Factors affecting the utilization of lignocellulosic biomass; compaction, handling and storage, and monetary value – A review

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Clifford Dueck, A.M. de Souza Cruz, and S. Cenkowski. 2017. Factors affecting the utilization of lignocellulosic biomass; compaction, handling and storage, and monetary value – a review. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada 59: 8.11-8.21. In recent history, fears of climate change and a possible looming energy crisis due to depleting fossil fuel reserves have stimulated research into the use of lignocellulosic biomass as an alternative energy source. Political and social will has promoted the use of biomass for both heat and electric energy generation. Legislation, particularly European, has been a driving force in promoting the use of biomass. Tax incentives, feed in tariffs (FIT), quota systems, and subsidies have assisted in making the use of biomass economically feasible. A simplified mathematical model to determine the market value of biomass is examined and some of its limitations are discussed. The difference in higher heating value (HHV) and lower heating value (LHV), criteria for rating biomass, is demonstrated using mathematical relationships. Significant differences in composition, quality, and energy values of densified biomass products depend on factors including chemical composition, physical characteristics, the use of binders, and storage and handling conditions. Improper storage conditions increase the risk of life and property loss. Ash contributes to premature equipment failure and lowers the biomass energy value. Biomass sources with high ash content may fail to meet standards for compacted biomass. Keywords: biomass, compaction, energy values, pellet quality

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INTRODUCTION

The European Union (EU) has defined biomass as the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry, and related industries, as well as the biodegradable fraction of industrial and municipal waste (European Union 2009). Biomass has low bulk density causing major problems during storage, handling, and transportation for further processing (Mani et al. 2003). A strategy to overcome these issues is densification by compaction of the raw materials into pellets or briquettes. Pellets are formed by an extrusion process, where the biomass is pressed in round cross-sectional dies in a pellet mill. Pellets have a length smaller than 38 mm (1.5 in.) and a diameter around 7 mm (0.3 in.). Briquettes are larger than pellets with diameters of at least 25 mm (1 in.) and are produced when the biomass is pressed in a die by a piston press. Briquettes can also be produced through a process called screw extrusion, where biomass is extruded by a screw through a heated die. The compacted biomass produced by a screw extrusion has better long term stability for storage and higher energy density properties compared to biomass produced using a piston press (Clarke and Preto 2011). While the shapes of pellets are limited to cylinders, briquettes can be made in various shapes including cylindrical, cubic or any polygon with or without a hollow core. In practice, many different combinations of operating conditions and modes are employed, resulting in final products of different characteristics. Two criteria are used to define the quality of pellets (densified biomass): their chemical composition and physical characteristics (Garcia 2010). The market value of densified biomass can be mathematically related to the specific energy of a standard fuel, such as heating oil.
For biomass utilization as an energy source, it must be compacted. The compaction process is affected by factors such as chemical and physical characteristics, the use of binders, and the source of the biomass. The objectives of the current review are to (i) analyze the factors affecting biomass compaction, (ii) review the subsequent treatment, storage, and handling of the compacted biomass, and (iii) examine the end value of the product.

**Energy values of densified biomass**
Tabárès et al. (2000), Werther et al. (2000), and Dorez et al. (2014) identified several features of biomass combustion from which a list of general characteristics of biomass suitable for use as a fuel source should include:

- **Ease of drying**: Energy used for drying biomass to acceptable moisture content (mc) levels lowers the net energy gain, reducing the commercial value and viability of use as an energy source. In addition, high mc also negatively influences the rate of volatilization.

- **High calorific value**: A positive linear relationship exists between calorific value and economic value. Specific energy J/kg and energy density J/m² are used to determine the feasibility of transport, storage, and utilization of biomass before and after densification.

- **High content of volatiles**: Volatiles provide the bulk of the energy for biomass and are linearly related to the available energy.

- **High combustion rate**: Chemical and physical characteristics affect the combustion rate of biomass products. The shape and size of briquetted biomass affect the rate and efficiency of volatilization.

- **Low activation temperature**: Adequate cellulose content will ensure a low activation temperature, which is required to maintain the combustion process. Low activation temperature is also referred to as low activation energy.

