

Bioresources for Sustainable Pellet Production in Zambia: Twelve Biomasses Pelletized at Different Moisture Contents

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The use of charcoal and firewood for cooking is common in Zambia, and its utilization is such that the deforestation rate is high, energy utilization is low, and unfavorable cooking methods lead to high death rates due to indoor air pollution mainly from particulate matter and carbon monoxide. By using an alternative cooking method, such as pellet stoves, it is possible to offer a sustainable solution, provided that sustainable pellet production can be achieved. In this study, 12 different available biomaterials were pelletized in a single pellet unit to investigate their availability as raw materials for pellet production in Zambia. The study showed that sicklebush and pigeon pea generated the same pelleting properties correlated with compression and friction and that both materials showed low moisture uptake. The study also identified two groups of materials that broadened the raw material base and helped to achieve sustainable pellet production. Group 1 consisted of materials with equal pelleting abilities (miombo, peanut shell, pigeon pea, and sicklebush) and Group 2 consisted of materials that showed low impact of varying moisture content (eucalyptus, miombo, peanut shell, pigeon pea, and sicklebush). The hardest pellet was made from *Tephrosia*, which was followed by *Gliricidia*.

Keywords: Biomass pellets; Single pellet press, Densification; Backpressure; Chemical composition

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INTRODUCTION

The fuel from biomass is increasing due to the transition away from fossil fuels. The use of biomass as fuel varies geographically. In Africa, biomass is used mainly as firewood and charcoal (Janssen 2012). In Lusaka, Zambia, 85% of urban households use charcoal and the estimated consumption per household per year is 1.3 tons of charcoal (Gumbo *et al.* 2013). To produce this amount of charcoal, 8 tons of wood are needed (Gumbo *et al.* 2013). The teardown of wood for the production of charcoal leads to deforestation, which in Zambia has been estimated to be between 250,000 and 300,000 hectares per year and is one of the ten highest deforestation rates in the world (Matakala *et al.* 2015). The total annual consumption of wood for biofuel in Zambia is nearly 14 million tons, of which annual charcoal production uses 6 million tons (Ryan *et al.* 2016). Charcoal production begins with the harvesting of biomass. Logs are then covered and burned in primitive charcoal piles, where up to 70% to 90% (Pennise *et al.* 2001; Janssen 2012) of the energy is lost. The combustion of the charcoal often occurs in stoves with an efficiency rate of approximately 12% to 27% (Bhattacharya and Abdulsalam 2002). According to the World Health Organisation (WHO), the indoor air pollution from particulate matter and carbon monoxide associated with these conventional cooking methods causes 4.5 million premature deaths

every year, which is more than malaria, HIV/AIDS, and tuberculosis combined (WHO 2016). Overall, the use of biomass in Zambia is both inefficient and unhealthy. This situation, along with an increasing population and energy need, is clearly not sustainable.

One step towards a sustainable solution is to use a cooking method that does not use charcoal and does not generate poisonous gases. Today, it is possible to cook food and generate heat from pellet stoves specifically designed for cooking; such pellet cook stoves are capable of optimal combustion (Bhattacharya and Abdulsalam 2002; Peša 2017; Souza *et al.* 2017). However, even if the pellet cook stove can solve the problems associated with human health through optimal combustion, pellets must be available. By pelletizing biomass, it is more economical to transport it due to the higher density and uniform size of the product, which also makes it easier to dose (McKendry 2002; Näslund 2003; Nielsen *et al.* 2009a; Stelte *et al.* 2011; Castellano *et al.* 2015). The density of pellets is especially important when they are used in pellet cookstoves because a sufficient amount of energy must be generated for the food being prepared.

However, to solve the problems with deforestation it is important that biomasses for pellet production are based on available waste and biomasses not used today. For countries where deforestation is an issue, a broad and variable raw material base becomes a must for sustainable energy production. However, one prerequisite for pellet production today is that the pellet producers must strive for a feedstock with a chemical composition that is as constant as possible (Frodeson *et al.* 2018). Furthermore, the knowledge relationship between densification and chemical composition is limited (Ramírez-Gómez 2016). This lack of knowledge and the need to strive towards equal chemical composition limits the possibilities for the sustainable utilization of all available raw materials.

