

Thermophysical properties of biofuel pellets made from paper wastes and energy crops under different pelleting conditions.

by

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ABSTRACT

Large amounts of paper wastes are produced in everyday life, such as paper towels and cardboard packaging boxes. The goal of this study was to explore the feasibility and optimize the processing conditions to pellet paper wastes to be used as fuel. A flat die pilot scale pelletizing unit was used to make pellets from paper towels and packaging boxes. The effects of different parameters on the pelleting process and quality (thermophysical properties) of pellets were evaluated. It was found that moisture content (MC) had the most significant effect on the pellet quality and the best quality for paper towel and cardboard box pellets was achieved at 45% and 35% MC (wb), respectively. Also, it was found that low processing temperature (60-70 °C) with proper conditioning or drying time improved the pellet quality. Two days of conditioning at room temperature or drying at 38 °C was found to be sufficient to achieve statistically significant improvement in the pellet quality parameters. The paper towel and cardboard box pellets achieved a maximum durability of 91.9% and 94.1% with a calorific value of 17195 and 17084 J/g, respectively. It was also found that the modified Henderson equation predicted the sorption behavior of the paper waste pellets more accurately than the Linear model and the Henderson equation. Properties of pellets made from four energy crops (miscanthus, prairie chord, switch grass and big blue stem) has also been investigated. There was no significant difference observed in the calorific values of the pellets made from these energy crops. Miscanthus resulted in the most durable pellets (roughly 97.5%). Pellets made from switchgrass and big blue stem had the highest bulk density (around 0.69 g/cm³). After second days of drying the average value of calorific value of the pellets made from the energy crops were 17853 J/g with an average bulk density 0.73 kg/m³ in

comparison to the average calorific value of 17139 J/g and bulk density of 0.69 kg/m³ for paper waste pellets.

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–Prophet Muhammad (may peace be upon him)

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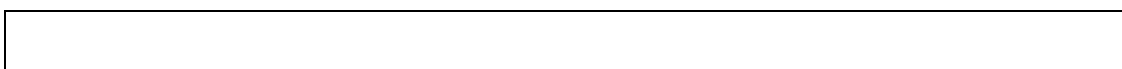
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CHAPTER I

INTRODUCTION

1.1 BIOMASS ENERGY

Over the last decades, the use of fossil fuels has become one of the biggest environmental concerns leading to a growing interest in the renewable energy sources. Biomass is regarded as third largest energy source and an abundant source of renewable energy (Bapat et al. 1997). Raw biomass itself could be used as a source for renewable energy but its low bulk density (around 150-200 kg/m³ for woody biomass) makes it difficult for transport and storage (Sokhansanj and Fenton 2006). Therefore, biomass densification is one of the key points in increasing its energy value per unit mass. In 2012, biomass energy was estimated to contribute roughly 10% of the global energy supply (Pichs Madruga et al. 2012). The wood pellet trade now involves bulk transport of 10 million tons annually and the number is getting bigger every year. North America has been considered a major supplier of biomass pellets with trade extended to Africa, Asia, Russia and South America (Whittaker and Shield 2017). Currently, the major consumer of biofuel pellets is the European Union where the EU government implemented the greenhouse gas reduction policy replacing majority coal or gas burning energy plants to biomass based energy plants (Wong 2012). It is mandatory for all EU countries to increase the renewable energy use by 32% by 2030 (Council of the European Union 2018).

1.2 BIOMASS DENSIFICATION

Due to the low energy density of biomass, a critical element of utilizing biomass energy is to densify biomass. Densification of biomass consists of complex mechanical processes, involving particle size reduction, material preparation and pelletizing. Biomass densification increases bulk density, which improves handling and reduces the transportation volume. It also improves pellet uniformity, which results in better combustion efficiency. A wide range of research has been conducted in pelletizing biomass to form quality pellets for use in bioenergy applications. Many investigations have been focussing on parameters of making uniform pellets, such as determining the optimal manufacturing process variables (moisture content, temperature, and particle size distribution). Many researchers also have been focussing on increasing the understanding of the bonding mechanism, exploring the effect of the addition of different binders and on analysing different densification systems available such as briquette presses, various pelletizing machines (e.g. flat die pelletizer and roller die pelletizer), agglomerators, roller presses, tablet presses and screw extruders. In addition, the effect and addition of some pre-treatment processes such as torrefaction, steam explosion, preheating and AFEX (ammonia fiber explosion) have been explored by Bonner et al. (2016). Finally, with the boom of pellet industry, a specific energy consumption of different pelletizing systems and the effect of pelletizing parameters on the specific energy consumption have become a main concern when considering the commercial point of view (Tumuluru et al. 2011).

1.3 BIOMASS MATERIALS AND PAPER WASTE

The primary biomass materials used for pellet manufacturing have been wood and woody residues such as wood chips, wood shavings and saw dust. With an increase in demand of biomass pellets, manufacturers have begun to use various agricultural residues such as crop residues, straw and energy crops (Verma et al. 2012). From 2012 to 2018 the pellet manufacturing industry have seen a significant growth where the pellet consumption raised from 19.5 million metric tonnes to 35.4 million metric tonnes within these six years. In 2017 to 2018 fiscal year alone the pelleting industry increased its market share by 13.3% (Strauss 2020). With this boom of the pelleting industry, efforts have been made to balance the biomass raw material supply chain. Use of waste materials such as tea waste, paper waste, cotton stalks, rapeseed cake, food waste, etc. has been another prime area of research for the past few years (Rosmarin 2018). Continuous efforts are made to find new biomass raw materials; however, the use of many raw materials have not been always successful as they frequently provide pellets with low quality that does not meet standards required by commercial bioenergy production.

Everyday life leaves lots of paper wastes, such as paper towels and cardboard packaging. With the huge consumption of these paper products, management of wastes has become an area of concern for many larger establishments. There is little information available on the suitability and processes of pelletizing paper wastes to be used as biofuels.

Another category of biomass material are energy crops, such as Miscanthus, prairie cordgrass, and switchgrass. Researchers (Moon et al. 2014; Lehmann et al. 2012; Y.H.

Li et al. 2018; De Jong et al. 2002; Collura et al. 2006) explored the effect of mixing Miscanthus with wood and agricultural residues and tested its combustion behavior and pyrolysis. Prairie cordgrass and switchgrass were studied by various researchers, including Maj and Piekarski (2013) and Sundaram et al. (2015). Maj and Piekarski (2013) identified the optimal moisture content for making prairie cordgrass pellets as 12-14% and suggested a chaff length of 3-8 mm as optimal for pelleting. Sundaram et al. (2015) investigated pellet manufacturing parameters and the ammonia fiber-expansion (AFEX™) pre-treatment behavior on prairie cordgrass and switchgrass. They found that prairie cordgrass and switchgrass at 20% moisture content when treated with AFEX™ with a screen size 2 mm results in more than a 20% increase in unit density. Karunanithy et al. (2012) discussed moisture sorption characteristics of dried prairie cordgrass and switchgrass feed stocks and found that both the crops follow a typical type II isotherm, similar to food materials. Big bluestem had also been explored by many scientists for making pellets. Theerarattananoon et al. (2011) suggested 6.5 mm screen size and 44.5 mm die thickness as optimal condition for producing pellets from big bluestem. Karunanithy et al. (2012) discussed the sorption isothermal behavior of big bluestem feed stock and suggested Modified Halsey model as a best fit model to predict the isotherm behavior.

However, the sorption isothermal behavior of the pellets made from some energy crops (Miscanthus, prairie cordgrass and switchgrass) is not available. Also, no data were available to compare the physical properties of the pellets made from these energy crops, when prepared using the same pelleting unit and the same processing parameters. Therefore, further research is needed to find out the isothermal behavior and comparison of the physical properties of the energy crops.

1.4 RESEARCH OBJECTIVES

The objectives of this research are as follows –

- 1.To determine the feasibility of using paper wastes to make biofuel pellets.
- 2.To determine the best pelleting conditions for wastepaper pellets for the range of 60-70 °C and 90-100 °C temperature and 15-55% moisture content (wb).
- 3.To compare thermophysical properties (bulk density, pellet density, diameter, durability, moisture content, calorific value, ash content, particle size) of pellets made from four energy crops (Miscanthus, prairie cordgrass, switchgrass, big bluestem).
- 4.To determine the sorption isothermal behavior of pellets made from paper waste and four energy crops (Miscanthus, prairie cordgrass, switchgrass and big bluestem).

CHAPTER II

LITERATURE REVIEW

2.1 DENSIFIED BIOMASS

Wood is often used as a raw material for the production of industrial pellets. As the supply of wood is limited, other materials have been explored and tested. Agricultural and waste residues are the current focus of researchers. Researchers are testing such potential materials as switchgrass (Hilton et al. 2013); barley straw (Serrano et al. 2011); corn stover (Shankar Tumuluru 2014); hay (Kirsten et al. 2016); corn cob waste (Miranda et al. 2018); reed canarygrass (Agar et al. 2018); garden waste (Pradhan et al. 2017); food waste and wood blend (Zhai et al. 2018) and were able to produce pellets meeting all the international quality parameters and successfully established standard operating condition for optimal pellet quality in all cases.

The manufacturing process of densified materials can be classified into three types: extrusion, pelletization and briquetting (Li and Liu 2000). Extrusion process occurs in four stages namely solid conveyance, initial compression, final compression and discharge and sometimes needs additional input of heat making it more unreliable for industrial pellet production (Tumuluru et al. 2011). Manufacturing of briquettes involves less processing steps in comparison to pelletizing, as briquetting does not require particle size reduction by hammer mills. Pellets have higher bulk density and lower ash content than that of briquettes (Cubero-Abarca et al. 2014); therefore, pellets are considered a preferable mode of densification in terms of logistics and the lower maintenance requirements of a boiler.

2.2 BONDING MECHANISM

There are several bonding mechanisms involved in pellet densification. The binding forces responsible for forming densified particles include: solid bridging; attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces, and interfacial forces and capillary pressure (Pietsch 2002, Rump 1962). Due to applied compression pressure, the lignin softens which helps the bonding of particles (Kaliyan and Morey 2009). Kaliyan and Morey (2009) reported formation of solid bridges due to melting of the particles at high temperature (above 50 °C) and pressure. At high temperatures, lignin present in the material softens, increasing the flowability of the material and assisting in the formation of bonds (Stelte et al. 2011a). Rump (1962) indicated that mechanisms of solid bridge formation is a result of particle crystallization, binder hardening and solidification of particles after curing.

The inter-molecular forces also help in bond formation by reducing inter-particle distances. Moisture present between the particles also activates the cohesion forces among the particles and thus helps in bond formation (Kaliyan and Morey 2008). Moreover, when particles are close enough to one another, forces such as valence forces, hydrogen bridges, and Van der Waal's forces are activated. It was found that Van der Waals forces are activated when the inter-particular distance is smaller than 10 Å and intermolecular adhesion forces act when the particles are closer to each other than 0.1 µm (Pietsch 2002, Rump 1962).

2.3 MOISTURE CONTENT

Moisture content of particles is reported as the most important factor for pelletizing (Samuelsson et al. 2012). The performance of different materials varies depending on their moisture content. The proportion of the moisture present in the material may have both positive and negative impacts on pellet quality, rendering it necessary to optimize the moisture content of the materials used. Higher moisture softens the lignin and allows extra lubrication to the die surface (Nielson et al. 2009). Moisture also reduces the glass transition temperature (T_g) of lignin and helps in bond formation by melting down lignin at a lower temperature (Stelte et al. 2011a). On the other hand, moisture content when in excess of 20% creates a steam pressure responsible for reducing the compressive force, resulting in the formation of weaker pellets. A possible explanation is that the hydrogen bonds are replaced with bonds formed by the cohesive forces of water particles and raw materials (Filbakk et al. 2011b, Nielson et al. 2009). Samuelsson et al. (2012) mentioned the effect of storage time on optimal moisture content. A longer storage time reduces fatty and resin acid content; therefore, materials stored for a longer period will need more moisture to form a stronger pellet. They found a positive correlation between moisture content and pellet durability for materials stored for durations of more than 120 days (Samuelsson et al. 2012).

Researchers have reported different optimal moisture contents for different materials. Obernberger and Thek (2004) reported that a moisture content in the range of 8-12% yields optimal pellet quality. Selection of the optimal moisture content varies depending on the types of pelletizer used and machine parameters. Examples of the optimal moisture contents reported by various researchers are: wheat straw, barley straw: 10% (Shankar Tumuluru 2016); Scots pine, beech: 11.3% (Serrano et al. 2011);

hay: 12% (Kirsten et al. 2016); switchgrass: 12-18% (Hilton et al. 2013); Miscanthus: 20-25% (Moon et al. 2014); Norway spruce: 10% (Stelte et al. 2011); lodgepole pine: 33-35% (Shankar Tumuluru 2016); poplar: 26.6% (Mediavilla et al. 2012).

2.4 BIOMASS COMPOSITION

Wood or waste biomass is mostly composed of cellulose, hemicellulose and lignin. Hemicellulose acts as a matrix which is distributed randomly. It is composed of an amorphous structure, which can be easily hydrolyzed. Cellulose acts as a skeleton of biomaterials. It is semi-crystalline in nature and is, therefore, resistant to hydrolysis (Tumuluru et al. 2011).

Lignin acts as a natural binder that helps in pellet formation. Wood generally has a lignin content in the range of 15-40%, depending on the species (Novaes et al. 2010). Agricultural residues such as straws need low moisture, typically less than 20% (Stelte et al. 2011b). Presence of lignin helps in pellet formation by forming solid bridges among the particle when exposed to high temperature and pressure (Van Dam et al. 2004). Lehtikangas (2001) found a strong positive correlation between the lignin content and the pellet durability.

Presence of extractives are also another important factor for pellet quality. Extractives are mainly organic compounds of low molecular weight, including fatty acids, waxes and their derivatives. Extractives help in reducing the wear between roller and die by providing extra lubrication (Puig-Arnavat et al. 2016). If the amount of lubricant is higher, the pelletization pressure may be reduced, resulting in weaker pellets (Stelte et al. 2011a). On the other hand, long storage times reduce the extractive content, and at low extractive content, more moisture is required to form quality pellets (Samuelsson et al. 2009). Filbakk et al. (2011) observed a positive correlation between the

extractives content and pellet durability when studying Scot pine pellets. Different parts of the plant have different extractives levels. Therefore, extractives have both positive and negative effects based on the amount of extractives being used. Bradfield and Levi (1984) however, mentioned a saturation point of 34% of lignin and additives above which they found a decrease in pellet quality.

Different parts of the plant contain different amounts of cellulose, hemicellulose and lignin. Plant bark contains more lignin than other parts of the plant (Filbakk et al. 2011a). Chen et al. (2015) observed an increase in the bonding strength by adding bark to a pellet. Therefore, mixing different parts of the plants or biomass feedstock is a good option to produce better quality pellets (Serrano et al. 2011).

2.5 SIZE REDUCTION

After optimal moisture content and temperature, the third most important factor affecting pellet durability is the size reduction (Carone et al. 2011). The most popular methods used for size reduction are: a knife mill, a disk attrition mill and a hammer mill (Pradhan et al. 2018). Industrial hammer mills now come with different screen sizes which allow to control the output particle size. Particle size has several effects on pelletizing, playing an important role in compaction, friction and material flow rate (Jezerska et al. 2016). Also, to form a stronger pellet, inter-particle forces play an important role. Size reduction increases the total surface area and helps in increasing the number of surface contact points, leading to more adhesion forces. It has been observed that the specific energy consumption decreases with an increase in screen size in the hammer mill size reduction (Mani et al. 2004). While pelletizing alfalfa, specific energy was found to be reduced from 30.51 kJkg^{-1} to 6.96 kJkg^{-1} when the

screen size of the hammer mill increased from 1.68mm to 4.76 mm (Ghorbani et al. 2009).

Different studies showed different effects of particle size on pellet quality. Bergström et al. (2008) studied the effect of particle size of Scot pine saw dust. They found that there is no significant effect of particle size on pellet bulk density, moisture content, abrasion resistance and moisture adsorption. Therefore, they suggested not to grind saw dust below 0.8 mm. Serrano et al. (2011) also demonstrated similar findings while experimenting with barley straw with a ring die pellet mill.

Carone et al. (2011) while experimenting with olive tree pruning residue, found an increase in pellet density with a decrease in particle size (4 mm, 2 mm and 1 mm). Experiments with poplar wood and wood straw found that a reduction in particle size (from 3.2 mm to 0.8 mm) increased pellet density, decreased diametric expansion and increased tensile strength (Shaw et al. 2009). A range of optimal particle sizes (0.6 mm to 0.8 mm) have been suggested by American Feed Manufacturing Association in 1966 for optimal pellet quality.

The amount of fine particle (hammered particles) present in the mixture also has significant effect on durability and pellet quality. It was reported that the particle mixture having more fine particles has a negative effect on the pellet quality. It was suggested that if the content of fine particles is more than 10-20%, it reduces the pellet quality. It also results in more friction on the roller and die (Kaliyan and Morey 2008). A high content of fine particles can result in the blockage of the die and rapid moisture loss due to reduced surface area (Bergström et al. 2008).

2.6 ADDITIVES

Many authors (Serrano et al. 2011; Mediavilla et al. 2012; Pradhan et al. 2017; Jiang et al. 2016; Mišljenović et al. 2016) have experimented with different binders and showed the effects of binders on pellet quality. The addition and selection of a binder is mostly focused on increasing pellet durability and its heating value. International standards for pellets specify that additives should comprise no more than 2% of the total raw materials of a pellet (European Pellet Council 2011). Commonly used binders for producing wood pellets include starch, protein, bentonite and ligno sulphate (Pradhan et al. 2018). They can be classified as starchy additives like corn or potato flour, sugary materials like molasses or cassava, lignin, cellulose, proteins and vegetable oil (European Pellet Council 2011).

The addition of molasses reduces the energy required for pelleting and it also helps to maintain a low glass transition temperature (Mišljenović et al. 2016). Emami et al. (2015) conducted experiments in which glycerol was added to agricultural residues. They recorded no significant change in durability but reported an increase in heating value and a decrease in ash content due to the addition of glycerol. Addition of microalgae with saw dust increased pellet quality and heating value and reduced pelletization energy. Hosseinizand et al. (2018) mentioned that the presence of oil in the microalgae increased the heating value and increased machine lubrication while pelletizing (Hosseinizand et al. 2018). Bentonite, when used as a binder, helps in binding action via its ion exchange properties and it is frequently used due to its low cost. The addition of glycerol to wood residues can increase the heating value of pellets from 17.98 MJkg^{-1} to 18.77 MJkg^{-1} (Lu et al. 2014).