Heat energy, per unit mass, obtained through thermochemical conversion of biomass is measured either as higher heating value (HHV) or lower heating value (LHV) (U.S. Department of Energy 2015). Both are reported as specific energy with units of J/kg. Higher heating value takes into account the latent heat of vaporization of water in the combustion products where the reactants start at close to 25°C and return the products close to 25°C. Lower heating value assumes that all of the latent heat of vaporization of water in the products is lost. The reactants start at about 25°C, but the products are returned at 150°C.

Higher heating values are measured empirically using a bomb calorimeter and the LHV is calculated from HHV using knowledge of the mass fraction of hydrogen in the reactants. Higher heating values can also be estimated based on ultimate analysis (Montero et al. 2016). In a typical application of biomass fuel, the latent heat of vaporization of water in the reactants is lost so LHV is a more practical measure of useful energy in a fuel. However, HHV is often reported, as it is easier to obtain and does not require an ultimate analysis to determine the hydrogen fraction in the reactants.

Higher heating value is generally reported in wet basis (wb) where the mass fraction of water in the reactants is included in the mass of the reactants. Montero et al. (2016) used Eqs. 1 and 2 to estimate the LHV from HHV. Eq. 1 takes the HHV of the fuel as measured in a bomb calorimeter then divides it by the dry matter expressed in decimals. This gives insight as to how mc lowers the useful calorific value of biomass fuel. Eq. 2 then relates the value found in Eq. 1 to the LHV, which is expressed as dry basis. This is the useful energy of biomass fuel:

$$HHV_{db} = \frac{HHV}{1-\frac{mc}{100}}$$

where HHV is higher heating value in dry basis (db) with units of MJ/kg db, mc is moisture percentage (% wb). If HHV is reported in dry basis the corresponding mc value will also be zero (0) and HHV will still be reflected accurately.

$$LHV_{db} = HHV_{db} - (9 \times 2.449 \times H)$$

where LHV is lower heating value dry basis (MJ/kg), H is mass fraction of hydrogen (kg), the constant 9 represents the mass (kg) of water produced by the combustion of 1 kg of hydrogen, and 2.449 MJ/kg is the vaporization enthalpy of water at 101.325 kPa and 25°C.

**Chemical characteristics**

**Chemical composition** The chemical composition of lignocellulosic biomass consists mostly of cellulose, hemicellulose, and lignin building blocks. The ratios of these building blocks vary significantly between species. Within a species, significant differences of the ratios of these building blocks can be attributed to soil types, growing conditions, and climate. Cellulose and hemicellulose (xylan) contain about 40-43% carbon content by mass and are comprised mostly of (CH₂O)n carbohydrates, while lignins have a higher average carbon content of 50-53% by mass (Gani and Naruse 2007; Pasangulapati et al. 2012). Although lignin volatiles begin breaking down at lower temperatures (200°C) than cellulose volatiles (370°C), the breakdown of cellulose volatiles is close to 90% completed by 400°C, whereas, the breakdown of lignin at 400°C is only 30% completed (Gani and Naruse 2007; Dorez et al. 2014). Biomass with a high lignin to cellulose ratio exhibits high char yield, high effective heat of combustion (EHC), high activation energy of combustion (Ea), and a low CO/CO₂ ratio (Dorez et al. 2014). However, it was also noted that low lignin to cellulose affects the degradation pathway of the latter, leading to charring and incomplete combustion of the cellulose (Dorez et al. 2014). Giudicianni et al. (2013) studied the effects of steam pyrolysis on cellulose, hemicellulose, and lignin reporting that lignin is responsible for the production of vapour phase with the highest higher heating value (HHV). Pasangulapati et al. (2012) reported that biomass with higher cellulose and...
Volatile matter is comprised of active and inactive portions. The active part is flammable gases consisting of low molecular weight hydrocarbons, carbon monoxide, and hydrogen. This is the main source of energy in biomass combustion and responsible for reactivation. The inactive or inorganic fraction of VM consists mostly of CO₂, NOₓ, SO₂, and SO₃. High content of volatiles promotes ignition at low temperatures, increasing efficiency of combustion (Montero et al. 2016).

