SUPPLY CHAIN MANAGEMENT OF ADVANCED WOOD PELLETS: STORAGE AND REAL TIME FIELD CHARACTERIZATION

by:

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Abstract

Canada announced plans to phase-out coal-fired electricity generation by 2030. Therefore, in 2014, the province of Ontario has phased out the use of coal in the production of electricity. Former coal powered generating stations have been converted to use biomass. Ontario Power Generation, Ontario's largest producer of electricity, has converted former coal powered Thunder Bay Generating Station (TBGS) to use advanced wood pellets (AWP), which are produced from thermally treated biomass. The thermal treatment with steam explosion makes the AWP more durable and water resistant as compared to conventional wood pellets, hence allowing TBGS to use the same handling and storage equipment they used for coal, including outside storage of AWP. However, the quality properties of AWP may degrade due to exposure to weather conditions while stored outside, affecting their performance as a fuel. The purpose of this study was to analyze the degradation of AWP while stored outside, and to give recommendations for the most effective storage approach to the industry. We examined the trends and level of degradation of AWP quality properties, while stored outside in uncovered and covered piles, through a period of 11 months. Additionally, we monitored internal temperature trends of the piles, to assess if there is any risk of self-heating, and tested fresh factory samples, which served as a baseline. The results showed that AWP moisture content is highly influenced by weather conditions (in the first place precipitation), with moisture content directly or indirectly affecting the rest of the properties. Furthermore, the covered pile displayed significantly better preservation of properties, while self-heating was not observed in any of the piles. We recommend covering AWP piles, especially in the winter months, to reduce snow pack that could thaw and penetrate into the pile in the spring. This study also contributes to the existing knowledge in the biomass area, since there are very few studies done on AWP storage and quality properties.

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Introduction

Due to the world trend and strong demand to reduce harmful pollution, greenhouse gas emissions (GHG) and to fight climate change, Canada announced plans to phase-out coal-fired electricity generation by 2030 (Ministry of Energy of Canada, 2010). Consequently, by 2014, the Canadian province of Ontario has completely eliminated coal power, which accounts for 12% of the total installed energy production that was generated by coal in Canada (Ministry of Energy Ontario, 2015). Ontario Power Generation (OPG), as the largest Ontario producer of electricity, has converted their existing coal power plants to use biomass, since this fuel, when compared to coal, can reduce GHG emissions if sustainably managed as a renewable resource (Pembina Institute, 2011). Wood pellets, OPG's targeted form of biomass fuels, are particularly well suited for use in retrofitted coal-fired generating stations. Moreover, wood pellets, over the full life cycle, can reduce GHG emissions by approximately 90% relative to coal and by 85% relative to natural gas (McKechnie *et al*., 2016).

This study's industrial partner, OPG's Thunder Bay Generating Station (TBGS), has converted from coal to advanced wood pellets in 2014, and since then is serving as a "peak" generating station, and complements renewable forms of electricity generation like wind and solar (Ontario Power Generation, 2014). Advanced wood pellets (also known as "steam exploded" or "black") are an industrial grade (8 mm), new form of biomass fuel, produced from steam-exploded biomass (forest or agricultural sources). Steam explosion is thermal pre-treatment in the production process, which makes the final product, advanced wood pellets, more durable and water resistant, when compared to conventional ("white") wood pellets (Lam, 2011).

Power producers have a high demand for securing their energy supply and thus having their fuel stored (Stelte, 2013). This brings us to one of the biomass conversion main challenges, from both an engineering and economic perspective, and that is the storage of the new wood pellet fuel. Given that conventional wood pellets are sensitive to moisture uptake, and they tend to swell and lose their structure when exposed to rain, they have to be stored indoors (Stelte, 2013), which makes conversion from coal to conventional wood pellets difficult, considering technical and safety issues (such as dust formations and self-ignition), and the cost of the indoor storage in silos.

However, using advanced wood pellets can avoid challenges of the indoor storage and make conversion projects simpler and less costly. For instance, OPG's Atikokan Generating Station converted from coal to conventional wood pellets, with the conversion cost being around 150 million dollars, while TBGS conversion cost was five million dollars, mainly due to the fact that advanced wood pellets did not need a silo storage facility (Ontario Power Generation, 2014). Because of water resistance and better durability, advanced wood pellets can be handled and stored much like coal, using existing fuel handling systems with minimal plant modifications (Ontario Power Generation, 2014). This means that advanced wood pellets can be stored outside, under the influence of various weather conditions, without excessive degradation of their quality properties. In spite of advanced wood pellets increased durability and hydrophobicity, long-term outside storage is expected to have a somewhat negative impact, resulting in advanced wood pellets degradation and drop in quality, affecting their performance as a fuel.

The main focus in this study is to assess the trends and the level of degradation of the advanced wood pellets, in terms of their quality properties, while these are stored outside in covered and uncovered piles. Furthermore, we investigated if there is any self-heating present in the outside stored advanced wood pellet piles. Recommendations to the industry on how to most effectively store advanced wood pellets were given based on the results of this study. And finally, we intended to contribute and to fill in the gaps in the existing knowledge in the biomass fuel area, since there is minimal available literature on advanced wood pellets storage and quality properties.

The specific objectives of this study are:

I) To conduct a comprehensive literature review of the most relevant and recent wood pellet published literature with emphasis on wood pellet production, storage, and quality properties.

II) To study the change in quality properties (ash content, bulk density, calorific value, durability, fines amount, fixed carbon, moisture content and volatile matter) of advanced wood pellets over different periods of time, when these are stored outside and are subjected to different weather conditions. The quality properties of uncovered advanced wood pellet pile were compared with those covered with a Walki tarp, and with a fresh factory sample that was never stored and is considered as a baseline.

III) To monitor temperature trends of advanced wood pellet piles over a period of one-year monthly, when these are stored outside and are subjected to different weather conditions, and to compare temperature trends of the uncovered pile with those covered with a Walki tarp.

1. Literature Review

1.1. Background

With the recent spike in global energy prices, growing concern over climate change, and the push for energy independence, alternative means of energy production became increasingly viable (Wilson, 2010). Biomass, used as a fuel, is one of the alternative means of energy production. It is a renewable energy source that has the potential benefits of decreasing pollutant generation and being CO_2 neutral (Agbor *et al*., 2014). It can simultaneously contribute to the increased use of renewable energy, reducing greenhouse gas (GHG) emissions, compliance with air pollutant (AP) emissions regulations, and encourage economic development in communities dependent on agriculture and forestry sectors (McKechnie *et al*., 2016), which entails significant socioeconomic and environmental benefits (Zamorano *et al*., 2012). Furthermore, behind only coal and oil, biomass stands as the third-largest energy resource in the world, and it plays an important role in the national economy, reducing the import of fossil fuels (Zamorano *et al*., 2011). And finally, due to the reasons mentioned above, biomass has recently attracted more interest from both political and scientific perspectives (Nunes *et al*., 2014).

Biomass is a combustible material usually burned to produce heat that can be used to generate motion in vehicles and electricity in power plants (Demirbaş, 2003). Biomass resources include various natural and derived materials mainly categorized as agricultural residues, wood and wood wastes, animal dung or municipal solid wastes (Vinterbäck, 2004). Because of high moisture content, irregular shape and size, and low bulk density, biomass is very difficult to handle, transport, store and utilize in its original form (Zamorano *et al*., 2011).

These are some of the reasons why biomass is being pelletized. Pelletized biomass, especially wood pellets, offers a more homogenous and energy-dense fuel with superior combustion characteristics, compared to raw biomass (Zhang *et al*., 2010). Therefore, wood pellets are particularly well suited for use in retrofitting coal-fired generating stations, either as a supplemental fuel ("co-firing" with coal) or as the primary fuel (McKechnie *et al*., 2016). As a result of these factors, wood pellet markets have rapidly grown, with 22 million tonnes of pellets produced globally in 2013 (FAO, 2013), a ten-fold increase over the past decade (Lamers *et al*., 2012).

Currently, there are three types of wood pellets in the market: conventional ("white") wood pellets, and two types of thermally treated wood pellets; torrefied wood pellets and advanced wood pellets (steam exploded; "black"). However, certain characteristics of conventional "white" wood pellets negatively impact their viability as a fuel for electricity generation. Conventional pellets are hydrophilic and will absorb moisture from their environment during transport and storage, degrading the mechanical integrity of pellets (Graham *et al*., 2014). Reducing water uptake requires storage of pellets in closed silos, which can therefore, as previously mentioned, significantly increase costs to retrofit coal-generating stations (McKechnie *et al*., 2016). Thermal treatment of wood pellets offers pellet durability improvements in terms of mechanical strength and moisture absorption resistance (Lam, 2011), which make them more suitable (when compared to conventional or "white" wood pellets) for utilization in existing coal fired heat and power plants (CHP-plants) (Stelte, 2013). For instance, advanced (steam exploded, "black") wood pellets can be used at coal-fired plants with minimal plant modifications. Due to their "coal like" properties, advanced wood pellets can be handled and stored (outside) much like coal (Stelte, 2013), which makes power plant conversion from coal to advanced wood pellets less costly than conversion to natural gas or conventional wood pellets as mentioned previously.

1.2. Wood Pellet Production

Wood pellet production in general is divided into the following steps (it should be noted that the required process steps differ depending on the kind of raw material used) (Obernberger and Thek, 2010):

1) Pre-treatment of raw material (Size reduction; Drying; Conditioning)
2) Pelletization
3) Post-treatment (Cooling; Screening)

1.2.1. Raw Material

Wood pellets are made from mostly pine and spruce (softwoods) both by-products of the wood processing industry (Järvinen and Agar, 2014), or as round wood chipped feeding a plant. Hardwoods can be mixed in with softwood, but successful production of hardwood pellets without binders is more difficult (Kofman, 2007). The raw materials most frequently used for pellet production are wood shavings, sawdust and wood dust (Obernberger and Thek, 2010). In addition to the above-mentioned raw materials, wood chips have gained increasing significance (Pellets, 2006) because sawdust is not available in sufficient quantities, due to existing utilization of this resource, for further extension of pellet production capacities (Obernberger and Thek, 2010). Furthermore, due to scarcity of sawdust over recent times, many pellet producers have considered producing pellets from chipped or ground round wood (Rinke, 2005). In Scandinavian countries, peat is added to the woody raw materials in pelletization (Nyström, 2008).

1.2.2. Pre-treatment

1.2.2.1. Size reduction

After drying, or of course as a primary step when the material is dry already, the raw material is ground up to the required particle size (Obernberger and Thek, 2010). Particle size depends on the diameter of pellets that are being produced. Larger diameter pellets are used on a larger scale, for example in power plants that were converted from coal to pellets, while smaller diameter pellets are being used in small-scale furnaces. If the wood chips or logs are being used as a raw material, they have to go through the first stage or the "course grinding stage", where the material is reduced to wood chips similar to those found from a pulp wood chipper (Tarasov, 2013). Wood shavings, sawdust and wood dust don't have to go through the first stage of grinding. Next, raw material has to be screened to avoid any impurities, i.e. stones, plastic and metal (Kofman, 2007). Lastly, raw material then goes into the final stage of size reduction, which is called the "fine grinding stage", which is generally done by hammer mills (Obernberger and Thek, 2010). Usually, pelletization requires biomass that is ground to particles that are no more than 3 mm in size (Ciolkosz, 2009).

1.2.2.2. Drying

The range of moisture content for the ground raw material just before entering the pellet mill lies typically between 8 and 12 wt.% (wet basis) for the pelletization of wood (Obernberger and Thek, 2010). The biomass feedstock is mostly wet and needs to be dried from 30-60% moisture content to about 10-15% (Fagernäs *et al.*, 2010). Moisture content is a critical variable and must be confined below 12% (Maciejewska *et al.*, 2006). All of the authors mentioned above specified different ranges of the desired moisture contents of the ground raw material before the pelletization process, which means that the desired moisture content depends on the producer. However, if the raw material does not meet the specified manufacturer's criterion, it has to be dried before pelletization. Otherwise, if it is too dry, the heat build-up induced by friction in the pelletizer burns the surfaces, but if it is too wet, the trapped steam pressure weakens internal bonds and reduces the mechanical properties, increasing breakage and dust during subsequent handling (Spelter and Toth, 2009).

There are two different techniques of drying; natural drying, which is the simplest form of drying, and forced drying. Natural drying is done by putting the material in loose heaps and turning it regularly (Obernberger and Thek, 2010). However, storage trials made clear that the optimum moisture content for pelletization cannot be reached by natural drying of wood (Stockinger and Obernberger, 1998).

Forced drying can be done with different types of dryers: tube bundle dryer, drum dryer, belt dryer, low temperature dryer and superheated steam dryer (Obernberger and Thek, 2010). Drying media can be flue gas, hot air, or superheated steam (Pang and Mujumdar, 2010). Furthermore, the heat for the dryer can be supplied by any kind of fuel, e.g. gas, oil, or even biomass (Kofman, 2007). Dryers can be based on direct or indirect drying techniques, or both can be used. The direct drying method is based on drying media being applied to the raw material, while indirect or contact drying works by heat being supplied by a heat exchanger through the metal walls (Mujumdar, 2011). Tube bundle dryers are heated indirectly, which means the material can be dried in a gentle manner at around 90ºC (Obernberger and Thek, 2010). In drum dryers, either direct or indirect heating can be applied. The inlet temperature of a drum dryer, ranges from 300 to 600ºC, depending on its construction (Obernberger and Thek, 2010). In the case of a belt dryer, which can be heated directly or indirectly, the inlet temperature varies between 90 and 110ºC, depending on the type of the dryer (Obernberger and Thek, 2010). Low temperature dryers are based on indirect drying technology and operating temperature ranges between 50ºC and 100ºC (Louis, 2011). And finally, superheated steam dryer operates with the steam that circulates in the dryer at a pressure of two to five bars and the material in the dryer reaches temperatures of 115 to 140ºC (Obernberger and Thek, 2010). In general, the rotary drum dryer is the most commonly used technology in the drying of wood biomass since it can be used to dry high volumes of materials with a wide range of initial moisture contents (Pang and Mujumdar, 2010; Thibault and Duchesne, 2004; Li *et al*., 2012). However, the choice of drying technology is highly dependent on the raw material that is used and the available heat source (Hein, 2011).

1.2.2.3. Conditioning

Conditioning denotes the addition of steam or water to the prepared raw materials (Obernberger and Thek, 2010). After the drying process, the moisture content of raw materials should be slightly underneath the optimum, so the conditioning will raise it again by about 2 % MC (Obernberger and Thek, 2010). Not only will it raise the moisture content to the optimum, but it will also act as a means to control the right temperature (120-130ºC) (Obernberger and Thek, 2010; Kofman, 2007) needed for pelletization, which is the next step in the wood pellet production process.

1.2.3. Pelletization

The next step in the wood pellet production process, after the pre-treatment (size reduction; drying; conditioning), is the actual pelletization process. In the pelletization process, raw wood is compacted into a homogeneous product with higher energy density and lower moisture content and made into uniformly sized cylindrical shapes, facilitating transportation, handling, and usage (Spelter and Toth, 2009). For this process a pellet mill is used (Figure 1).

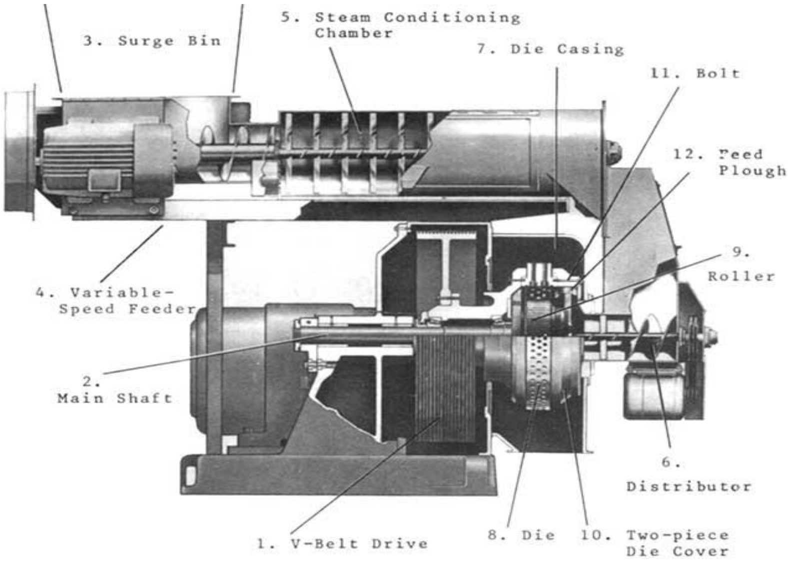

Figure 1. Pellet mill for wood (Wang, web source: www.akgbioguide.com).

Large scale producers usually use ring or flat die pellet mills, with ring die mills being the most common (Haslinger, 2005). The main parts of any ring die pellet mill are die ring and fixed rollers. The material is fed to the rollers sideways and pressed through the bore-holes of the die from the inside to the outside (Obernberger and Thek, 2010). An infinite string comes out of the die that either breaks up into pieces randomly or gets cut into the desired length by knives (Obernberger and Thek, 2010). At the end of production, vegetable oil is added to the pellet mill to lubricate the last pellets, as it will be easier to start the press next time avoiding the last pellets becoming stuck in the die (Kofman, 2007).

