use of a small screen size resulted in an increase both in the bulk and particle density of shives. After grinding with a small screen size (3.2 mm), bulk density increased 2.1 times from the initial bulk density of shives for the Biolin material. The adhesion coefficient of shives increased from 0.14 to 0.20 as screen size decreased, while the coefficient of internal friction decreased from 3.83 to 2.18 kPa with the use of smaller screens.

The flax shives contained a relatively large amount of crude fiber (65.59%), cellulose (53.27%), hemicelluloses (13.62%), and lignin (20.53%) in their chemical composition. The canola meal had a large percentage of proteins (30.51%) and fat (30.57) in its chemical composition. Specific heat capacity of the flax shives ranged from 1506 to 2664 J/(kg $^{\circ}$C) and increased with increasing a moisture content (8-14%) and temperature (15-80 $^{\circ}$C). The combustion energy of shives was 17.67 MJ/kg at a moisture content of 8.1% (w.b.).

There was a significant effect of grinding on both unit density and durability of the pellets. The smallest screen size (2.4 mm) gave the highest unit density (1010 kg/m^3) in the pellets. Durability of pellets ranged from 66.0 to 88.0%, and the highest durability was found in shives ground with a screen size of 2.4 mm. The use of the smallest screen size resulted in the highest unit density and durability of pellets produced using the single-pelleter.

The effects of three levels of particle size, moisture content, and canola meal content on various pellet properties were investigated for pellets made from flax shives obtained from Biolin Inc. and processed using the pilot-scale pellet mill. At the lowest moisture content (8%), the change in pellet length increased as screen size was increased from 3.2 to 6.4 mm. However, at the highest moisture content (14%), the change was decreased as the screen sizes were increased. There were also the effects of interaction of screen size and canola meal, and interaction of screens and moisture content on the change of length of pellets during storage. ANOVA of change in diameter illustrated only the effect of interaction of moisture and canola meal content. However, the backward selection of parameters in linear regression models showed there was a significant effect of moisture and canola meal and their interaction on change in diameter. At the highest canola meal content, the smallest change in diameter occurred at the lowest moisture content, while the largest change in diameter occurred at the highest moisture content. The use of lower canola meal resulted in the lowest value at a lower moisture content in dimensional stability.

Although there were no significant effects of factors and their interactions on the pellet unit density from ANOVA, further investigation using a linear regression with the backward selection method showed the effect of canola meal and moisture content interaction. The unit density increased with decreasing moisture content at a higher canola meal inclusion. However, moisture content did not have an effect on the unit density at low canola meal. Unit density was the lowest at the highest canola meal inclusion and moisture content.

In the regression model using parameters for moisture content, canola meal, and their interaction, the significant effects on the bulk density of the pellets were found. The highest bulk density was obtained (682 kg/m^3) from shive mixtures using the smallest amount of canola meal (18%) at the lowest moisture content (8%). At a higher canola meal content, the bulk density increased by increasing the screen size. However, there was no effect of the screen sizes at the low canola meal inclusion. A higher bulk density was obtained from shives with a medium moisture content (11% w.b.) at a smaller screen size (3.2 mm). The highest particle density was obtained by using a larger canola meal at a smaller screen size, while the lowest particle density was obtained with the use of a larger screen at a higher canola meal conclusion. Also, the highest particle density was obtained when a medium moisture content, smaller screen and higher canola meal was used.

A higher hardness and higher durability were found for the shive pellets that were produced with the use of a small amount of canola meal at a higher moisture level. The moisture absorption of shive pellets was significantly affected by only the moisture content. However, there were no effects of screen size and canola meal levels on moisture absorption. Pellets that were produced at lower moisture content resulted in a higher percentage of moisture. In terms of hardness and durability, the best level of the processing parameters are a higher moisture content (14% w.b.) and lower canola meal inclusion (18%) to produce the hardest and more durable pellets.