The most limiting step for a variable raw material base for a pellet producer is when the pressure from the roller wheel, hereinafter referred to as P_{roller} , compresses the biomass through the die channels. This step can be divided into three sub processes: compression, flow, and friction (Nielsen 2009). For all three sub processes there are several parameters of importance: the chemical composition, moisture content (MC), and particle size of the biomass (Nielsen 2009). The friction is important for two reasons: i) to generate the right temperature, so that strong bonds can be generated within the pellets; and ii) to create a backpressure sufficient to build up P_{roller} (Nielsen 2009; Frodeson *et al.* 2018). The variable P_{roller} is usually between 210 MPa and 450 MPa (Nielsen *et al.* 2009b; Seki *et al.* 2013), and the die temperature often reaches 100 °C to 130 °C (Nielsen *et al.* 2009a). The die channel length can be divided into two parts, an active part where friction occurs and an inactive part that is needed to ensure that there is enough thickness of the die for mechanical strength. The length of the active part of the channels is chosen based on a specific material. This means that for a specific die, the length must be adjusted so that the backpressure does not exceed the P_{roller} limit (Holm *et al.* 2007). This could facilitate pellet production and counteract corresponding problems, such as die blocking and high-energy costs during production (Pastre 2002).

One way to avoid die blocking is by purposely adding water to act as a lubricant in the die. Water also affects the possibilities of generating strong bonds in the pellets (Kaliyan and Vance Moray 2009). However, adding the right amount of water is important. The optimal moisture content (MC) has been determined to be 5% to 10% when pressing pellets from woody materials and 10% to 15% from grass (Stelte *et al.* 2012).

In addition to water, the chemical composition of the biomass also affects the densification process (Frodeson *et al.* 2018). The chemical composition varies between biomasses and there are mainly four different types of biomass: woody plants, herbaceous plants/grasses, manures, and aquatic plants (McKendry 2002). Of these four, woody plants and herbaceous plants/grasses are best suited as raw materials for solid biofuel due to their

lower MC (McKendry 2002). The chemical composition of the biomass consists of different proportions of lignin, polysaccharides (cellulose, hemicellulose, and others), proteins, extractives, and ash (Frodeson *et al.* 2018). Wood consists of tightly bonded fibers compared to herbaceous biomass that has more loosely bonded fibers, indicating a lower proportion of lignin that binds the cellulose fibers (Castellano *et al.* 2015). Studies show that woody biomass yields harder pellets than herbaceous and grassy biomass, probably due to the higher amounts of lignin and lower amounts of extractives present (Stelte *et al.* 2011; Castellano *et al.* 2015). However, it is also determined that lignin is not necessary to produce high quality pellets, as pure cellulose can yield pellets with the required properties (Frodeson *et al.* 2018). Extractives are considered to create weak boundary layers in pellets, which can cause them to break more easily (Stelte *et al.* 2011; Castellano *et al.* 2015). Extractives also have a lubricating effect. This can reduce friction in the active part of the press channel, which can reduce the energy demand and lower the temperature (Stelte *et al.* 2011; Castellano *et al.* 2015). Because different chemical components have different impacts on the pelleting process, it is important to have knowledge of both compositions in addition to their ability to be pelletized as single sources as well as in mixtures.

Several studies have evaluated and tested biomasses common in Zambia, such as bamboo (Poppens *et al.* 2013; Liu *et al.* 2016), cassava (Lockenus 2014; Zhu *et al.* 2015), eucalyptus (Almeida *et al.* 2012; Castellano *et al.* 2015), peanut shell (Fasina 2008; Stasiak *et al.* 2015; Bai *et al.* 2017), African pine (Castellano *et al.* 2015; Andersson 2017), pigeon pea, and sicklebush (Andersson 2017). Even if there are a number of studies, most of them are based on one or a few numbers of biomasses, meaning that it is difficult to evaluate them against each other. There is also a lack of knowledge on how pellets from these materials are affected by storage. The storage of the pellets can be challenging, especially in areas where air humidity is high and shifting (Demirbas 2002). Zambia has a tropical climate with three different seasons: dry and cold, dry and warm, and wet and hot (CIA 2018). Shifting humidity can cause breakage of pellets and affect the amount of energy obtained by combustion (Demirbas 2002; Hartley and Wood 2008; Thek and Obernberger 2010). Therefore, when evaluating biomasses as raw materials for pellet production in Zambia, moisture uptake is an important quality parameter to measure. Beyond moisture uptake, the compression and maximum generated backpressure are also important parameters to evaluate. However, to investigate small quantities of biomasses for pellet production, it is advantageous to use a single pellet press. A single pellet press is also an easy way to predict different behavior in different materials (Holm *et al.* 2011) and to predict trends in pellet mechanical properties when evaluating biomass (Mišljenović *et al.* 2016).