**Ash** Ash is the inorganic residue remaining after the combustion of fixed carbon (Montero et al. 2016). Percentage (%) of ash is calculated using Eq. 7. Ash content is determined according to (ASTM Standard D1102 2013):

\[
Ash = \frac{E}{F} \times 100
\]

where Ash is percentage (%) of ash, E is mass of inorganic residue remaining after combustion, F is the mass of the sample before combustion (dry basis).

The use of biomass, with large amounts of ash, is restricted to industrial users with specialized ash removal equipment. Ash content is often corrosive, causing premature equipment failure. Ash with low sinter and flow temperatures complicates the ash removal process and reduces the effectiveness of heat exchangers. Ash residues increase maintenance costs, lower efficiencies, and shorten equipment life (Jing et al. 2012; Wang and Massoudi 2013). Ash content can also lower the HHV of fuel (Jenkins et al. 1996; Montero et al. 2016). Duca et al. (2014) found that ash content alone could be a good representative parameter for a first, rapid quality assessment. Ash, while causing problems, depending on its composition, can find practical sustainable utilization as a fertilizer and for the treatment of eroded soils (Montero et al. 2016).

Ash consists of various elements. Chlorine, one of the elements included in ash composition is detrimental to the environment and equipment. Chlorine ions combine with hydrogen to form hydrogen chloride, a source of corrosion. Ash in biomass is responsible for equipment failure and operating difficulties. Alkali metals, in the presence of chlorine or sulphur, are the leading contributors to this problem (Turn et al. 1997).

Numerous pretreatment studies have been conducted attempting to reduce the negative effects of ash on both biomass. Hemicellulose levels resulted in higher CO and CO₂ concentrations, while biomass with higher lignin levels resulted in significantly higher CH₄ concentrations.

**Proximate analysis** When considering biomass thermal conversion, proximate analysis is one of the most important characterization methods (Garcia et al. 2013). Proximate analysis can be used to estimate the caloric value of biomass. The analysis determines the quantity of four categories: moisture, volatile matter (VM), fixed carbon, and ash content. Montero et al. (2016) reviewed four equations (Table 1) that correlate HHV with proximate analysis and compared these theoretical values of HHV to the actual HHV values obtained from their study. The range of deviation of theoretical to the actual (measured) values was from 0.20 to 24.07%. This demonstrates that empirical modelling of HHV from a proximate analysis may be limited in its application.

**Moisture** Moisture content (mc) is the free water held by adsorption or absorption. Moisture content for forages is generally determined using a standard (ASABE 2012b). Moisture can be determined on a wet basis (wb) Eq. 3 or dry basis (db) Eq. 4:

\[
m_{cbw} = \frac{A-B}{A} \times 100
\]

\[
m_{cwb} = \frac{A-B}{B} \times 100
\]

where A is the sample mass before drying and B is the sample mass after drying.

**Volatile matter** Volatile matter is the fraction, except moisture that is released when the fuel is heated to high temperatures in the absence of air (Montero et al. 2016). It is determined according to ASTM standard E872 (ASTM Standard E72 2013) and is calculated using Eq. 5 (Montero et al. 2016):

\[
VM = L - m_{cwb}
\]

where

\[
L = \frac{c-d}{c} \times 100
\]

Where VM is volatile matter percentage (%), L is percentage (%) of mass loss, mcₜw is the moisture content wet basis expressed in in percentage (%), C is mass of the sample before heating (dry basis), and D is the mass (dry basis) of the sample after heating.

### Table 1. Compilation of equations correlating the HHV values with proximate analysis. Modified from Montero et al. (2016).