1.2.4. Post-treatment

1.2.4.1. Cooling

Once the pellets leave the pellet mill, they are plastic and hot (Kofman, 2007). The temperature of the pellets, directly after the process, can vary between 80 and 130ºC (Obernberger and Thek, 2010). Counter flow coolers and belt coolers are most often used for cooling the pellets. During cooling, the pellets become rigid and lose moisture, so that the final moisture content after the cooler can be as low as 6% (Kofman, 2007). Furthermore, cooling enhances mechanical durability of the pellets as well (Obernberger and Thek, 2010). After the cooling and during the storage, pellets will take up moisture from the surrounding air and stabilize at moisture content between 8 and 10% (Kofman, 2007).

1.2.4.2. Screening

At all stages of the production where dust might arise, the air is drawn off and filtered (during grinding, drying, after cooling, before packaging or loading). That includes screening as the final stage of production, to ensure a small amount of fines in the final product, before transport and packaging is removed (Obernberger and Thek, 2010).

1.2.5. Thermal (Pre-) Treatment of Biomass in the Wood Pellet Production

Since biomass has some disadvantages as fuel (low calorific value, high moisture content, hygroscopic nature, smoking during combustion) (Zanzi *et al*., 2002), thermal treatment is used to upgrade the biomass (Van der Stelt *et al*., 2011). Thermal treatment produces raw material (biomass) with increased heating value and hydrophobicity (Chen *et al*., 2015), better physical properties like grindability, particle shape, size and distribution, pelletability, and improved composition properties like carbon and hydrogen content (Nunes *et al*., 2014).

Due to its potential applications for making thermally treated wood pellets, which can be used as a high quality feedstock in gasification for high quality syngas production and as a substitute for coal in thermal power plant and metallurgical processes, thermal treatment has attracted great interest in recent years (Chen *et al*., 2015). Thermal treatment of biomass can be done by torrefaction, to produce torrefied products (including wood pellets), or steam explosion, to produce steam exploded products (including steam exploded/advanced/”black” wood pellets).

1.2.5.1. Torrefaction

Torrefaction of biomass can be described as a mild form of pyrolysis at temperatures typically ranging between 200 and 300ºC, in an inert and reduced environment (Tumuluru *et al*., 2011), under the exclusion of oxygen and at ambient pressure (Obernberger and Thek, 2010). It is a thermo-chemical process based on the decomposition of hemicelluloses, which is the dominant reaction, while the cellulose and lignin fractions remain almost unaffected (Nunes *et al*., 2014). Due to this treatment, the carbon content and calorific value of torrefied biomass increases by 15-25%, while the moisture content decreases to < 3%, compared to raw biomass (Tumuluru *et al*., 2011). Torrefied biomass is brown to blackish brown in colour, it has a smoky smell and properties similar to coal (Uslu *et al*., 2008; Post van der Burg, 2010). Torrefied products can substitute charcoal in a number of applications such as fuel for domestic cooking stoves, residential heating, manufacture of improved solid fuel products such as fuel pellets, compacted fireplace logs and barbecue briquettes for commercial and domestic use. They can be blended with coal and co-fired in a Pulverized Coal Boiler (PBC) (Bourgeois and Doat, 1985; Girard and Shah, 1991; Zanzi *et al*., 2002). And finally, torrefied wood is more uniform than untreated wood, which results in easier packaging and transportation, higher efficiency and higher quality fuel in general (Zanzi *et al.*, 2002).

1.2.5.2. Steam Explosion

Steam explosion of biomass, also named as Masonite technology (DeLong, 1981), is a pre-treatment process that opens up the fibers, and makes the biomass polymers more accessible for subsequent processes, i.e. fermentation, hydrolysis or densification processes (Stelte, 2013). More precisely, according to the patent from 1926, during the steam explosion process, wood chips are steam heated at a temperature of about 285ºC and a pressure of 3.5 MPa for about 2 minutes. The pressure is increased rapidly to about 7 MPa (70 bar) for about 5 seconds, and the chips are then discharged and exploded at atmospheric pressure into pulp (Mason *et al.*, 1926). In general, steam explosion can also be described as a process in which biomass is treated with hot steam (180 to 240ºC) under pressure (1 to 3.5 MPa) followed by an explosive decompression of the biomass that results in a rupture of the biomass fibers rigid structure (Stelte, 2013). In addition, it is important to mention that no chemicals are used in the process of steam explosion, except water (Garotte *et al.*, 1999). The equipment for steam explosion is presented in figure 2.

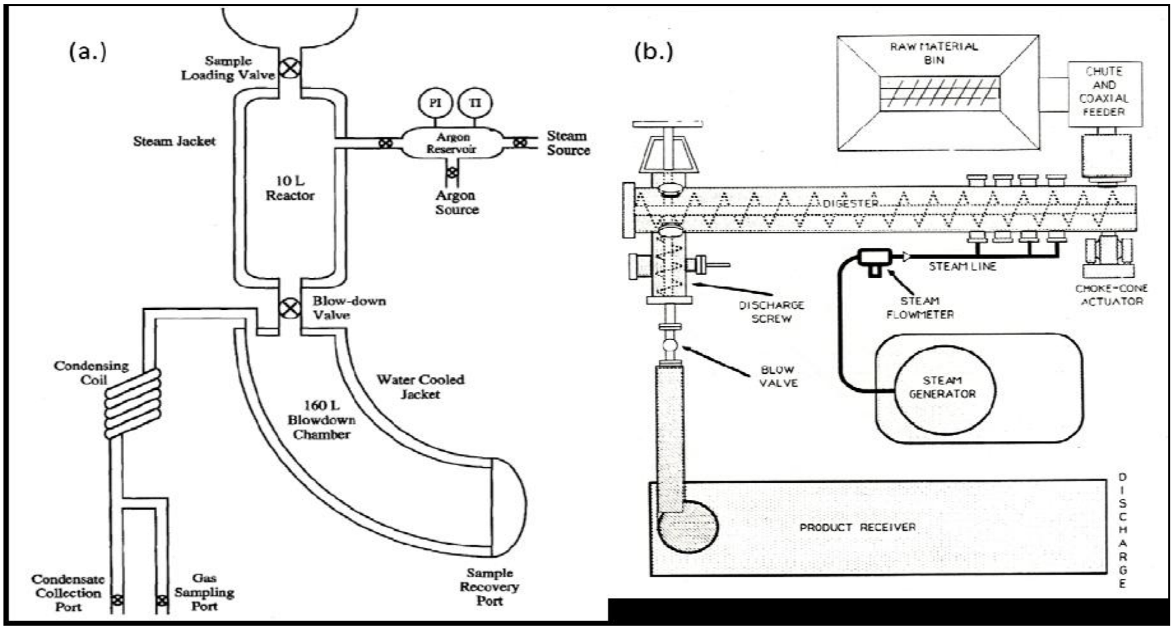

Figure 2. Steam explosion equipment: (a.) Batch (Turn *et al.*, 1998) and (b.) Continuous System STAKE II Pilot Facility Having a Maximum Capacity of 4 t/h Located in Sherbooke, Quebec, Canada (Heitz *et al.*, 1990).

Steam explosion as a pre-treatment process increases the calorific value of biomass due to the removal of moisture and volatiles, and the thermal degradation of hemicelluloses. While the carbon content of the biomass increases, oxygen and hydrogen are removed. Furthermore, biomass becomes more hydrophobic, its mechanical structure is more rigid, and in general it has more “coal like” properties (Stelte, 2013). The wood pellets produced from steam-exploded biomass are dark brown in colour (Obernberger and Thek, 2010). Finally, all the above-mentioned characteristic makes advanced (steam exploded; “black”) wood pellets more suitable (when compared to conventional or “white” wood pellets) for utilization in existing coal fired heat and power plants (CHP-plants) (Stelte, 2013).

1.3. Wood Pellet Supply Chain

1.3.1. Transportation

After they have been produced, wood pellets need to be transported to the end user. Depending on the end user needs and requirements, the product can be distributed in many forms, including consumer-bags, big-bags, tank trucks, bulk containers, railcars and ocean vessels (Obernberger and Thek, 2010).

Consumer-bags (10-25 kg) are mostly made of plastic or recyclable material and transported on 800 kg pallets wrapped with plastic foil (Obernberger and Thek, 2010; Protic *et al*., 2011). Another packaging possibility is reusable big ("jumbo") bags containing 1-1.5 m^3. The former are used in households, where, for instance, pellet stoves are used, while the latter are intended for bigger, mostly industrial customers (Protic *et al*., 2011).

Tank trucks (with pneumatic feed) are used in cases where an appropriate residential or commercial storage facility is in place (such as bunkers or silos). These trucks suck up the pellets in the factory, and blow them into the silo at the receiving end (Kofman, 2007).

Furthermore, wood pellets can also be transported as a bulk in 20 or 40-foot containers, which are loaded onto trucks, ships or trains (Obernberger and Thek, 2010).

However, industrial big-scale users mainly use railcars and/or ocean vessels as a main method of transportation from the pellet factory to the pellet utilization facility. Railcars with capacity of 85 to 100 tonnes (in North America) are extensively used for transportation of pellets from manufacturing plants to loading facilities for ocean vessels (Obernberger and Thek, 2010). As already mentioned, for overseas transportation of large volumes of pellets, ocean vessels (bulk carriers) are used, especially on the trans-Atlantic route from Northern America to

Europe (Stelte, 2012). The size of the vessels usually ranges from 1500 to 50000 deadweight tons (dwt) (Obernberger and Thek, 2010).

1.3.2. Storage

Since conventional wood pellets are sensitive to the outside weather conditions, such as moisture uptake when exposed to rain, pellet producers, intermediate buyers and consumers need an adequately sized indoor storage space (Stelte, 2012). Two main storage types are silos and a flat storage. Silos, the most common way of storing pellets on a large-scale, are vertical with a tapered (hopper) bottom and vertical with a flat bottom. The size of silos usually range from 50 to 10000 m^3 (Obernberger and Thek, 2010). As mentioned earlier, flat storage i.e. A-frames are the second type of wood pellet storage. They are used for large storage of pellets in a range from 15000 to 100000 m^3 (Obernberger and Thek, 2010; Stelte, 2012). However, as mentioned before in this literature review, thermally treated wood pellets (including steam exploded) exhibit higher energy density, hydrophobicity, and greater durability in outdoor storage than conventional pellets (Graham *et al*., 2014; Koppejan, 2012; Obernberger and Thek, 2010), which means that with the “coal like” steam exploded (advanced, “black”) wood pellets (Stelte, 2013) indoor storage could be replaced with outdoor storage.

1.3.2.1. Self-Heating During the Storage

Spontaneous heating of carbonaceous materials, including wood pellets, is a common phenomenon, occurring in particular, when large quantities of materials are stored for extended periods (Larsson *et al*., 2011). The stored pellets temperature increase due to heat release from biological oxidations associated with microorganism (Meijer and Gast, 2004;

Maheshwari, 2000; Martínez-Inigo *et al*., 1999), and heat released from chemical oxidations (Pauner and Bybjerg, 2007; Rupar-Gadd, 2006; Wadso, 2007). In large-scale silo storage of wood fuel pellets self-heating has become a serious problem, sometimes causing self-ignition (Blomqvist and Persson, 2008). Self-ignition/spontaneous combustion often happens from inside of a piled combustible material, when the temperature reaches 200ºC, starting with invisible combustion/smoldering and followed by heavy smoke, visible charring of the pellets, which may or may not be followed by an explosion (Guo, 2013). The accidental fires have become the biggest concern during the storage and handling, which could cause real danger to the workers, enormous economy loss, damage to the storage structure, and air pollution (Guo, 2013). However, studies have shown that air ventilation inside of the storage facility is a very effective approach for reducing self-heating (Guo, 2013) and, therefore, lowering the risk of self-ignition.

2. Wood Pellet Quality Properties

Main parameters/properties, which affect wood pellet quality, and which are included in this study, are:

- Moisture content
- Calorific value
- Mechanical durability
- Fines amount
- Bulk density
- Ash content
- Volatile matter
- Fixed carbon

The parameters/properties that are mentioned above are usually measured for standards compliance. There are two main standards: North American (PFI) and the European Union standard (CEN/TS prEN 14961-1) (Tarasov, 2013). PFI and prEN 14961-1, with parameter values provided in Table 1, are designed for residential grade wood pellets, which are used on a smaller scale, mostly in residential heating systems. There are still no standards or label of quality for the industrial grade wood pellets (Verhoest and Ryckmans, 2012), which are used on a larger scale, for instance in co-generation with coal or as a complete replacement for coal in power generation. However, proposed Industrial wood pellet specifications: I1-100% biomass; I2-100% biomass and large co-firing; I3- <20% co-firing (Verhoest and Ryckmans, 2012) are in Table 2. These standards set the desired values for the freshly produced wood pellets, which come straight from the factory, to the end user. However, the quality properties of pellets cannot only be influenced during pellet production but can also change during transportation and storage

(Obernberger and Thek, 2010). A detailed description of each of the parameters/properties is provided in this chapter, together with the section, which explains the influence of storage on wood pellet quality properties.

Table 1. Summary table of wood pellet parameter interdependencies and the EU and PFI standard values (Obernberger and Thek, 2010; Pellet Fuel Institute, 2010).

Wood Pellet Parameter	Unit	Interdependencies	prEN-14961	PFI
Moisture content	%	Calorific value, mechanical durability, bulk density	≤10	≤8
Calorific value	MJ/kg	Moisture content, C, H and N content, ash amount	≥16.5	N/A
Mechanical durability	%	Moisture content, particular density, fines, particle size distribution, binding agents use	≥97.5	≥96.5
Bulk density	kg/m³	Moisture content, particular density	≥600	≥640
Ash content	%	Dust emissions, calorific value, content of minerals (sand etc.)	≤0.7	≤1.0
Fines	%	Mechanical durability	N/A	<0.5

Table 2. Industrial wood pellet specifications (Verhoest and Ryckmans, 2012).

Wood pellet parameter	Unit	CEN standard	ISO TC238 reference	I1 Industrial w. pellet spec.	I2 Industrial w. pellet spec.	I3 Industrial w. pellet spec.
Water content	weight % ar	EN 14774	same	≤10%	≤10%	≤10%
Bulk (apparent) density	kg/m³	EN 15103	same	≥600	≥600	≥600
Net calorific value at constant pressure	GJ/ton ar	EN 14918	≥17	≥16.5	≥16.5	≥16.5
Ash Content	weight % DM	EN 14775	1.5%-same-5%	≤1.0%	≤1.5%	≤3%
Fines ≤ 3.15 mm	weight % ar	EN 15149	same	≤4%	≤5%	≤6%
Durability	weight % ar	EN15210	same-97.5-96.0	≥97.5%	≥97%	≥96.5%

2.1. Moisture Content

Moisture content (MC %) is the moisture (water) in fuel removable under specific conditions (Obernberger and Thek, 2010). It is given as a percentage of the original sample mass (oven dry condition) (Tarasov, 2013).

Moisture content can be calculated on a wet basis and on a dry basis, using the following equations (Obernberger and Thek, 2010; ASTM E 871 – 82, 2006):

Wet basis (w.b.) -

$$MC = \left(\frac{W_i - W_o}{W_i}\right) * 100$$

Dry basis (d.b.) -

$$MC = \left(\frac{W_i - W_o}{W_o}\right) * 100$$

Where,
MC - moisture content in the analysis sample, %
W_i - initial green weight of the sample, g
W_o - oven dry weight of the sample, g

Wet basis is the condition in which the solid fuel contains moisture (water in a fuel), while the dry basis is the calculation, where the solid fuel is free from moisture (Obernberger and Thek, 2010). In this study, all of the moisture content results are presented on a dry basis (see Materials and Methods chapter). However, all other reference moisture contents (throughout Literature Review and Discussion chapters) are on a wet basis, unless otherwise stated.

Moisture content is considered an important property of biomass fuels as moisture can affect net calorific value, combustion, and gasification. The higher the moisture content, the lower the combustion efficiency and hence calorific value of the fuel (Obernberger and Thek, 2010; Graham, 2015). Furthermore, the moisture content also affects pellet mechanical strength (durability and fines) and bulk density (Obernberger and Thek, 2010; Tabil *et al.*, 2011). During wood pellet production, moisture content of the final product can be manipulated with factors such as use of different raw materials and the use of different additives. When additives are used, these decrease the final moisture content of the wood pellet (Tarasov, 2013). The use of starch as a binding agent requires the raw material moisture content to be between 12.5 and 13%, whereas lignosulphonate requires the raw material moisture content to be between 9 and 10.5 % (Mediavilla *et al.*, 2012). If lignosulphonate is used, the final moisture content of the wood pellet is 5.9%, compared to 9.3% moisture content in wood pellets produced from the standard raw material (Kuokkanen *et al.*, 2011). Furthermore, when raw material (with 12.1% MC) was mixed with 1% wheat starch, and the same amount of oxidized corn-starch, the final moisture content of the wood pellet was 7.6% (Stahl *et al.*, 2012).

According to prEN 14961 standard and the Industrial Wood Pellet Specifications (Table 1 and Table 2), the moisture content of wood pellets is set to be no more than 10% (w.b.), while PFI standard sets the limit to 8% (w.b.) (Table 1).

As mentioned earlier in this chapter, moisture content, as one of the most important quality properties, can change during the storage (Obernberger and Thek, 2010), affecting the majority of other wood pellet quality properties.