2.7 PELLETING TEMPERATURE

Temperature is another important factor in densifying biomass. The action of a roller on a die during pelleting causes a rise in temperature of the pellet mill over the period of running time. It has been reported that pelletizing above the glass transition temperature improves the pellet quality (Kaliyan and Morey 2008). Wood pellets need 100-130 °C to form strong inter-particle bonds (K. Nielson et al. 2009). However, the glass transition temperature changes depending on the material used. For pelletizing Miscanthus, optimal temperature was noted as 105 °C (Moon et al. 2014). Wheat straw has a glass transition temperature in the range of 53-63 °C but it was recommended to maintain a minimum temperature of 100 °C so that the negative effects of the extractives can be overcome (Whittaker and Shield 2017). Also, the positive effect of higher temperatures has been noted while pelletizing beech and Scots pine (K. Nielson et al. 2009), beech, Norway spruce and straw (Stelte et al. 2011)

Some researcher reported negative effects of higher pelleting temperature. Larsson et al. (2012) mentioned that a temperature range of 65 °C gave optimal pellet quality for canarygrass pellets. The irregularity of the pellet dimensions at higher temperatures was also reported by Larsson and Rudolfsson (2012) and they advised to use lower temperatures to avoid discontinuation in the production conditions.

2.8 PELLETIZING PRESSURE

The pelletizing pressure is mainly created by roller-die and material friction. There are several factors which affect the pelletizing pressure such as dimensions of a roller and die, particle size and bulk density of the feed and the rotation speed of the roller

(Alakangas and Paju 2002). Holm et al. (2006) mentioned that pelletizing pressure is directly proportional to pre-stretching pressure and inversely proportional to Poisson's ratio of the material. They also mentioned that pelletizing pressure increases exponentially with compression ratio. Compression ratio is the ratio of channel (the holes present in the die) length to channel diameter. Thus, a higher L/D ratio increases the pelletizing pressure. Optimal pelletizing pressure should be selected such that it needs less input energy but gives a pellet with maximum quality (Pradhan et al. 2018). Durable pellets are found to be formed in the pressure range between 115 and 300 MPa (Whittaker and Shield 2017). Durable pellets were found to be formed at higher pressure, but the volume compaction of pellets are limited after a certain pressure is achieved (Adapa et al. 2009)

CHAPTER III

METHODOLOGY

3.1 BIOMASS MATERIALS AND ADDITIVES

Two paper waste products were tested - paper towels (Tork 1-Ply Universal Single fold Hand Paper Towels, Essity Canada Inc. Philadelphia, PA) and cardboard packaging. The paper towel was made of 100% recycled content (100% recycled fibre with at least 40% post-consumer fibre). The cardboard boxes were collected from a nearest grocery store, which had been discarded by the store after receiving shipments.

The energy crops tested were Miscanthus (*Miscanthus sacchariflorus*); prairie cordgrass (*Spartina pectinata*); switchgrass (*Panicum virgatum L.*) and big bluestem (*Andropogon gerardii Vitman.*). The crops were grown at the Ian M. Morrison Research Farm at Carman, MB and were harvested in the fourth year of production. Crops were harvested on October 30, 2018, when they were cut, transported to the University of Manitoba in Winnipeg and dried at room temperature.

A special type of yeast *Rhodospiridium babjvae*, an oleaginous and carotenogenic strain of yeast obtained from the University of California at Davis was used as an additive. The purpose of using this yeast in pellet manufacturing is to increase the

calorific value. The strain was grown on a modified minimal medium originally described by Zhou et al. (2012) but contained 40 g/L glucose as the carbon source. Growth was carried out in a 15 L New Brunswick bioreactor with 10 liters working volume of Zhou medium at 22 °C with impeller stirring at 400 rpm. Continuous culturing conditions were grown for 48 hours, then 70% of the growth medium and yeast cells were harvested. Next, the reactor was filled with new growth medium, and grew yeast for another 48 hours continuously for 3 months.

With tissue paper pellets and cardboard box pellets 2% of yeast were used as an additive. An experiment was also carried out using 2% of fatty acid (collected from industrial waste fatty acid biproduct) as additives with tissue paper pellet. Effect of mixing of another biomass with cardboard box pellets were also evaluated with an experimental trial of 10% big blue stem with 90% cardboard box particles.

3.2 SIZE REDUCTION OF THE BIOMASS

The size reduction of the energy crops was executed using a hammer mill (Model 1128, Schutte Buffalo USA, NY). This machine consisted of 16 hammer blades, 4 blades in a row attached to a circular plate. The hammer blade rotates in a clockwise direction. This machine was accompanied by a dust collector (Grizzly Model- G0443) run by a 1.5 hp motor. It collected dust, formed while hammering wood chips through air suction and stored it in a collector bag.

For paper towel and paper boxes, a micro cut shredder machine (Fellowes Powershred 225Mi) was used. The shredded particles were of uniform sizes of 5/64" x 15/32 (2.0 x 11.9 mm)

3.3 SAMPLE PREPARATIONS

The shredded or hammered particles were then hydrated by spraying water. The spraying and mixing were continued manually to ensure uniform mixing. The amount of water sprayed was varied to achieve a required moisture content for further experiments.

After moisturizing, the samples were kept in a sealed container for at least 24 hr at room temperature to ensure appropriate moisture absorption for lignin softening.

3.4 PELLETIZING

Pelletizing was carried out by a lab-scale flat die rotating roller. The machine runs by a 10 hp motor (Brook Crompton-Type WP-DA132MVX-D4) with a 600-volt power supply. It consisted of a single grooved roller connected by a shaft in midway with the die plate. The die plate diameter was 100.3 mm with an individual die hole diameter of 7.80 mm.

The clearance between the roller and the die was fixed throughout the experiment and the roller slightly touched the die plate allowing the roller to move smoothly onto the die plate. The heat generated by the roller-die-particle friction while in action caused the die temperature to be raised to 60-70 °C, which, after 15-20 minutes of running time, increased to 90-110 °C.

3.5 CONDITIONING AND DRYING

After pelleting, the pellets were spread out over a sieve to allow cooling down and the pellets were conditioned to room temperature (20 °C) and relative humidity of approximately 20%. The pellets were kept on the sieve for 5 days.

Pellets made from energy crops were dried in oven at 38 °C at 20% RH for five consecutive days.

3.6 DETERMINATION OF PELLETT PROPERTIES

3.6.1 Moisture content

Moisture content of the pellets was measured according to the ASAE standard S358.2. Samples about 25 g were placed in aluminum dishes and dried in an oven at 103 °C for 24 h. Moisture content on both dry basis (db) and wet basis (wb) were determined as per the (ASAE S358.2 2012) standard.

3.6.2 Particle size distribution

The particle size distribution was determined according to the European Standard EN 15149-2:2010 (E). Six mesh wire sieves (2.8, 2.0, 1.4, 1.0, 0.5, and 0.25 mm) plus a collecting pan were used in this method. A sample not less than 50 g was used and measured to a precision of the nearest 0.1 g. Sieving was done by an automatic sieving machine (WS Tyler- Model RX-812). Sieves was vibrated for 30 min to make sure all the particles passed through the corresponding sieves (European committee for standardization. 2010).

The geometric mean diameter was calculated as per ASAE S319.2 standard, using the following equations (citation):

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

where,

d_i = Nominal sieve opening of the i^{th} sieve, mm.

d_{i+1} = Nominal sieve opening in next larger i^{th} sieve, mm.

d_{gw} = Geometric mean diameter by mass of sample, mm.

$\overline{d_i}$ = Geometric mean diameter of particles on i^{th} sieve; mm.

$$\overline{d_i} = (d_i \times d_{i+1})^{1/2}$$

W_i = Weight of material in i^{th} sieve.

The size distribution of particles collected by the pan was determined with another set of smaller sieves of 0.212, 0.180, 0.160, 0.150, and 0.125 mm. It was found that almost 80% of the sample mass was collected on the 0.160 mm sieve. Almost 12% of the particles was collected on 0.212 mm which were mainly big chunks of particles and almost 2%, 3% and 2.8% on 0.180 mm, 0.150 mm, 0.125 mm sieves respectively. Therefore, for calculating geometric mean diameter, the size of the particles collected by the pan was treated as 0.160 mm.

3.6.3 Pellet density

Pellet density (ρ_p), in g/mm^3 , was determined using the following formula after weighing the individual pellet and measuring its volume:

$$\rho_p = \frac{m_p}{V_p} \quad \dots(3.2)$$

Where, m_p = Mass of individual pellets in g. (determined by an electrical balance with an accuracy of 0.001g)

V_p = Volume of the pellet in mm^3 , which was found by calculating using the following equation:

$$V_p = \frac{\pi}{4} D^2 L \quad \dots(3.3)$$

Where D = Diameter in mm of the pellet.

L= Length of the pellet in mm.

3.6.4 Bulk density

The bulk density of the pellets was measured by using an apparatus described by the Canadian Grain Commission as “Determining Test Weight”(Canadian Grain Commission 2019). A cylindrical cup of volume 0.5 L with an inside diameter of 90 mm and a height of 77.5 mm was used. A cox funnel with an opening of 38.1 mm and a drop height of 44.1 mm was used to fill pellets to the cylindrical cup (Canadian Grain Commission 2019). As per ASTM E873 – 82, the holding cup with the sample was dropped five times to allow some compaction and any excess filled portion was removed by levelling with a rod before taking the final mass measurement (ASTM E873-82 2019).

3.6.5 Calorific Value

The calorific value of the pellets was measured according to ASTM E711 – 87 (citation). A bomb calorimeter (IKA(R) C 200, Germany) was used for this experiment. Approximately 1 g sample was placed in the oxygen bomb calorimeter under controlled conditions. The temperature increase and the net calorific value was recorded as displayed on the calorimeter screen , in units of joules per gram (ASTM E711-87 2004) with three replications.

3.6.6 Durability

Pellet's durability was tested according to the ASAE S 269.4 standard using a rectangular tumbling drum with inner dimensions of 300 x 300 x 125 mm. To increase the tumbling effect, the drum was equipped with a baffle of 230 mm length. The drum was connected to a motor by a shaft which transferred the rotary motion from the motor to the drum. The drum was set to rotate 500 times at 50 rpm.

A representative sample of 500 g was used for durability testing in triplicate. The pellet samples were sieved manually using a 3.15 mm round-opening sieve to remove smaller particles or small broken pellets. The mass of the sample after tumbling was expressed as a percentage of the initial sample mass represented pellet durability (Temmerman et al. 2006).

3.6.7 Equilibrium moisture content

Equilibrium moisture content of the pellets was determined by keeping the pellets at a constant temperature of 21 °C while maintaining different relative humidities achieved by using various salt solutions (Table 3.1). Seven desiccators were used to keep the relative humidity constant.

A sample of pellet about 25 g was placed in each desiccator for 7 days and moisture content was then measured as per ASAE S358.2 (ASAE S358.2 2012)

Table 3.1 Different salt solution in the desiccator and their corresponding relative humidity (Rockland 1960)

Saturated Salt Solution	Relative humidity at 20-22 °C
Lithium chloride (LiCl)	11.3%
Potassium acetate (CH ₃ COOK)	22.5%
Magnesium chloride (MgCl ₂)	32.8%
Magnesium nitrate (Mg (NO ₃) ₂)	52.9%
Potassium iodide (KI)	68.9%
Sodium chloride (NaCl)	75.3%
Potassium Chloride (KCl)	86.8%

3.7 EXPERIMENTAL DESIGN AND DATA ANALYSIS

The two main parameters that affect pellet properties are moisture and temperature during pelleting. Due to the closed construction of the pelletizer used in this experiment, there was little opportunity for friction heat to escape, resulting in a quick rise of temperature and loss of moisture from the biomass materials. The experiment was conducted using a wider range of moisture content (from 15-55%; wb) in order to determine its effect on the pellet quality. By controlling the amount of feeding and introducing some air flow from the feeding point; temperature of pellets was kept in the range of 50-70 °C, otherwise, temperature of pellets would reach 90-110 °C.

The first set of experiments was conducted with paper towel as a raw material. Seven moisture contents were tested: 15, 20, 25, 30, 35, 45 and 55%; wb at two temperature levels of 50-70 °C (LT-lower temperature) and 90-110 °C (HT-higher temperature).

The experimental design was carried in 7 x 2 factorial design with two replications for each experimental combination.

Table 3.2 A 7 x 2 factorial design for paper towel pellet.

		Factor A: Moisture Content						
		A1=15%	A2=20%	A3=25%	A4=30%	A5=35%	A6=45%	A7=55%
Factor B: Temperature	B1=LT	LT/15%	LT/20%	LT/25%	LT/30%	LT/35%	LT/45%	LT/55%
	B2=HT	HT/15%	HT/20%	HT/25%	HT/30%	HT/35%	HT/45%	HT/55%

where LT=Low temperature and HT= High temperature, Considering Moisture content as factor A and temperature as factor B.

The statistical analysis was carried out using ‘SAS® University Edition’. To investigate the effect of selected parameters, a response surface model using ‘proc rsreg’ function was implemented. The means were compared using one-way or two-way ANOVA and Tukey’s LS-means comparison to find the significant effect or significant changes. Using a ‘proc glm’ statement in SAS, a second order polynomial model function (equation 3.4) describing the interaction between the selected factors was fitted with the experimental results.

$$Y_i = \beta_0 + \sum_{i=1}^7 \beta_1 A_i + \sum_{i=1}^7 \beta_2 A_i^2 + \sum_{j=1}^2 \beta_3 B_j + \sum_{j=1}^2 \beta_4 B_j^2 + \sum_{i=1}^7 \sum_{j=1}^2 \beta_5 A_i B_j \quad \dots(3.4)$$

Where Y_i = Response variables.

Y_i = Calorific value, durability, bulk density, pellet density.

β_0 = Value of intercept of the regression line.

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ = The values of regression coefficients for the individual linear, quadratic and interaction cross product terms.

A_i = Control variables (moisture content).

B_j = Control variables (temperature).

The significance of this polynomial model (how effectively the model can predict the response variable) was evaluated by considering outliers using residuals, analyzing R^2 , adjusted R^2 , P value and by the lack of fit test and by visual inspection of plots. Finally, based on desirability function analysis, the optimal pellet processing parameters have been selected.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 EFFECT OF MC AND TEMPERATURE ON PELLET CALORIFIC VALUE

4.1.1 Pellet prepared from paper towels

Figure 4.1 shows MC (wb) of the output pellets made from shredded paper towels when processed at different particle initial moisture content (the MC at which the shredded particles were conditioned before pelletizing).

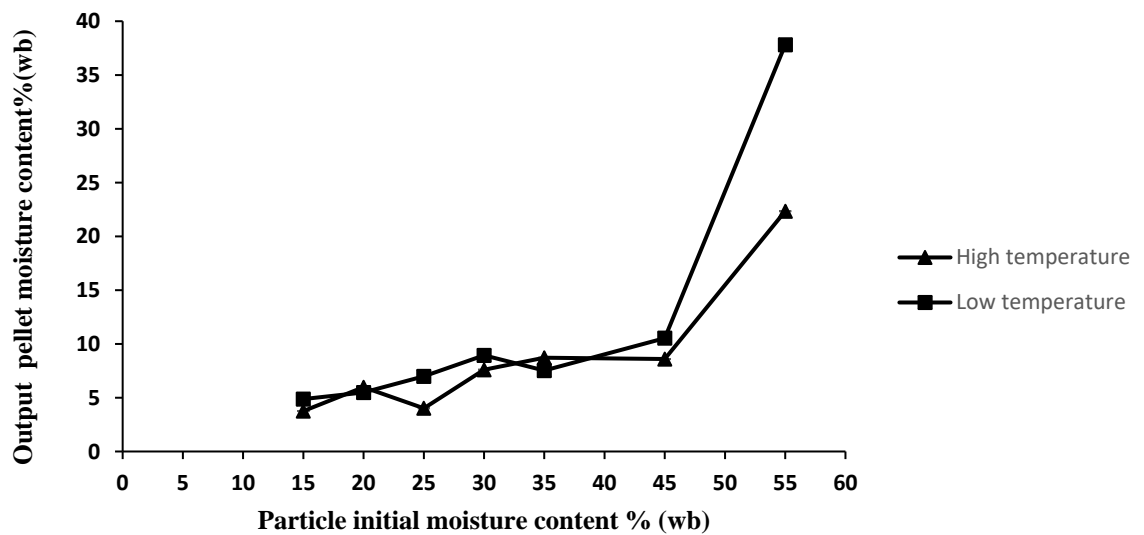


Figure 4.1 Change in output pellet moisture content (wb) with an increase in particle initial moisture content when processed at low temperature (LT:60-70 °C) and high temperature (HT:90-110 °C) range for paper towel pellet.

The change in MC of pellets at different particle moisture contents was found to be significant ($p < 0.05$) for both low (60-70 °C) and high processing temperature (90-110 °C). The relationship can be expressed by the following polynomial equation:

$$PMC = 0.031 - 0.449 MCP + 0.002 T - 0.009 MCP \times T + 2.419 (MCP)^2$$

Where PMC= Pellet moisture content % (w.b)

MCP= Moisture content of the particle % (w.b)

T = Temperature (°C).

This model was found to be adequate with $R^2 = 0.86$ (for range MC:15%-55% and Temperature: 50-110 °C). Compaction and heating caused lowering moisture content of pellets than the initial particle moisture content. Pellets made at low temperature showed a decrease in MC by 69% with respect to the initial particle MC and at high temperature the decrease in moisture was as high as 74%.

The calorific value of biomass generally decreases with increasing MC. According to Gebgeegziabher et al. (2013) higher moisture content of particles reduces the combustion temperature, which leads to incomplete combustion resulting in a lower calorific value. Also, at high moisture during combustion, some energy is being used up for moisture evaporation which also lowers the gross calorific value. The measured calorific value of pellets prepared from the paper towel decreased with the particle moisture content before pelleting in a linear fashion (figure. 4.2). At high processing temperature, the calorific value was found to be higher, as high temperature led to some moisture evaporation during pelleting.