<table>
<thead>
<tr>
<th>Equation</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>( HHV_{db} = -0.0368 + 0.2218VM + 0.2601Ash )</td>
<td>(Sheng and Azevedo 2005)</td>
</tr>
<tr>
<td>( HHV_{DB} = 0.3536FC + 0.1559VM - 0.0078Ash )</td>
<td>(Parikh et al. 2005)</td>
</tr>
<tr>
<td>( HHV_{db} = 0.3543FC + 0.1708VM )</td>
<td>(Cordero et al. 2001)</td>
</tr>
<tr>
<td>( HHV_{db} = 0.312FC + 0.1534VM )</td>
<td>(Demirbaş 1997)</td>
</tr>
</tbody>
</table>

HHV is higher heating value (MJ/kg), FC is the percentage of fixed carbon, VM is percentage of volatile matter and Ash is percentage of ash; percentages are by mass in the dry biomass sample.
equipment and the environment. Common pretreatments methods for lowering ash content include washing with water and acid washing. Pretreatments may be used to lower ash content, raise the melting temperature, or both (Jenkins et al. 1996; Turn et al. 1997; Arvelakis et al. 2001; Davidsson et al. 2002).

In the EU, standards for densified biomass require the content and melting point of ash to meet certain levels. Products that do not meet the standards may be downgraded to a lower standard or disqualified from use (European Pellet Council 2011).

**Fixed carbon** Fixed carbon content is calculated as the mass of sample remaining after moisture, VM and ash have been accounted for as shown in Eq. 8:

\[
FC = 100 - As \%_{db} - VM \%_{db} - M \%_{db}
\]

where FC is percentage (%) of fixed carbon (dry basis).

Equations correlating HHV with proximate analysis (Table 1) show a linear relationship between fixed carbon and HHV. The effect of fixed carbon on HHV is about twice as profound as that of VM (Montero et al. 2016).

**Ultimate analysis** Ultimate analysis is done, using an element analyzer, to determine the mass percentages of carbon, hydrogen, nitrogen, oxygen, and sulphur (C, H, N, O, and S) of biomass (Montero et al. 2016). Numerous equations have been derived to estimate HHV from ultimate analysis. In general carbon and hydrogen increase HHV linearly. Increased hydrogen raises the HHV to a greater degree than an equal increase in carbon.

**Physical characteristics**

Physically measurable attributes of the product include durability, a function of moisture, particle size distribution, and processing conditions as well as density and physical dimensions.

**Durability** Durability is a function of moisture, density, and the quality and quantity of activated binding materials. The presence of binding materials together with increased density enhances durability while high mc is detrimental (Olorunnisola 2007). There is a direct relationship between the amount of lignin, a natural binder, and mechanical durability (Lehtikangas 2001). Poor durability presents not only logistical and storage difficulties but also increases health and environmental risks. Moisture and pressure, during compaction, are more significant factors of durability (Lehtikangas 2001). Moisture and pressure, during compaction, are more significant factors of durability (Lehtikangas 2001). Moisture and pressure, during compaction, are more significant factors of durability (Lehtikangas 2001). Moisture and pressure, during compaction, are more significant factors of durability (Lehtikangas 2001).

Pellet durability is determined by tumbling in a dust-tight enclosure for 10 min at 50 rpm. The enclosure is 125 by 300 by 300 mm with a 230 mm long by 30 mm wide baffle positioned diagonally along the back of the enclosure (300 by 300 mm face). The enclosure is rotated horizontally with the rotation shaft fixed at the center to the outside of the 300 by 300 mm face. After tumbling the pellets, the contents of the enclosure are screened using an appropriate screen size for the dimensions of the pellets being tested (as dictated by the standard). Durability is then defined as the percent of the original mass of the sample remaining on the screen.

Temmermann et al. (2006) compared the ASABE (2012a) standard to other standards and concluded that for pellets it gave the least variation amongst repetitions of the same sample source. Pellets with a durability rating higher than 97.5% measured by tumbling as defined by ASABE Standard S269.5 (ASABE 2012a) are considered, in Europe, a high quality biofuel, in terms of durability (Temmermann et al. 2006).

**Moisture content** Moisture facilitates internal heat energy transfer during compression of the biomass and is essential for the softening of lignins. Conversely, high mc reduces combustion temperature, hindering the release of the chemical energy in the products (Oanh et al. 2011). Therefore, the maximum moisture of biomass for transformation into pellets or briquettes should not exceed 10% (Voicea et al. 2013). Li and Liu (2000) found that for densification, mc equal to or less than 4% resulted in instability of briquettes due to the hygroscopic nature of the materials. Moreover, it was noted that while the acceptable range for mc was 5-12%, the optimal was in the neighbourhood of 8%.