2.2. Calorific Value

The calorific value or heating value is the energy amount per unit of mass or volume released from complete combustion (Obernbereger and Thek, 2010). There is gross calorific value (HHV-High Heating Value) and net calorific value (the effective heating value or LHV-Low Heating Value). The gross calorific value is a measured value of the specific energy of combustion for a mass unit of a fuel burned in oxygen in a bomb calorimeter under specified conditions, while the net calorific value is a calculated value of the energy of combustion for a mass unit of a fuel burned in oxygen in a bomb calorimeter under such conditions that all the water of the reaction products remains as water vapour at 0.1MPa (Obernberger and Thek, 2010). Calorific value is determined by using a bomb calorimeter (Parr Instrument Co., 2007). The gross calorific value (HHV) can also be calculated using the following equation (Gaur and Reed, 1998):

$$HHV\ = 0.349C + 1.1783H - 0.1034O - 0.0211A + 0.1005S - 0.0151N$$

Where,
HHV – the gross calorific value (high heating value), kJ/g
C - mass fraction of carbon
H - hydrogen
O - oxygen
A - ash
S - sulphur
N – nitrogen

Furthermore, the values of the gross calorific value can be adjusted to take into account the moisture content (MC) of the tested samples, and hence the net calorific value (LHV), using the following equation (Nolan *et al.*, 2009):

$$LHV = HHV * \left(1 - \frac{MC}{100}\right) - \left(\frac{4.18 * MC}{100}\right)$$

Where,
LHV – the net calorific value (low heating value), MJ/kg
HHV – the gross calorific value (high heating value), MJ/kg
MC – moisture content, %

The calorific value is a very important wood pellet property as it defines customer value. The higher the heating value, the more energy from the same amount of product can be produced (Tarasov, 2013).

The calorific value of wood pellets is dependent on three major factors: raw material (softwood or hardwood species) that is used in the production process, the moisture content, and the single pellet density.

Wood pellets made from softwood species have a gross calorific value between 19.66 and 20.36 MJ/kg, while wood pellets made from hardwood species are ranging between 17.63 and 20.81 MJ/kg (Telmo and Lousada, 2011). The net calorific value for softwood pellets is between 15.63 and 16.94 MJ/kg, and the range for hardwood pellets is 14.41 to 17.91 MJ/kg (Telmo and Lousada, 2011). In general, in Canada, the average gross calorific value of softwoods is 21.18 MJ/kg and for the hardwoods is 19.35 MJ/kg (Kryla, 1984).

The calorific value has a strong linear dependence on the moisture content (Ciolkosz, 2010). If the moisture content goes up, the calorific value goes down (Obernberger and Thek, 2010). For example, if the moisture content of wood pellets is 10% (w.b.), the gross calorific value will be around 19 MJ/kg and the net calorific value will be around 17.5 MJ/kg. When the moisture content increases for 10% (w.b.), both gross and net calorific value will decrease for around 2.5 MJ/kg, following the linear trend (Ciolkosz, 2010).

Regarding single pellet density (the ratio of the sample mass and its volume including pore volume) influence on the calorific value, it has been noted that more dense particles show a longer burnout time (Temmerman *et al*., 2006; Obernberger and Thek, 2004).

Therefore, to conclude, both prEN 14961 standard and the Industrial Wood Pellet Specifications (Table 1 and Table 2) state that the wood pellets calorific value should be ≥16.5 MJ/kg, while North American PFI standard still does not have a determined value for this quality property.

2.3. Mechanical Durability and Fines Amount

The mechanical durability (or just durability) is the ability of densified fuel (e.g. briquettes, pellets) to remain intact, e.g. resist abrasion and shocks during handling and transportation (Obernberger and Thek, 2010). Durability as a quality property is closely related to the amount of fines (or just fines), even more, it determines the amount of fines. Since low durability results in more fines, which may create problems during transportation, storage, feeding and combustion (Filbakk *et al*., 2011), durability is an important wood pellet property. Fines are defined as the aggregate of all material smaller than 3.15 mm (Obernberger and Thek, 2010).

The most often used methods to test durability of densified products are the Tumbling Can, Holmen tester and Ligno tester (Kaliyan and Morey, 2009).

The tumbling method, commonly used in feed manufacturing industries in the U.S. (Winowiski, 1998), is used to estimate the pellet quality in terms of pellet durability index (PDI), or percent durability. It simulates the mechanical handling of pellets and predicts the possible fines produced to mechanical handling (ASABE Standards, 2003).

Next, the Holmen tester, which is more widely used in Europe than in North America, simulates pneumatic handling of pellets, due to the pneumatic conveyors common in European feed mills (Kaliyan and Morey, 2008). The Ligno tester, which uses air to circulate the pellets and therefore tests their durability and fines, is a recent device for testing the durability (Winowiski, 1998). Detailed description of the Ligno tester work principle is given in the Materials and Methods chapter.

Durability is expressed as percentage of the initial mass retained on the sieve, using the following equation:

$$DU = \left(\frac{M_f}{M_i}\right) * 100$$

Where,
$DU -$ durability, %
$M_i -$ initial mass of pellets, g
$M_f -$ final mass of pellets after the test, g

Fines are calculated using the following equation:

$$F_a = M_i - M_f$$

Followed by:

$$F = \left(\frac{F_a}{M_i}\right) * 100$$

Where,
F – fines amount, %
F_a – weight of fines, g
$M_i -$ initial mass of pellets, g
$M_f -$ final mass of pellets after the test, g

There are a number of factors affecting wood pellet durability, including: moisture content, particle size, additives, lignin, thermal pre-treatment, and process variables.

As discussed earlier in this paper, in the section of Wood Pellet Production in the Literature Review chapter, some water (moisture) is necessary in the pelletizing process for the development of intermolecular forces. Too much moisture content adversely affects pellet quality (Wilson, 2010). However, increasing the moisture content from 10 to 15% (w.b.) increases durability from 62 to 84% (Kaliyan and Morey, 2006).

Regarding particle size, it was found that finer particle sizes generally correspond with higher pellet durability as larger particles serve as fissure points (MacBain, 1966). Furthermore, mixture of particle sizes increases inter-particle bonding and eliminates inter-particle spaces, which consequentially leads to increased durability (Payne, 1978; Kaliyan and Morey, 2006; Shaw, 2008).

Additives (or a binder), a liquid or solid that forms a bridge or causes a chemical reaction to make strong inter-particle bonding, is added when durability values of pellets do not match with the quality standards (Kalyian and Morey, 2008).

Lignin acts as a binder in biomass raw material. At higher temperatures, lignin softens and helps the binding process (Kalyian and Morey, 2008).

Thermal pre-treatment was also discussed earlier in this paper. Heat activates inherent binders in biomass, which promotes the formation of solid bridges (Kalyian and Morey, 2008). That results in wood pellets having a more rigid structure (Stelte, 2013).

All factors mentioned above refer to the raw material (biomass) prior to entering the pelletization process in the pellet mill. However, process variables refer to those parameters that are inherent to the pellet mill itself: die dimension and the gap between the roller and die

(Wilson, 2010). Die consists of an annular matrix of perforations characterized by length to diameter ratio. Pellet durability increases with length to diameter ratio, but too large a ratio will block the die and choke the mill (Heffner and Pfost, 1973). The gap between the roller and die is the space between the annular matrix and the roller that forces raw material through the die. Optimal gap for manufacturing the most durable pellets is between 2.0 and 2.5 mm, while further increasing the gap to 5.0 mm significantly reduces pellet durability (Robohm and Apelt, 1989).

According to the prEN-14961 standard, mechanical durability has to be ≥ 97.5% (Table 1), while the PFI standard allows the mechanical durability to be as low as 96.5% (Table 1). There is no set value for fines amount in prEN standards, but PFI standards set the value for fines to <0.5% (Table 1). Furthermore, there are three different mechanical durability and fines amount specifications (I1, I2, and I3) included in the Industrial Wood Pellet Specification (Table 2). According to I1, mechanical durability has to be ≥ 97.5%, while fines amount has to be ≤ 4%. I2 follows with ≥ 97% for the mechanical durability and ≤ 5% for fines amount. And finally, I3 sets the mechanical durability limit to ≥ 96.5% and fines amount limit is at ≤ 6%.

2.4. Bulk Density

The bulk density is the mass of a portion of a solid fuel divided by the volume of the container that is filled by that portion under specified conditions (Obernberger and Thek, 2010). It can also be defined as the ratio of the sample mass and its volume including pore volume (Temmerman *et al*., 2006). High bulk density is preferable, since the higher the bulk density, the higher becomes their energy density, which consequently leads to less transport and storage costs (Obernberger and Thek, 2010). Bulk density is calculated using the following equation (Obernberger and Thek, 2010):

$$\rho_b = \frac{m_b}{V_b}$$

Where,
ρ_b - bulk density, kg/ m^3
m_b - mass of bulked good, kg
V_b - volume of bulked good, m^3

Bulk density of wood pellets can also be roughly estimated by dividing the particle density by 2 (Obernberger and Thek, 2010).

Wood pellet bulk density is dependent on the type of raw material, moisture content, grind size, particle density, and pre-treatment (Mani *et al.*, 2006; Obernberger and Thek, 2010). Raw materials with larger particle size and higher moisture content reduce bulk density of the product (Tumuluru *et al.*, 2010). However, decrease in hammer mill screen size during production of pellets leads to increase of bulk density (Tabil *et al.*, 2011).

Increase in particle density leads to increase in single pellet density, which should directly lead to an increase in bulk density (Thek and Obernberger, 2010).

Pre-treatment of raw material causes a decrease in bulk density due to disintegration of organized lignocellulosic structure of biomass (Tabil *et al.*, 2011).

In prEN-14961 standard and Industrial Wood Pellet Specification (Table 1 and Table 2), it is stated that bulk density of wood pellets must not be lower than 600 kg/m^3, while PFI standard (Table 1) sets the limit to ≥640 kg/m^3.

2.5. Ash Content

The ash content (or total ash) is the mass of inorganic residue remaining after combustion of a fuel under specified conditions, typically expressed as a percentage of the mass of dry matter in fuel. Main ash forming elements in wood are calcium, magnesium, silicon, and potassium (Obernberger and Thek, 2010). It is desired for ash content to be as low as possible, especially for small-scale residential users, since low ash content means longer emptying intervals for the ash box. Furthermore, high ash content can decrease stove efficiency and potentially degrade internal metal components. However, if the pellets are used on a large, industrial scale, low ash contents are less important because large installations are built in a more robust way that can handle higher ash contents (Obernberger and Thek, 2010). Obernberger and Thek (2004) used two different methods to determine the ash content of wood pellets (loss of ignition at 550°C according to Swedish SS 187171 standard and at 815°C according to German DIN 51719 standard). The relative difference as relating to the determination at 550°C was calculated according to equation:

$$\Delta_{ash} = 100 - \frac{X_{ash,815}}{X_{ash,550}} * 100$$

Where,
Δ_{ash} - relative difference in ash content, %
$X_{ash,550}$ – ash content as determined at 550°C according to SS 187171
$X_{ash,815}$ – ash content determined at 815°C according to DIN 51719

The ash content that is determined at 815°C is generally beneath the one determined at 550°C (Obernberger and Thek, 2010). It is concluded that the ash content of solid biomass fuels should generally be determined at 550ºC, which has been taken into account in the European standard EN 14775 (Obernberger *et al.*, 1998).

Ash content of wood pellets is highly and directly influenced by the raw materials used in the production. In general, softwoods have lower ash contents (average of 0.71%) than hardwoods (average of 0.91%) (Gaur and Reed, 1998). Additionally, Table 3 also shows ash content of softwoods, hardwoods, bark, and straw. However, ash content of wood pellets can be higher than the ash content of the raw material, due to external factors, such as different impurities and additives (such as bark and sand) which increase ash content (Hansen *et al*., 2009).

Table 3. Typical ash contents of different types of biomass (Stockinger and Obernberger, 1998; Obernberger, 2007; Obernberger 1997).

Fuel type	**Typical ash content wt. % (d.b.)**
Softwood (without bark)	0.4 - 0.8
Hardwood (without bark)	1.0 - 1.3
Bark	2.0 - 5.0
Straw	4.9 - 6.0

High ash content can have a negative impact on stove efficiency, it can also display a negative effect on the calorific value, which is easy to see from the equation for *HHV* (Gaur and Reed, 1998) in the Calorific Value section.

Finally, ash content has a direct dependence on dust emissions, which means the higher the ash content the higher are dust emissions (Hartmann and Herranen, 2005).

PrEN 14961 standard requires ash content to be 0.7%, or lower (Table 1), while PFI standard and I1 Industrial Wood Pellet Specification require ash content to be ≤ 1.0% (Table 1 and Table 2). As mentioned earlier, industrial wood pellets that are being used on a larger scale, don't have to meet residential standards regarding ash content (except I1). I2 Industrial Wood Pellet Specification requires ash content to be ≤ 1.5%, while I3 Industrial Wood Pellet Specification allows ash content to be as high as 3% (Table 2).

2.6. Volatile Matter and Fixed Carbon

Carbon (C), together with hydrogen (H) and oxygen (O), is the main component of biomass fuels (since cellulose, hemi-cellulose and lignin consist of these elements) (Obernberger and Thek, 2010). Concentrations of these elements have an impact on both gross and net calorific values (Obernberger and Thek, 2010). Higher concentrations of carbon in woody biomass, compared to herbaceous biomass, give a higher gross calorific value of woody biomass (Obernberger and Thek, 2010).

The volatiles are that part of the organic content of the fuel that is released in 7 min at a temperature of 900^{0}C under exclusion of air (EN 15148, 2009). The volatiles influence thermal degradation and combustion behaviour of the biomass (Van Loo and Koppejan, 2008).

Table 4 shows concentrations of carbon and volatiles in different biomass materials.

The determination of the concentration of carbon is regulated by prEN, while the volatile matter has to be determined according to EN 15148.

Specific values for the concentration of carbon and volatile matter are not specified in any of the standards that were mentioned earlier (prEN 14961, PFI, or Industrial Wood Pellet Specification).

Table 4. Concentrations of fixed carbon (C) and volatiles in different biomass materials (Van Loo and Koppejan, 2008).

Fuel type	**Fixed Carbon (C) wt. % (d.b.)**	**Volatiles wt. % (d.b.)**
Wood chips (spruce, beech, poplar, willow)	47.1 - 51.6	76.0 - 86.0
Bark (coniferous trees)	48.8 - 52.5	69.6 - 77.2
Straw (rye, wheat, triticale)	43.2 - 48.1	70.0 - 81.0
Miscanthus	46.7 - 50.7	77.6 - 84.0

2.7. Influence of Storage on Biomass Fuel Quality Properties

Biomass fuels, including wood pellets, are always sensitive to air humidity as they tend to either absorb or release moisture. Unfavourable storage conditions can cause moisture and weight increases (Obernberger and Thek, 2010). Since moisture uptake negatively impacts the rest of the properties, it is important to ensure dry storage conditions, which is mostly done by placing the wood pellets indoors. However, outdoor storage is also an option with wood chips or thermally treated wood pellets.

Most of the past literature has focused on the pellet quality tests and comparisons after manufacturing. Very few studies focus directly on property changes and wood pellet degradation during indoor or outdoor storage.

Since the purpose of this research is on the outdoor storage of wood pellets, this section will focus on the outdoor storage of both wood chips and wood pellets, in regards to their quality property changes.

Outdoor storage of wood chip piles, for example, showed that the moisture content of wood chip piles followed the average rainfall, although natural drying did occur throughout the storage period taking the moisture content of the chips from 50% down to 30%. No clear trends were observed within ash content and calorific value (First Renewables Ltd., 2002).

Furthermore, the outdoor storage of Willow chips is influenced by the weather pattern, especially the rainfall, which has a negative impact on moisture content and net calorific value. Willow chips that are stored indoors undergo gradual drying and increase in net calorific value (Graham, 2015).

Since moisture content is the largest factor in the efficiency of biomass for heat and power generation, biomass users are considering covering the biomass piles with tarps, when stored outside, to prevent water getting into the pile and hence raising the moisture content of the stored product. Studies have shown that both uncovered and covered wood chip piles are able to dry to similar levels without the investment of the covering paper (biomass tarp). However, if the wood chip pile is covered with a biomass tarp, the increased rate of drying can occur in the center of the pile. That applies only when the tarp is removed two months before the use of the product to allow for surface drying, conditional on time of the year. Furthermore, one of the main benefits of covering wood chip piles with biomass tarp is to minimize contamination of the wood chips in the winter months by snow and ice. If the piles are left uncovered to allow drying during summer months and then are covered before snowfall and fall rains, snow and rain contamination can be avoided (Seargeant, 2014).

Shape of the biomass piles can also have a significant impact on the drying of the biomass when stored outside. The most drastic drying occurs when the piles are formed into conical shapes;

proper shape and conical peak to the pile appear to satisfy water shedding, and moisture dissemination (Seargeant, 2014).

Conventional ("white") wood pellets, when stored in bags, over different periods of time, show a tendency to equilibrate to moisture content of about 11%; they don't show significant changes in the bulk density, ash content, or calorific value, and no temperature surges. Finally, storage of conventional wood pellets in bags resulted in breaking up of the pellets, and in the decrease of the pellet durability (Lehtikangas, 2000).

Storing conventional wood pellets in an environment where the pellets are exposed to high humidity can result in pellets moisture rising to as high as 13% (Graham, 2015). Furthermore, in humid conditions, the conventional wood pellets can increase in volume 30% (Fasina and Sokhansanj, 1996), which is caused by the moisture uptake. Storing thermally treated ("black") wood pellets in a covered and ventilated storage environment, results in gradual increase in moisture content over time due to exposure to humidity but after 20 months in storage, the moisture content is still below 10% (Graham, 2015). However, the moisture content of the outside stored thermally treated wood pellets, is highly influenced by humidity and especially rainfall. If the rainfall increases, thermally treated wood pellets will absorb moisture (Graham, 2015).

Thermally treated wood pellets also decrease in net calorific value, with more significant decrease for the pellets stored outside. While the net calorific value of the conventional wood pellets also decreases during the indoor storage, the decrease is smaller (approximately 5%) (Graham, 2015).