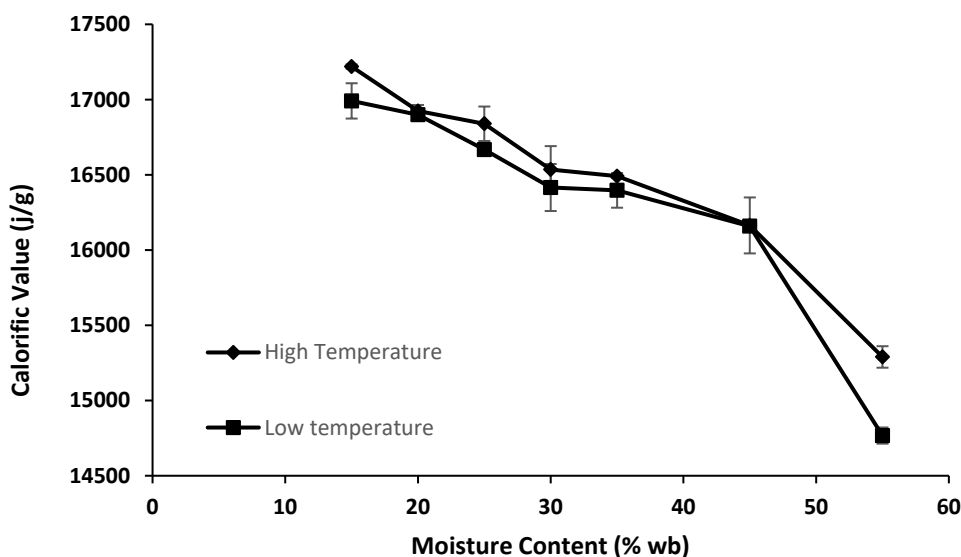


Figure 4.2 Change in calorific value with the increase in particle moisture content for paper towel pellets at low temperature (LT:60-70 °C) and high temperature (HT:90-110 °C). Vertical bars represent standard deviations.

The experimental data were fitted against a polynomial equation. The model was found to be significant at 5% significance level with $R^2=0.93$ (for range MC:15%-55% and Temperature: 50-110 °C). All the terms (except temperature) are also found to be significant (t value >0.05).

$$CV = 16998 + 196.413 MCP - 0.361 T + 18.398 (MCP \times T) - 8864.294 MCP^2.$$

Where, CV = Calorific value (j/g).

MCP= Moisture content (% w.b).

T= Temperature (°C).

4.1.2 Pellets prepared from cardboard boxes

Figure 4.3 shows the loss of moisture during pelleting for pellets made from paper waste derived from cartons and different cardboard boxes. The experiment was carried out at low temperature (60-70 °C) as there has been a negative correlation

observed between high temperatures and pellet quality for pellets made from paper towel. The experiment was carried out at MC of 15, 25 and 35% (wb). Thus, in comparison to paper towel pellet, the cardboard box paper pellets lost almost 9% less moisture during processing. This could be due to the thickness of the shredded particle. The cardboard box paper particles, being thicker than paper towel particles, trapped more moisture in their cell walls.

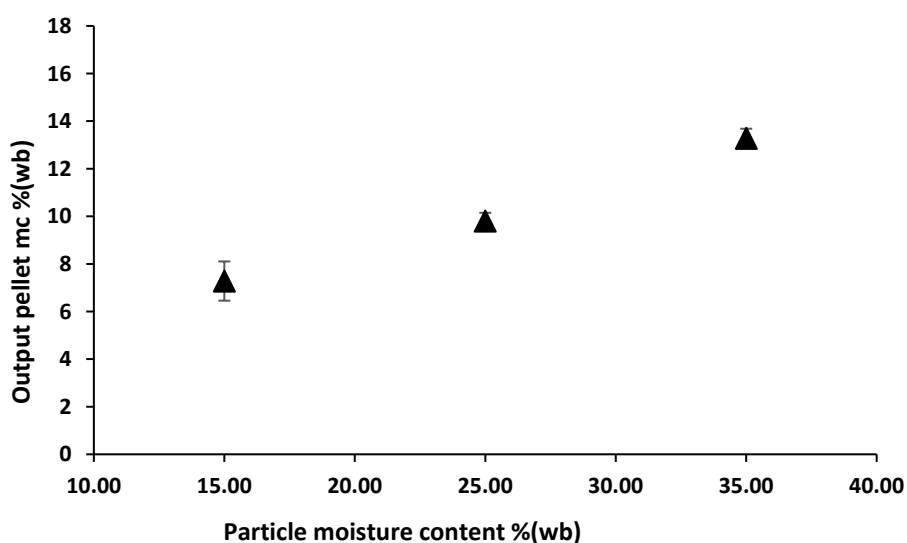


Figure 4.3 Change in output pellet moisture content (wb) with the increase in particle moisture content when pelletizing cardboard paper at the low temperature (LT:60-70 °C) range.

Figure 4.4 shows the change in calorific value for cardboard pellets with moisture content of pellets right after pelleting. As demonstrated, the calorific value was inversely proportional to MC of the pellet. However, the calorific value of the pellets increased after a period of drying, as drying brought MC (details are discussed in Chapter 4.5.2)

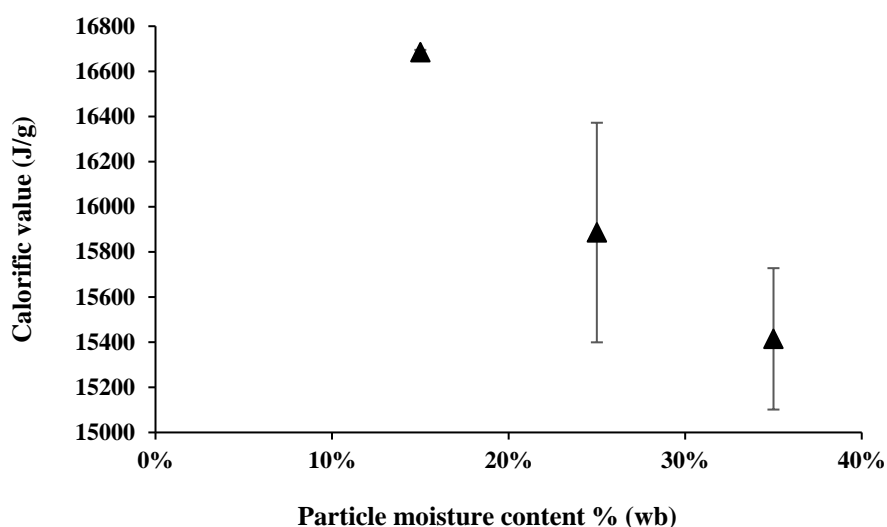


Figure 4.4 Change in calorific value with the increase in particle moisture content for pellets prepared from cardboard boxes.

4.2 EFFECT OF MC AND TEMPERATURE ON PELLET DURABILITY

4.2.1 Pellets prepared from paper towel

Figure 4.5 shows the effect of moisture content of shredded paper towel on the durability of pellets when compacted at lower (60-70 °C) and higher (90-110 °C) temperatures at different moisture contents. Durability was found to increase significantly ($P < 0.05$) with moisture content. At 45% moisture content the durability value reached to almost 92% in comparison with 67% durability at 15% moisture content (wb) for the low temperature treatment. Durability of pellets processed at the lower temperatures (60-70 °C) was significantly ($P < 0.05$) higher than that processed at high temperatures (90-110 °C) with an average difference of 9-10%.

Moisture softens the lignin providing extra lubrication, as well as reduces the glass transition temperature (T_g), leading to stronger bond formation (Stelte et al. 2011).

Filbakk et al. (2011a) and Nielson et al. (2009b) indicated that, after the compression

was released, moisture in a pellet changes to steam which relaxed the pellet, yielding a weaker pellet. Also at higher temperature the free moisture steams away causing a decrease in resultant particle moisture content. Johnson (2015) also reported the initial condensation as a cause of disintegration of compacted biomass. However, the current experiments showed an increase in durability at higher moisture. This can be explained as follows: the pelletizer used had an open inlet that allowed the excess steam to escape, thus reducing steam pressure at higher moisture of paper towel.

Nielson et al. (2009) and Stelte et al. (2011) mentioned the positive effect of higher temperature on durability. In this case the material used was paper waste. Shredded paper particles having very thin cell wall contain a very small amount of bound water, and most of the moisture present is in the free state. The higher temperature allowed for easy evaporation of free moisture from the paper particles resulting in less durable pellets processed at higher temperature.

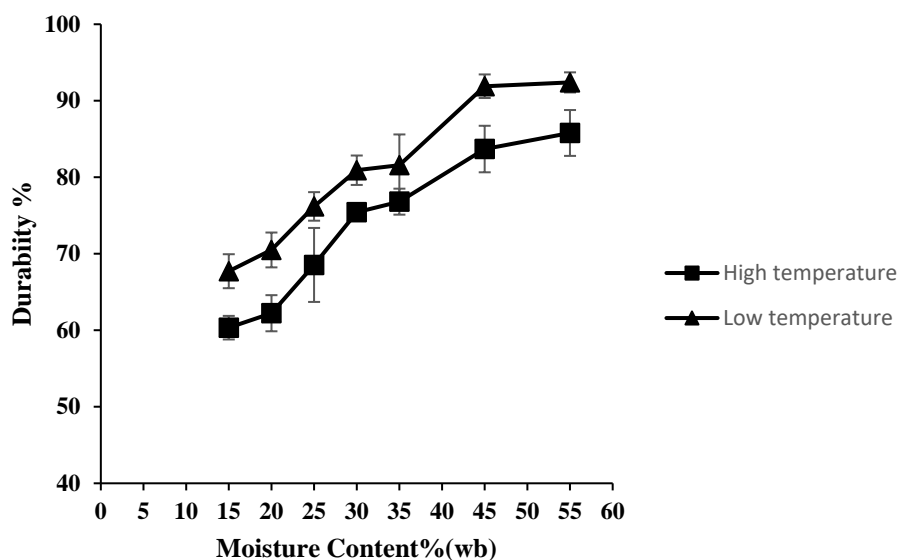


Figure 4.5 The effect of moisture content on the durability of pellets processed at lower temperature (LT:60-70 °C) and higher temperature range (HT:90-110 °C) for paper towel pellet. Vertical bars indicate standard deviations (replicates n=3)

The ANOVA of polynomial model for durability exhibited the F value higher than the tabulated F value at $\alpha = 0.05$ and a higher determination coefficient, $R^2 = 0.947$ (for range MC:15%-55% and Temperature: 50-110 °C). This indicated the model accurately represents the relationship between the control parameters. The final response model was written as follows:

$$DB = 62.716 + 137.251 MCP + 106.650 MCP^2 - 0.251 T + 0.064 (MCP \times T)$$

Where, DB= Durability (%).

MCP=Particle moisture content % (wb).

T= Temperature (°C).

4.2.2 Pellets prepared from cardboard boxes

For pellets made from cardboard boxes, durability also showed a strong positive correlation with moisture ($r=0.907$). Paper waste derived from boxes, being thicker than paper towel, could retain more moisture during pellet manufacturing. This resulted in more durable pellets at a lower MC than pellets made from paper towel particle. Specifically, at low temperature range 60-70 °C at 25% moisture content (% wb), box paper pellets attained a durability of 91%, compared to 76% for paper towel pellets. Pellets made from boxes paper achieved a durability of 94% at MC of 35%, compared to 81% durability for paper towel pellets. There was a sharp increase in durability observed for changing in moisture content from 15% to 25%. Change in MC from 25% to 35% did not showed a significant increase in durability.

A possible explanation for the increase in durability associated with cardboard paper box pellet is the glue present in between the plies of the paper sheet. At higher temperatures and pressures the glue can melt, contributing to an increase in the

particle adhesion forces. Figure 4.6 shows the change in durability of pellets made from cardboard paper boxes at different particle moisture contents.

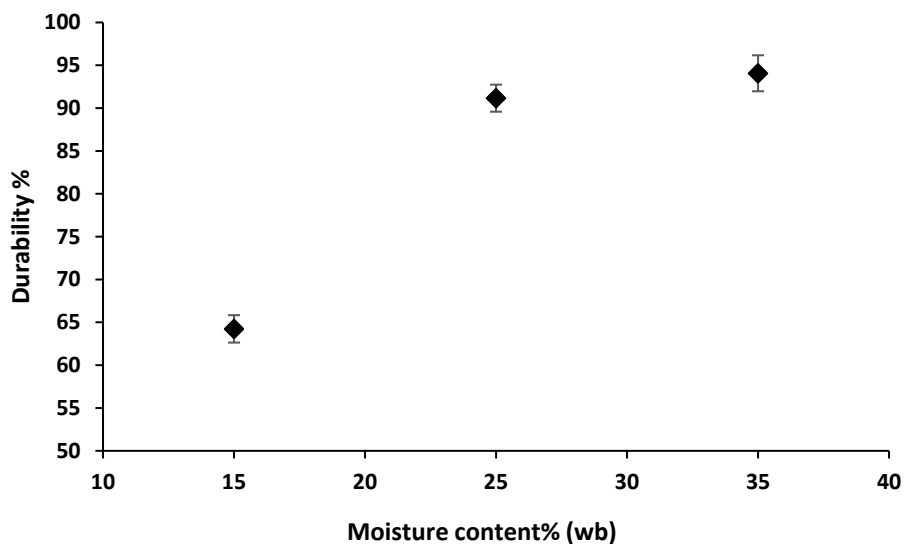


Figure 4.6 The effect of moisture content of paper box particle on durability of pellets processed at lower temperature (60-70 °C) range for paper box pellet.

4.3 EFFECT OF MC AND TEMPERATURE ON PELLET DIMESNIONS

4.3.1 Pellets prepared from paper towel

The dimensions (diameter and height) of the pellets did not follow any significant trend with respect to the particle moisture (Figure 4.7). A test of significance was carried out in SAS using Tukey's means comparison. There was no significant difference found amongst all the experiments carried out in different ranges of moisture content. The effect of processing temperature on pellet diameter was also found to be insignificant at 5% significance level.

There was no significant ($P > 0.05$) change in height for change in moisture content from 20 to 35% wb, but there was a significant difference noticed between 15 and

45% MC. The effect of temperature was also found to be significant. At lower temperatures (60-70 °C) longer (on an average 7% longer) pellets were formed than at higher temperatures (90-110 °C). It was found that at 45% MC and at low temperature, the pellets were longest among all the experimental trials (fig. 4.7).

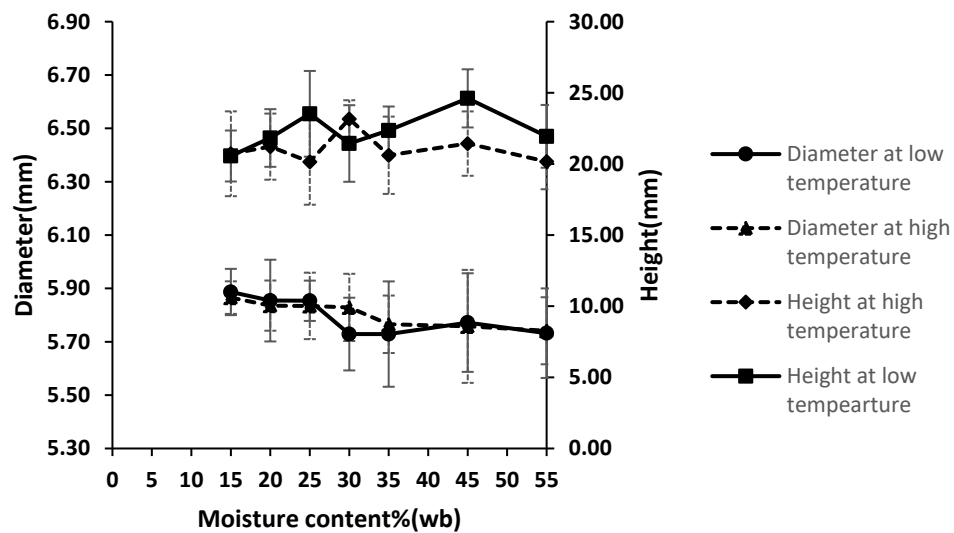


Figure 4.7 Effect of particle moisture content on the pellet diameter and height of the pellets made from paper towel at Low temperature (LT:60-70 °C) and High temperature (HT:90-110 °C). The vertical bars represent standard deviations.

Figure 4.8 shows the effect of particle moisture content on pellet density. Tukey's LS means comparison showed there was no significant ($P>0.05$) change in pellet density for the moisture range between 15 and 45% wb. There was a significant change (decrease) observed in pellet density at MC between 35 and 55% (wb) as there was a sudden and significant drop observed in the value of pellet density at 55% MC (wb). The effect of temperature on pellet density was also found to be insignificant.

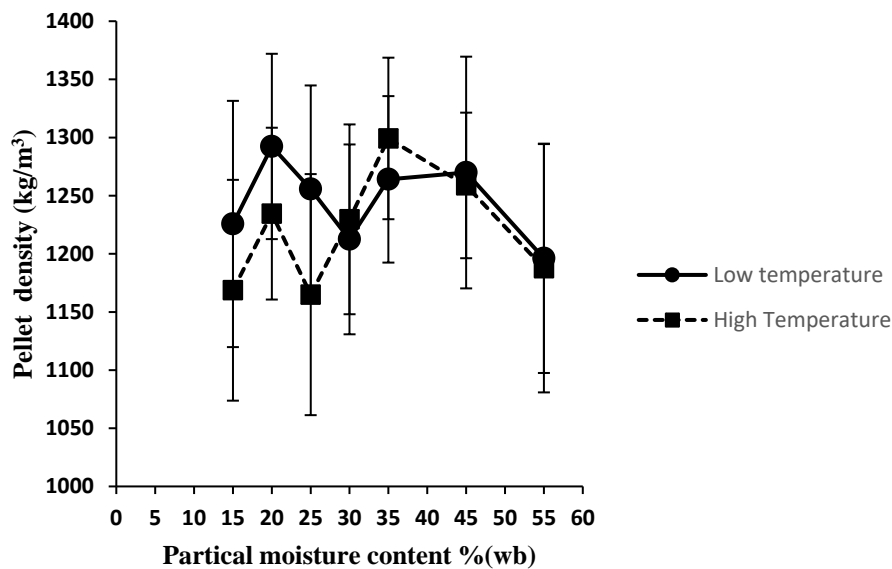


Figure 4.8 Effect of particle moisture content on pellet density of the pellets made from paper towel at Low temperature (LT:60-70 °C) and High temperature (HT:90-110 °C). Vertical bars represent standard deviations.