Sokhansanj et al. (2005) noted that for fibrous materials the optimum mc before densification should be between 8-12% and that of starch and protein rich materials it could be as high as 20%. Serrano et al. (2011) found that for barley straw mc of 19-22% (wb) before
compaction was necessary to produce good quality pellets, but the final mc of the pellets, after compaction, did not exceed 6-8% as the compaction process removed moisture. Whereas, mc of 23% or higher resulted in wet pellets with a final mc close to 15%. Moisture facilitates agglomeration of particles, however, excess amounts render the biomass incompressible. Moreover, high mc makes the pellets susceptible to mould and risks being higher than European standards for compacted biomass allow.

Factors that are known to affect the optimal mc include; the quantity and composition of the lignins, the hygroscopic nature of the material, and particle size. Quantity and composition of the lignins, as well as the hygroscopic nature of the material, are functions of the species, growing conditions, environment, and storage conditions. It is, therefore, advisable that producers routinely do quality evaluations to ensure consistency when these factors are suspect to variation.

**Particle size** According to Kaliyan and Morey (2009), particle size is an important factor which influences the durability and strength of compacted biomass. Therefore, the analysis of particle size distribution of the biomass prior to compaction is critical. Small particles may produce denser briquettes, however, they also require higher pressures and temperatures to agglomerate the particles without the addition of binders (Eriksson and Prior 1990). However, the excess presence of fines, particles that separate from the product during handling and storage, cause problems with ash melting, disturb feeding systems, cause health hazards, and raise the risk of explosion (Toscano et al. 2013). Therefore, the ratio of small to larger particles should be balanced to ensure that the surface area of the particles does not exceed the coating abilities of the binding agent being used.

Serrano et al. (2011) found that there was no significant difference in durability between particles passing through a 4 mm or 7 mm sieve. It was noted that this contradicted the study done by Kaliyan and Morey (2009), but that the latter work was done with particle sizes smaller than 1 mm, for animal feed. Mani et al. (2004) found that considerably more energy is required to mill particles to smaller sizes when using a hammer mill. While noting that decreased particle size generally resulted in higher densities, Serrano et al. (2011) found no significant correlation between density and durability. Moreover, Kashaninejad et al. (2014) found that grinding straw with a 3.2 mm screen yielded significantly more durable pellets than straw ground with a 1.6 mm screen. Therefore, it is noted that the benefits of reduced particle size on durability reacheas its maximum and that size reduction beyond this limit is not only wasted energy it can also be detrimental to product durability.

Briquettes generally have more interlacing of particles than pellets, as the demands for comminution are lower for briquettes than for pellets (Sokhansanj et al. 2005; Sánchez et al. 2014). A lower demand on comminution for briquettes lowers the energy demands in the pre densification stage.

**Processing conditions** Two principle-processing conditions for quality pellets are temperature and pressure. High pressure forces the natural binding materials, such as lignin, out of the cell walls, making them available to bind particles together. High temperatures activate these binders by softening them to a liquid state. In the liquid state, the binders adhere to the biomass particles. During the cooling process, these binders solidify, thereby, forming solid bridges (Kaliyan and Morey 2010). Under high temperatures and pressure proteins also denature allowing them to act as binding agents (Kaliyan and Morey 2009).

Serrano et al. (2011) found that temperatures above 100°C resulted in loss of durability due to excess moisture loss. Higher pressure increases durability (Kashaninejad et al. 2014), however, according to the test methods used it appears that the effect of increasing pressure on durability plateaus after a certain point. This may or may not be the case as a harsher testing method for durability may, yield a significant relationship between increased pressure and durability. However, Mani et al. (2006b) found that increasing the pressure from 5 to 15 MPa showed a significant increase in durability of corn stover pellets with no sign of a plateau effect. Preheating biomass before compaction, using a screw press with heated die, reduces overall energy inputs and lengths equipment life. To further save electrical energy during this process Bhattacharya et al. (2002) successfully built and tested a preheating system powered by biofuel briquettes. Electrical energy savings were reported at about 35% of total electrical energy consumption. Bhattacharya et al. (2002) did not mention the additional costs of labour for running the stove, however, it appears to be assumed that labour costs were not as much of a concern, in Thailand, as the cost of electricity.