Even though freshly produced thermally treated wood pellets have higher mechanical strength than freshly produced conventional wood pellets, after the storage, conventional wood pellets show higher resistance to mechanical degradation than the outside stored thermally treated wood pellets (Graham 2015). As mentioned earlier, high rainfall and humidity contribute to the increase in moisture content, which results in pellets swelling and a drop in mechanical strength (Graham, 2015). However, mechanical degradation is low for thermally treated wood pellets, which are stored inside (Graham, 2015).

This study looks at the properties mentioned in the literature review for covered and uncovered thermally treated pellets over a period of one-year to determine the feasibility of storing thermally treated pellets outdoors in Northwestern Ontario, Canada.

3. Materials and Methods

3.1. Study Site

The study took place at the Thunder Bay Generating Station (TBGS) (48°21'39.1"N 89°13'10.8"W), located in Thunder Bay, Ontario, Canada. More specifically, in the outside storage depot, where the generating station formerly stored their previous fuel (coal). Two piles of advanced wood pellets ("steam exploded"; "black") were built there in January 2016. The piles were built using advanced wood pellets that were delivered from factory to TBGS in October 2015, and were uncovered and stored in larger piles and outside since then. The piles for this study were divided by treatment, one pile was uncovered and one pile was covered with a biomass tarp (Walki cover paper). Each pile was measured at 1.4 m tall, 4.6 m wide and 5.8 m long.

3.2. Sample Collection

Sample collection began in February 2016, with samples being collected once a month until December 2016 (11 months in total). The sampling scheme was divided between which pile the sample was collected from and the location of the sample. Every month, nine samples from the covered pile and nine samples from the uncovered pile were collected, totalling 18 samples, with each sample weighing approximately 2 kg. One sample was collected from the top, four samples from the middle and four samples from the base (two from the base core and two from the base edge) of each pile. One from the top, four middle, and two base edge samples were taken from a depth of 30 cm. Two samples from the base core of the pile were retrieved using a device called a "sample thief". A "sample thief" consists of two plastic tubes, one with a larger diameter and one with a smaller diameter, where the smaller tube is inserted into the larger tube to retrieve a sample from the base core. The two “sample thieves” were placed at the base of each pile when the piles were initially being built. The advanced wood pellet samples were then placed into plastic, air-tight Ziploc bags and labelled with location in the pile, covered or uncovered pile and date of collection. In addition pile temperature was recorded at each sample period (described below).

In August 2016, 10 kg of fresh factory sample was received for testing straight from the factory, sealed in an air-tight plastic bag padded with air bubbles to neutralize the impact of transportation.

3.3. Advanced Wood Pellet Quality Properties Testing

The advanced wood pellet quality properties were tested in laboratories at the Faculty of Natural Resources Management at Lakehead University, Thunder Bay, Ontario, Canada. Moisture content, calorific value, mechanical durability, fines amount and bulk density were tested at the Lakehead University Wood Science Testing Laboratory. Ash content, volatile matter and fixed carbon were tested at the Forest Resources & Soils Testing Laboratory.

3.3.1. Moisture Content

Moisture content was determined following the American Society for Testing Materials International (ASTM) Standard Test Method for Moisture Analysis of Particulate Wood Fuels (ASTM E 871 – 82, 2006). This test method covers the determination of total weight basis moisture in the analysis sample of particulate wood fuel (ASTM E 871 – 82, 2006). The moisture content testing followed this procedure:

- A tray was placed onto the “Sartorius ED2202S” scale and tarred

- Initial (green) sample was then placed into the tray and weighed to 100±0.5 g and to the nearest 0.01 g; exact weight was recorded,
- The sample was placed into the open, non-porous metal tray and put into the “HotPack” drying oven for 48 hours at the temperature of 103±1°C,
- The now oven dried sample was cooled to room temperature,
- Oven dry sample was then weighed in a tarred tray on a scale; exact weight was recorded.

Moisture content was calculated using the following equation (ASTM E 871 – 82, 2006):

$$MC = \left(\frac{W_i - W_o}{W_o}\right) * 100$$

Where,
MC - moisture content in the analysis sample, %
W_i - initial green weight of the sample, g
W_o - oven dry weight of the sample, g

The nine samples per pile for each month were tested for moisture content. This same testing procedure was used to determine the moisture content of fresh factory sample.

3.3.2. Calorific Value

Calorific value was determined following the ASTM Standard Test Method for Gross Calorific Value of Refuse-derived Fuel by the Bomb Calorimeter (ASTM E 711-87, 2004). This test method covers the determination of the gross calorific value of a prepared sample of solid forms of refuse-derived fuel (RDF) by the bomb calorimeter method (ASTM E 711-87, 2004).

For this research, a “Parr 6200” oxygen bomb calorimeter was used together with “Parr 6510” water handling system. Prior to calorific value testing in the bomb calorimeter, samples were ground in the "Wiley-Mill" grinder and screened through 2 mm mesh. Prepared ground samples were then put into the air-tight plastic containers. After that, samples were placed into specimen metal containers, weighed to 1.7±0.1 g on the "Mettler Toledo ML" scale to the nearest 0.0001 g, and then put onto the holder, where a fuse wire was attached to the holder and placed into the sample. The holder with the sample was then placed into the bomb, closed firmly and filled with oxygen to 450 psi. The bomb was then put into a metal bucket filled with 2 L of distilled water. Once the oxygen filled bomb was inside of the bucket, the bucket was placed into the calorimeter chamber and fuse wires were connected to the bomb. Next, the calorimeter lid was shut. Now, prior to firing the run, the original weight of the sample was input into the calorimeter software. Finally, once the run is fired and completed and the sample burnt, the bomb calorimeter calculated the gross heat of combustion using the equation (Parr Instrument Co., 2007);

$$H_c = \frac{(W * T) - e_1 - e_2 - e_3}{m}$$

Where,
H_c– gross heat of combustion, MJ/kg
T – observed temperature rise, ^{o}C
W – energy equivalent of the calorimeter and bomb bucket combination being used, MJ/^{o}C
e_1– heat produced by the burning of the nitrogen portion of the air trapped in the bomb to form nitric, MJ
e_2 – heat producing by the formation of sulphuric acid from the reaction of sulphur dioxide, water and oxygen, MJ
e_3 – heat produced by the fuse wire and cotton thread, MJ
m – mass of the sample, kg

Net calorific value was calculated using the equation for LHV-lower heating value (see Wood Pellet Quality Properties chapter, Calorific Value section).

For this testing, nine samples from each pile were bulked into four separate groups: top, middle, base core and base edge. That gave us eight bulked samples (four for each pile) per month. Each sample was tested three times and the average was recorded as the final net calorific value. Gross calorific value samples were bulked into one sample for each pile per month, and all the samples were tested three times, the average was recorded as the final gross calorific value. Fresh factory sample was tested three times and the average was recorded as the final calorific value.

3.3.3. Mechanical Durability and Fines Amount Testing

Mechanical durability and fines amount were tested according to the Austrian Standard EN 15210-1: Determination of mechanical durability of pellets and briquettes (Austrian Standards Institute, 2009). The machine used was the "Ligno-Tester EX II", with an integrated 3.15 mm sieve inside of its chamber. The machine has two different test settings, with the first being for mechanical durability (DU) and the second for fine material amount (F) testing. Both settings work by blowing air into the chamber where the sample is placed, the air forces the pellets against each other and the walls of the machine chamber, which allows the sieve to then separate the broken particles and fines from the sample. "Sartorius ED2202S" scale was used for both tests. Also, "wet" ("as received") samples were used for both mechanical durability and fines amount testing.

3.3.3.1. Mechanical Durability

For the mechanical durability test, 100±0.5 g of sample was weighed on the scale to the nearest 0.01 g and the weight was recorded. The sample was then put into the "Ligno-Tester", which was set to the mechanical durability (DU) setting. The machine was then turned on and it tumbled the sample for 60 seconds. At the test's completion, the sample remaining in the chamber was weighed on the scale and the final weight was recorded.

Mechanical durability was calculated using the equation (Austrian Standards Institute, 2009):

$$D_u = \left(\frac{m_a}{m_e}\right) * 100$$

Where,
D_u– mechanical durability, %
m_a – weight of the sample after the test, g
m_e– weight of the sample before the test, g

The nine samples per pile for each month were tested for mechanical durability. The same procedure was used to test the fresh factory sample.

3.3.3.2. Fines Amount

In the case of fines amount testing, 300±0.5 g of sample was weighed on the scale to the nearest 0.01 g. The sample was then put into the "Ligno-Tester", which was set to the fine material amount (F) setting. That setting blows the air into the chamber with the sample for 30 seconds. The sample remaining in the chamber after the test was then weighed again and the final weight was recorded.

Fines amount was calculated using the following equations (Holmen, 2011):

$$F_a = mE - mA$$

Followed by:

$$F = \left(\frac{F_a}{mE}\right) * 100$$

Where,
F – fines amount, %
F_a – weight of fines, g
$mE-$ weight of the sample before the test, g
$mA-$ weight of the sample after the test, g

Testing was done for each group of bulked samples (top, middle, base core and base edge), for both piles every month. The same testing procedure was used to determine the fines amount of the fresh factory sample.

3.3.4. Bulk Density

Bulk density was measured according to the ASTM Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels (ASTM E 873-82, 2006).

For this measurement, a 1000 cm³ glass cylinder was used. The cylinder was weighed on the "Sartorius ED2202S" scale to the nearest 0.01 g and the weight was recorded. Next, the cylinder was evenly filled with the sample to the mark of 1000 cm³. The cylinder was then dropped five times from the height of 15 cm on a non-resilient surface to induce sample settlement (ASTM E 873-82, 2006). After the sample was settled, additional pellets were added to the cylinder to fill it back up to the 1000 cm³ mark. Now the full cylinder was weighed again and the final weight was recorded. Bulk density was calculated with the following equation (ASTM E 873-82, 2006):

$$B_d = \frac{W_{cs} - W_c}{V_c}$$

Where,
B_d - bulk density, g/cm³
W_{cs} - weight of the cylinder and the sample, g
W_c - weight of the cylinder, g

V_c – volume of the cylinder, cm^3

The final results were all converted from g/cm^3 to kg/ m^3.

Each group of bulked samples (top, middle, base core and base edge) for each pile and for every month were tested three times. The average was recorded as the final result for each group. The fresh factory sample was tested using the same method. Sufficient quantity of the base core sample of the uncovered pile, needed for the bulk density test, was not retrieved in December, due to the frosted state of the pile, hence it is missing from the results.

3.3.5. Ash content, Volatile Matter and Fixed Carbon

Ash content was measured as per the ASTM Standard Test Method for Ash in Wood (ASTM D 1102-84, 2007). This test method covers the determination of ash, expressed as the percentage of residue remaining after dry oxidation (oxidation at 580 to 600ºC) of wood or wood products (ASTM D 1102-84, 2007).

Volatile matter was measured according to the ASTM Standard Test Method for Volatile Matter in the Analysis of Particulate Wood Fuels (ASTM E 872-82, 2006). This test method determines the percentage of gaseous products, exclusive of moisture vapour, in the analysis of particulate wood fuel that is released under the specific conditions of the test. The particulate wood fuel may be sander dust, sawdust, pellets, green tree chips, hogged fuel, or other types of particulate wood fuel having a maximum particle volume of 16.39 cm^3 (1 in.^{3}) (ASTM E 872-82, 2006).

The fixed carbon was calculated, using the resultant of the summation of percentage moisture, ash and volatile matter subtracted from 100 (ASTM E 870-82, 2006).

These quality properties were tested with the “TGA-601 Thermogravimetric Analyzer”, which is used to determine the composition of organic, inorganic, and synthetic materials. The analyzer measures weight loss as a function of temperature in a controlled environment (Leco, 2001).

The sample preparation for the “TGA-601 Thermogravimetric Analyzer” was as follows (Leco, 2001):

- Samples were ground through a large “Wiley-mill” and then again through a small “Wiley mini mill” (40 mesh),
- Samples were stored in air-tight plastic containers,
- Samples were dried for at least 48 hours at 65ºC; weights were recorded before and after drying.

Prepared samples were then input into the analyzer, which brought the samples up to 107ºC for 2 hours (under air atmosphere) to determine moisture content, followed by bringing up the temperature up to 950ºC for 7 minutes (under nitrogen atmosphere) to determine volatile matter. Finally the samples were brought to 575ºC for 2 hours (under oxygen atmosphere) to determine ash content (Leco, 2001). All results were expressed in percentages (%).

One bulked sample from each pile was tested for every month together with one fresh factory sample.

3.4. Pile Temperature

The device used for measuring temperatures was the “Omega HH12B”, which has two 30 cm long probes. Probes were inserted into the pile (30 cm deep) and two temperatures for each location were recorded to the nearest 0.1ºC.

Pile temperatures were measured at the same time and locations within the piles, where the rest of the samples were being collected (except for the base of the pile, where temperature was measured at three locations, not four, due to the nature of the piles). The average of those two temperatures was recorded as the final result for that specific location in the pile. Due to unforeseen circumstances, September is missing from the pile temperature results.

3.5. Statistical Analysis

Statistical analysis was performed using the three-way ANOVA, without the three-way interaction term. The response variables (*Y*) were: moisture content, calorific value, mechanical durability, fines amount, bulk density, and pile temperature. Assumptions of the tests were checked using diagnostic plots. The R program was used to evaluate the relationship between predictor variables on the response variable (R Core Team, 2013). The "lm" function, which is a part of the R base package, was used to evaluate the three way ANOVA's.

4. Results

This chapter presents the results of advanced wood pellet quality properties, in terms of their degradation over time, when stored outside in the uncovered and covered piles, together with the pile temperature, and the results of the fresh factory sample quality properties. The results of the following quality properties are presented: moisture content, calorific value (net and gross), mechanical durability, fines amount, bulk density, ash content, volatile matter, and fixed carbon. Additionally, weather history for Thunder Bay, ON, Canada (for the year of 2016) is provided, in order to better understand advanced wood pellets behaviour while stored outside, and to help explain the results. Weather history includes air temperature, total precipitation, and relative humidity, and it is the closest representation of the weather conditions, which occurred at the study site at the time of this research.

Each quality property is presented in its own section, with graphs and ANOVA tables provided for the moisture content, net calorific value, mechanical durability, fines amount, bulk density, and pile temperature. For the gross calorific value, ash content, fixed carbon, and volatile matter, tables with monthly values are provided.

Average (grand mean) values, which are mentioned in the following sections, are presented, in the grand mean tables. Grand mean tables for the moisture content, net calorific value, mechanical durability, fines amount, bulk density, and pile temperature, with the values for both uncovered and covered pile, including the locations (top, middle, base edge, base core) in the pile, and time (month) of the sampling, can be found in Appendix A.

Percentage change between starting (February) and ending (December) values, for each quality property and pile, can be found in the Fresh Factory Sample section, in Table 15.

We also tested a sample of four years old advanced wood pellets stored outside. However, the exact history of their storage conditions is not known so they were not included in the main study results and can be found in the Appendix B. These advanced wood pellets were from a different producer than the pellets included in the main study.

4.1. Moisture Content

Figure 3 displays the average moisture content values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Both uncovered and covered piles started with approximately the same moisture content values (14. 83% for the uncovered, and 13.5% for the covered pile) in February, at the beginning of this research. Moisture content gradually rose during March and April, with the moisture content for the uncovered pile in April being 24.11%, while for the covered pile being 17.10%. A drop in moisture content occurred in May, for both uncovered (18.79%) and covered (15.9%) pile. In June, however, moisture content experienced a significant rise, especially in the uncovered pile (34.01%), and in the covered pile with 24.19%. Next, in July, moisture content for the uncovered pile dropped again to 20.58%, while the covered pile experienced slight drop to 23.63%. After July, the moisture content in the uncovered pile kept rising all the way to November, when it was at its peak with 41.35%, then dropped again to 36.85% in December. Covered pile, after July, kept losing its moisture content until September (19.29%), and then it started to accumulate moisture again, until November (27%), following a slight drop in December (26.72%).

In terms of locations, highest moisture content of the uncovered pile was recorded in base edge, while lowest value was in the middle of the pile. Furthermore, in the covered pile, highest values were recorded in the middle of the pile while lowest were in the base core (for data see Appendix A).

Table 5 shows that all three factors (pile, month, and location) as well as all three interactions (pile:month, pile:location, and month:location) were statistically significant.