The combustion energy was 19.17 MJ/kg for single pellets without canola meal, while the combustion energy of the pellets with canola meal inclusion produced by the pilot scale mill was 20.47 MJ/kg. Due to the inclusion of the canola meal in shives, combustion energy of the pellets was increased. Two levels of canola meal for shive pellets did not have a significant effect on the emissions. However, there were significant differences between shive pellets and commercial wood pellets on the emission measurements. Low emissions of methane (1.29 ppm) and oxygen (164.3 ppt) were found from the combustion of flax shive pellets. These emissions were relatively lower than methane (1.63 ppm) and oxygen (176.6 ppt) from the combustion of commercial wood pellets. The other emissions including nitrogen, nitrogen oxide, and carbon dioxide were higher for shive pellet combustion than those emissions from wood pellets.

5. CONCLUSION

Society has started to use renewable sources of energy as a substitute for non-renewable fossil fuels as an energy source. Biofuels from biomass can be an alternative energy source and meet human energy needs. Biomass materials such as sawdust, shavings, corn stover, switchgrass, and others have been studied extensively. The major problems are that they are difficult to handle and are costly to transport and store due to their low bulk density. It is necessary to densify these materials into pellets or briquettes.

Densification of various biomass is affected by both raw material properties and process variables. Raw material properties such as particle size, particle size distribution, densities, moisture content, and chemical components were studied on various types of biomass before processing. Therefore, the properties of densified products made from biomass were studied extensively, considering parameters that included density, hardness, durability, and moisture absorption.

In this research, flax shives from two flax straw processing companies were used to manufacture biofuel pellets using both a single-pelleting unit and a pilot-scale pellet mill.

The first objective was to characterize the flax shives from the two sources and the following conclusions can be drawn.

1. Small screen size (i.e., 2.4 mm screen for the first source and 3.2 mm screen for the second source) to grind the flax shives resulted in a decrease in moisture content.

2. Shives ground with a screen size (i.e., 2.4 mm) produced a smaller mean geometric particle size than those ground with a larger screen (i.e.,6.4 mm).

3. Better separation of shive particles to determine the particle size distribution was achieved by using a larger number of sieves in the separation process.

4. The use of the smaller hammer mill screen resulted in an increase in both bulk and particle density of shives.

5. The use of a 3.2 mm screen size as compared to a screen of 6.4 mm resulted in an increase in the adhesion coefficient of shives from 0.14 to 0.20 and a decrease in a coefficient of internal friction from 3.83 to 2.18 kPa.

6. The shives contained crude fiber (65.59%), cellulose (53.27%), hemicelluloses (13.62%), and lignin (20.53%) when the moisture content of the shives was 7.9% (w.b.).

7. Specific heat capacity of flax shives ranged from 1.5 to 2.7 kJ/(kg°C) and increased when the moisture content was increased from 8 to 14% (w.b.) and the temperature was increased from 15 to 80°C.

8. The flax shives had the combustion energy of 17.67 MJ/kg at a moisture content of 8.1% (w.b.).

The second objective of this study was to find the effect of variables such as screen size, moisture content, and the addition of canola meal used as a binder on the properties of the pellets. The following conclusions can be drawn:

1. In the pelleting of flax shives using the single-pelleter, the smallest screen size (2.4 mm) resulted in the higher unit density (1010 kg/m^3) and higher durability (88%) of the pellets than those produced with the larger screen.

2. Pellets manufactured by the pilot-scale pellet mill using the addition of 18% canola meal and the screen size of 6.4 mm at all moisture levels produced the highest unit density. The highest bulk density (682 kg/m^3) was obtained from shive mixtures with 18% canola at a moisture content of 8% (w.b). Shives with a moisture content of 11% (w.b.) from a screen size with an opening of 3.2 mm and the addition of 24% canola meal produced the pellets with highest particle density.

3. In terms of dimensional stability, the lowest change occurred in the length of the pellets that were produced using 18% canola meal and a moisture content of 14% (w.b). However, the lowest change occurred in the diameter of the pellets that were made at 8% (w.b) moisture content with mixture containing the highest canola meal (24%). The lowest change noticed in the ratio of length/diameter of pellets were those produced at 8% (w.b) moisture content and 18% canola meal from shives ground with the smallest screen size (3.2 mm).