**Storage time** Samuelsson et al. (2009) reported that storing saw dust for 140 days prior to pelleting, greatly reduced fatty and resin acids and that this change increased the pellet density as well as pellet durability. The postulation made as a result of these findings was that the fatty and resin acids might serve to block the binding sites between the woody particles. As this form of binding is common to both pellets and briquettes the assumption that this applies also to briquettes should be valid, although, no studies, of such a nature, could be located by the authors.

**Use of binders**

Biomass compaction can be accomplished with or without the use of additional binding compounds. When compression is done without additional binders, quality depends on the plastic deformation of particles. The use of binders reduces the need for high pressure, which, lowers energy input requirements (Lu et al. 2014). As an example, straw, which is low in lignin, a natural binder, requires twice the energy per unit mass for pelletization than wood or willows (Carroll and Finnan 2010). Many different materials can be used as a binder. Some commonly used substances are starch, cane molasses, sulphites liquor (a by-product of paper production), and vegetable or mineral coal tar (Paula et al. 2011). Careful attention should be
Sawdust is one of the most important by-products of the lumber industry. Briquettes produced from wood sawdust, due to high lignin content, have higher calorific values than other agricultural residues (Emerhi 2011). Additionally, the use of briquettes made from sawdust displaces other fuel use, which in turn may assist in lowering anthropogenic GHG emissions. Emerhi (2011) observed that a good strategy was to produce briquettes from a 70:15 sawdust to starch ratio. The heating value of briquettes made from sawdust of *Azadirachta indica* bound with starch was reported as 33.09 MJ/kg (Sotannde et al. 2010), with the following composition: 84.70% fixed carbon, 3.35% low ash, and 11.95% VM.

In comparison with other biofuel materials currently used, sawdust briquettes also have a higher bulk density per energy unit, less moisture, lower ash content, lower levels of fixed carbon, chlorine, and sulphur (Sánchez et al. 2014). Amongst sources of biomass for briquetting and pelleting, sawdust has proven itself as the gold standard.

Table 2 compares sawdust to other agricultural materials. The low ash, sulphur, and chlorine contents of sawdust biomass, when compared with other sources, result in lower corrosion rates and lengthen equipment service life. **Straw** The principle argument for using straw as a thermochemical energy source is its inherent CO₂ neutrality. It is a ubiquitous, inexpensive, and underutilized source of biomass. Montero et al. (2016) analysed and compared the results of numerous studies, including their own, concluding that factors influencing HHV and ash quality include the type of wheat variety, type of climate, and soil conditions. HHV values ranged from 14.9 to 20.3 MJ/kg, while ash quantity from 4.6 to 17.0%, based on proximate analysis. Moreover, ash generated from straw combustion can be used as a fertilizer and for treatment of eroded soils (Montero et al. 2016). A significant challenge when using straw is the quantity and quality of ash (inorganic materials). Wheat straw contains large quantities of alkali metals (K, Na), alkali earth metals (Ca, Mg), silicon, chlorine, and sulphur (Arvelakis et al. 2001). Ash, a source of corrosive elements, is harmful to equipment, requires more frequent cleaning, hinders combustion, and sinters, causing cleaning and heat transfer complications. Various techniques of leaching have been studied as a possible means of reducing the ash content in wheat straw (Jenkins et al. 1996; Arvelakis et al. 2001; Davidsson et al. 2002). Arvelakis et al. (2001) studied the thermal properties of ash from leach treated and untreated wheat straw in fluidized bed combustion and found that leaching removed an insignificant amount of the alkali metals and chlorine, resulting in a minimal reduction in ash agglomeration.
Jenkins et al. (1996), on the contrary, found that leaching of wheat straw was able to bring the ash content down from 13 to 4.2%, representing a 68% decrease. The conclusion of the latter study reported washing to be an effective method of reducing alkali metals, chlorine, and sulphur and that the ash of washed straw was more refractory at high temperatures. The results of the two studies mentioned above appear to contradict each other. Davidsson et al. (2002) reported washing methods to be ineffective at removing alkali from cellulose and Montero et al. (2016) reviewed seven sources of wheat straw for cellulose content and reported values ranging from 28.8 to 57.1%. Neither Arvelakis et al. (2001) nor Jenkins et al. (1996) analysed their specimens for cellulose, hemicellulose or lignin composition and this may be the reason for the discrepancies in their conclusions.