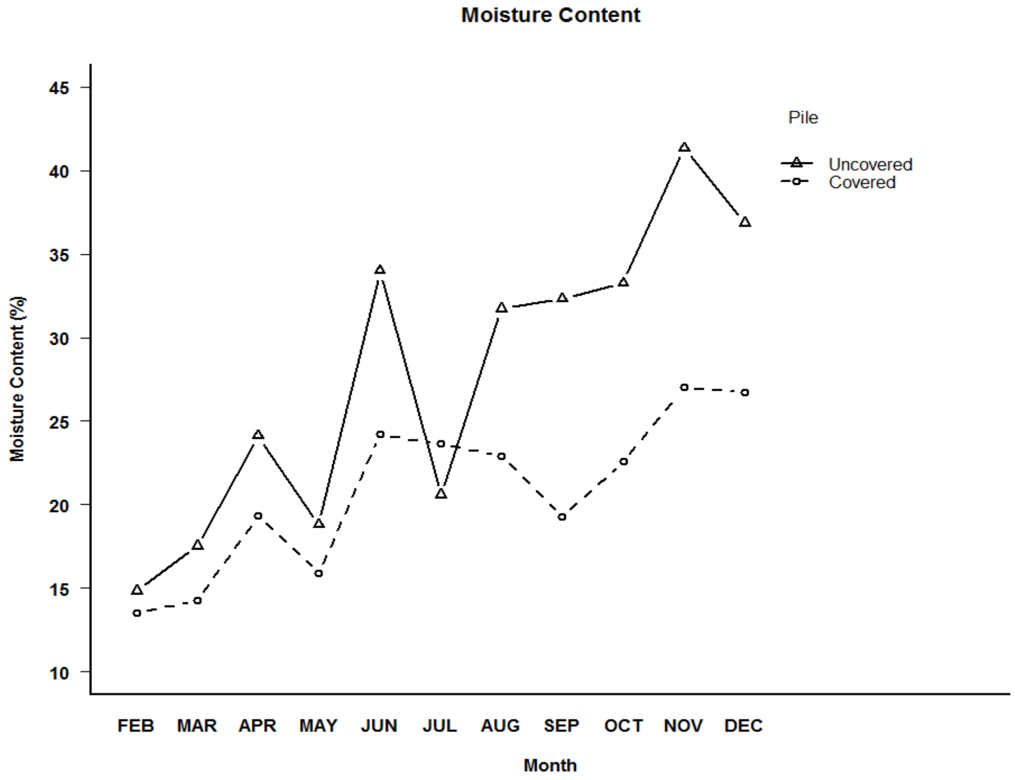

Figure 3. Moisture content (%) plot for the uncovered and covered pile.

Table 5. ANOVA table for the moisture content (%).

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	
Pile	1	1053.4	1053.36	111.1692	1.315e - 11	***
Month	10	3476.7	347.67	36.6922	4.335e - 14	***
Location	3	462.2	154.06	16.2594	1.845e - 06	***
Pile:Month	10	588.7	58.87	6.2125	4.454e - 05	***
Pile:Location	3	531.8	177.25	18.7068	4.960e - 07	***
Month:Location	30	893.1	29.77	3.1417	0.00122	**
Residuals	30	284.3	9.48			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

4.2. Calorific Value

Figure 4 displays the average net calorific values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). At the beginning of this research, in February 2016, uncovered pile started with the net calorific value of 18.98 MJ/kg, and covered pile with 18.77 MJ/kg. Covered pile kept approximately the same values until May (18.94 MJ/kg), while the uncovered pile followed a drop to 17.79 MJ/kg in April, and then it escalated to 18.74 MJ/kg in May. Both uncovered and covered piles had a significant drop in the net calorific values in June (16.46 MJ/kg for the uncovered, and 17.38 MJ/kg for the covered pile). In July, the uncovered pile had higher net calorific value, at 18.76 MJ/kg, and the net calorific value of the covered pile also rose to 18.08 MJ/kg. After July, the net calorific value for the uncovered pile kept dropping until September (16.36 MJ/kg), while the covered pile had the net calorific value of 18.46 MJ/kg in September. Next, the uncovered pile experienced the net calorific value rise again in October (16.91 MJ/kg), and then drop in November (16.39 MJ/kg), with the final value in December being 16.63 MJ/kg. The net calorific value of the covered pile, however, kept dropping from September to December, with the final value at the end of this research being 17.59 MJ/kg.

Net calorific value of the uncovered pile was most affected at the base edge, whereas least affected location was middle part of the pile. In the covered pile, lowest net calorific values were recorded at the top of the pile and the highest values were recorded at the base edge of the pile (for data see Appendix A).

Table 6 shows that all three factors (pile, month, and location) as well as all three interactions (pile:month, pile:location, and month:location) were statistically significant.

Table 7 shows the average gross calorific values of advanced wood pellets, in both uncovered and covered piles, through 11 months (February to December 2016).

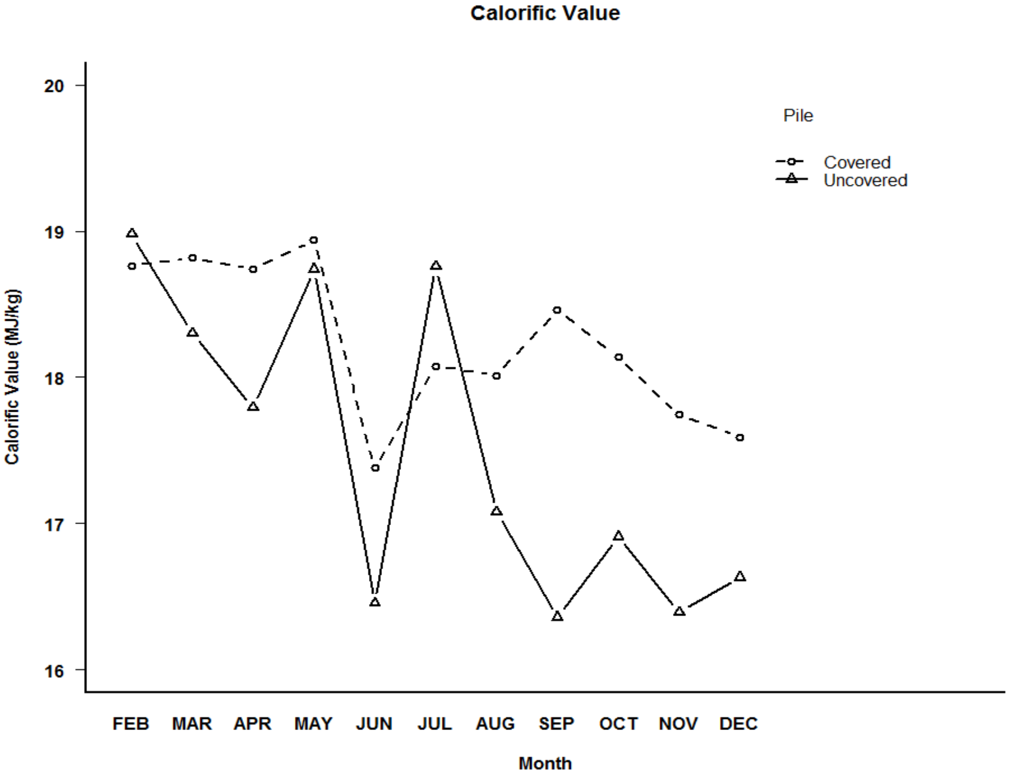

Figure 4. Net calorific value (MJ/kg) plot for the uncovered and covered pile.

Table 6. ANOVA table for the net calorific value (MJ/kg).

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	
Pile	1	12.387	12.3874	34.6103	1.934e - 06	***
Month	10	43.520	4.3520	12.1595	4.775e - 08	***
Location	3	4.545	1.515	4.2329	0.013109	*
Pile:Month	10	11.823	1.1823	3.3035	0.005394	**
Pile:Location	3	12.003	4.0009	11.1785	4.321e - 05	***
Month:Location	30	20.069	0.669	1.8691	0.045977	*
Residuals	30	10.737	0.3579			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

Table 7. Gross calorific values (MJ/kg) for the uncovered and covered pile.

GROSS CALORIFIC VALUE (MJ/kg)												**Pile Average**
Pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Uncovered	19.79	20.15	20.28	20.77	21.26	21.30	19.50	20.99	21.29	21.23	20.50	20.64
Covered	20.04	20.49	20.56	20.85	20.87	21.07	20.96	20.84	20.75	20.69	20.80	20.72

4.3. Mechanical Durability

Figure 5 shows the average mechanical durability values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Both piles started with almost the same values in February (99.23% for the uncovered, and 99.32% for the covered pile). The uncovered pile followed a drop in mechanical durability all the way from February to October, with October value being 88.76%. In November, the uncovered pile values started to rise again, with the final value in December being 93.48%. Mechanical durability in the covered pile followed a slight drop throughout all the months until November, when the value reached 96.86%. And finally, in the month of December, the mechanical durability of the covered pile elevated to 97.56%.

Location in the uncovered pile with the lowest mechanical durability values was base edge, and the highest values were recorded in the base core. Lowest values of the covered pile were at the top of the pile, while highest were in the base core (for data see Appendix A).

Table 8 shows that all three factors (pile, month, and location) as well as two interactions (pile:month, pile:location) were statistically significant.

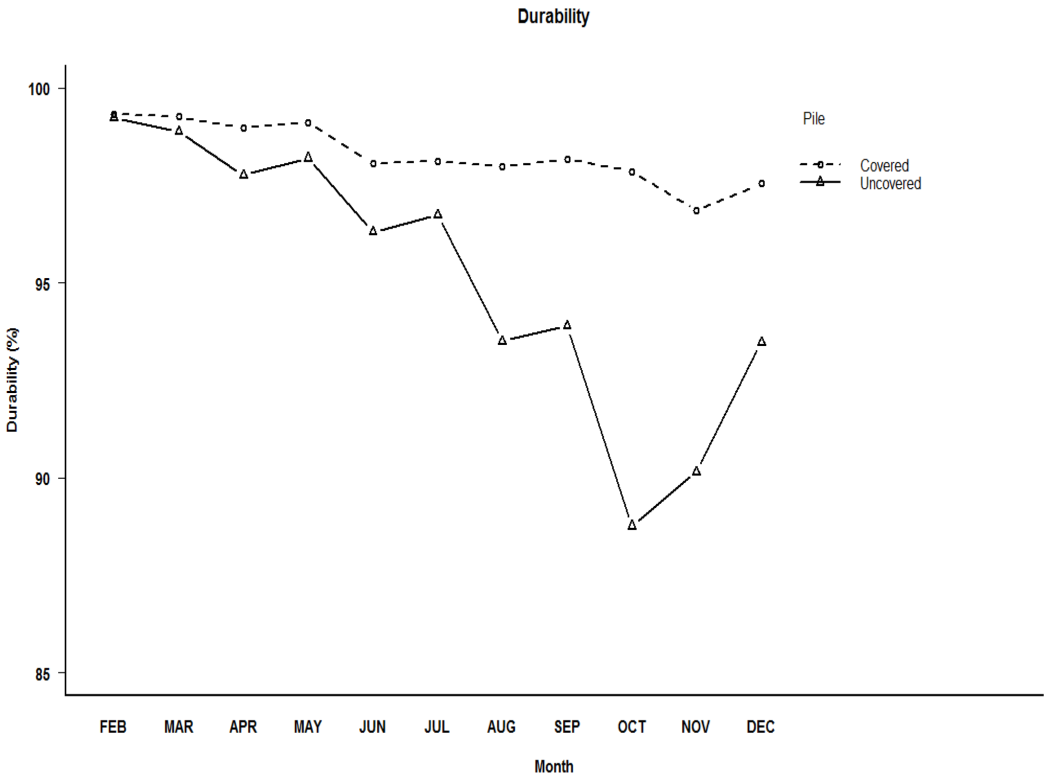

Figure 5. Mechanical durability (%) plot for the uncovered and covered pile.

Table 8. ANOVA table for the mechanical durability (%).

	Df	Sum Sq	Mean Sq	F value	Pr (>F)	
Pile	1	214.89	214.885	97.7049	5.991e - 11	***
Month	10	352.95	35.295	16.0479	1.863e - 09	***
Location	3	31.35	10.451	4.7521	0.0079174	**
Pile:Month	10	166.11	16.611	7.5529	7.204e - 06	***
Pile:Location	3	47.39	15.798	7.1829	0.0008976	***
Month:Location	30	63.10	2.103	0.9653	0.5482829	
Residuals	30	65.98	2.199			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

4.4. Fines Amount

Figure 6 shows the average fines amount values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Uncovered and covered piles started with the fines amount of 0.10% in February. Uncovered pile values rose to 0.45% in April, following ups and downs until being 0.29% in July. After July, the fines amount of uncovered pile values kept rising to 0.90% in November, and then followed a drop to 0.74% in the month of December. Covered pile values kept rising from 0.10% in February to 0.44% in June, following a drop until 0.23% in September. After September, covered pile values have risen through the months of October, November, and December, with the final value being 0.45%.

Base edge of the uncovered pile was the location with highest fines amounts while middle of the pile had lowest amounts. The covered pile, however, displayed the lowest amounts in the base edge and the highest ones at the top of the pile (for data see Appendix A).

Table 9 shows that all three factors (pile, month, and location) as well as two interactions (pile:month, pile:location) were statistically significant.

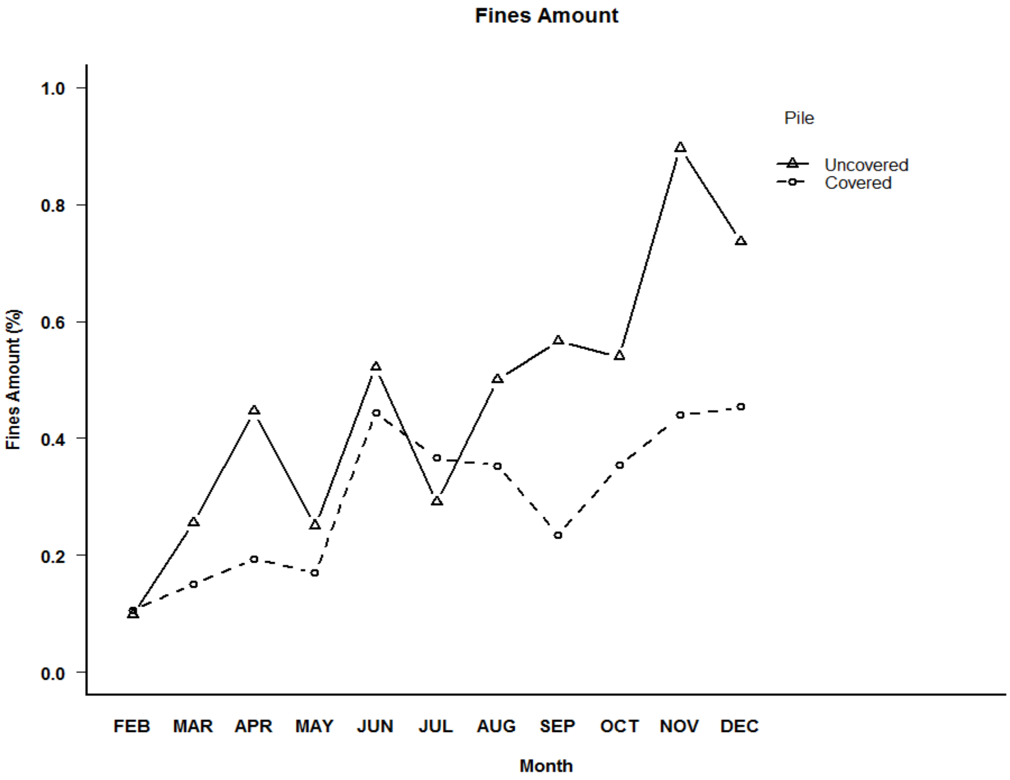

Figure 6. Fines amount (%) plot for the uncovered and covered pile.

Table 9. ANOVA table for the fines amount (%).

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**	
Pile	1	0.61536	0.61536	58.5078	1.567e - 08	***
Month	10	2.32539	0.23254	22.1095	3.479e - 11	***
Location	3	0.12906	0.04302	4.0903	0.0150949	*
Pile:Month	10	0.48183	0.04818	4.5812	0.0005591	***
Pile:Location	3	0.2284	0.07613	7.2388	0.0008566	***
Month:Location	30	0.40087	0.01336	1.2705	0.2580528	
Residuals	30	0.31553	0.01052			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

4.5. Bulk Density

Figure 7 shows the average bulk density values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). The bulk density of the uncovered pile started at 753.81 kg/m^3 in February, following a constant drop all the way to July, when it was 664.11 kg/m^3. After July, the bulk density of the uncovered pile rose to 682.79 kg/m^3 in September, and then in October, dropped again to 652.39 kg/m^3. Next, bulk density of the uncovered pile rose after October, to the November value of 720.81 kg/m^3. The final value for the uncovered pile in December, however, was lower than the earlier month (697.81 kg/m^3). Covered pile started with a bulk density of 745.76 kg/m^3 in February, with a constant drop until October, when the value was 684.82 kg/m^3. Bulk density in the covered pile during November and December behaved in the same way as in the uncovered pile, with November value of 709.24 kg/m^3 and December value of 695.73 kg/m^3.

Lowest bulk densities of the uncovered pile were shown at the base edge and the highest bulk densities were in the base core of the pile. Lowest values of the covered pile were at the top of the pile, while base edge showed highest bulk density values (for data see Appendix A).

Table 10 shows that two factors (pile, and month) as well as two interactions (pile:month, pile:location) were statistically significant.