The pellet cook stove could be a solution to the problems with deforestation and health risks related to food cooking in Zambia. An important parameter is to find a solution for pellet production as a sustainable utilization of the biomasses. Such a solution could be to gather and collect different biomass wastes and produce pellets in a pellet plant. However, there is a lack of information on how different types of biomasses available in Zambia affect densification. This limits the possibilities of using a varied biomass waste stream for pellet production.

The aim of this study was to increase knowledge on how twelve waste biomasses, available in Zambia, would serve as a raw material base in a pellet production facility. One objective was to investigate the work for compression, friction, and maximum backpressure during pelletization produced at different MC levels, as well as the pellets' solid density, hardness, and moisture uptake. Another objective was to investigate their availability and suitability as raw materials in general.

EXPERIMENTAL

The methods used for the materials are divided into a literature-based background description of each material, its properties, and its chemical composition. The tested materials are then presented, followed by a description of the method for the laboratory study for evaluation of the mechanical properties of the tested materials.

Material Background

The tested materials were bamboo, cassava peel, cassava stem, eucalyptus, *Gliricidia*, peanut shell, *Lantana camara*, miombo seed capsules, pigeon pea, pine, sicklebush, and *Tephrosia*. A general background on the materials is briefly described and the chemical composition based on the literature are summarized in Table 1.

Bamboo

Bamboo is a group within the grass family (Roskov *et al.* 2014) and occurs naturally in tropical, subtropical, and temperate areas (Bystriakova *et al.* 2004; Kelchner 2013). The majority of species are lignified and woody, but some are herbaceous; both types can be found in Zambia (Kelchner 2013). Zambia is one of four countries that has the highest diversity of woody bamboo in Africa (Bystriakova *et al.* 2004). Bamboo grows wild among pine plantations in the Copperbelt Province, Zambia. It is considered to have low value for construction and manufacturing. Many bamboo products are domestically used and can be important in both household and local economies (Bystriakova *et al.* 2004). It is an important plant for stabilizing soil, has a rapid growth, and can mature in 3 years to 5 years after the cultivation period and is, therefore, thought to be able to help reclaim deforested land through plantation (Akwada and Akinlabi 2018). Bamboo is perishable after harvest, requiring preservation methods and short supply chains (Poppens *et al.* 2013). Its properties as a material vary between growing sites and seasons, and it is difficult to harvest mechanically (Poppens *et al.* 2013).

Cassava

Cassava, or *Manihot esculenta*, also known as “manioc,” can grow up to 5-m-high and is grown mainly for its starch-rich root, which is a basic food ingredient in many countries in Asia, Africa, and Central and South America (Reinhardt *et al.* 2013). In 2016, 1 million tons of cassava root were produced in Zambia (FAO 2017). It has been estimated that 80% of the peel waste from this cassava root could be used for pellet production (Kemausuor *et al.* 2014). The stems and branches can be as much as 50% of the root mass (Zhu *et al.* 2015). The stems and branches are wasted after harvest (Zhu *et al.* 2015), and this surplus is often cleared from fields in readiness for the next season's growth and are abandoned or burned in the wild, causing emissions and environmental problems (Zhu *et al.* 2015).

Eucalyptus

Eucalyptus spp. belongs to the family of myrtle plants (Roskov *et al.* 2014). *Eucalyptus* species, also known as “blue gum,” are 25-m- to 50-m-tall evergreen trees (Rejmánek and Richardson 2011), often planted in Mediterranean and tropical countries because they are fast growing and lucrative (Ducouso *et al.* 2012). South Africa is highly dependent on plantations of exotic forest species, especially eucalyptus (Rejmánek and Richardson 2011; Ducouso *et al.* 2012), which is becoming the most frequently planted genus in Africa (Ducouso *et al.* 2012).