Davidsson et al. (2002), studied the effects of washing techniques for alkali removal, demonstrating, that acid leaching is more effective than leaching with water and can reduce alkali emissions by close to 70% when analysed in a vacuum pyrolysis setting. The above study concluded that fuel washing for biomass with high ash content, such as wheat straw, can improve the combustion properties, however, it is unnecessary and provides no significant benefit for low ash fuels such as wood.

Storage and handling
Storage and handling conditions of pellets profoundly affect both performance of pellets and safety to personnel. According to Brožek (2013) Directive No. 14-2009 of the Ministry of Environment of the Czech Republic: Briquettes from Wood Waste requires that Briquettes from wood waste must guarantee a minimum 9 months storability. During this time the changes in briquette size, density, and must me not exceed the limit of 10%. Brožek (2013) concluded that pellets should be stored in closed plastic bags to eliminate or minimize air and moisture diffusion. Variations in pellet size, density, and may be quick ways to determine the quality of a storage method, however, factors such as toxic gas accumulation should be monitored before entering a pellet storage facility with no or low levels of ventilation (Emhofer et al. 2014).

The danger of gaseous emissions has only been recently addressed after several fatalities involving CO poisoning (Alakoski et al. 2016). The revelation of this risk has resulted in the need to retrofit many non-ventilated residential pellet store rooms in Europe, where toxic or fatal CO levels often accumulate (Emhofer et al. 2014). Alakoski et al. (2016) conducted a short review on the gaseous emissions of pellets, with the following findings. The gaseous emissions of compacted biomass results in the reduction of quality through dry matter losses. The risks associated with off-gassing of compacted biomass include death or harm to personnel and consumers, loss of property through fire and explosion, and degradation of product quality. Off-gassing of CO, CH₄, CO₂, N₂O, aldehydes, and non-methane volatile organic compounds (NMVOC) displaces oxygen and has resulted in numerous deaths by CO poisoning. Investigation into the cause of off-gassing reveals that it is primarily not biological degradation, but rather chemical auto-oxidative degradation of fats and fatty acids. Furthermore, as temperature, relative humidity (RH), and oxygen availability increase so do gaseous emissions. As the chemical process of auto-oxidation advances small particles break off the pellet creating a fine dust. When dry, this dust creates an explosion hazard. Whereas, when RH is high, these hydrophilic particles absorb moisture and the increased surface area is ready colonized by bacteria and fungi. The microbial growth leads to self heating and may result in a fire hazard due to spontaneous combustion (Alakoski et al. 2016; Wang et al. 2016). To prevent damp pockets from self heating in large silos it may be necessary to flood the silo with nitrogen gas (Whittaker and Shield 2017). Care should also be taken during handling to avoid repeated dropping from large heights as the damage and breaking into fines increases exponentially with each drop (Whittaker and Shield 2017).

Value of densified biomass products
It is a straightforward process to evaluate the financial cost of biomass fuel. A simple sum of all expenses divided by the sum of the product. Expenses include logistics of transportation, storage, and handling as well as material and processing costs. The product, densified biomass has an energy value and specific properties, such as ash content and composition, particle size, and durability which can be determined using well established methods.

It is, however, more difficult to make a precise calculation of the market value for densified biomass or briquettes. One method is to use the principle of energy equivalent using fuel-oil or wood as these are usually replaced by densified biomass products (Quirino 1991). By considering the LHV of the briquette and its boiler burning efficiency it is possible to relate the value of the densified biomass to the cost of an established standard. The example in Eqs. 10 to 13 uses the cost of heating oil to determine the value of briquettes.