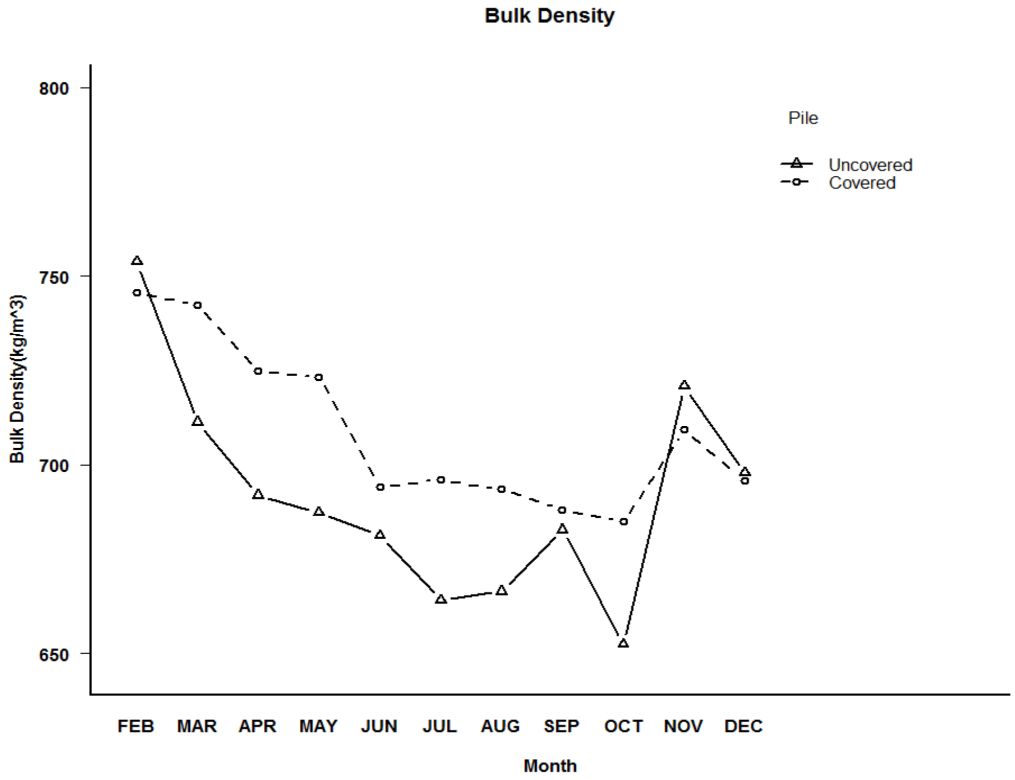

Figure 7. Bulk density plot (kg/m³) for the uncovered and covered pile.

Table 10. ANOVA table for bulk density (kg/m³).

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**	
Pile	1	6459	6459.3	54.9262	3.632e - 08	***
Month	10	45511	4551.1	38.6999	4.453e - 14	***
Location	3	435	144.9	1.2324	0.3158139	
Pile:Month	10	6659	665.9	5.6625	0.0001149	***
Pile:Location	3	3683	1227.7	10.4397	7.988e - 05	***
Month:Location	30	4932	164.4	1.3979	0.1848894	
Residuals	29	3410	117.6			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

4.6. Ash Content

Table 11 shows the ash content values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Uncovered pile started with 0.36% ash content in February (which was the highest ash content recorded). The lowest ash content value was in July (0.16%), while the final value in December was 0.18%. In February, as well as in May, the covered pile had the highest ash contents (0.39%). The lowest ash contents in the covered pile were in June and October, with the same values of 0.29%. The final December ash content value for the covered pile was 0.30%.

Table 11. Ash content (%) values for the uncovered and covered pile.

ASH CONTENT (%)												Pile Average
Pile	Month (year 2016)											
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Uncovered	0.36	0.32	0.29	0.29	0.19	0.16	0.17	0.18	0.18	0.18	0.18	0.23
Covered	0.39	0.38	0.38	0.39	0.29	0.31	0.31	0.32	0.29	0.28	0.30	0.33

4.7. Fixed Carbon

Table 12 shows the fixed carbon values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Uncovered pile started with 21.6% of fixed carbon in February, which was the highest recorded fixed carbon value. The lowest value of fixed carbon for the uncovered pile was in August (18.1%), and the final value in December was 19.8%. Covered pile started with 21.6% of fixed carbon in February. However, the covered pile had the highest fixed carbon in

March (21.6%), the lowest was in August (19.3%), and the final fixed carbon value in December was 20.5%.

Table 12. Fixed carbon (%) values for the uncovered and covered pile.

FIXED CARBON (%)											Pile Average
Pile	Month (year 2016)										
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Uncovered	21.6	21.0	20.9	20.8	18.9	20.1	18.1	20.0	20.0	19.5	19.8	20.1
Covered	21.5	21.6	21.1	21.1	19.9	20.2	19.3	21.0	20.6	21.0	20.5	20.7

4.8. Volatile Matter

Table 13 shows the volatile matter values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). Uncovered pile started with 75.5% of the volatile matter in February, which was also the highest volatile matter recorded. The lowest value recorded for the uncovered pile was 58.0% in November, and the final value in December was 60.1%. The highest recorded value of the covered pile's volatile matter was 75.6% in February, and the lowest recorded value was 65.0% in December.

Table 13. Volatile matter (%) values for the uncovered and covered pile.

VOLATILE MATTER (%)												Pile Average
Pile	Month (year 2016)											
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Uncovered	75.5	69.2	68.0	70.1	63.4	71.7	65.2	60.2	62.0	58.0	60.1	65.8
Covered	75.6	71.9	71.8	71.6	67.4	68.1	67.1	67.6	66.0	65.4	65.0	68.9

4.9. Pile Temperature

Figure 8 shows the average pile temperature values of advanced wood pellets, in both uncovered and covered piles, through 11 months of the outside storage (February to December 2016). The lowest recorded average pile temperature for the uncovered pile was in March (-6.88ºC), and the highest temperature was in July (24.02ºC). The lowest temperature in the covered pile was in February (-5.41ºC), and the highest was in July (27.26ºC).

Lowest temperatures were recorded at the base edge of the uncovered pile and the highest ones were at the top of the pile. Covered pile had lowest temperatures in the base core and highest at the top (for data see Appendix A).

Table 14 shows that all three factors (pile, month, and location) as well as two interactions (pile:month, month:location) were statistically significant.

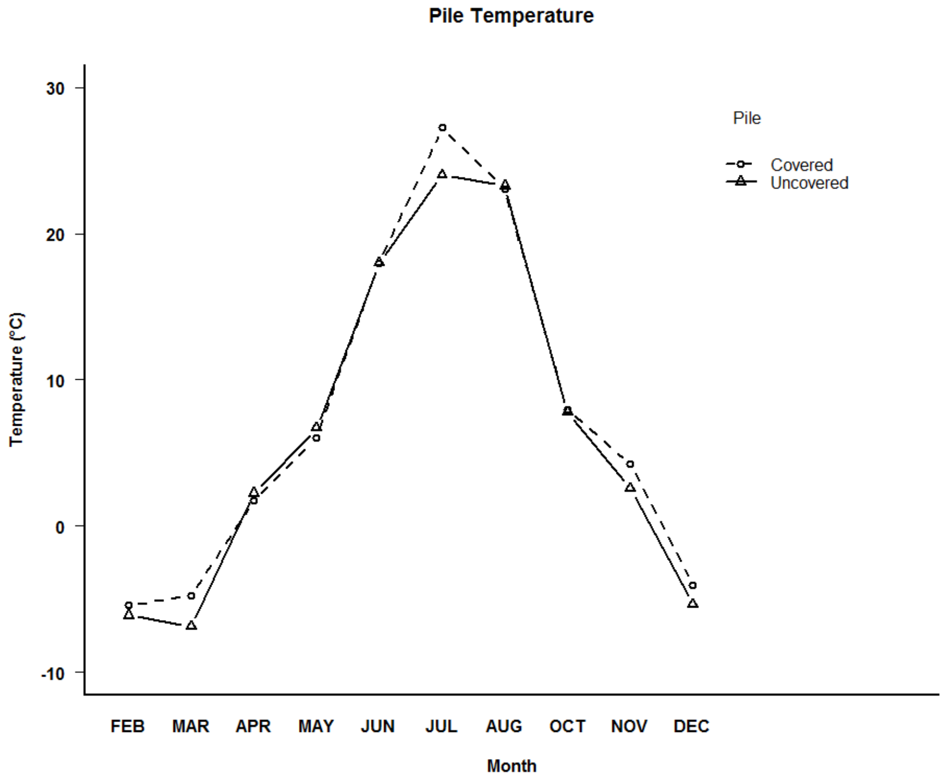

Figure 8. Pile temperature (°C) plot for the uncovered and covered pile.

Table 14. ANOVA table for the pile temperature (°C).

	Df	**Sum Sq**	**Mean Sq**	**F value**	**Pr (>F)**	
Pile	1	12.2	12.24	11.1871	0.002429	**
Month	9	9863.8	1095.98	1001.8372	<2.2e - 16	***
Location	3	19.1	6.35	5.8080	0.003376	**
Pile:Month	9	29.3	3.26	2.9796	0.013444	*
Pile:Location	3	5.5	1.85	1.6891	0.192879	
Month:Location	27	96.7	3.58	3.2753	0.001481	**
Residuals	27	29.5	1.09			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1						

4.10. Weather History for Thunder Bay, ON, Canada (Feb-Dec 2016)

Figures in this section are showing monthly values of the weather history in Thunder Bay, Ontario, Canada, for the period in which this study took place, from February to December 2016. Figure 9 displays monthly maximum, mean and minimum air temperatures. While the lowest mean air temperature was recorded in February (-11ºC), the highest was recorded in July (18ºC). Figure 10 shows total monthly precipitation. The lowest precipitation was in December (less than 20 mm) and the highest was in June (220 mm). Apart from only June, high total precipitation was also recorded in November, with 150 mm. Figure 11 displays monthly maximum, mean and minimum relative humidity. Mean values for the relative humidity varied from as low as 67% in April to as high as 83% in November.

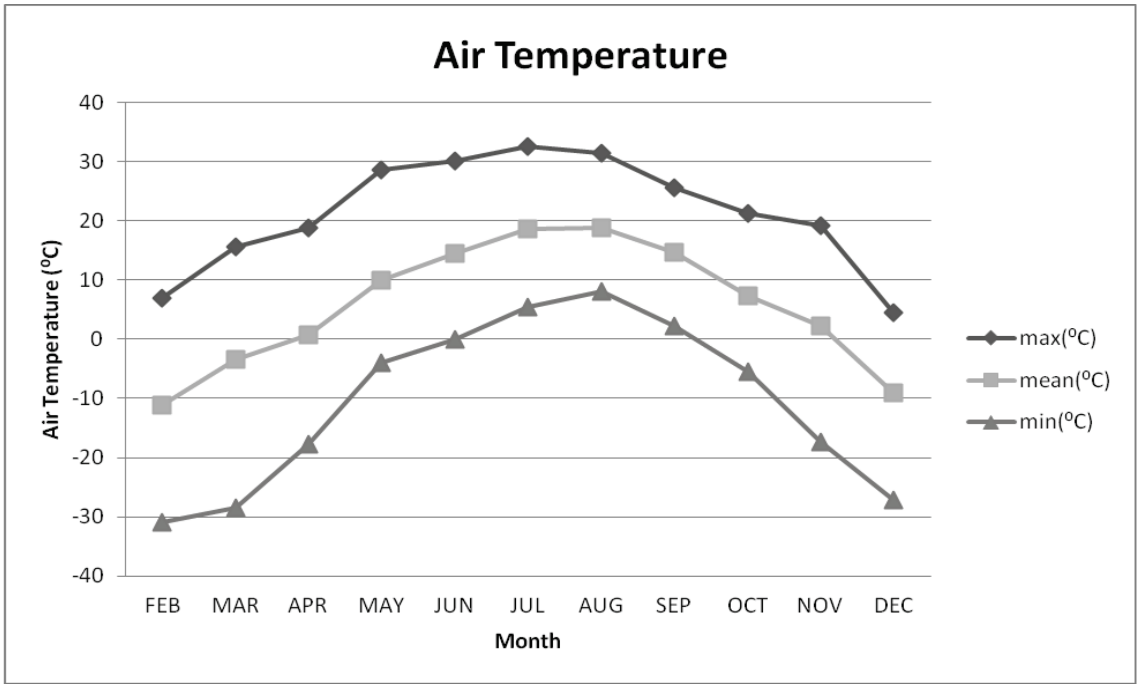

Figure 9. Air temperature (ºC) plot for Thunder Bay, ON, Canada (Feb-Dec 2016); *source:thunderbay.weatherstats.ca.*

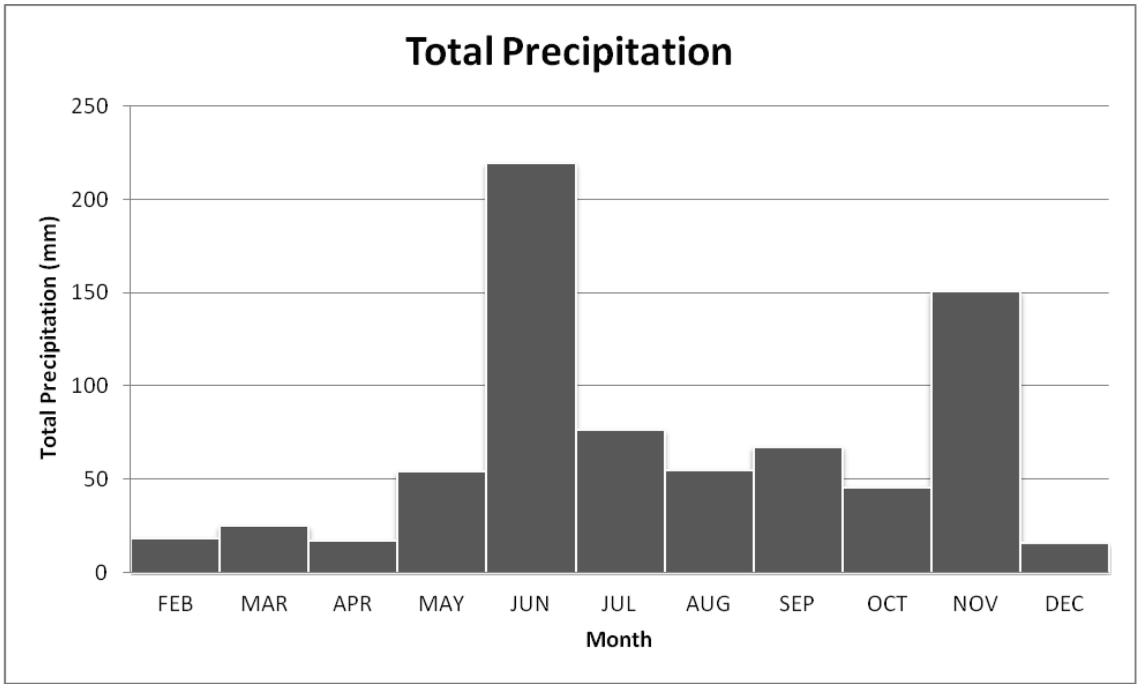

Figure 10. Total precipitation (mm) plot for Thunder Bay, ON, Canada (Feb-Dec 2016); *source: thunderbay.weatherstats.ca.*

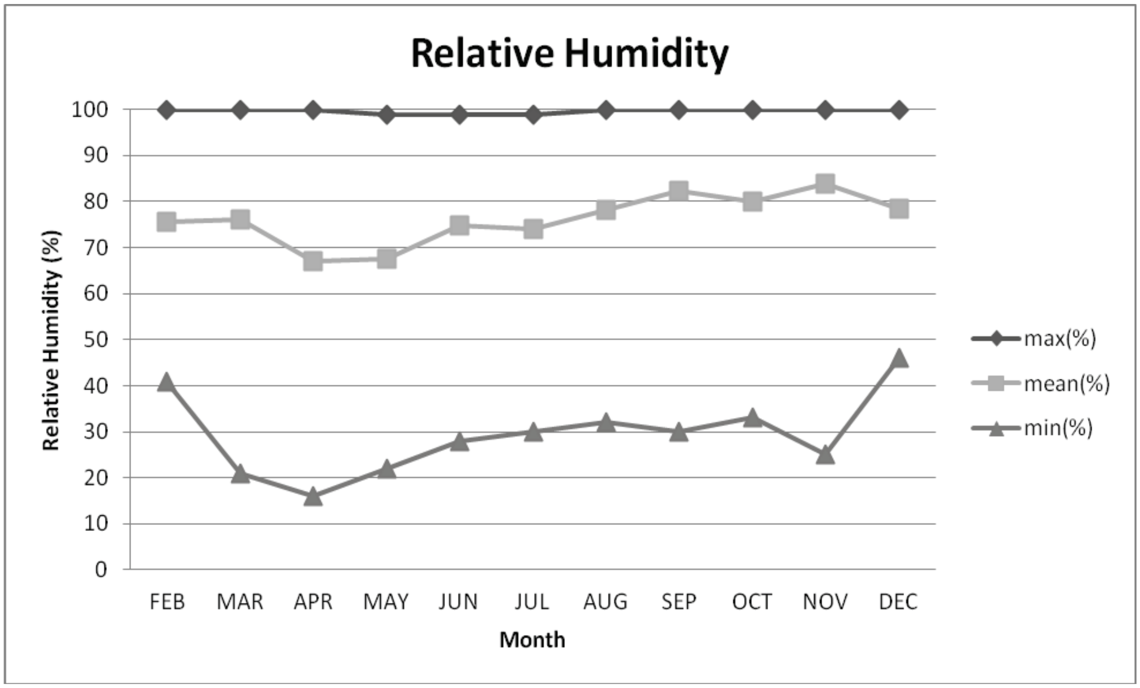

Figure 11. Relative humidity (%) plot for Thunder Bay, ON, Canada (Feb-Dec 2016); *source: thunderbay.weatherstats.ca.*

4.11. Fresh Factory Sample

Table 15 displays quality property values of the fresh factory sample which was never stored outside and is considered as a baseline, together with starting (February) and ending (December) values of the uncovered and covered piles, as well as percentage change between starting and ending values.

Table 15. Quality property values of the fresh factory sample with starting and ending values of the uncovered and covered pile.