Table 1. Chemical Composition of All Tested Materials Based on Literature

Material	Plant Part	Chemical Composition (%)										Reference
		Cellulose	Hemi-cellulose	Holo-cellulose	Lignin	Proteins	Extractives	Lipids	Ash	Starch	Others	
Bamboo (Moso)	Stem and leaves	42 to 50	24 to 28		24 to 26							(Liu <i>et al.</i> 2014)
Cassava	Stem	28.86 ± 1.78	21.12 ± 2.28		30.62 ± 0.95	1.47 ± 0.40		0.70 ± 0.01	7.34 ± 0.27		9.89	(Nanssou <i>et al.</i> 2016)
		22.80	28.80		22.10	3.68			1.90	15.00		(Pooja and Padmaja 2015)
		35.2	24.3		33.8				2.2		3.5	(Han <i>et al.</i> 2011)
	Peels	9.71 ± 1.04	32.36 ± 1.08		16.89 ± 0.76	3.70 ± 0.15		1.70 ± 0.10	11.38 ± 0.11		24.26	(Nanssou <i>et al.</i> 2016)
		14.17	23.40		10.88	5.29			3.70	29.84		(Pooja and Padmaja 2015)
	Leaves	17.30	27.65		20.10	19.96			2.50	2.43		(Pooja and Padmaja 2015)
Eucalyptus	Chips from whole trees	19.15	34.33		30.31	1.15	6.85		2.83			(Castellano <i>et al.</i> 2015)
<i>Gliricidia</i>	Stem	41.44 ± 0.51	35.31	76.75 ± 0.71	27.23 ± .17							(Abe <i>et al.</i> 2018)
<i>Lantana camara</i>	-			75.03	18.21		8.46				2.31 (silica)	(Deo and Acharya 2010)
	Branches/leaves	44.1 ± 1.72		61.1 ± 2.53	32.25 ± 1.57				2.30 ± 0.11			(Kuhad <i>et al.</i> 2010)
Miombo (<i>Brachystegia spiciformis</i>)	Pod	37.7			16.8							(Mtambanengwe and Kirchmann 1995)
	Rachis	30.0			15.4							(Mtambanengwe and Kirchmann 1995)

Peanut shell	Shell	30.73	25.86		30.57	7.94					4.94 (fat)	(Bai <i>et al.</i> 2017)
Pigeon pea	Stalk	42.71 ± 3.18	18.33 ± 1.40		2.31 ± 0.13	7.77 ± 0.58						(Samanta <i>et al.</i> 2013)
Pine	Stem	40 to 45	25 to 30		26 to 34							(Liu <i>et al.</i> 2014)
Pine <i>Pinus elliottii</i>	Waste from lumber industry	-	-	61.2 ± 1.1	33.8 ± 1.0		4.5 ± 0.1		0.8 ± 0.1			(Poletto <i>et al.</i> 2012)
Sicklebush (<i>Dichrostachys cinerea</i> , <i>Marabou</i>)	Branches	39.5 ± 0.43	21.7 ± 0.35		32.1 ± 0.37		3.8 ± 0.15		1.9 ± 0.04	1.0		(Soudham <i>et al.</i> 2011)
Sicklebush (<i>Dichrostachys cinerea</i>)	Wood including bark	40 ± 4	21 ± 3		30 ± 3							(Fernández <i>et al.</i> 2015)
<i>Tephrosia candida</i>	Whole plant 1 m above ground	32.10	4.20		4.70	17.20		9.00	8.50			(Odedire and Babayemi 2007)

Some species, including *Eucalyptus grandis*, are considered invasive (Anonymous 2018). Its water consumption is also a concern, especially in countries where water availability is limited (Farley *et al.* 2005; Albaugh *et al.* 2013). For use as biomass, blue gum wood may be available after three years (Rejmánek and Richardson 2011). *E. grandis* is known to have more impermeable characteristics than other woods (Jankowsky and Santos 2005). Sawdust from *Eucalyptus* spp. is a residual that is available in some Zambian sawmills.