4. The unit density of pellets increased with decreasing moisture content at higher canola meal content.

5. The highest bulk density of pellets was obtained from a shive mixture at a moisture content of 8% (w.b.) with the addition of 18% canola meal.

6. The highest particle density was found in the pellets that were produced with the use of highest canola meal content (24%) and the smallest screen size (3.2 mm).

7. The only significant effect on the hardness of pellets was the level of canola meal. The highest hardness was found in the pellets that produced with the use of 18% canola meal.

8. Since the handling of pellets is very important, durability can be used as a basis of judging for the overall pellet quality. The highest durability was obtained for

the pellets that were produced with less canola meal (18%) at the highest moisture content (14% w.b.).

9. The only significant effect on moisture absorption of pellets was for moisture content.The lowest moisture absorption was found for the pellets that were produced at a moisture content of 14% (w.b.).

The third specific objective of this study was to measure the heat of combustion of the flax shive pellets and to analyze the gas emissions from burning pellets. The following conclusions can be drawn:

1. Values of the combustion energy of the flax shive pellets produced with and without canola meal were 20.47 and 19.17 MJ/kg. The addition of the canola meal in the shive mixture resulted in an increase in the combustion energy of the pellets due to the fat content in the canola meal.

2. The canola meal contents (22 and 30%) in the shive pellets did not result in the difference in emissions. However, significant differences were found between shive pellets and commercial wood pellets in emissions. Emissions from flax shive pellets were lower in methane (1.29 ppm) and oxygen (164.3 ppt) than emissions from commercial wood pellets having methane (1.63 ppm) and oxygen (176.6 ppt).

In conclusion, densification of flax shives into fuel pellets improved the handling characteristics, increased bulk density and energy content. The most durable pellets were produced at a higher moisture and lower canola meal content. Emissions from combustion of densified fuel pellets from flax shives had less methane and oxygen than emissions from commercial wood pellets.

6. RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations are suggested for future research studies:

1. We need to know more about the costs of grinding and specific energy consumption. This study indicates that the use of a 3.2 mm screen in a hammer mill is more than adequate. Grinding of biomass with smaller screen sizes is probably not required and would be too costly.

2. Moisture content of about 14% (w.b.) probably would be ideal for densification. Materials that are stored in dry conditions may arrive at the pelleting plant with a moisture content as low as 8% (w.b.) or lower and in this case a small amount of water would need to be added. Wet materials with a moisture content of 18% or more would have to be dried. The optimum moisture content for pelleting needs to be established in more detail.

3. Lower grades of canola meal could be used as a biological binding agent. The levels of canola meal used in this study were probably higher than the optimum value. Therefore, more research is needed on the use of lower levels of canola meal as a binder. Other binders should be considered.

4. There is a need to find out more about the optimum preheating temperature of materials going into the pelleting equipment. Steam conditioning may help with the adhesion of particles. Also, the combination of preheating and steam conditioning of materials may reveal an interaction between these two factors on the quality of final products.

5. Development of equipment that will give commercial levels of throughput of the pellets is needed. Consideration the processing parameters such as pressure, time, feedstock speed, and die geometry as related to throughput is necessary.