Quality property	Fresh factory sample	Uncovered pile			Covered pile		
		Start	End	% change	Start	End	% change
Moisture content (%) (dry basis)	8.27	14.83	36.85	148.82	13.50	26.72	97.92
Net calorific value (MJ/kg)	20.11	18.98	16.63	-12.38	18.77	17.59	-6.29
Gross calorific value (MJ/kg)	21.04	19.79	20.50	3.59	20.04	20.80	3.79
Mechanical durability (%)	99.11	99.23	93.48	-5.79	99.32	97.56	-1.77
Fines amount (%)	0.08	0.10	0.74	640.00	0.10	0.45	350.00
Bulk density (kg/m³)	756.19	753.81	697.81	-7.43	745.76	695.73	-6.71
Ash content (%)	0.45 (@MC 5.8%)	0.36	0.18	-50.00	0.39	0.30	-23.08
Fixed carbon (%)	23.19 (@MC5.8%)	21.60	19.80	-8.33	21.50	20.50	-4.65
Volatile matter (%)	72.00 (@MC 5.8%)	75.50	60.10	-20.40	75.60	65.00	-14.02

5. Discussion

The results of advanced wood pellet quality properties, in terms of their degradation over time, when stored outside in the uncovered and covered piles, together with the pile temperature, and the results of the fresh factory sample quality properties are discussed in this chapter.

We focus on quality properties in regards of meeting the industrial wood pellet specifications (I1, I2, and I3) (see Table 2.), with lesser emphasis on the EU and PFI residential wood pellet standards (see Table 1.), since advanced wood pellets are mostly industrial grade wood pellets. We also discuss the interdependencies between different quality properties, and how these affect each other (interdependencies can be found in Table 1.), as well as the significance of the difference between the uncovered and covered piles.

All this is done by placing the weather history of the study site in the context of the results and findings of this research.

The grand mean values that are stated in the Results chapter, can be found in the Appendix A. Majority of general discussion, in terms of quality properties interdependencies and correlations, and influence of storage on the quality properties, can be found in the Wood Pellet Quality Properties chapter.

5.1. Moisture Content

The moisture content of both uncovered and covered pile had a general trend of gradually rising from the beginning of the outside storage period in February, to December (see Figure 3). The uncovered pile experienced peaks that differed from the gradual rise, with a low peak in May (18.79%), high peak in June (34.01%), then low peak again in July (20.58%), with the highest peak in November (41.35%). Moisture content high and low peaks in the uncovered pile were mostly related to the weather conditions (see Figure 10.), matching total precipitation peaks. Similar results were found in Graham's (2015) study, where the moisture content of the outside stored wood pellets followed the average rainfall. Total precipitations high peaks were in June (approx. 220 mm), and in November (150 mm) (see Figure 10.), the same time when the uncovered pile moisture content had its high peaks. Apart from high moisture content peaks in June and November, a high peak occurred in April, due to the snow melting on the top of the pile and all around the pile, according to the field notes, which were being taken at the moment of sampling. After high total precipitation peaks, lower total precipitation followed (in July and December), when drying of advanced wood pellets in the uncovered pile occurred, resulting in lower moisture contents. In the month of December, moisture content of the uncovered pile was lower than month before due to the significantly lower total precipitation than the month before (see Figure 10.).

The covered pile, however, did not experience exactly the same high and low peaks as the uncovered pile. The rise of the moisture content of the covered pile through 11 months of the outside storage was more gradual, with slighter high peaks in April and June, due to the same reasons as for the uncovered pile, that being higher relative humidity in the air. It is important to mention that in June, the biomass tarp was blown off from the covered pile by the wind, and it is unknown for how long (maximum of three weeks). The moisture content of the covered pile was lower than the moisture content of the uncovered pile for most of the time, except in July, when, according to the field notes, condensation occurred in the covered pile. When tarp was removed from the pile to collect the samples, a thin layer of water was observed on the inside part of the biomass tarp. In July, biomass tarp trapped the moisture inside the pile, not allowing the drying of wood pellets in the sun and warm weather, at least not on the same level as in the uncovered pile, resulting in moisture content being lower for the uncovered pile (20.58%) than for the covered pile (23.63%). Hogland and Marques (2003) stated that the convection pushes the moisture toward the surface of the piles, which would explain higher moisture contents in the covered pile, since the moisture was pushed to the outside rim of the pile but was not able to evaporate due to the coverage with biomass tarp. Furthermore, higher air temperature which occurred in July allowed for higher water holding abilities so the heated air convection can transport significant levels of moisture and can also allow for increased moisture retention from surface air sources as it is pushed toward the exterior of the pile (Tóvári *et al.*, 2012).

However, as expected, the covered pile kept the moisture content trends more consistent and significantly lower (see Table 1.) than the uncovered pile, through all the 11 months, resulting in the final moisture content value for the covered pile being more than 10% lower than for the uncovered pile. The results are similar to Seargeant (2014), where drier conditions occurred in the wood chip pile that was covered with biomass tarp. These results also confirm that biomass covering paper provides protection and shielding from rain and snow (Walki Group Oy, 2013).

Moisture content directly affects the net calorific value, mechanical durability, and bulk density (Obernberger and Thek, 2010; Wilson, 2010; Hansen *et al.*, 2009; Samuelsson *et al.*, 2012; Tabil *et al*., 2011). The negative effect of the increase in moisture content onto the net calorific value and the mechanical durability can be seen in figures 1, 2, and 3, with matching high and low peaks for moisture content and net calorific value. This can be confirmed by Obernberger and Thek (2010), who stated that higher the moisture content, lower the net calorific value.

In this study, moisture content was calculated on a dry basis. However, wood pellet specifications that were mentioned earlier (Table 1 and 2) in the Wood Pellet Quality Properties chapter state the moisture content values on a wet basis. Therefore, moisture contents were calculated on a wet basis, and all the following moisture contents in this section are wet basis.

While the Industrial Wood Pellet Specification (I1, I2, and I3) and residential wood pellet prEN standard (Table 1 and 2) state that the wood pellet moisture content should be ≤10%, the PFI standard (Table 1) is more strict, prescribing the moisture content to be ≤8%. However, specifications and standard values apply only to freshly produced pellets that come straight from the factory. Advanced wood pellets in this research did not meet any of the specifications/standards, since the starting values in February were 12.91% for the uncovered, and 11.79% for the covered pile, and the general trend of moisture content was gradually rising until December. However, it has to be taken into account that the wood pellets used for this research were already stored outside for five months, prior to the beginning of this research in February 2016 (see Materials and Methods chapter). If we apply a fresh factory sample to a freshly delivered load in October 2015, that means that the fresh load (with initial moisture content of 8.27% - see Fresh Factory Sample section in the Results chapter) gained only ~4% of moisture content during first five months of the outside storage in the larger piles, prior to the start of this research. Graham (2015) stated that thermally treated wood pellets displayed the resistance to moisture ingress and absorption during the first six months of the outside storage, which could explain why the pellets started absorbing moisture at the beginning of this study. Final moisture content for the uncovered pile in December was 16.75% higher, and for the covered pile it was 10.17% higher than the recommended value in the Industrial Wood Pellet Specification.

Moisture content (dry basis) total percentage change from February to December was 148.82% for the uncovered and 97.92% for the covered pile (Table 15).

5.2. Calorific Value

The main focus of this study is on the net calorific value, since it is, when compared to the gross calorific value, a more accurate measure of energy content; during combustion, moisture is evaporating and this process requires energy (Telmo and Lousada, 2011).

Moisture content (see Figure 3) and the net calorific value (see Figure 4) plots are displaying very clear correlations/interdependencies (see Table 1) between these two quality properties. It can be seen that the net calorific value is, for the most part, following the same general trends as the moisture content, with opposite high and low peaks (see Figures 3 and 4), i.e. the higher the moisture content, the lower the net calorific value, which was reported byObernberger and Thek (2010), which are consequently related to total precipitation peaks (see Figure 10) as well. The general trend of both uncovered and covered piles is a drop in the net calorific values through 11 months of testing. As mentioned above, the net calorific value of the uncovered pile mostly followed high and low moisture content peaks, with low peaks at times when the moisture content was at its high peaks, and vice versa. Net calorific value of the covered pile also experienced the same peaks as the moisture content, but preserving the net calorific value higher than the uncovered pile, except in July, which also confirmed the negative correlation with the moisture content. Covered pile had significantly higher net calorific values, with the final value in December being 0.96 MJ/kg higher than for the uncovered pile in the same month. Graham's (2015) study reported the similar net calorific trends, where thermally treated wood pellets showed a decrease in net calorific value during storage, the drop being more significant for the pellets stored outdoors as the increase in moisture content was higher.

Apart from moisture content, a negative impact on the calorific value was the ash content. 1% increase in the ash content leads to a 0.2 MJ/kg gross calorific value decrease in the case of energy crops (Monti *et al*., 2008). However, this study did not show any clear correlations between calorific value and ash content in any of the piles.

Furthermore, there is a positive correlation between fixed carbon and volatile matter (Tarasov, 2013). Wood pellets with high volatile matter and fixed carbon content combust easily (Chaiyaomporn and Chavalparit, 2010). This can be confirmed by this study as well, since the net calorific values of both uncovered and covered piles, through 11 months of the outside storage, had similar general trends to fixed carbon trends, and especially volatile matter trends, where the correlations were even more clear.

Higher bulk density produces higher energy density (Obernberger and Thek, 2010), which means that the energy density directly depends on the net calorific value, and consequently, interrelationship between calorific value and bulk density is indirect (Tarasov, 2013). No direct correlations, in terms of matching high and low peaks (which is the case for moisture content and net calorific value), were recorded between the net calorific value and bulk density in both uncovered and covered piles. However, bulk density and net calorific value, in both piles, had the same general trend over the 11-month period, that being a drop in values.

PrEN standard and Industrial Wood Pellet Specification (I1, I2, and I3) state a calorific value of ≥16.5 MJ/kg (PFI standard does not have a specific calorific value stated) (see Tables 1 and 2). While the covered pile net calorific values were meeting the ≥16.5 MJ/kg criterion through the whole length of this study, not dropping below 17.38 MJ/kg (value recorded in June), the uncovered pile net calorific values slightly dropped below the standard in the month of June (16.46 MJ/kg), September (16.36 MJ/kg), and November (16.39 MJ/kg). As mentioned earlier, months of June and November had the highest precipitations (see Figure 8.). However, in the final month of December, the net calorific value of the uncovered pile met the standard, with 16.63 MJ/kg.

Net calorific value total percentage change from February to December was -12.38% for the uncovered, and -6.29% for the covered pile (Table 15).

Due to the previously mentioned reasons, we mainly focused on the net calorific value. However, in addition to the net calorific value results, the gross calorific values of the uncovered and covered piles were tested. Statistical analysis was not made for the gross calorific values due to the small size of the data set (see Materials and Methods chapter).

Variables, which influence the gross calorific value are discussed in the Wood Pellet Quality Properties chapter. Telmo and Lousada (2011) stated that wood pellets made from softwood species have the gross calorific values between 19.66 and 20.36 MJ/kg. Advanced wood pellets in this study, which are made from softwood, had the average gross calorific values higher than previously mentioned 19.66 to 20.36 MJ/kg. The average gross calorific value of the uncovered pile was 20.64 MJ/kg, while the covered pile had 20.72 MJ/kg, which might be due to thermal treatment (in this case steam explosion) of the advanced wood pellets, which increases softwood's raw materials calorific value (Chen *et al.*, 2015). This is likely due to the removal of hemicelluloses, therefore increasing the overall content per mass of lignin and cellulose, with lignin being a high heat value chemical which raises the heating values of the pellets, while in the conventional wood pellets hemicelluloses fraction is still intact (Nunes *et al.*, 2014; Demirbaş, 2001). Gross calorific values of both uncovered and covered piles slightly fluctuated through 11 month of the outside storage, with the lowest value recorded in August (uncovered pile - 19.50 MJ/kg), and the highest recorded in July (covered pile – 21.07 MJ/kg). Moisture content also indirectly affected the gross calorific value, since washing out of the chemicals from the piles was observed after rainy weather, which could be decreasing the gross calorific values through loss of wood extractives like tannin, which has high heat values (Howard, 1972).

5.3. Mechanical Durability and Fines Amount

The mechanical durability of the uncovered and covered piles followed the drop through 11 months of the outside storage (Figure 5). The drop was more conspicuous in the uncovered pile, while the covered pile experienced a slighter and more gradual drop. The main reason for the drop in mechanical durability, according to this study, is the level of moisture content, since the moisture is the main factor affecting durability (Obernberger and Thek, 2010). Tarasov (2013), however, postulated that moisture content displays a positive correlation with mechanical durability. Mentioned positive correlation refers to the freshly produced wood pellets, and how different levels of moisture in the production affect the mechanical durability of the finished product. However, this research showed negative correlation between these two quality properties. Both piles displayed decrease in durability when the increase in moisture content was present. Negative correlation was especially visible in the uncovered pile, where, after high precipitations in June (see Figure 10), and absorbing a lot of water, pellet integrity was disrupted, and durability rapidly started to drop. After October, when the uncovered pile came to its lowest recorded durability value (88.76%), November and December durability rose, due to the freezing weather that occurred, which prevented the water penetrating into the pellets, hence preventing the water damaging the pellets integrity. To confirm, Graham's (2015) study also stated that the mechanical durability of the outside stored thermally treated wood pellets is very likely to be negatively affected by rainfall and water absorption. To conclude, the covered pile displayed significantly higher durability values through all of the 11 months, always remaining higher than in the uncovered pile, with much more consistency. This can be explained by Graham's (2015) study where outside stored thermally treated wood pellets showed a strong correlation between the increase in the moisture content of the pellets and the decrease in mechanical strength, therefore we had lower durability in the uncovered pile than in the covered one, due to almost always higher moisture content occurring in the uncovered pile.

Durability has a direct negative correlation with fines amount (Filbakk *et al.*, 2011). Consequently, a rise in moisture content indirectly, but negatively, impacts the fines amount, which can be clearly seen from Figure 6. Fines amount in the uncovered and covered piles followed a rise through 11 months with the rise being more noticeable and with more dramatic high and low peaks in the uncovered pile. Both piles had matching high and low peaks with moisture content. Covered pile kept fines amount significantly lower than the uncovered pile for most of the time, except in, again, July, when the fines amount of the covered pile was 0.37%, and of the uncovered pile was 0.29%, due to the earlier mentioned condensation which occurred underneath the biomass tarp, and prevented the pile from drying.

All of the standard/specification values are in Tables 1 and 2, in the Wood Pellet Quality Properties chapter. Mechanical durability of the covered pile always met all of the standards/specifications (see Tables 1 and 2) through 11 months, with the lowest value (97.56%) recorded at the very end of this study. Mechanical durability of the uncovered pile, though, after July, dropped below all of the standards and specifications, due to losing its mechanical strength and integrity, caused by increase in the moisture content (Obernberger and Thek, 2010).

In terms of fines amount, both piles were meeting all of the Industrial Wood Pellet Specifications (I1, I2, and I3) through all of the 11 months of research. PFI standard, however, is stricter, when it comes to fines amount (specified value is <0.5%). Fines amounts of the covered pile still managed to be within the PFI standard through all of the 11 months, while the uncovered pile fines amounts stopped meeting the standard in June, until the end in December (except in July, when the value was meeting the standard with 0.29%), due to lower mechanical durability which directly and negatively affects the fines amount (Filbak *et al.*, 2011).

5.4. Bulk Density

Bulk density of both the uncovered and covered piles followed a drop through 11 months of this study (Figure 7). Both piles, however, after months of dropping in values, displayed high peaks in November, when the covered pile showed the lower bulk density than the uncovered pile for the first time during the outside storage. In general, the covered pile preserved significantly higher bulk density values, but only until November. In December, both the uncovered and covered pile had approximately the same final bulk density values.

Bulk density displays a strong negative correlation with moisture content (Tarasov, 2013; Tabil *et al.*, 2011; Samuelsson *et al.*, 2012). Furthermore, increase in the moisture content results in pellet swelling (Graham, 2015), which explains the drop in bulk density as the moisture content rose. High peaks of bulk density values in November are not completely understood.

Advanced wood pellets from both uncovered and covered piles were meeting all of the standards/specifications mentioned earlier through all 11 months. Despite their gradual drop in bulk density, advanced wood pellets, at the end of the 11 month outside storage period, stayed well above all of the standards/specifications, with the final values being higher than 695 kg/m^3.

5.5. Ash Content, Fixed Carbon, and Volatile Matter

Statistical analysis was not done for the ash content, fixed carbon, and volatile matter, due to the size of their data sets. Because of that, we cannot talk about the significances in the differences between month and/or piles.

Correlations between ash content, fixed carbon, volatile matter and the other quality properties were discussed earlier in this chapter. Fixed carbon and volatile matter values are not specified in any of the standards or specifications mentioned in this study.

Ash content of both piles displayed a slight drop through 11 months of the outside storage. The drop was more noticeable in the uncovered pile (from 0.36% in February to 0.18% in December), while covered pile was more consistent (from 0.39% in February to 0.30% in December). Ash content in the covered pile always remained higher than in the uncovered pile. Graham's (2015) study, however, reported higher ash content values for the outside stored thermally treated wood pellets. The ash content values throughout Graham's (2015) study were mostly higher than 1%, in some months being more than 3%. No clear trends in Graham's (2015) study in the ash content values were observed, but starting values were general higher than the final values, like in this study.

Advanced wood pellets from both piles are meeting all of the ash standards/specifications mentioned in this study through all 11 months.

Fixed carbon of both piles had very slight variations and no clear trends were observed. For the uncovered pile, final value was 1.8% lower than the starting value, while for the covered pile the final value was 1% lower than the starting value.

Volatile matter of both piles had a general trend of drop in values through 11 months. The covered pile generally kept volatile matter values higher than the uncovered pile, except in July, when it had 3.6% lower value. Volatile matter was closely correlated to the moisture content and the net calorific value, in a way that higher moisture content and lower volatile matter lowered the net calorific value. Chemicals, such as volatile matter, were washed out of the piles during high precipitations, explaining the drop in volatile matter.