Gliricidia

Gliricidia spp. belongs to the family of pea plants (Roskov *et al.* 2014). *Gliricidia sepium* is one of the most common trees in the northern parts of southern Africa, Mexico, and Central America (National Research Council 1980). It is a fast-growing hardwood tree that can grow up to 15-m-high (National Research Council 1980). It has nitrogen-fixing properties and can be rotated with other plants to prevent soil degradation (Akinifesi *et al.* 2006; Montero-Solís *et al.* 2017). *G. sepium* has high propagation, initial growth, and biomass exchange, as well as having the ability to be chopped after harvest (National Research Council 1980; Fuwape and Akindele 1997). It is also an important tree forage crop due to its high nutritive value, with protein comprising approximately 21% of the tops and dry matter (Man and Wiktorsson 2002). *G. sepium* has poisonous roots, bark, leaves, and seeds, and has shown great potential against plant parasites (Aragón-García *et al.* 2008; Adekunle 2009). *Gliricidia* is grown in the eastern province in Zambia to prevent soil degradation and to improve agriculture. Its twigs and trims are waste that can be collected, but in relatively small amounts.

Lantana camara

Lantana camara is a species within the verbena family (Roskov *et al.* 2014). This poisonous shrub mostly originates from Central and South America, although some species are believed to originate from Africa and India (Parsons *et al.* 2001). It has been widely distributed in approximately 60 countries throughout the tropic, sub-tropic, and warm temperate regions of the world (Parsons *et al.* 2001). *L. camara* is one of the world's top 100 most invasive species and was the first weed to be placed under biological control (Parsons *et al.* 2001; Patel 2011). In South Africa, *L. camara* was placed under biological control in the 1960s, but without success, causing huge economic and ecological issues (Baars and Naser 1999). *L. camara* is a favored firewood plant but its disadvantage is that it has a short/fast burning time (Tabuti *et al.* 2003). It can be used as a biomass in the manufacturing of paper, but is difficult to harvest and, therefore, is considered uneconomical (Kuhad *et al.* 2010).

Miombo

Miombo is the vernacular word for the genus *Brachystegia* (Roskov *et al.* 2014). *Brachystegia spiciformis* is the most extensive species of *Brachystegia* in savanna woodland, covering much of central and southern Africa including Zambia (Mtambanengwe and Kirchmann 1995). However, miombo woodland is threatened by conversion to agriculture and miombo is being used for charcoal or wood fuel, which can damage biodiversity and ecosystems if it is not regulated (Mtambanengwe and Kirchmann 1995). It is a deciduous tree with a flat crown that can be 8-m- to 20-m-high. Fruits are flat pods/seed capsules, usually 90-mm-long, but occasionally up to 140 mm (Dharani 2011). Mature seed capsules fall to the ground and become available as biomass.

Peanut

Peanut, or *Arachis hypogaea* L., also called groundnut, is a member of the family Leguminosae (Nwokolo 1996). The peanut is not a true nut, but rather a legume much like beans or peas (Nwokolo 1996). It is a major crop in the tropical, subtropical, and warm-tempered areas of Asia, Africa, Oceania, North America, and Europe (Heuzé *et al.* 2017). The peanut shell is a major part of the industrial waste of peanut producing countries (Heuzé *et al.* 2017). In 2016, nearly 160,000 tons of peanuts were produced in Zambia (FAO 2017), whereof the nut is approximately 71% to 79% of the weight and the remainder is shell (Hamm *et al.* 2018). Shane *et al.* (2016) estimated that 53,000 tons of peanut shell waste is available in Zambia.

Pigeon pea

The pigeon pea, or *Cajanus cajan*, belongs to the legume family (Roskov *et al.* 2014). It is a food crop that has been cultivated for a long time in Africa and Asia and is a common crop in the tropical and sub-tropical regions (Odeny 2007; FAO 2017). The majority of today's production comes from India (Odeny 2007; FAO 2017). It can grow up to 3.6-m-high, has edible protein-rich peas, improves soil, can withstand drought, and can grow on nutrient-poor soils (Anonymous 2005). It has been evaluated to be an important crop with great potential for success in Africa, and its production hardly requires any external input (Odeny 2007; FAO 2017). The stems and stalks are woody, and approximately 2 tons of stalks are available per hectare during each growing season (Samanta *et al.* 2013).