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APPENDIX A

FIGURES SHOWING CHARACTERISTICS OF FLAX SHIVES

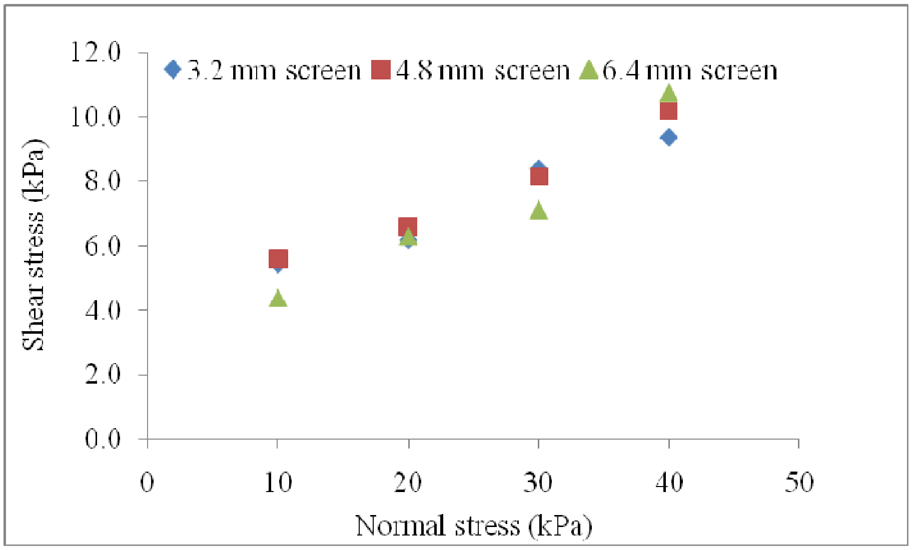

Figure A.1 Normal stress-shear stress plot for friction measurement of shives.

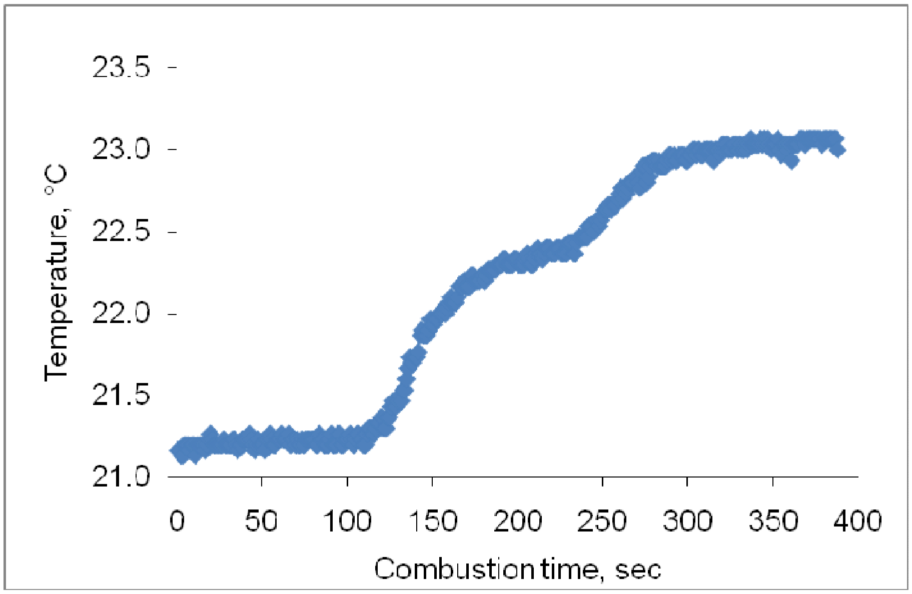

Figure A.2 Temperature change during combustion of flax shives.

APPENDIX B

ANOVA TABLES

Table B. 1 Analysis of variance of particle diameter of ground flax shives.

Source	df	Mean square	
		Biofibre Inc	Biolin Inc.
Screen sizes	2	0.00381478**	0.02489591**
Error	6	0.00014767	0.00038381

**p< 0.01.

Table B. 2 Analysis of variance of densities of ground flax shives (Biofibre Inc.).

Source	df	Mean square	
		Bulk density	Particle density
Screen sizes	2	73.31*	9168.75**
Error	6	7.53	178.61

**p < 0.01, *p<0.05.

Table B.3 Analysis of variance of densities of ground flax shives (Biolin Inc.).

Source	df	Mean square	
		Bulk density	Particle density
Grinding treatment	2	1084.96**	629.067^{ns}
Error	6	36.69	907.473

**p < 0.01, ns = not significant.

Table B.4 Mean squares from Analysis of variance of unit density and durability of pellets produced from flax shives obtained from Biofibre Inc.

Source	df	Unit density	Durability
Between groups	2	232.051*	1482.32**
Within groups	24	54.130	5.71

**p < 0.01, * p<0.05.

Table B.5 Mean squares from Analysis of variance of change in length, diameter, and ratio of length/diameter of pellets.