Let: \( LHV_{oil} = 41.0 \frac{MJ}{kg} \) (10)

Let: \( LHV_{briquette} = 15.9 \frac{MJ}{kg} \) (11)

Using the efficiency ratings for the boilers as \( \eta_{oil}=0.92 \) and \( \eta_{briquette}=0.80 \) we can combine Eqs. 10 and 11 to calculate the equivalence index to oil in Eq. 12:

\[
E_{oil} = \frac{LHV_{briquette} \times \eta_{briquette}}{LHV_{oil} \times \eta_{oil}} = 0.337
\]

where \( E_{oil} \) is the Equivalence index.

Using the calculated equivalence index from Eq. 12 we can calculate the value of the briquette in Eq. 13:

\[
Value_{briquette} = Cost_{oil} \times E_{oil} = 0.337 \times Cost_{oil}
\]
logistics of transport, storage or handling. Moreover, the differences in percentage and composition of ash, which leads to equipment failure are missing from the example.

Economic value, however, is governed not only by expenses and revenue, but also by political, social, and taxation policies. In recent history, Europe has been promoting the use of renewable resources (RES) with measures such as feed in tariffs (FIT’s), tax incentives, and biofuel quota systems (Carneiro and Ferreira 2012). Feed in tariffs are subsidies paid to energy companies to use biomass fuel for electricity generation. Without these incentives, the use of RES would be economical challenging or possibly not feasible. Carneiro and Ferreira (2012) studied the economics of an electric power plant, in Portugal, using RES assuming the existence of FIT. When extrapolating the data, with the assumption of a linear fit, a minimum $72/MWh FIT is required to achieve a net zero internal rate of return (IRR). The economics of one region, however, may not always transfer to other regions. Hu et al. (2014), for example, found that briquettes made from corn stover would be economically feasible in rural China.

Stolarski et al. (2013) noted that the EU market gives a higher prominence to pellets, as automation is easier with pellets than briquettes, however, briquette production consumes less energy and can, therefore, compete with pellets on local markets and makes them more eco-friendly.

Criteria used for evaluating the value of biomass pellets are not limited to the economic value, but also include environmental, social, and political factors. Political values subsume energy independence and offer a strategy to slow urbanization (Carneiro and Ferreira 2012; Hu et al. 2014). Biomass pellets lower GHG emissions, when compared to coal. They can provide employment in rural sectors and can advance regional and country energy independence.

Currently, the extensive use of biomass in industrialized European countries is mandated by political forces and is reinforced through penalties and rewards. As such, in developed countries, the cost of using biomass is artificially deflated to the point where its price is palatable to the masses in contrast with traditional energy sources. In rural areas of non-developed countries, the use of biomass is governed by financial strain and the lack of inexpensive alternatives. In this case, the cost of alternatives is high due to a lack of infrastructure and biomass, therefore, is an attractive alternative.

CONCLUSIONS
Biomass, a readily available and environmentally benign energy source, has low specific energy values and, therefore, needs to be densified through compaction to make it viable. The quality of compacted biomass varies depending upon factors such as the source, pretreatments, such as acid washing or leaching, particle size, and processing conditions, including pre processing storage time and conditions. Higher proportions of VM lead to lower reactivation energy, promoting ignition at lower temperatures and an increase in the efficiency of combustion. Greater proportions of FC result in higher values of HHV. Excess milling produces too many fines, which in turn increases the risk of explosion and fire; moreover, it uses too much energy and may lead to premature equipment failure. Binders can impact ash content, HHV, and durability. The processing conditions can activate the inherent binders and regulate moisture to strengthen the product or serve to dry the product too much, wherein, weakening the product. The true economic value of biomass is convoluted by the introduction of tax exemptions and other political means, which in recent history have served to raise its market value by legislating an increase in demand. Sawdust has lower overall ash, chlorine, and sulphur contents than wheat straw, which serves to simplify its incorporation as an energy resource.

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