4.3.2 Pellets prepared from cardboard boxes

Figure 4.9 shows the change in pellet dimensions (diameter and height) for pellets made from cardboard paper. Tukey's LS-mean comparison identified the change in both diameter and height as insignificant ($P > 0.05$) at a higher MC (more than 15% wb). Though at lower particle moisture content (15% wb) comparatively shorter and non-uniform pellets were formed, so average pellet density (figure 4.10) was found to be lower than pellets made at higher moisture. Due to formation of non-uniform pellets, it showed a higher value of standard deviation. Therefore, the change in pellet density with the change in particle moisture content was found to be statistically insignificant at the 5% confidence interval.

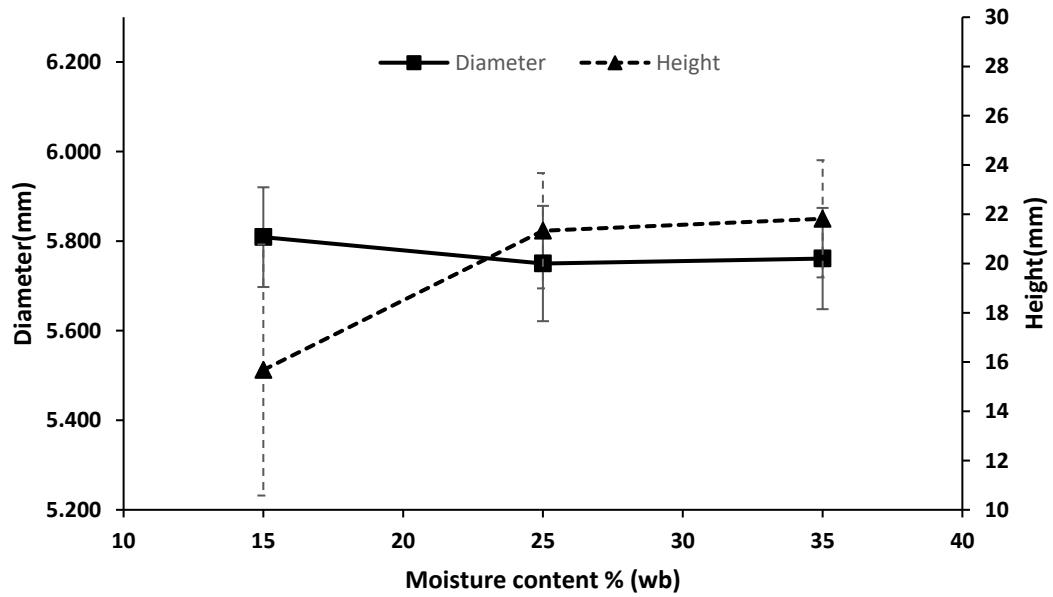


Figure 4.9 Effect of particle moisture content on the pellet diameter and height of the pellets made from cardboard paper. The vertical bars represent standard deviations.

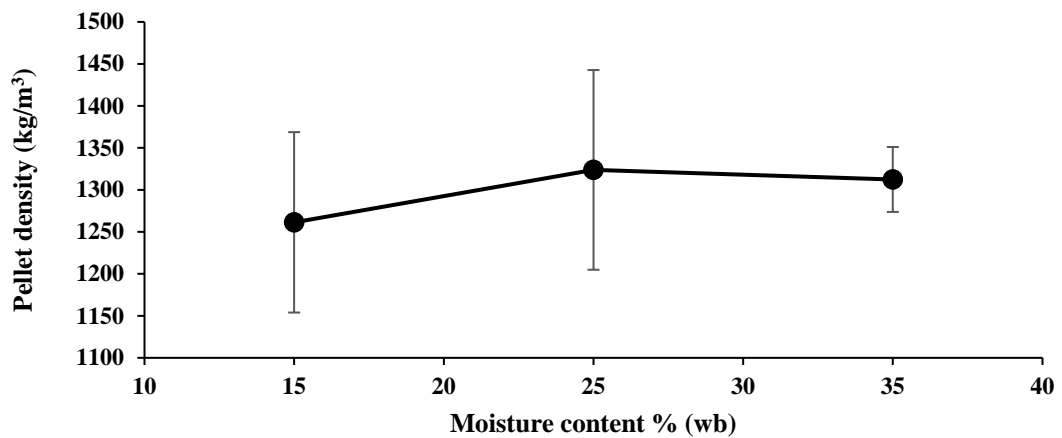


Figure 4.10 Effect of particle moisture content on pellet density of the pellets made from paper towel. Vertical bars represent standard deviations.

4.4 EFFECT OF ADDING ADDITIVES

4.4.1 Pellets prepared from paper towel

For pellets made at 35% MC (w.b) with 2% fatty acids as additives and pellets made at 45% moisture content with 2% yeast as additives, higher calorific values were observed (table 4.2) than pellets made without any additives. Fatty acids, being oily in nature, provided additional lubrication during flat die press and helped in maintaining lower temperature range. This prevented some of the moisture from the evaporation. It was found that after 5 days of drying, free fatty acids increased the calorific value by 2% when compared with the pellets made at 45% particle MC without any additives. In case of durability, no significant ($P>0.05$) effect on durability of paper towel pellets were found due to the addition of these two additives. This will be discussed in chapter 4.5 in greater details. The addition of yeast did not affect the durability, but it did increase the calorific value by 1%.

4.4.2 Pellets prepared from cardboard boxes

Two more experiments were carried out at 35% MC, mixing cardboard paper waste with 2% yeast and 10% big blue stem (BBS) as the energy crop. It was observed that using additives or mixing paper waste with energy crops helped in retaining moisture during processing, resulting in pellets with a higher moisture. At higher moisture of 25 and 35% (wb), the loss of moisture was found to be around 60%. While using additives (yeast) or mixing cardboard paper with BBS reduced the loss of moisture to 50% during processing (table 4.2).

In this case, by adding 2% yeast, the durability increased to a value of 96% in comparison to the pellets made at same moisture content (35% (wb)) without any yeast. After adding 10% energy crop such as big blue stem, durability of cardboard paper pellets increased to 97% (table 4.6). Adding yeast to the paper particle increased the calorific value even though MC of the pellets supplemented with yeast was higher than the pellets without any additives. Adding big blue stem significantly reduced the calorific value of the pellet by 6.5% in comparison to the pellets made at 35% MC without any additives (table 4.4 and 4.5). Adding BBS caused some extra moisture to be trapped inside the pellet that may lead to the decrease in calorific value.

4.5 EFFECT OF EQUILIBRATION (CONDITIONING)

4.5.1 Pellets prepared from paper towel

As the output moisture content of pellets leaving the pelleting machine was found to be very high, the pellets were allowed to equilibrate/condition at room temperature (20°C) and at RH 20%-22%. No additional air flow or heating was used. The pellets were allowed to equilibrate for five consecutive days, and moisture content, bulk density and calorific values were measured every 24 h during the equilibrating period. The pellets lost 46% of their moisture within 24 h of equilibration and the equilibrium was reached in 2 days (figure 4.11). The observed fluctuation in moisture after 3 days could be attributed to the fluctuations in temperature and relative humidity in the room. Figure 4.14 shows the Tukey's LS means test of significance for pellets made from paper towel. The vertical bars of the same color indicate no statistical difference, bars having different color represents statistical significance. The bar shows same color after 2nd day of equilibration, which confirmed that the pellets reached the equilibrium in 2 days. A

sudden change on day 4 could be due to changes in the room conditions, RH from 20% to 24%.

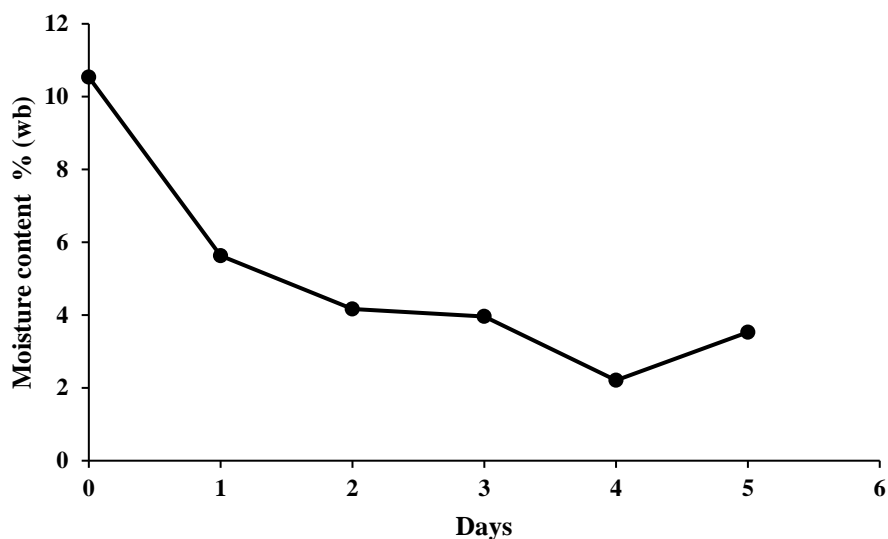


Figure 4.11 Changes of moisture content of pellets prepared from paper towel while equilibrating for five days in room temperature and RH (20%) after compaction.

After five days of equilibration at the room conditions, the calorific value of paper towel pellets was found to increase by 7.5% from its initial calorific value (figure 4.12). Most of this increase (roughly 5%) was noted after the first day of equilibration. Further statistical analysis showed that the changes in the calorific value were not significant after the second day of conditioning (figure 4.14).

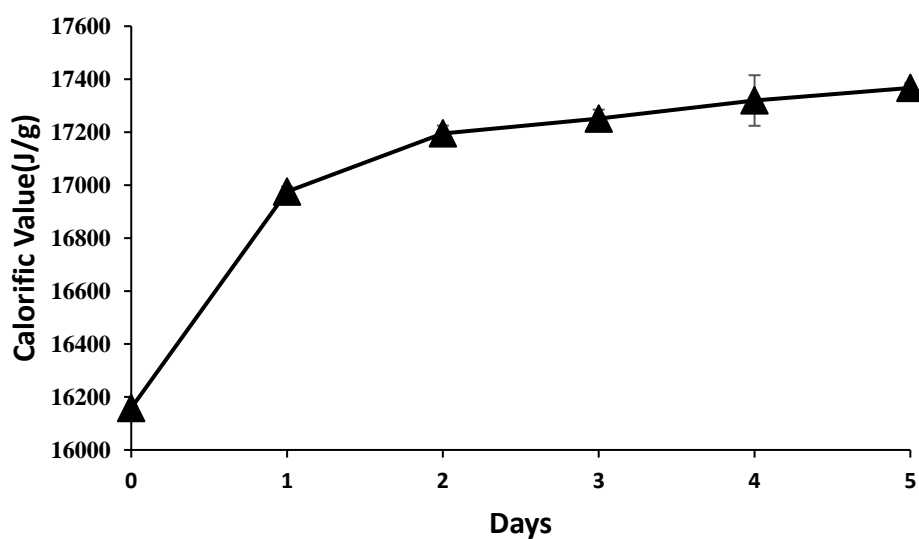


Figure 4.12 The effect of equilibration time on the calorific value of pellets made from paper towel.

The bulk density was also found to increase with conditioning time (Figure 4.13).

Most of this increase occurred in the first day (9.1% after the first day of conditioning) and there was no significant ($P>0.05$) change in bulk density between day 2 and day 3, nor between day 4 and day 5. However, the change in bulk density between day 2 and day 4, as well as day 2 and day 5 was significant, which could be a result of fluctuations in room temperature and humidity in day 4 and 5.

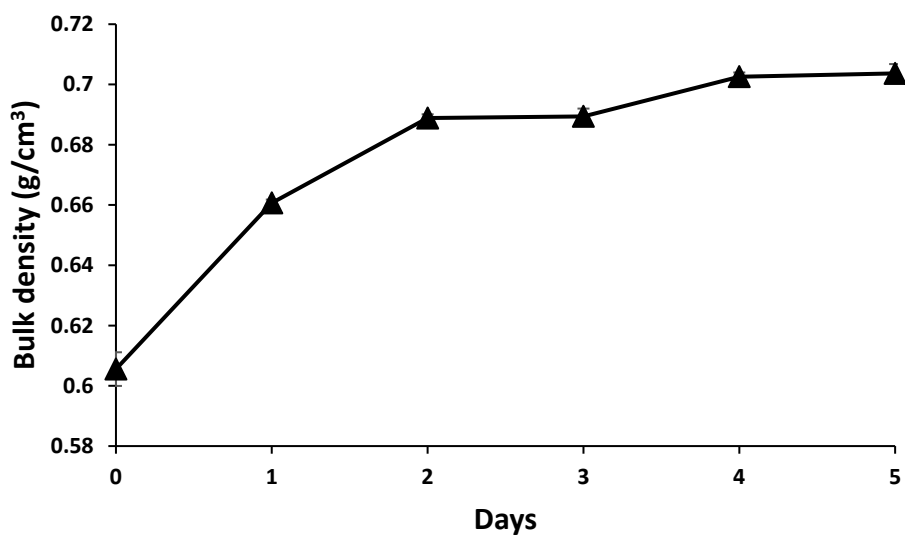


Figure 4.13 The effect of equilibration time on bulk density of pellets made from paper towel.

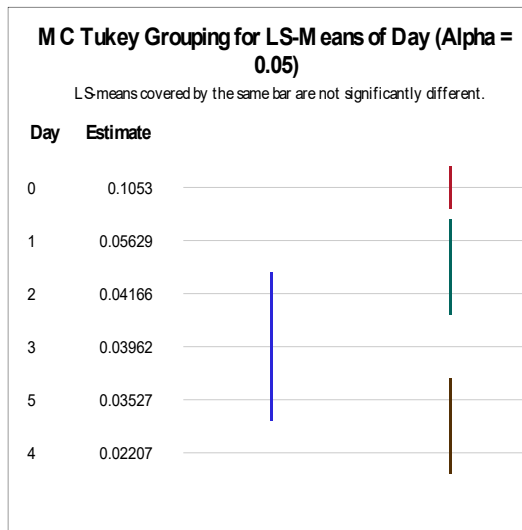
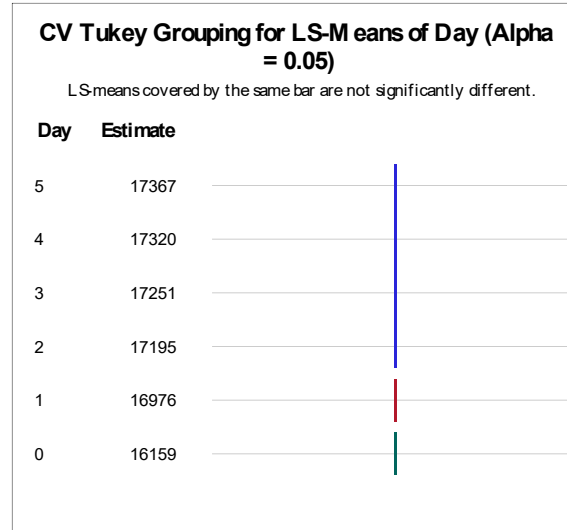
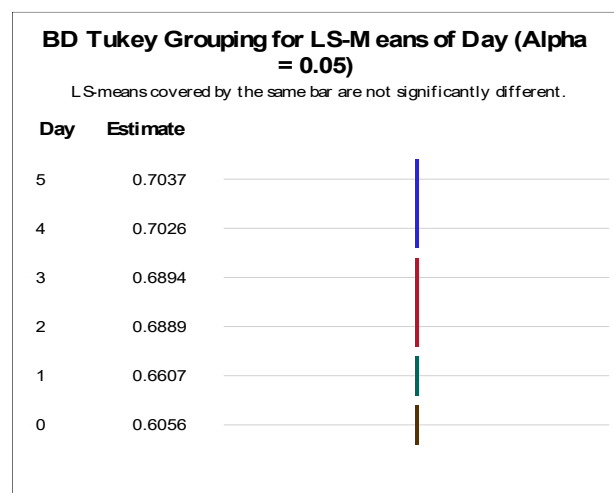
a**b****c**

Figure 4.14 Tukey's LS-mean test of significance on a) moisture content (w.b); b) calorific values(j/g); and c) bulk density(g/cm³) within 5 days of equilibration period for pellets made from paper towels. (The order of equilibration day has been maintained as per decreasing order of the corresponding value of the parameter.)

4.5.2 Effect of additives on pellet

A comparison of properties of pellets made with and without additives after equilibrating for five consecutive days- indicated that after the first day of conditioning moisture content of pellets made without any additives, with fatty acids and with yeast decreased by 46%, 51% and 71%, respectively (Tables 4.1, 4.2, 4.3). This caused a major increase in calorific value after first day of conditioning. The calorific value increased by 5%,6% and 13% respectively for pellets made without any additives, with fatty acid and with yeast. After five days of drying the calorific value of these pellets increased up to 17367, 17640, and 17474 J/g respectively.

Tukey's test indicated that neither additive (fatty acid and yeast) had a significant ($P>0.05$) effect on MC after one day of conditioning (figures 4.15, 4.16). For both additives, after 3 days of conditioning, changes in bulk density were also found to be insignificant to the change in bulk density in day 4 and day 5. For calorific value, the most significant change was noted after the first two days of conditioning.

Table 4.1 Change in moisture content during the five days of the equilibration period for pellets prepared from clean paper towel and same pellets with additives (fatty acids or yeast).