Source	df	Length	Diameter	Length/Diameter
Screen size (X_1)	2	0.011^{ns}	0.001^{ns}	0.004^{ns}
Canola meal (X_2)	2	0.548*	0.014^{ns}	0.464*
Moisture content (X_3)	2	1.496**	0.104^{ns}	1.675**
X_1*X_2	4	0.548*	0.028^{ns}	0.504*
X_1*X_3	2	1.690**	0.046^{ns}	1.250**
X_2*X_3	1	1.015**	0.622*	0.053^{ns}
X_1*X_2*X_3	1	0.001^{ns}	0.001^{ns}	0.005^{ns}
Error	5	0.051	0.051	0.054

**$p < 0.01$, *$p<0.05$, ns=not significant.

Table B.6 Mean squares from Analysis of variance of pellet unit density.

Source	df	Mean square
Screen size (X_1)	2	595.65^{ns}
Canola meal (X_2)	2	10928.475^{ns}
Moisture content (X_3)	2	8120.461^{ns}
X_1*X_2	4	159.482^{ns}
X_1*X_3	2	2180.175^{ns}
X_2*X_3	1	4753.125^{ns}
X_1*X_2*X_3	1	1596.125^{ns}
Error	5	3982.70

ns=not significant.

Table B.7 Mean squres from Analysis of variance of bulk and particle density, and porosity of shive pellets.

Source	df	Bulk density	Particle density	Porosity
Screen size (X_1)	2	130.854^{ns}	18109.112*	74.111^{ns}
Canola meal (X_2)	2	3784.314^{ns}	4826.477*	70.673^{ns}
Moisture content (X_3)	2	2438.121^{ns}	251507.553*	1087.459*
X_1*X_2	4	826.749^{ns}	6644.965*	45.014^{ns}
X_1*X_3	2	129.306^{ns}	30424.375*	83.301^{ns}
X_2*X_3	1	779.078^{ns}	21520.967*	49.900^{ns}
X_1*X_2*X_3	1	109.216^{ns}	3251.123*	28.125^{ns}
Error	5	2813.389	486.902	15.270

*$p<0.01$, ns=not significant.

Table B.8 Analysis of variance of hardness of flax shive pellets.

Source	df	Mean square
Screen size (X_1)	2	2864.888^{ns}
Canola meal (X_2)	2	65009.074*
Moisture content (X_3)	2	5842.130^{ns}
X_1*X_2	4	2386.603^{ns}
X_1*X_3	2	381.035^{ns}
X_2*X_3	1	215.541^{ns}
X_1*X_2*X_3	1	2294.930^{ns}
Error	5	7173.317

*p<0.05, ns=not significant.

Table B.9 Analysis of variance of durability of flax shive pellets.

Source	df	Mean square
Screen size (X_1)	2	317.421^{ns}
Canola meal (X_2)	2	516.764^{ns}
Moisture content (X_3)	2	529.290*
X_1*X_2	4	63.724^{ns}
X_1*X_3	2	82.458^{ns}
X_2*X_3	1	132.641^{ns}
X_1*X_2*X_3	1	12.007^{ns}
Error	5	148.978

*p<0.05, ns=not significant.

Table B.10 Analysis of variance of moisture absorption of flax shive pellets.

Source	df	Mean square
Screen size (X_1)	2	128.440^{ns}
Canola meal (X_2)	2	185.422^{ns}
Moisture content (X_3)	2	11833.223*
X_1*X_2	4	351.082^{ns}
X_1*X_3	2	114.605^{ns}
X_2*X_3	1	0.068^{ns}
X_1*X_2*X_3	1	228.413^{ns}
Error	5	136.852

*p<0.05, ns=not significant

Table B.11 Mean squares from Analysis of variance of emissions of flax shive pellets and wood pellets from combustion.

Source	df	Nitrogen (ppt)	Oxygen (ppt)	Methane (ppm)	Nitrogen oxide (ppm)	Carbon dioxide (ppt)
Pellets	2	36.08**	214.7**	0.172**	1.306**	106.8**
Error	9	1.4	15.9	0.019	0.071	12.9

**p<0.01.