Pine

The genus *Pinus* of the Pinaceae family contains approximately 90 species (Roskov *et al.* 2014). They are often dominant components of the vegetation over large parts of the northern hemisphere (Richardson 1998). *Pinus* spp. has been cultivated in many countries in the Southern hemisphere and it forms the foundation of exotic forestry. The most important species in the South African forest industry is *Pinus patula*, which is also one of the most problematic invasive species alongside *Pinus pinaster* and *P. radiata* (Moran *et al.* 1999; Anonymous 2018). The invasive species cause problems, such as reducing the drainage of water from mountains, reduction of pastures, and posing of fire hazards, which threaten the survival of domestic plants (Moran *et al.* 1999; Anonymous 2018). Zambian sawmills are a source for pine sawdust, usually including a small proportion of pine bark from when the logs are sawn.

Sicklebush

Sicklebush, or *Dichrostachys cinerea*, is a legume in the Fabaceae family. It originates from Africa and is currently found in countries along the equator (Roskov *et al.* 2014). Sicklebush is a hardwood bush with edible fruits and seeds and can be up to 7-m-high (Pedroso and Kaltschmitt 2012; Fernández *et al.* 2015). It has rather small dimensions that make it unsuitable as a construction timber and often used as fuel or fencing (Roskov *et al.* 2014). It has nitrogen-fixing properties and can be used to control erosion in soil (Pedroso and Kaltschmitt 2012; Fernández *et al.* 2015). Sicklebush can easily become invasive (Pedroso and Kaltschmitt 2012; Fernández *et al.* 2015).

Tephrosia

The genus *Tephrosia* consists of 345 different species in the Fabaceae family (Roskov *et al.* 2014). It originated in Africa, but it now exists, for example, in South America, India, and other countries along the equator (Orwa *et al.* 2009). It is an annual or perennial tree or shrub with woody or soft herbaceous branches (Orwa *et al.* 2009). Primarily small-scale and low-income farmers, who cannot afford synthetic pesticides to counter pests when storing crops (Kamanula *et al.* 2010), use *Tephrosia vogelii* as a pesticide plant. *T. vogelii* is poisonous and planted as a hedge around fields in Zambia to keep cattle from crops (Orwa *et al.* 2009). The stalks and branches can be used as fuel and can be cut often (Orwa *et al.* 2009). It also enriches the soil quality through nitrogen fixation and acts as a green field cover (Kamanula *et al.* 2010). *Tephrosia candida* has been found to provide approximately 10 tons of dry matter per hectare (Odedire and Babayemi 2007).

EXPERIMENTAL

Materials

The tested materials were 1) Bamboo (Bamb), 2) Cassava peel (CasP), 3) Cassava stem (CasS), 4) Eucalyptus (Euca), 5) *Gliricidia* (Glir), 6) *Lantana camara* (Lant), 7) Miombo seed capsules (Miom), 8) Peanut shell (PeaS), 9) Pigeon pea (PigP), 10) Pine (Pine), 11) Sicklebush (Sick), and 12) *Tephrosia* (Teph) (see Fig. 1).



Fig. 1. Pictures and parts of plants of all tested materials

Methods

Single pellet study

All materials were evaluated at three different MCs, 5%, 7.5%, and 10% (wet basis), for a total of 36 test series. Some of the materials were delivered as sawdust and others as bark or stem. The bark, stem, and branches were first sawn, in a Bosch (GCM 8 SJL; Stuttgart, Germany), to sawdust, and all materials were ground in a Culatti Mikro Hammer Mill (DFH 48; Limmatstrasse, Zurich, Switzerland) with a sieve size of 2 mm to attain uniform particle sizes.

The method for moistening was that all materials were placed in 45 °C for 48 h to ensure that the materials had equal starting positions. After the MC (%) was measured according to SS-EN 14774-1 (2009) on a wet basis, each test material was divided into three equal parts; water was added to correspond to 5.0%, 7.5%, and 10.0%. The method for moistening the material has been described in earlier work (Frodeson *et al.* 2018). The materials were sealed in plastic bags and stored for 24 h before conducting any tests.