Name of additives	No additives	2% Fatty acid	2% yeast
Day	MC	MC	MC
0	10.53%±0.005	12.92%±0.001	18.21%±0.038
1	5.62%±0.004	6.24%±0.001	5.33%±0.003
2	4.16%±0.001	4.10%±0.001	3.72%±0.002
3	3.96%±0.004	3.75%±0.004	3.43%±0.004
4	2.21%±0.002	2.01%±0.001	3.29%±0.004
5	3.53%±0.004	3.37%±0.007	2.71%±0.002

Table 4.2 Change in calorific value during the five days of the equilibration period for pellets prepared from clean paper towel and same pellets with additives (fatty acids or yeast)

Name of additives	No additives	2% Fatty acid	2% yeast
Day	Calorific value	Calorific value	Calorific value
0	16158.5±9.19	15998±77.32	14981.75±142.90
1	16975.5±19.09	17082.5±176.07	17073±61.49
2	17195±29.70	17458.5±23.33	17382±7.07
3	17251±33.94	17464±43.84	17464±43.84
4	17319.5±95.46	17684.5±24.74	17466.67±62.43
5	17367±18.38	17640.5±61.52	17474±25.46

Table 4.3 Change in bulk density during the five days of the equilibration period for pellets prepared from clean paper towel and same pellets with additives (fatty acids or yeast).

Name of additives	No additives	2% Fatty acid	2% yeast
Day	Bulk density	Bulk density	Bulk density
0	0.606±0.005	0.605±0.006	0.634±0.005
1	0.661±0.001	0.6506±0.008	0.679±0.12
2	0.688±0.001	0.669±0.006	0.680±0.001
3	0.689±0.003	0.677±0.007	0.689±0.01001
4	0.702±0.001	0.685±0.003	0.691±0.004
5	0.703±0.001	0.686±0.007	0.709±0.0.11

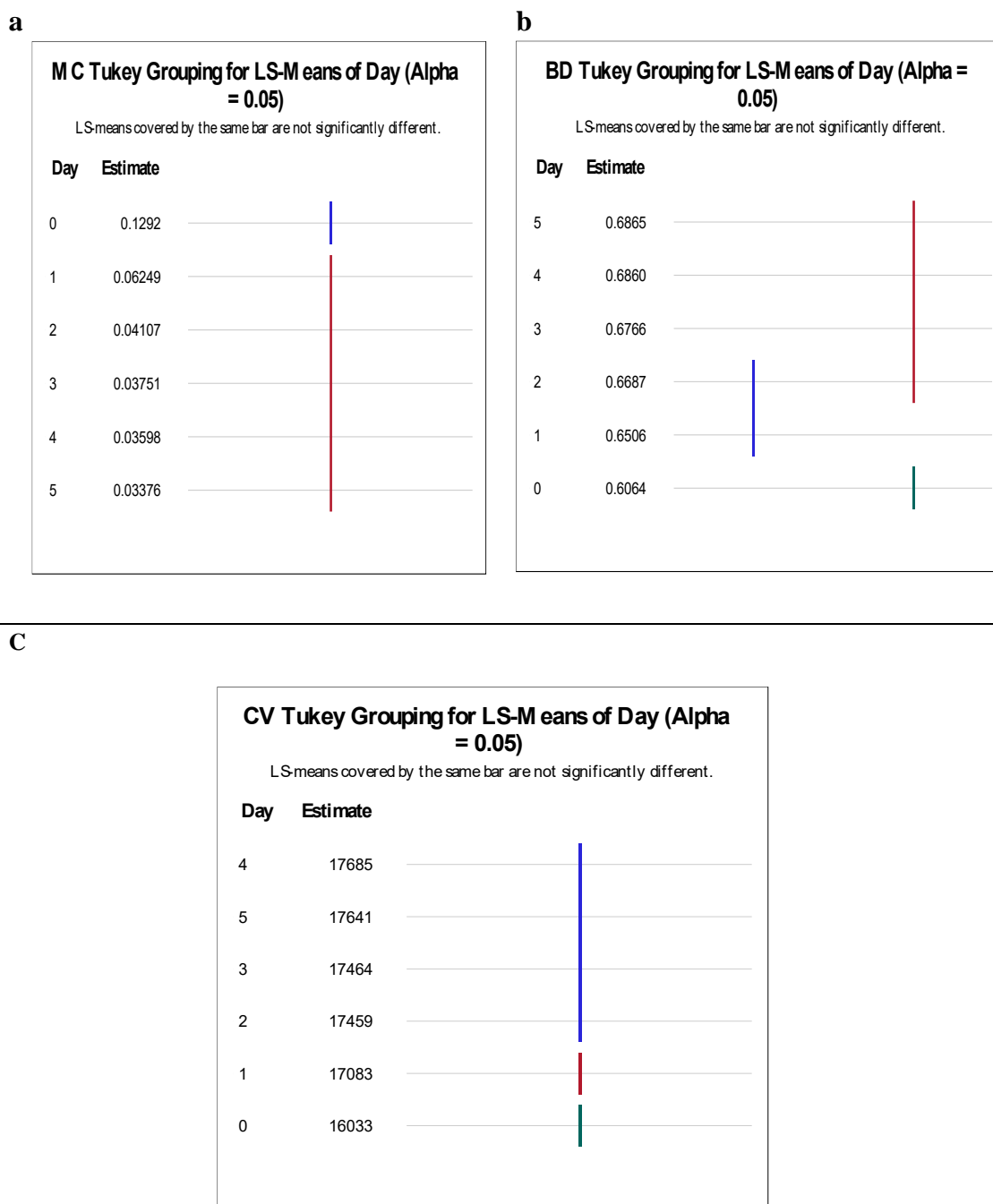


Figure 4.15 Tukey's LS-mean test of significance on paper towel pellet's (with fatty acid as additive). Changes in a) moisture content, b) calorific value, and c) bulk density during 5 days of equilibrating period. (The order of equilibration day has been maintained as per decreasing order of the corresponding value of the parameter.)

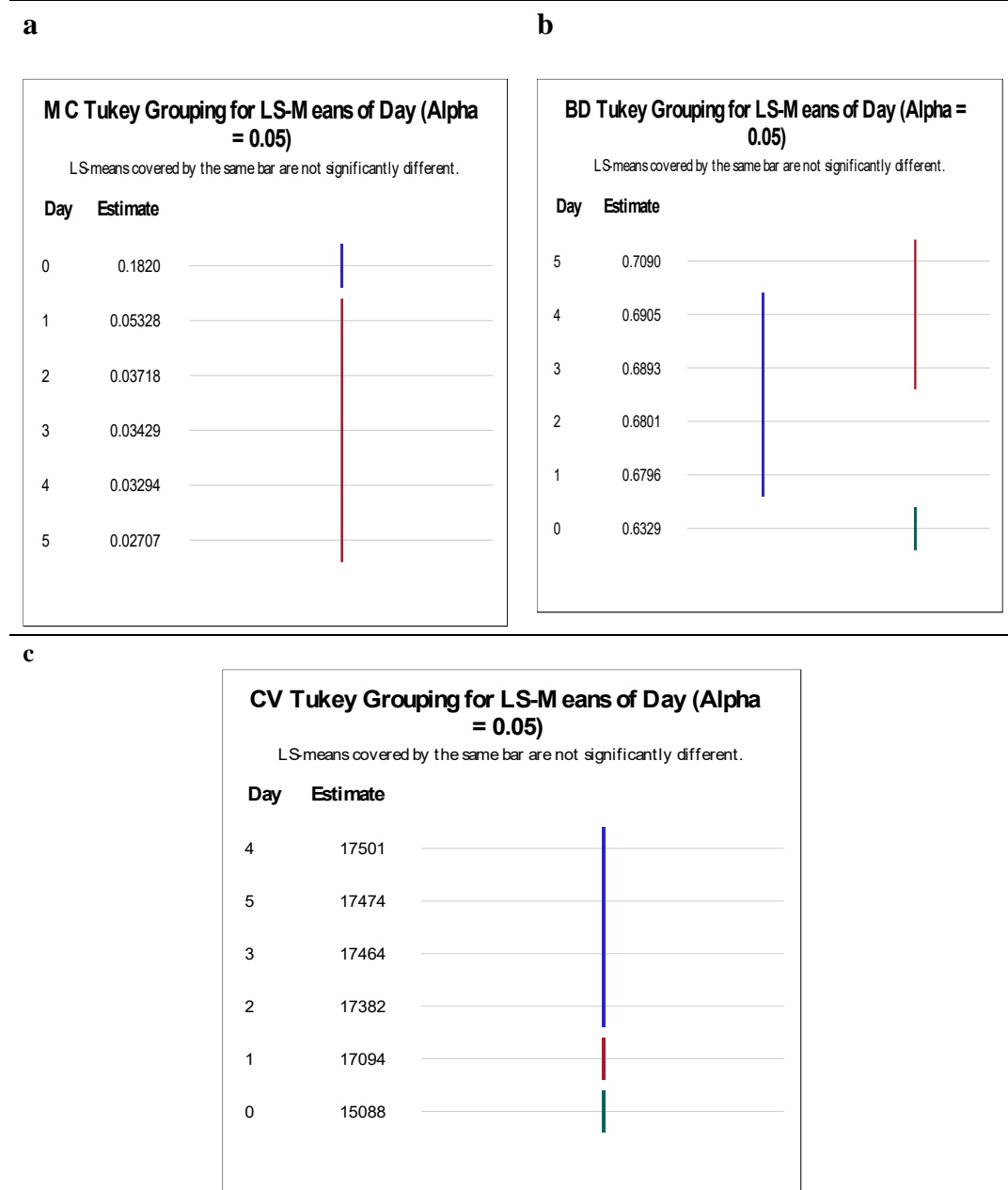


Figure 4.16 Tukey's LS-mean test of significance on paper towel pellet's (with yeast as additive) Changes in a) moisture content (wb), b) calorific value(j/g) and c) bulk density(g/cm^3) during 5 days of equilibrating period. (The order of equilibration day has been maintained as per decreasing order of the corresponding value of the parameter.)

Figure 4.15 shows the change in durability for paper towel pellets with and without additives, before and after equilibrating in room temperature at 20% RH. A two-sample paired t-test was carried out to determine the effect of drying on the change in durability. For pellets with no additives, the probability value was found to be 0.0025

which is less than 0.05 ($P_r = 0.025 < 0.05$), so the change in durability before and after equilibration is significant. For pellets made with yeast, the probability value is 0.0361 which is greater than 0.05 ($P_r = 0.361 > 0.05$) which means that the change in pellet durability is not significant after equilibrating at room temperature. For pellets made with fatty acid, the probability value is 0.0521 which is slightly greater than 0.05 ($P_r = 0.0521 > 0.05$). This value is close to the threshold value of 0.05, so it can be said that there is a minor change in durability after equilibrating. From practical point of view the value of this durability after equilibration is so close that it will make no difference in buying choice of pellets. So in conclusion, yeast and fatty acid additives had a very minor effect which can be considered as no significant effect in increasing durability after equilibrating in room temperature.

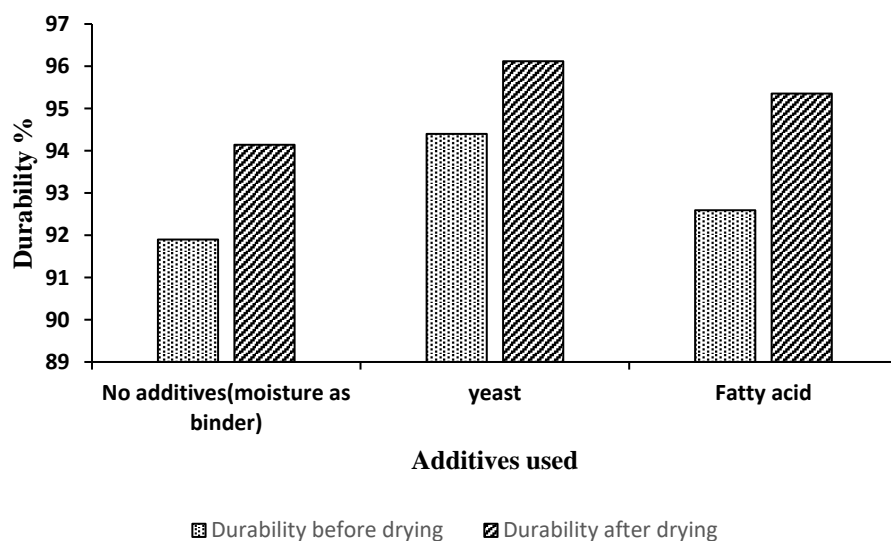


Figure 4.17 Change of durability of paper towel pellet after 5 days of drying (equilibrating) in room temperature with and without adding additives.

4.1.1 Pellets prepared from cardboard boxes (with and without additives)

Table 4.5 and 4.6, shows changes in calorific value and bulk density of pellets made from cardboard box paper during the 5-day equilibration period. The samples tested were pellets made at 35% MC with no additives and compared to (i) pellets made at 35% MC with 2% yeast mixture, and (ii) with 10% mixture of big blue stem. After five days of equilibrating the calorific value of the pellets increased by almost two percentage points with the addition of 2% yeast. But calorific value decreased by almost two percentage points with the addition of 10% energy crop (BBS, big blue stem). A minor increase in bulk density was observed with the addition of BBS. Least square means comparison shows there is no significant change in MC after the second day of equilibration. The bulk density of the pellets did not show any significant change after the first day of equilibration. In the case of pellets made without additives, and with BBS, there is no significant change observed in calorific value after the first day of equilibration. But for the pellets made with yeast showed significant change in calorific value after the 2nd day of equilibration but after the 3rd day change was insignificant. So this was observed that adding additives made the pellets more responsive to change in environment, this could be due to the difference of compaction level of the pellets as additives provided extra lubrication while processing.

Table 4.4 Changes in moisture content during 5 days of equilibrating pellets in room temperature and the effect of additives used in cardboard paper pellets¹.

Name of additives	No additives	2% Yeast	10% BBS
Day	MC	MC	MC
0	13.28%±0.006	16.13%±0.009	16.35%±0.53
1	4.60%±0.004	5.33%±0.003	5.65%±0.003
2	4.34%±0.001	3.52%±0.001	4.52%±0.004
3	3.91%±0.002	2.57%±0.001	3.62%±0.001
4	3.63%±0.003	3.52%±0.001	3.32%±0.001
5	2.92%±0.001	3.22%±0.001	2.94%±0.001

Table 4.5 Changes in calorific value during 5 days of equilibrating pellets in room temperature and the effect of additives used in cardboard paper pellets².

Name of additives	No additives	2% Yeast	10% BBS
Day	Calorific value	Calorific value	Calorific value
0	15414.67±313.3	15457±188.9	14400.5±395.2
1	16933±79.2	17044.50±27.6	16315±56.6
2	17084±35.4	17266±89.1	16746.33±384.1
3	17093±53.7	17414.50±64.3	16770.5±150.6
4	17114.5±21.9	17489±18.4	16763.50±78.5
5	17141±21.2	17455.5±102.5	16758±285.6

Table 4.6 Changes in bulk density during 5 days of equilibrating pellets in room temperature and the effect of additives used in cardboard paper pellets.

Name of additives	No additives	2% Yeast	10% BBS
Day	Bulk density	Bulk density	Bulk density
0	0.670±0.006	0.672±0.006	0.691±0.001
1	0.695±0.001	0.685±0.001	0.700±0.0001
2	0.701±0.001	0.698±0.001	0.7003±0.003
3	0.704±0.003	0.701±0.001	0.701±0.0001
4	0.706±0.002	0.699±0.001	0.703±0.001
5	0.708±0.001	0.700±0.006	0.711±0.001

¹ SD represents standard deviation and BBS represents energy crops big blue stem.

² SD represents standard deviation and BBS represents energy crops big blue stem.

4.6 DESIRABILITY FUNCTION ANALYSIS FOR PELLETS MADE FROM PAPER TOWEL

A rank-based desirability function analysis was performed to find out the optimal manufacturing parameters of the tissue pellets, which would give the best combination of quality parameters. The pellet quality parameters considered in the desirability function analysis included durability, bulk density, and calorific value. Early analyses of results indicated that pellets' properties stabilized after 2 days of conditioning at room conditions. Therefore, 2-day (stabilized) values of durability, bulk density and calorific value were used for desirability function analysis. A desirability index for each parameter was calculated based on the equation 4.1, with the lower the index, the better the pellet quality. The composite desirability (d_G) was calculated as the geometric mean of the three individual indices as per equation 4.2 (Salmasnia et al. 2012). Based on the composite desirability values, the ranking of all experiments was determined by using the Rank function in Microsoft Excel. The highest value of score would represent the optimal combination (the best overall pellet quality).

$$d_i = \left(\frac{y_j - y_{\min}}{y_{\max} - y_{\min}} \right)^r \quad \dots(4.1)$$

Where y_j = corresponding quality value.

y_{\min} = Minimum value of the quality parameter.

y_{\max} = Maximum value of the quality parameter.

$r = 1$, As equal weightage considered for all the parameters.

$$d_G = \sqrt[w]{(d_1^{w1} \times d_2^{w2} \times \dots \times d_i^{wi})} \quad \dots(4.2)$$

Where d_G = Composite desirability.

d_i = Individual desirability index.

W=Weight factor =1, As equal weightage considered for all the parameters and all the pellets quality parameters (durability, bulk density and calorific value) have given equal priority for calculating composite desirability index.

Of the 16 experiments (pelleting conditions) for the paper towel, the two experiments with the addition of additives fatty acids (2%) and yeast (2%) were ranked the highest (rank-16 and 15, respectively) (Table 4.7). This could be due to the presence of free fatty acid and oily material in yeast and fatty acid additives. Presence of fatty acids increased the calorific value and oily material helped in maintaining lower processing temperature by providing extra lubrication therefore resulted in more durable pellet. Without additives, the experiment with 45% (wb) particle moisture content at low temperature (60-70°C) was the highest (the 14th) (Table 4.7).

Table 4.7 Desirability function analysis for paper towel pellet.