5.6. Pile Temperature

Graham's (2015) study stated that the temperature in the outside stored thermally treated wood pellet piles showed a stable behaviour and the trend followed the ambient temperature trend. The same can be confirmed by this study, in both uncovered and covered piles. Temperatures of the piles were following air temperature trends (see Figure 9), with no signs of self-heating. Temperatures in both piles were matching through the whole research, except in July, when the covered pile experienced a 3.24ºC higher temperature than the uncovered pile. Once again, rise in temperature was connected to the condensation that occurred in the covered pile, negatively affecting the quality properties of the advanced wood pellets in the covered pile, which was discussed and explained earlier in this chapter (see Moisture Content section).

5.7. Fresh Factory Sample

The average values of the quality properties of eight different conventional (white) wood pellet producers were: moisture content – 4.56%; bulk density – 690.5 kg/m^3; fines amount – 0.06%; volatile organic compounds (volatile matter) – 85.06%; fixed carbon – 9.88%; ash content – 0.48%; gross calorific value – 20.12 MJ/kg; net calorific value – 19.09 MJ/kg; mechanical durability – 98.02% (Tarasov, 2013).

Next, the average values of the quality properties of three different thermally treated (torrefied) wood pellets were: moisture content – 8.37%; bulk density – 653.3 kg/m^3; volatile matter – 82.17%; fixed carbon –17.37%; ash content – 0.47 % (Peng *et al.*, 2014).

Comparison of the quality properties of the fresh factory sample of thermally treated (steam exploded; advanced) wood pellets from this study, with the Tarasov (2013) and Peng *et al.* (2014) results are as follows:

The fresh factory sample had higher moisture content than the conventional wood pellets, but lower than torrefied wood pellets. Next, it had noticeably higher bulk density and lower volatile matter than both conventional and torrefied pellets. Furthermore, the fresh factory sample had slightly lower ash content and higher fixed carbon than conventional and torrefied pellets. Both net and gross calorific values of the fresh factory sample were higher than the net and gross calorific values of the conventional pellets. The fresh factory sample had higher mechanical durability than the conventional wood pellets.

Production of the conventional, torrefied, and steam exploded wood pellets, and how the production affects their quality properties, can be found in the Literature Review chapter.

Average quality property values of both uncovered and covered advanced wood pellet piles, at the beginning of this study in February, had lower quality than the advanced wood pellet fresh factory sample, except the mechanical durability, ash content, and volatile matter, which were of higher quality. As previously mentioned, the pellets we used were stored outside in larger piles prior to this study, so that would have degraded their quality properties comparing to the fresh factory sample. In addition the piles for this study were taken from the edge of the larger pile, which also may have had an effect on results. However, the reasons for the higher quality of the mechanical durability, ash content, and volatile matter of the pellets at the beginning of this study, compared to the fresh factory sample, could be due to using a different biomass feedstock in the manufacturing process. Additionally, storage in larger piles prior to this study might have preserved mentioned quality properties.

All of the quality property values of the fresh factory sample are fitting well within all of the standards/specifications (prEN, PFI, and all of the Industrial Wood Pellet Specifications).

6. Conclusions

The purpose of this study was to determine the level of degradation in the quality properties of advanced wood pellets, and if these produce any self-heating, while stored outside in the uncovered and covered piles. Furthermore, we wanted to investigate if covering the pile with biomass tarp will improve preservation of the properties, when compared to the uncovered pile. And finally, we wanted to recommend to the industry on how to store advanced wood pellets (to tarp or not to tarp), to minimize the degradation.

Conclusions for this study based on the results presented are as follows:

- The quality properties of the advanced wood pellets, if stored outside, were highly dependent on the weather conditions. Especially pellet moisture content, which directly followed the trends of total precipitation, dry, and freezing weather.
- Moisture content, as one of the most important wood pellet quality properties, has displayed an impact (either direct or indirect) on other quality properties.
- In general, the covered pile, compared to the uncovered pile, has shown superior preservation of quality properties. However, during dry summer months, the uncovered pile has shown better properties due to better exposure to the sun and wind; hence easier drying of wood pellets occurred.
- Furthermore, during dry summer months, biomass tarp caused condensation in the covered pile, thus enhancing the level of wood pellet degradation.
- Apart only from moisture content, all of the quality properties of the advanced wood pellets in the covered pile were meeting the industrial specifications through the whole length of the study. The uncovered pile did not meet the industrial specifications in terms

of the moisture content from the start of the research, while net calorific value and mechanical durability did not meet the specifications after the fifth month of testing.

- There was no self-heating in any pile at any time during this study. Pile temperatures followed the surrounding air temperature trends.
- Advanced wood pellets fresh factory sample met all of the standards and specifications.

Recommendations to the industry based on the results of this limited in size study are as follows:

- Covering the piles of advanced wood pellets should be taken into consideration, particularly during spring and winter months, to prevent the penetration of rain and snow into the pile.
- Advanced wood pellets in the uncovered pile significantly started to degrade after five to six months of testing. Taking into account that tested pellets were already stored outside for five months prior to the beginning of this study, optimal outside storage period without covering the piles would be up to one year. If the piles are covered, however, outside storage period could possibly be extended to up to two years, before the pellets fall below the industrial specifications. Long-term storage is an important part of supply chain management of the advanced wood pellets, especially for peaking power plants like Thunder Bay Generating Station. Peaking plants have to be able to accumulate their fuel on a long-term basis and burn it only when the grid demands to.
- In terms of the future directions of the research, we suggest to carry out a larger scale (in terms of size of the piles) study on degradation of the outside stored advanced wood pellets, which we were not able to do due to the resource limitations. Regarding the length of the study, it would most probably take more time for larger scale piles to show clear

trends in quality properties. On the other hand, the length of this study (11 months) was more than enough to clearly observe the trends in small scale piles, with clear trends appearing only after the first couple of months of outside storage.

- Finally, it was noticed that during the winter months a yellow appearance in the snow around the piles was observed. It would be worth studying the content of this yellowing (likely tannins form the pellets) to determine if this requires some sort of protective layer on the ground where the pellets are piled to ensure no chemicals are leaching into the soil below and potentially entering water tables or accumulating in a concentrated manner at the site over time.

7. References

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Appendix A

Advanced wood pellet quality property grand mean value tables

Table A-1. Moisture content (%) grand mean values for the uncovered pile.

MOISTURE CONTENT (%) - UNCOVERED PILE												**Location average**
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	13.51	15.61	23.05	21.87	32.56	33.10	34.81	27.95	35.35	39.46	28.33	27.78
Base edge	16.39	20.26	27.66	20.48	34.36	18.20	31.28	34.08	32.08	42.52	40.63	28.90
Middle	14.80	17.55	23.86	16.11	35.80	10.70	29.94	31.27	30.71	41.37	38.03	26.38
Top	14.61	16.64	21.87	16.72	33.33	20.34	31.00	36.07	34.99	42.05	40.42	28.00
Monthly average	14.83	17.51	24.11	18.79	34.01	20.58	31.76	32.34	33.28	41.35	36.85	

Table A-2. Moisture content (%) grand mean values for the covered pile.

MOISTURE CONTENT (%) - COVERED PILE												**Location Average**
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base Core	12.41	12.35	15.17	19.61	26.52	25.84	20.54	14.23	14.17	14.62	13.23	16.97
Base Edge	12.62	14.80	15.39	10.95	18.77	20.13	17.96	13.52	14.18	22.58	23.77	18.92
Middle	13.80	14.18	16.92	14.72	25.40	20.25	22.16	19.48	25.73	28.99	29.88	24.31
Top	15.19	15.61	20.90	18.34	26.09	28.30	30.92	29.94	36.17	41.82	40.01	24.11
Monthly Average	13.50	14.23	17.10	15.90	24.19	23.63	22.89	19.29	22.56	27.00	26.72	

Table A-3. Net calorific value (MJ/kg) grand mean values for the uncovered pile.

NET CALORIFIC VALUE (MJ/kg) - UNCOVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	18.9286	18.6319	17.7621	18.1415	16.4593	16.7894	16.5501	17.1662	16.5769	15.6811	17.8621	17.3227
Base edge	19.0790	17.6719	17.2172	18.4421	16.3086	19.4185	17.3112	16.0372	16.7484	16.0779	15.7854	17.2816
Middle	18.7482	18.6629	17.8634	19.2083	16.4254	20.2508	17.2500	16.6251	17.0417	16.5530	16.4994	17.7389
Top	19.1709	18.2325	18.3313	19.1766	16.6376	18.5777	17.2073	15.6039	17.2783	17.2582	16.3758	17.6227
Monthly average	18.9817	18.2998	17.7935	18.7421	16.4577	18.7591	17.0797	16.3581	16.9113	16.3926	16.6307	

Table A-4. Net calorific value (MJ/kg) grand mean values for the covered pile.

NET CALORIFIC VALUE (MJ/kg) - COVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	18.8851	18.7537	19.0804	18.3077	17.1185	17.4197	19.0830	18.9770	19.5873	19.5473	19.4002	18.7418
Base edge	18.5748	18.8246	18.6429	19.4080	18.1130	19.2305	18.8217	19.4829	19.2432	18.2729	17.7308	18.7587
Middle	18.9102	19.0272	18.8546	19.3155	17.3166	18.6485	17.8149	17.6949	17.6158	17.1774	17.0880	18.1331
Top	18.6898	18.6562	18.3941	18.7184	16.9687	17.0042	16.3339	17.6801	16.1068	15.9768	16.1436	17.3339
Monthly average	18.7650	18.8154	18.7430	18.9374	17.3792	18.0757	18.0134	18.4587	18.1383	17.7436	17.5907	

Table A-5. Mechanical durability (%) grand mean values for the uncovered pile.

MECHANICAL DURABILITY (%) - UNCOVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	99.3240	99.0862	98.3398	98.4297	97.7713	96.3167	95.6528	95.5346	94.6428	92.7756	95.1396	96.6376
Base edge	99.2299	98.8321	96.6411	97.7741	96.3569	95.2775	90.6341	93.8535	82.6644	87.0820	90.8900	93.5669
Middle	99.1001	98.9524	97.9158	98.5254	94.6863	96.9912	91.6133	93.5106	85.2817	89.8752	93.8850	94.5761
Top	99.2771	98.7049	98.1688	98.0844	96.4222	98.3974	96.1124	92.6776	92.4566	90.8602	93.9892	95.9228
Monthly average	99.2328	98.8939	97.7664	98.2034	96.3092	96.7457	93.5032	93.8941	88.7614	90.1483	93.4760	

Table A-6. Mechanical durability (%) grand mean values for the covered pile.

MECHANICAL DURABILITY (%) - COVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	99.3729	99.4270	99.0603	98.7314	97.9850	97.9256	98.3248	98.8123	99.0365	99.5111	98.9879	98.8341
Base edge	99.3914	99.2529	99.1207	99.4668	98.5782	98.4955	97.6873	98.7036	99.3804	98.1577	98.2300	98.7695
Middle	99.2994	99.2644	98.9743	99.2704	98.0531	98.4663	98.3766	98.1977	97.4826	97.0157	96.9652	98.3060
Top	99.2248	99.1047	98.7539	99.0029	97.6373	97.5715	97.5617	97.0131	95.5525	92.7707	96.0516	97.2950
Monthly average	99.3221	99.2623	98.9773	99.1179	98.0634	98.1147	97.9876	98.1817	97.8630	96.8638	97.5587	

Table A-7. Fines amount (%) grand mean values for the uncovered pile.

FINES AMOUNT (%) - UNCOVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	0.0799	0.1498	0.4128	0.2664	0.4129	0.4966	0.4999	0.5058	0.4433	1.1191	0.8333	0.4745
Base edge	0.0766	0.3932	0.5565	0.2996	0.4989	0.2066	0.5626	0.5792	0.6288	0.7731	0.8316	0.4915
Middle	0.1398	0.1999	0.5059	0.2130	0.5228	0.1629	0.4666	0.6093	0.5260	0.7988	0.6664	0.4374
Top	0.0966	0.2794	0.3126	0.2232	0.6528	0.2961	0.4730	0.5724	0.5624	0.8945	0.6120	0.4523
Monthly average	0.0982	0.2556	0.4470	0.2506	0.5219	0.2906	0.5005	0.5667	0.5401	0.8964	0.7358	

Table A-8. Fines amount (%) grand mean values for the covered pile.

FINES AMOUNT (%) - COVERED PILE												Location average
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	0.0899	0.1133	0.1099	0.2199	0.4853	0.5132	0.3198	0.0933	0.1963	0.1598	0.2331	0.2303
Base edge	0.0599	0.1300	0.1632	0.0933	0.3099	0.2965	0.2927	0.1297	0.2064	0.2832	0.4495	0.2195
Middle	0.1230	0.1433	0.2766	0.1763	0.4231	0.2565	0.3329	0.3066	0.3359	0.3966	0.4997	0.2973
Top	0.1466	0.2129	0.2230	0.1931	0.5566	0.3993	0.4662	0.4100	0.6757	0.9194	0.6327	0.4396
Monthly average	0.1049	0.1499	0.1932	0.1707	0.4437	0.3664	0.3529	0.2349	0.3536	0.4398	0.4538	

Table A-9. Bulk density (kg/m^3) grand mean values for the uncovered pile.

BULK DENSITY (kg/m^3) - UNCOVERED PILE												**Location average**
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	767.7867	720.5400	711.4067	687.4167	695.4833	674.4233	692.0067	669.8100	663.9867	727.2233	X	701.0083
Base edge	747.2767	691.4200	673.3800	662.6600	678.2867	649.5567	660.2100	689.3533	645.0833	721.2500	694.8333	683.0282
Middle	744.5700	713.2467	690.7667	703.1867	670.1367	665.2600	639.8200	675.5467	636.5900	708.2467	692.4767	685.4406
Top	755.6133	719.8967	692.2367	695.9767	680.9267	667.2133	673.5700	696.4367	663.9000	726.5000	706.1233	698.0358
Monthly average	753.8117	711.2759	691.9475	687.3100	681.2084	664.1133	666.4017	682.7867	652.3900	720.8050	697.8111	

Table A-10. Bulk density (kg/m³) grand mean values for the covered pile.

BULK DENSITY (kg/m³) - COVERED PILE												Location average
Location in the pile	Month (year 2016)											
	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Base core	757.0533	744.1500	739.9767	710.9267	712.0167	700.6633	694.8500	690.1000	680.4033	681.9833	677.9667	708.1900
Base edge	749.6667	756.0767	723.6833	742.2933	707.2567	700.6167	682.0500	696.0800	696.1467	724.0250	697.5467	715.9493
Middle	738.3200	743.7800	724.4433	740.7267	693.9533	684.1833	701.7100	695.0933	677.0967	719.1367	707.8767	711.4836
Top	737.9800	725.6000	711.4967	699.0133	663.4667	698.7333	695.3633	671.1333	685.6233	711.8100	699.5333	699.9776
Monthly average	745.7550	742.4017	724.9000	723.2400	694.1734	696.0492	693.4933	688.1017	684.8175	709.2388	695.7309	

Table A-11. Pile temperature (ºC) grand mean values for the uncovered pile.

PILE TEMPERATURE (ºC) - UNCOVERED PILE												**Location average**
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	-4.90	-5.65	3.95	8.60	18.20	22.80	22.35	X	6.90	1.90	-7.20	6.70
Base edge	-7.00	-5.90	2.00	5.85	17.75	22.63	21.95	X	7.05	2.75	-5.25	6.18
Middle	-7.03	-7.58	2.70	6.71	18.08	23.79	22.69	X	6.08	2.70	-5.18	6.30
Top	-5.50	-8.38	0.35	5.65	18.00	26.85	26.15	X	11.05	3.00	-3.80	7.34
Monthly average	-6.11	-6.88	2.25	6.70	18.01	24.02	23.29	X	7.77	2.59	-5.36	

Table A-12. Pile temperature (ºC) grand mean values for the covered pile.

PILE TEMPERATURE (ºC) - COVERED PILE												**Location average**
Location in the pile	**Month (year 2016)**											
	Feb	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
Base core	-4.40	-6.20	2.50	6.20	17.40	24.85	21.35	X	7.60	2.10	-5.70	6.57
Base edge	-5.15	-2.85	2.23	7.30	17.90	26.18	21.13	X	8.18	3.58	-6.08	7.24
Middle	-6.30	-4.78	1.74	6.10	18.14	28.16	24.18	X	8.23	3.73	-4.55	7.47
Top	-5.80	-5.20	0.58	4.40	18.60	29.85	25.60	X	7.85	7.50	0.25	8.36
Monthly average	-5.41	-4.76	1.76	6.00	18.01	27.26	23.07	X	7.97	4.23	-4.02	

Appendix B

Four years old advanced wood pellet quality property grand mean value tables

Table B-1. Quality property grand mean values of the four year old advanced wood pellets stored outside.

Quality property	Four year old advanced wood pellets
Moisture content (%) (dry basis)	52.10 (Feb4/16)
Calorific value_net/gross (MJ/kg)	16.9393 (@MC 28.64%) / 20.5899 (@MC 0%)
Mechanical durability (%)	94.5203 (@MC 28.64%)
Fines amount (%)	0.4949 (@MC 28.64%)
Bulk density (kg/m³)	702.5233 (@MC 28.64%)
Ash content (%)	0.48 (@MC 19.8%)
Fixed carbon (%)	20.8 (@MC 19.8%)
Volatile matter (%)	63.2 (@MC 19.8%)