The densification

Pellets were produced in a single pellet unit located at the Department of Environmental and Energy Systems at Karlstad University (Karlstad, Sweden). The press was a 137-mm high and 120 mm wide steel cylinder with an 8.2-mm cylinder bore within which an 8.0-mm piston compressed the biomass against a removable bottom plate. The temperature of the steel cylinder was controlled with two heating coils, and was set at 100 °C. After equilibration, a 10-mm-long steel piston plug was placed in the bottom of the die hole to allow for a longer distance to measure friction. A 13-mm-long nylon plug was then fitted before a 1 g sample of the test material was added into the die. Finally, a 13-mm-long nylon plug was placed above the sample. The nylon plugs ensured that the temperature at both ends of the pellets was equal.

The samples were compressed by the piston at a velocity of 30 mm/min, to a desired pressure of 14 kN. After a retention time of 10 s at full pressure, the piston ejected the pellets out just after the bottom plate was removed and the steel plug fell out from the die hole. The single pellet press and the method for producing pellets has been described in more detail by Frodeson *et al.* (2018). Five pellets were produced for each test series. After pelletizing, each pellet was directly cooled down to ambient room temperature using a small fan, and then stored in a closed plastic bag at the same temperature for further tests and analyses.

Measuring

During the densification, the force was logged three times per second. The compression and friction work were calculated by integrating the force and time determined from the logged data by using numerical integration trapezoid method. The compression step was determined over the time it took to increase the force from 1 kN to 14 kN. The friction work was determined over a total distance of 20 mm and started when the force reached 0.5 kN. For both compression and friction, the piston speed was constant, (30 mm/min). The compression and friction work were depicted as W_{comp} (J) and W_{fric} (J), respectively. The maximum friction force needed for the piston to press out the pellet was read as the highest value generated in the process. This value, depicted as F_{max} (kN), represented the maximal potential backpressure.

The pellets produced were analyzed through measuring the pellet's solid density (g/cm^3); first, by sanding the ends of the pellets, and then by measuring their volume and

weight. The pellet hardness (kg) was measured using a KAHL motor-driven hardness tester (K3175-0011; KAHL, Reinbek, Germany). All of the results are presented as the average value of five pellets.

The pellet parts that were left after the hardness test were used for the moisture uptake test. Before moisture uptake testing, the pellets were dried in 50 °C air for 24 h and then stored in a climate test chamber (C+10/200; Clima Temperatur Systeme GmbH (CTS), Hechingen, Germany) at 30 °C and 90% relative humidity (RH) until equilibrium was reached. The weight of the pellets was tested before they were placed in the climate test chamber, measured every hour for the first 8 h, and then periodically measured afterwards to determine when the equilibrium was reached.

RESULTS AND DISCUSSION

During the preparation of the biomasses, prior to as well as after the densification, some distinctive properties of each biomaterial were noted. Bamb had a smell of soil; CasP had a spongy middle; Euca was reddish with a typical woody smell; Glir was hard and woody; Lant was dark green and had a strong scent of herb; Pine was orange with a typical woody smell; Teph was yellow and created a notable amount of dust while being ground; Miom made less dust during grinding compared to all of the other biomasses; Bamb had intact particles and the pellets were grassy and softer; PeaS like Bamb crumbled easily at the ends; and Teph made shiny smooth pellets. Table 2 shows a compilation of the data for all of the materials collected in connection with the single pellet study.