Exp no	Particle moisture content (wb)	Temp (°C)	Durability	Bulk density	Calorific value	Desirability Index			Composite desirability function	Rank*
						Durability	Bulk density	Calorific value		
1	15%	50-70	67.72%	0.6781	17298	22.88%	-0.0218	0.5480	-0.1398	7
2	20%	50-70	70.50%	0.67302	17259	31.50%	-0.0269	0.4379	-0.1548	9
3	25%	50-70	76.19%	0.6704	17201	49.15%	-0.0295	0.2740	-0.1584	11
4	30%	50-70	80.92%	0.6697	17197	63.81%	-0.0302	0.2627	-0.1717	12
5	35%	50-70	81.58%	0.66897	17199	65.86%	-0.0309	0.2684	-0.1762	13
6	45%	50-70	91.90%	0.668	17203	97.86%	-0.0319	0.2797	-0.2059	14
7	55%	50-70	92.40%	0.65987	17104	99.41%	-0.04	0.0000	0.0000	2
8	35% + Fatty acid	50-70	92.59%	0.6541	17458	100.00%	-0.0458	1.0000	-0.3578	16
9	45% + Yeast	50-70	92.03%	0.66013	17382	98.26%	-0.0398	0.7853	-0.3131	15
10	15%	90-110	60.34%	0.6999	17294.5	0.00%	0	0.5381	0.0000	2
11	20%	90-110	62.23%	0.682	17285	5.86%	-0.0179	0.5113	-0.0812	5
12	25%	90-110	68.54%	0.679	17267	25.43%	-0.0209	0.4605	-0.1348	6
13	30%	90-110	75.43%	0.67598	17201	46.79%	-0.0239	0.2740	-0.1453	8
14	35%	90-110	76.81%	0.67148	17195	51.07%	-0.0284	0.2571	-0.1551	10
15	45%	90-110	83.69%	0.67089	17104	72.40%	-0.029	0.0000	0.0000	2
16	55%	90-110	85.79%	0.6698	17101	78.91%	-0.0301	-0.0085	0.0586	1

*the higher the score, the better

4.7 SORPTION ISOTHERM OF PAPER PELLETS

4.7.1 Pellets prepared from paper towel

Adsorption and desorption curves (figure 4.18) did not follow the same pattern indicating a small hysteresis effect. At a lower RH (below 60%), the desorption EMC is found to be higher than the adsorption EMC. Above 60% RH the desorption EMC was found to have a lower value than adsorption EMC.

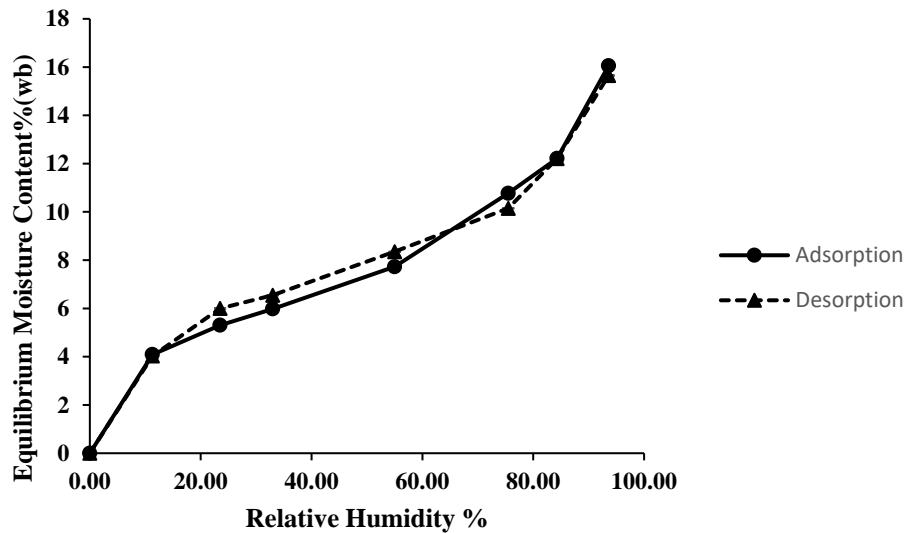


Figure 4.18 Equilibrium moisture content curve for adsorption and desorption for pellets made from paper towel.

The equilibrium moisture data were fitted against some established equations that have been used by other researchers, mostly for wood pellets. Lee et al. (2019) and Hartley and Wood (2008) fitted the EMC curve against Henderson equation $EMC = \frac{\ln(1-RH)/K}{C}$ for wood pellets (RH range 11%-90%) and reported the R^2 values of 0.968 and 0.998, respectively. Avramidis and Siau (1987) used the linear relation $EMC = K \cdot RH$ (RH range 11% -57%, wood pellet) to find the line of best fit, with an

R^2 value of 0.996. In this research, both the Henderson equation and a linear equation was used to fit the data, and a proposed exponential model was suggested in this research to better represent the data ($EMC=K \cdot \exp(RH/C)$) (table 4.8).

Table 4.8 Prediction of EMC behaviour with Linear, Henderson and Proposed exponential model for pellets prepared from paper towel.

Model name	Equation	Co- efficient	SSD	Range of applicability for RH used (%)
Henderson's model.	$EMC = [\ln(1 - RH)/K]^{1/C}$	K= -22.5 C= 1.2	0.002684896 ($R^2=0.9642$)	11-93
Linear model	$EMC = K \cdot RH$	K=0.157	0.00134914 ($R^2=0.9701$)	11-93
Proposed exponential model.	$EMC = K \cdot \exp(RH/C)$	K=0.0331 C=0.616	0.0002203 ($R^2=0.9909$)	11-93

The modified Henderson equation predicted the EMC better than the other two models, in particular at the lower RH up to 60% (figure 4.19). Above that range though the predicted EMC value showed a slight deviation from the data. This pattern is probably caused by the nature of cellulose and lignin softening at RH higher than 60%. This softening is likely responsible for the data spread at higher RH (Engelund et al. 2012).

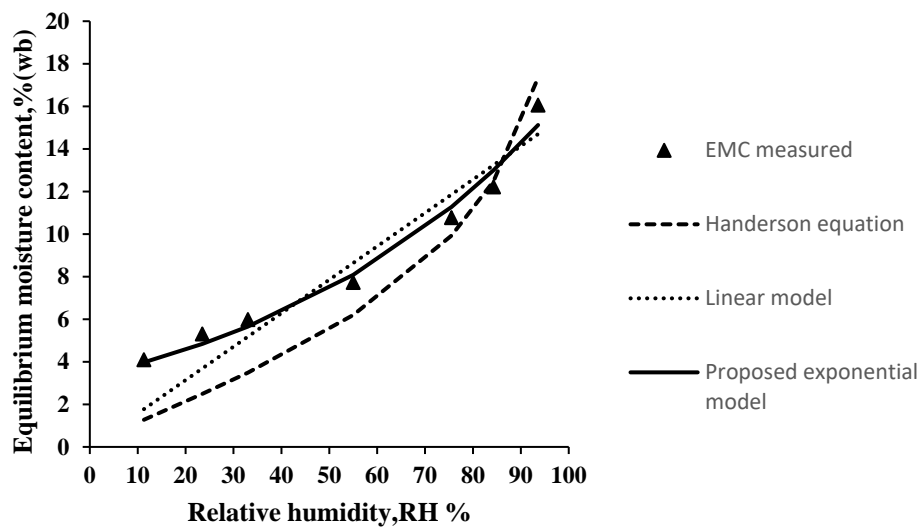


Figure 4.19 The simulation results based on equations in Table 4.3 and validated against experimental results for pellets made with paper towel.

4.8 ENERGY CROPS

4.8.1 Energy crops and experimental parameters

The energy crops used in this experiment were Miscanthus; prairie cordgrass; switchgrass and big bluestem. The two most important pelletizing parameters, moisture content and temperature, were kept constant (30% wb and maximum processing temperature 80 °C) in this experiment to compare some important pellet properties, bulk density, pellet density, durability, calorific value and ash content. Experiments were carried out in a completely randomized order.

4.8.2 Comparison of the bulk density

Figure 4.20 shows the change in bulk density of four different energy crops at constant moisture content and temperature. At 30% moisture content and at maximum processing temperature range 80 °C, Miscanthus and prairie cordgrass showed almost

similar bulk density in the range of 0.66 g/cm^3 . The bulk density of switchgrass and big bluestem was found in the range of 0.69 g/cm^3 . Both switch grass and big blue stem showed higher bulk density than Miscanthus and prairie cordgrass. A test of significance using ANOVA Tukey's LS-Means at 5% significance level was performed. There was no significant difference observed in the bulk density between Miscanthus and prairie cordgrass. Switchgrass and big bluestem also did not show any significant differences in bulk density between them. But there is a significant difference in bulk density between Miscanthus or prairie cordgrass and switchgrass or big bluestem.

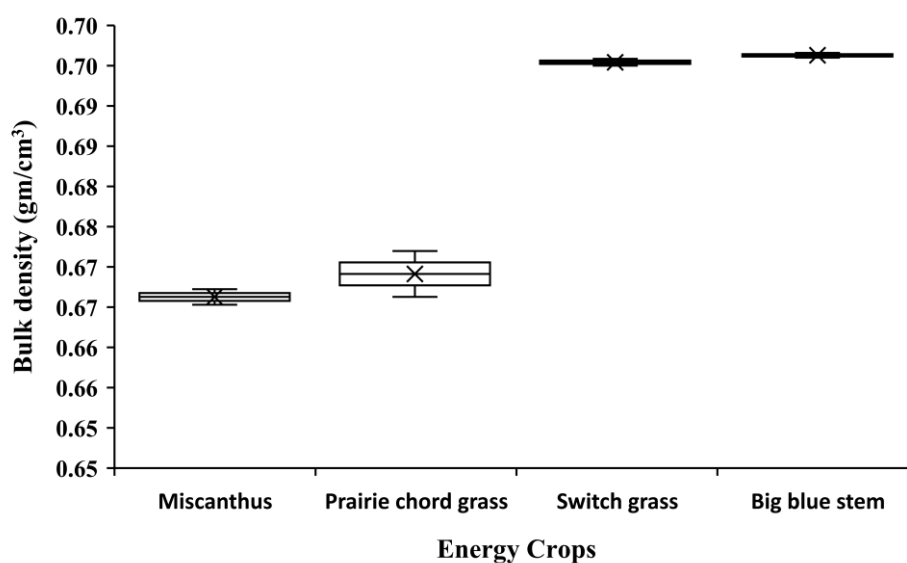


Figure 4.20 Change in bulk density of the pellets made from energy crops at constant particle moisture content (30%) (wb) and processing temperature ($80 \text{ }^\circ\text{C}$). The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

4.8.3 Comparison of pellet dimensions

At constant moisture content and processing temperature (30% w.b and maximum $80 \text{ }^\circ\text{C}$), prairie cordgrass produced comparatively thicker pellets and big bluestem

produced comparatively slender pellets among the four energy crops (figure 4.21). Statistical significance test at 5% confidence interval shows there is no significant change in diameter between Miscanthus pellet and pellets made from switchgrass. Pellets made from prairie cordgrass and big bluestem were significantly different in diameter from each other and from Miscanthus or switchgrass.

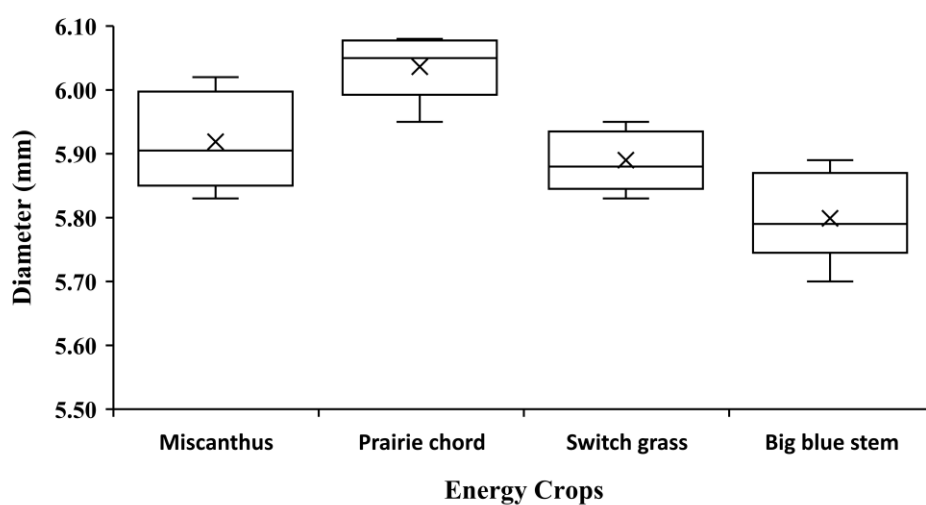


Figure 4.21 Change in diameter of the pellets made from energy crops at constant particle moisture content (30% wb) and processing temperature (maximum 80 °C). The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

Figure 4.22 shows the comparison of pellets height made from four different energy crops. Statistical significance test at 5% significance level also did not find any significant change in pellets heights among pellets made from four different energy crops.

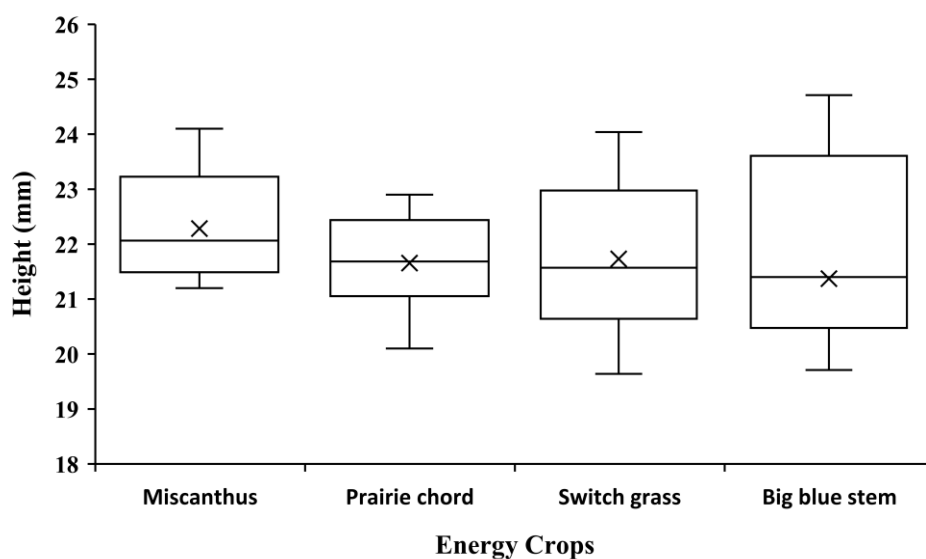


Figure 4.22 Change in height of the pellets made from the energy crops at constant particle moisture content (30% wb) and processing temperature (maximum 80 °C). The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

In spite of significant changes in a pellet diameter, the height of the pellets showed no significant change. This led to the change in pellet density to be insignificant ($P > 0.05$). Figure 4.23 compares the change in pellet density made from four different energy crops. There is no significant change observed in pellet density of the pellets made from four different energy crops.

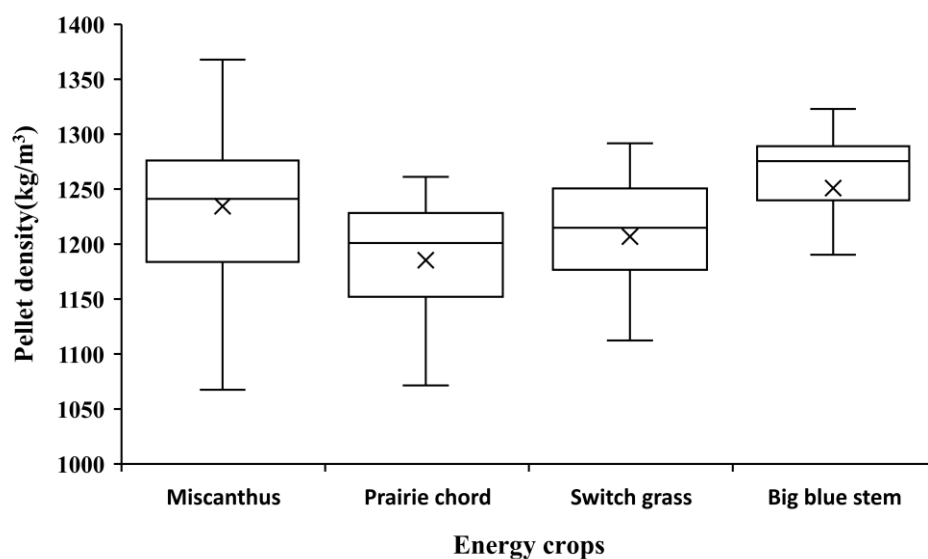


Figure 4.23 Change in pellet density of the pellets made from the energy crops at constant particle moisture content (30% wb) and processing temperature (maximum 80 °C). The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

4.8.4 Comparison of pellet durability

For the same moisture content of particles of 30 % wb and processing temperature in the range of 80 °C, all four energy crops showed durability value greater than 95%.

The durability was tested right after pellets left the pelletizer and again after 5 days of drying at 38 °C and 22% RH. Figure 4.24 shows the change in pellet durability before conditioning. Among the four energy crops Miscanthus had comparatively higher durability of 97.5%. Tukey's LS-means comparison at 5% significant level did not find any significant difference in durability before drying among Miscanthus, prairie cordgrass and switchgrass. Durability (before drying) of big bluestem were found to significantly less than the other energy crops.

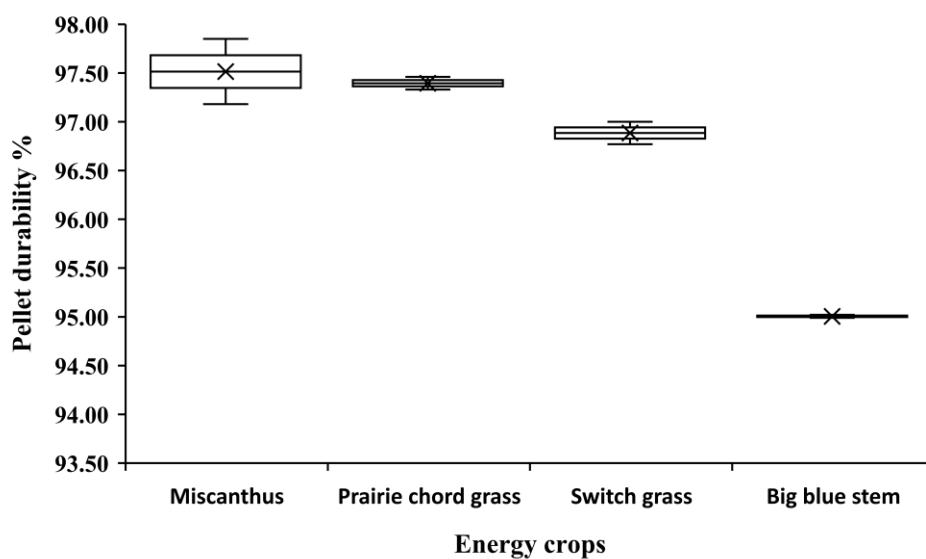


Figure 4.24 Durability of the pellets made from the energy crops at constant particle moisture content (30% wb) and processing temperature (maximum 80 °C) right after pelletizing. The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

Figure 4.25 shows the change in durability after 5 days of drying at 38 °C and 22% RH. After the drying step Miscanthus and prairie cordgrass showed comparatively higher durability among all the energy crops. At 5% significant level the change in durability between Miscanthus and prairie cordgrass was found to be insignificant. Both energy crops achieved a durability of 98% after 5 days of drying. After the drying step durability of switchgrass showed little improvement but the value is significantly smaller than Miscanthus and prairie cordgrass but significantly higher than big bluestem. Big bluestem showed the lowest durability even after drying. It achieved an average durability of 95.5% after drying. The change in durability after drying was also found to be insignificant and was significantly smaller than the other three energy crops.

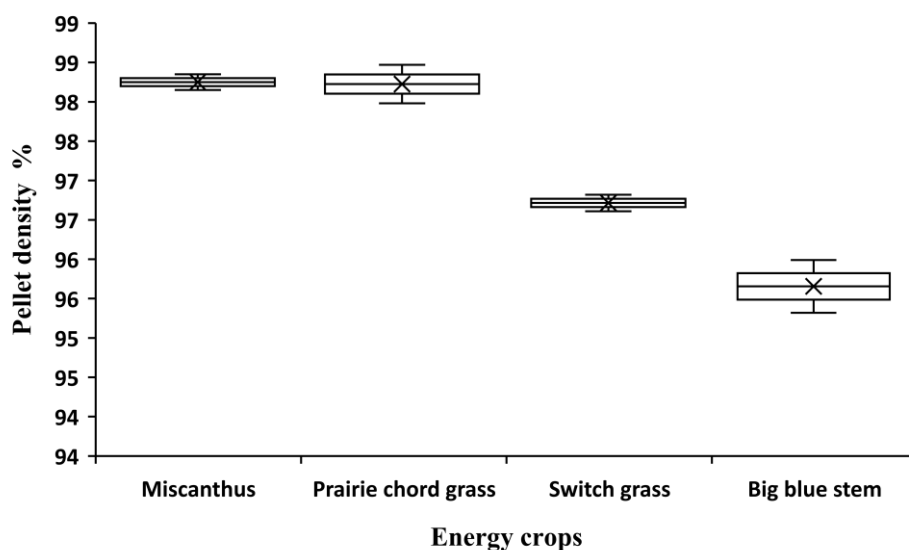


Figure 4.25 Durability of the pellets made from the energy crops at constant particle moisture content (30% wb) and processing temperature (maximum 80 °C) after 5 days of drying at 38 °C and 22% RH. The horizontal lines represent the quartile lines and vertical bars represent the standard deviations with lowest and highest value marked.

4.8.5 Comparison of calorific values

The calorific value of the pellets is directly dependent on the moisture present in the pellets. The processing temperature was kept to a range of 50-80 °C. As temperature was maintained over a range therefore, there is some variation observed in the moisture content of pellets leaving the pelleting machine. Table 4.9 shows the initial moisture content (right after leaving the pelletizer) of the pellets made from different energy crops and corresponding calorific value along with MC and calorific value after 5 days of drying at 38 °C. Tukey's significance test of LS-means comparison did not find any significance differences ($P > 0.05$) in calorific value after 5 days of drying. Therefore, it can be concluded that calorific values of all the pellets made from four energy crops are statistically identical.

Table 4.9 Moisture content (% wb) and calorific values of pellets made from energy crops and their corresponding change after 5 days of drying at 38 °C and 22% RH.

Energy crops	MC % before drying (wb)	Calorific value(j/g)	MC% (wb) after 5 days of drying	Calorific value after 5 days of drying (J/g)
Miscanthus	6.67±0.003	16650±48.7	4.28±0.0004	17895.5±12.0
Prairie Chord	12.89±0.007	16544±34.6	4.64±0.0006	17873±28.2
Switch grass	10.21±0.003	16948±256.7	4.93±0.0002	17867.5±36.0
Big blue stem	11.91±0.002	16789±115.1	5.0±0.0002	17950.5±57.2

4.8.6 Effect of drying on pellet quality for Energy crops

As the moisture of pellets made from energy crops was very high (around 6-12% wb), it was necessary to dry the pellets after they were pelletized. These pellets were dried in a temperature and humidity-controlled chamber at 38 °C and 22% RH for five consecutive days.

Figure 4.26 shows the change in moisture content of the energy crop pellets dried in the indicated conditions for five days. Most of the moisture was lost after first day of drying. Tukey's LS- means comparison was carried out to check the test of significance (at 5% significance level) after each day of drying. It was observed that after second day of drying there is no significant change in moisture content for all four energy crop pellets. Therefore, equilibrium have been achieved after the 2nd day of drying.

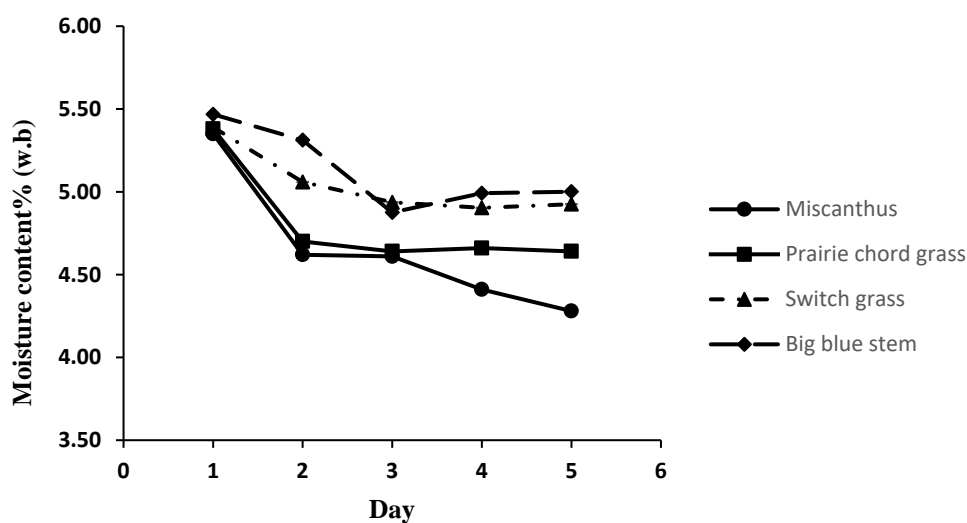


Figure 4.26 Change in moisture content of pellets made from energy crops during conditioning at 38 °C and 22% RH over the 5-day period (3 replicates).

Figure 4.27 shows the change in bulk density of energy crop pellets during five days of drying at 38 °C and 22% RH. The majority increase in bulk density was observed after the first day of drying. Statistical significance test (Tukey's LS-means) at 5% significant level found that the change in bulk density after the 1st day of drying is significant but drying over the period from day 2 to day 5 is statistically insignificant. It can be concluded that one day of drying at 38 °C and 22% RH is sufficient to get the best bulk density for the energy crop pellets.

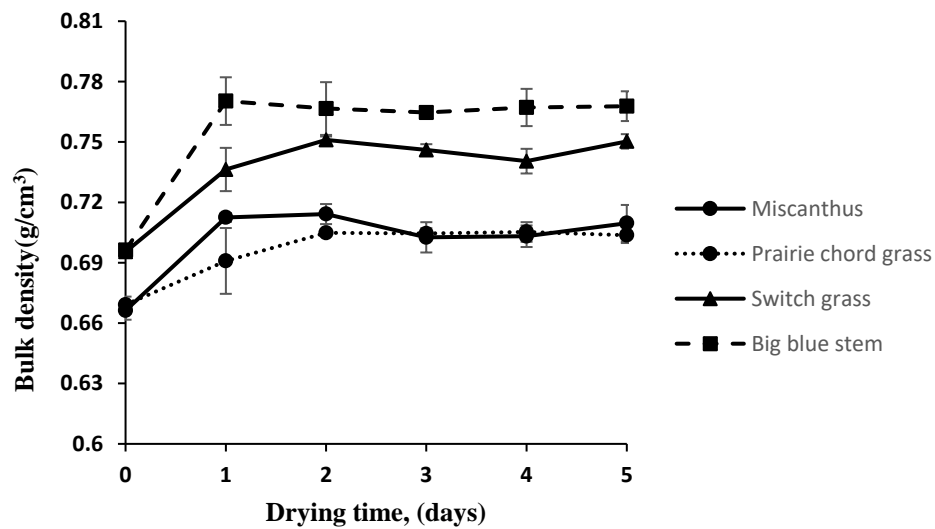


Figure 4.27 Change in bulk density of the pellets made from the energy crops with drying time within 5 days of drying at 38 °C and 22% relative humidity.

Loss in moisture during drying led to an increase in calorific value of the energy crop pellets. Figure 4.28 below shows the change in calorific value over the time of 5 days of drying. All energy crop pellets lost majority of free water during the 1st day of drying. This caused a significant increase in calorific value. Miscanthus, switchgrass and big bluestem showed almost 5%-6% increase in that value and prairie cordgrass showed 10% increase in the calorific value after the 1st day of drying. After the 1st day of drying a slight increase in calorific value for rest of the four days of the drying period was observed, however it was statistically insignificant at 5% level.

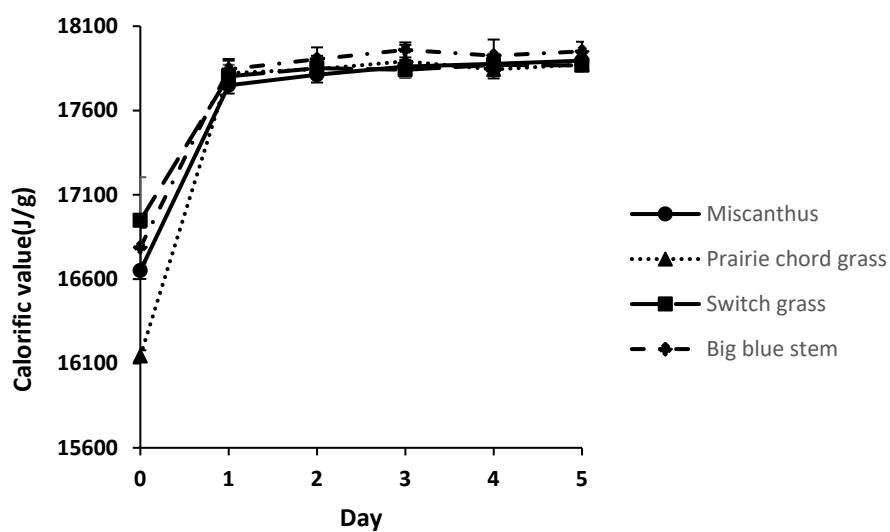


Figure 4.28 Change in calorific value of the pellets made from four different energy crops over 5 days of drying at 38 °C and 22% RH.

4.8.7 Sorption isotherm of pellets of energy crops

Figure 4.29 shows the relation between EMC and RH for pellets made from energy crops (Miscanthus, prairie cordgrass, switchgrass and big bluestem). Both adsorption and desorption experiments were carried out in replicates with 2 replications.

Adsorption and desorption curves (figure 4.29) did not follow the same pattern indicating a small hysteresis effect. Above 60% RH the desorption EMC was found to have a lower value than adsorption EMC.

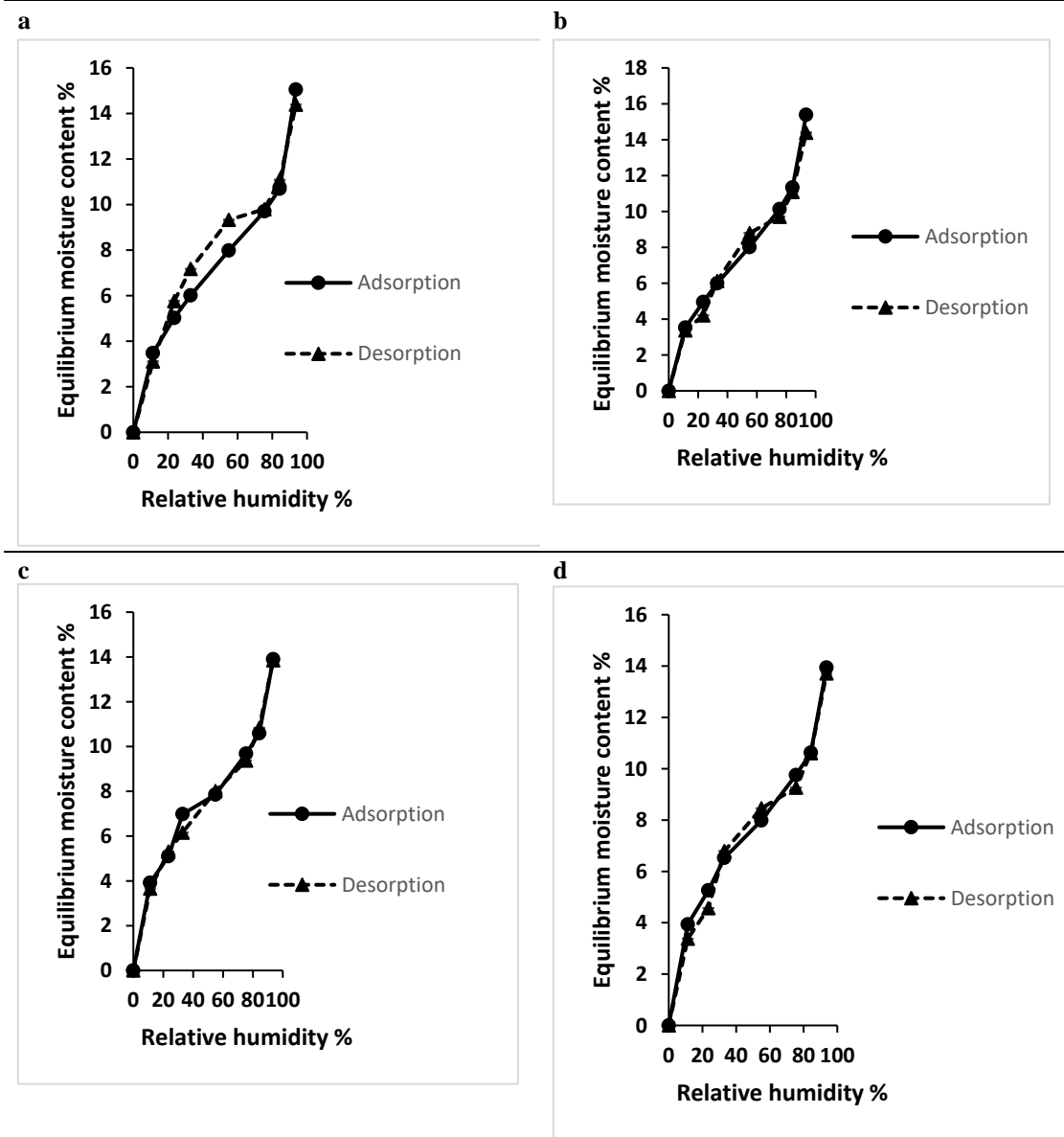


Figure 4.29 Equilibrium moisture content curve for adsorption and desorption for pellets made from a) miscanthus b) Prairie chord grass c) switch grass d) big blue stem.

The equilibrium moisture data were fitted against some established equations like Henderson's equation, linear equation, and the proposed exponential equation discussed in chapter 4.7. Table 4.10 illustrates different equations and corresponding value of the constant that has been equated by Microsoft Excel solver pack in order to set the minimum value of sum square deviations (SSD). The smallest value of SSD indicates the line of best fit. It was found that Henderson's equation showed the

lowest value of SSD for all four (energy crops. Though the proposed exponential model predicted the EMC value more accurately in case of paper waste (chapter 4.7) but for energy crops (wood or cellulose based material) Henderson's predicted the value more accurately. Lee et al. (2019) and Hartley and Wood (2008) also suggested Henderson's equation as line of best fit when dealing with wood pellets.

Figure 4.30 shows the graphical representation of the accuracy of predicted value of EMC from standard equations and actual measured value of EMC. This has been observed that, Henderson's equation predicted the EMC accurately at lower RH range up to 60%. Above that range though the predicted EMC value showed a slight deviation from the Henderson line, still its spread ne allows for a good EMC prediction. This pattern is probably caused by the nature of cellulose and lignin softening at RH higher than 60%. This softening can be responsible for this data spread at higher RH (Engelund et al. 2012).

Table 4.10 Prediction of EMC behaviour with Linear, Henderson and proposed exponential equation for pellets prepared from energy crops (miscanthus, prairie chord grass, switch grass, big blue stem).

Model name	Equation	Co-efficient	SSD	Range of applicability for RH used (%)	Materials used
Henderson's model.	$EMC = [\ln(1 - RH)/K]^{1/C}$	K= - 185.75 C= 2.15	0.000253137 (R ² = 0.986)	11-93	Miscanthus
Linear model	EMC= K. RH	K=0.146	0.001355997 (R ² = 0.961)	11-93	Miscanthus
Proposed exponential model	EMC=K. exp (RH/C)	K=0.033 C=0.648	0.000446457 (R ² = 0.976)	11-93	Miscanthus
Henderson's model	$EMC = [\ln(1 - RH)/K]^{1/C}$	K= - 149.732 C= 2.08	0.000153031 (R ² = 0.993)	11-93	Prairie cordgrass
Linear model	EMC= K. RH	K=0.150	0.001150415 (R ² = 0.968)	11-93	Prairie cordgrass
Proposed exponential model	EMC=K. exp (RH/C)	K=0.033 C=0.626	0.000307651 (R ² =0.984)	11-93	Prairie cordgrass
Henderson's model.	$EMC = [\ln(1 - RH)/K]^{1/C}$	K= - 479.87 C= 2.55	0.000193144 (R ² =0.986)	11-93	Switchgrass
Linear model	EMC= K. RH	K=0.142	0.001710832 (R ² =0.966)	11-93	Switchgrass
Proposed exponential model	EMC=K. exp (RH/C)	K=0.038 C=0.763	0.00034565 (R ² =0.975)	11-93	Switchgrass
Henderson's model.	$EMC = [\ln(1 - RH)/K]^{1/C}$	K= - 438.45 C=2.51	0.000128235 (R ² =0.991)	11-93	Big bluestem
Linear model	EMC= K. RH	K=0.143	0.00157109 (R ² =0.972)	11-93	Big bluestem
Proposed exponential model	EMC=K. exp (RH/C)	K=0.038 C=0.751	0.000258531 (R ² =0.982)	11-93	Big bluestem

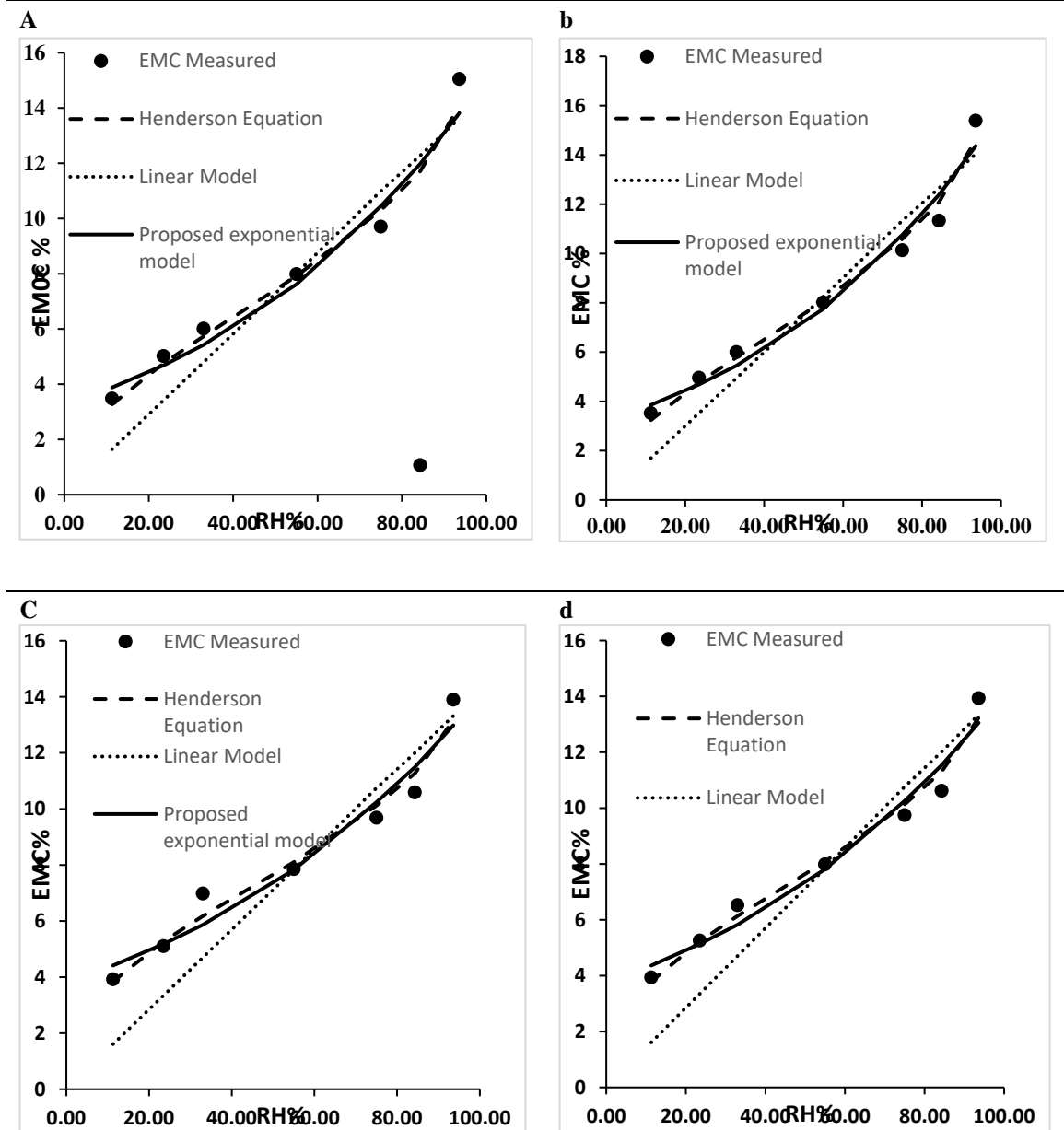


Figure 4.30 The simulation results based on equations in Table 4.8 and validated against experimental results for pellets made with a) Miscanthus b) prairie cordgrass c) switchgrass d) big bluestem.

4.9 Ash content

Higher ash content is an undesirable parameter of biofuel pellets. The suggested range of ash content is less than 5% as suggested by international pellet standard (Barbanera et al. 2015). Higher ash content is responsible for reducing the heating value of the fuel. It also causes different problems in boiler while burning. Dust emission, clinker

formation and sintering are some of the common problems caused by higher ash content (Oberberger and Thek 2004). Figure 4.31 shows the comparison of ash content of biofuel pellets made from paper waste (paper towel and cardboard box) and energy crops. Among all these biomass pellets paper towel pellets had lowest ash content of approximately 2.9%, whereas cardboard box had the highest ash content of 5.3%. Among all the energy crops Miscanthus had the lowest ash content of value 3.6%. Prairie cordgrass, switchgrass and big bluestem had ash contents almost in the similar range, with an average value of 4.5%, 4.8% and 4.9% respectively. Figure 4.32 shows Tukey's LS means comparison for the values of ash content. The same colour of bar represents no significant difference. The paper towel pellets and Miscanthus pellets were covered in the same color of bar, showing there is no significant difference in ash content % between them. Pellets made from card box had significantly higher ash content. There was very minor differences in the ash content % of prairie cordgrass, switchgrass and big bluestem was observed but were statistically insignificant.

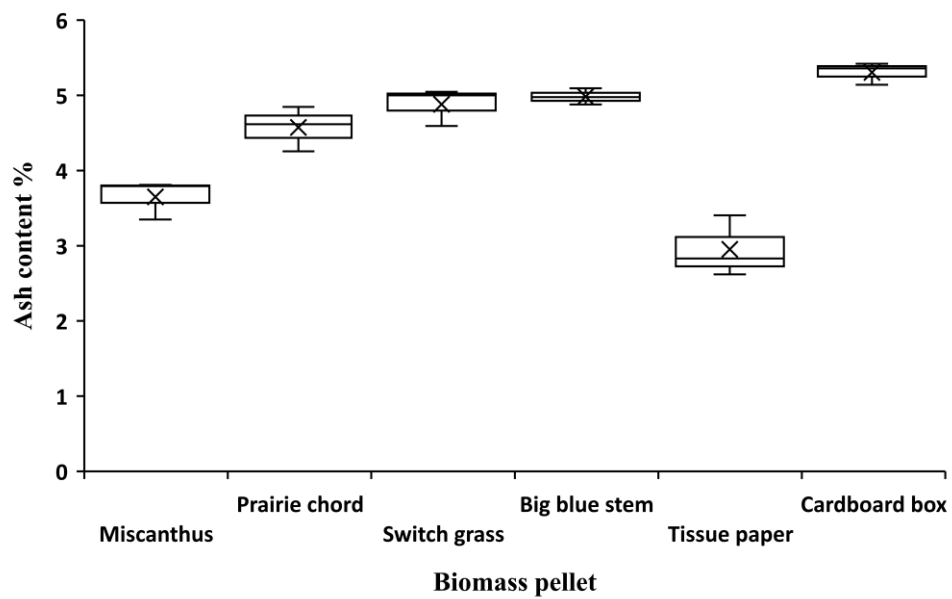


Figure 4.31 Comparison of ash content % made from paper waste (paper towel, cardboard box) and energy crops (Miscanthus, prairie cordgrass, switchgrass and big bluestem).

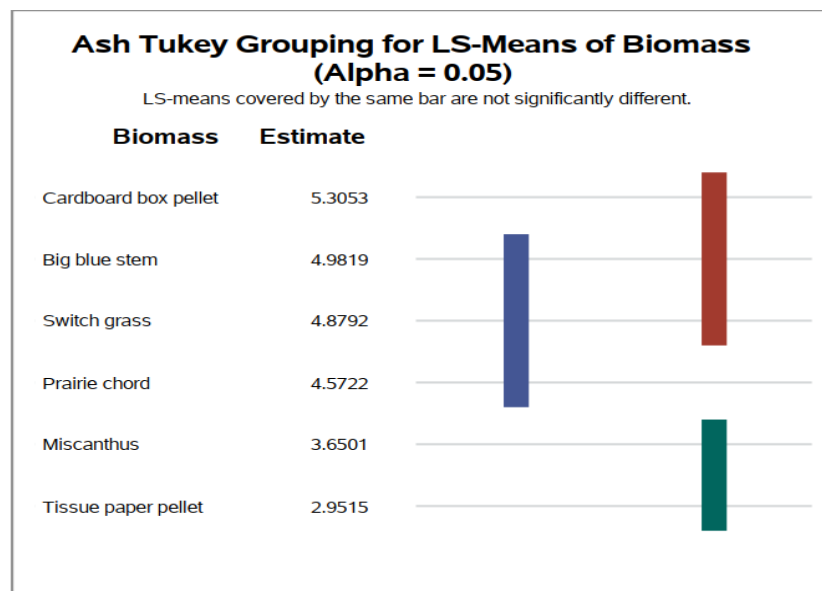


Figure 4.32 Tukey's LS means test of significance of ash content % of pellets made from paper waste (paper towel, cardboard box) and energy crops (Miscanthus, prairie cordgrass, switchgrass and big bluestem). (The order of equilibration day has been maintained as per decreasing order of the corresponding value of the parameter.)

CHAPTER V

CONCLUSION AND RECOMENDATIONS

5.1 CONCLUSION

Paper waste (paper towel and cardboard boxes) can be successfully used to make biofuel pellets with higher calorific value, durability and bulk density. Pellet quality was affected by processing conditions. Specifically, paper towels and cardboard boxes processed at 45% and 35% MC (wb), respectively, at low temperatures (60-70 °C) produced pellets of best quality. Cardboard box pellets were found to be superior in quality over paper towel pellets. Conditioning/equilibrating after pelleting significantly improved the pellet quality. Two days of equilibration at 20 °C and 20% RH period was found to be enough for any significant changes in pellet quality.

Energy crops (Miscanthus, prairie cordgrass, switchgrass and big bluestem) are suitable for making high quality biofuel pellets. The durability of pellets made from energy crops were as high as 97.5% while their calorific value reached 17959.5 J/g with a bulk density of 0.69 g/cm³, and these quality parameters are quite comparable to wood pellets.

A proposed exponential equation ($EMC = K \cdot \exp(RH/C)$) and Handerson's equation ($EMC = [\ln(1-RH)/K]^{1/C}$) were found to be adequate in predicting the isothermal behavior of the pellets made from both paper waste and energy crops.

5.2 SUGGESTION FOR FUTURE WORK

The two most commonly used pelleting units are - pilot scale flat die pelleting unit and industrial scale ring type pelleting unit. This research was conducted using pilot scale flat die pelleting unit for both paper waste and energy crops. For paper pellets, pelleting conditions were studied under different moisture contents and variable temperatures. There can be slight deviation in processing parameters when pelleting is done using ring type pelleting unit. So further research can be carried out using ring type pelleting unit to find out the optimal processing parameters (temperature, moisture, pelleting pressure) that gives optimal pellet properties (calorific value, bulk density, durability) in an industrial set up.

In this experiment, the energy crops pelleting were carried out at fixed particle moisture content (30% wb) and fixed temperature range (80 °C) to compare the quality of the manufactured pellets. However the optimal processing parameters (temperature, moisture, pelleting pressure) were not studied in this research. So further research is suggested to find the optimal manufacturing conditions (temperature, moisture, pelleting pressure) of these energy crops using both pilot scale pelleting unit and ring type pelleting unit that gives optimal pellet properties (calorific value, bulk density, durability)

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APPENDIX A

PELLETS MADE FROM PAPER TOWEL

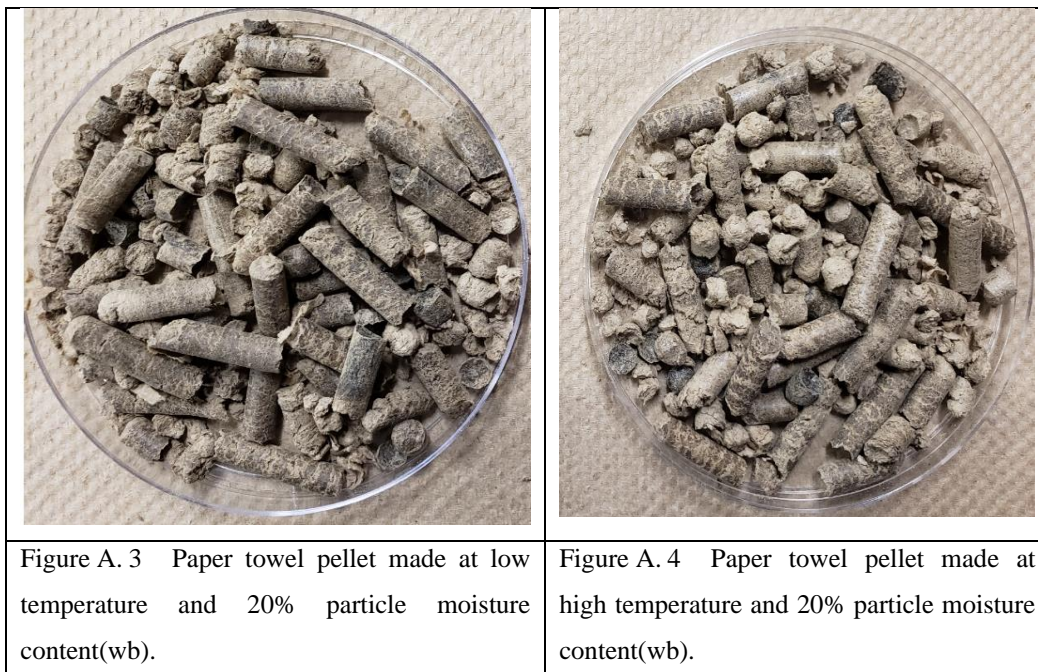
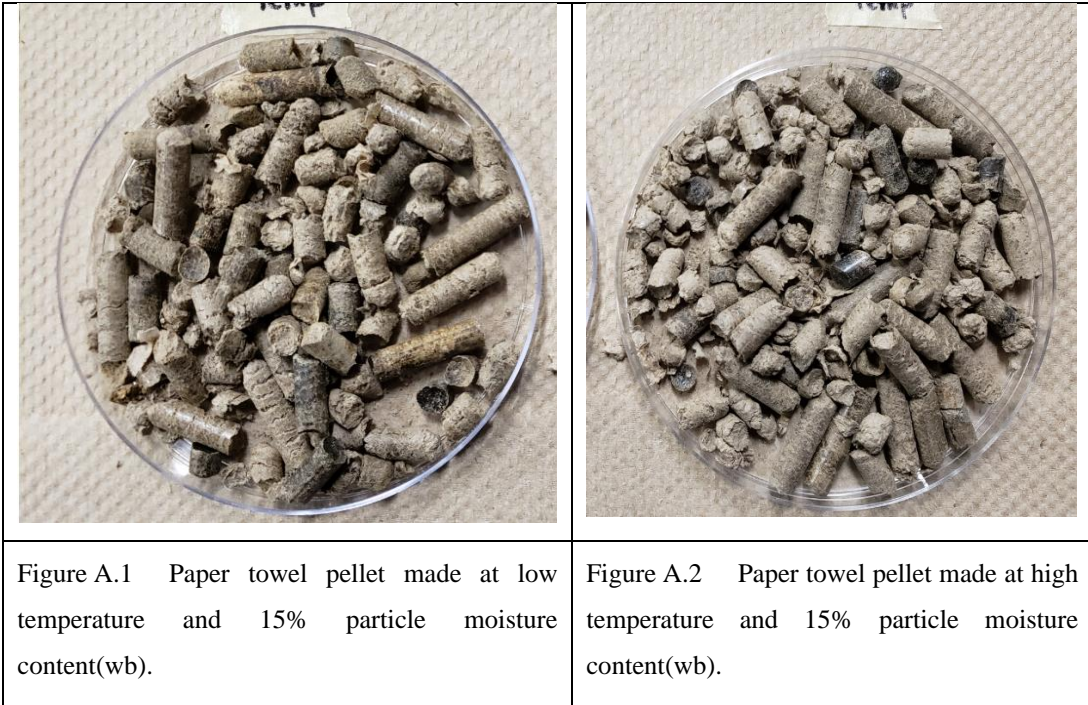




Figure A. 5 Paper towel pellet made at low temperature and 25% particle moisture content(wb).



Figure A. 6 Paper towel pellet made at high temperature and 25% particle moisture content(wb).



Figure A. 7 Paper towel pellet made at low temperature and 30% particle moisture content(wb).



Figure A. 8 Paper towel pellet made at high temperature and 30% particle moisture content(wb).



Figure A. 9 Paper towel pellet made at low temperature and 35% particle moisture content(wb).



Figure A. 10 Paper towel pellet made at high temperature and 35% particle moisture content(wb).



Figure A. 11 Paper towel pellet made at low temperature and 45% particle moisture content(wb).



Figure A. 12 Paper towel pellet made at high temperature and 45% particle moisture content(wb).



Figure A. 13 Paper towel pellet made at low temperature and 55% particle moisture content(wb).



Figure A. 14 Paper towel pellet made at high temperature and 55% particle moisture content(wb).

APPENDIX B

PELLETS MADE FROM PAPER BOX



Figure B.15 Paper box pellet made at low temperature and 35% particle moisture content(wb) with no additives added.



Figure B. 16 Paper box pellet pellet made at low temperature and 35% particle moisture content(wb) with yeast as additives.

APPENDIX C

PELLETS MADE FROM ENERGY CROPS



Figure C. 17 Miscanthus pellet made at low temperature (maximum 80 °C) and 30% particle moisture content(wb) no additives added.



Figure C. 18 Prairie chord grass pellet made at low temperature (maximum 80 °C) and 30% particle moisture content(wb) no additives added.



Figure A. 19 Switch grass pellet made at low temperature (maximum 80 °C) and 30% particle moisture content(wb) no additives added.



Figure A. 20 Big blue stem pellet made at low temperature (maximum 80 °C) and 30% particle moisture content(wb) no additives added.