Work and Force During the Production of Pellets

The energy needed for compression, W_{comp} , is shown in Fig. 2. Of all tested materials, pine required the highest W_{comp} , followed by Euca, Glir, and Bamb. Both CasP and CasS generated the lowest W_{comp} . According to the results in Fig. 2, the woods (red and blue colored) had a higher W_{comp} compared to the herbaceous biomasses (green and brown colored); only Sicklebush and Teph had the same level W_{comp} as the herbaceous biomasses. The fact that Euca, Glir, and Bamb generated higher W_{comp} can be explained by the presence of xylan within the hemicellulose. In a newly published study by Frodeson *et al.* (2018), xylan is identified as a component that affects the densification process and can explain the difference during the pelletizing of hardwood *versus* softwood (Frodeson *et al.* 2018). *Gliricidia sepium* is a hardwood tree (National Resource Council 1980) and xylan is the main component in the hemicellulose for both bamboo and eucalyptus (Maekawa 1976; Patt *et al.* 2006). Xylan together with glucomannan, which both are polysaccharides, are the two most common biomass hemicellulose components (Fengel and Wegener 1989). However, there is a deviation between them because xylan has many more side groups connected to the functional groups compared to glucomannan (Fengel and Wegener 1989). No or few side groups means that the polysaccharide is rather linear or stiff, whereas numerous side groups means that it is rather flexible or highly branched (Fengel and Wegener 1989). Thus, the particles have a greater degree of elasticity and more work is required to press them together (Frodeson *et al.* 2018). However, this did not explain why pine had the highest value of W_{comp} .

Table 2. Data From Moisture Content, Work for Compression, Friction, and Maximum Force During Densification of the Pellets, and Pellet Density and Hardness. Standard deviation was used for calculation the error.

	MC ln (%)	$W_{comp.}$ (J)	$W_{fric.}$ (J)	F_{max} (kN)	Pellet Solid Density (g/cm ³)	Hardness (kg)
Bamb	5.0	87 ± 7.6	110 ± 7.5	5.0 ± 0.2	1.164 ± 0.01	31 ± 5
	7.4	80 ± 3.3	116 ± 7.6	5.3 ± 0.3	1.187 ± 0.02	43 ± 6
	8.4	67 ± 4.9	112 ± 7.3	4.9 ± 0.2	1.208 ± 0.02	42 ± 8
CasP	5.2	60 ± 4.8	42 ± 2.7	2.3 ± 0.2	1.335 ± 0.01	16 ± 3
	7.0	46 ± 2.1	31 ± 4.1	4.0 ± 0.6	1.400 ± 0.01	35 ± 1
	8.1	44 ± 3.9	75 ± 12.2	7.1 ± 0.7	1.402 ± 0.01	49 ± 1
CasS	5.4	48 ± 2.4	21 ± 5.0	0.7 ± 0.1	1.205 ± 0.01	35 ± 3
	7.4	44 ± 1.1	24 ± 1.8	0.9 ± 0.1	1.195 ± 0.01	33 ± 4
	8.8	41 ± 0.8	30 ± 1.3	1.2 ± 0.1	1.160 ± 0.01	31 ± 1
Euca	5.3	91 ± 4.0	96 ± 6.9	4.1 ± 0.4	1.205 ± 0.01	18 ± 6
	7.0	89 ± 4.0	85 ± 5.7	3.6 ± 0.3	1.195 ± 0.01	32 ± 3
	10.5	83 ± 4.0	93 ± 6.3	3.9 ± 0.2	1.161 ± 0.01	28 ± 3
Glir	5.3	104 ± 15.5	90 ± 2.2	3.9 ± 0.1	1.140 ± 0.01	31 ± 1
	7.2	85 ± 10.4	76 ± 4.7	2.6 ± 0.2	1.217 ± 0.01	52 ± 3
	8.8	66 ± 2.8	60 ± 1.7	2.4 ± 0.1	1.225 ± 0.01	59 ± 1
Lant	5.5	89 ± 11.6	86 ± 8.9	3.7 ± 0.4	1.229 ± 0.02	27 ± 4
	6.8	68 ± 5.5	54 ± 11.2	2.4 ± 0.6	1.263 ± 0.01	34 ± 2
	9.7	42 ± 1.9	24 ± 1.8	1.4 ± 0.1	1.240 ± 0.01	38 ± 3
Miom	4.3	66 ± 6.6	49 ± 2.9	2.1 ± 0.1	1.169 ± 0.01	26 ± 4
	5.8	63 ± 2.0	45 ± 4.1	2.1 ± 0.2	1.212 ± 0.00	38 ± 5
	7.7	59 ± 3.3	43 ± 2.3	2.2 ± 0.2	1.217 ± 0.01	48 ± 4
PeaS	4.8	71 ± 6.0	39 ± 9.6	2.4 ± 0.1	1.184 ± 0.01	19 ± 1
	7.9	61 ± 0.9	34 ± 1.5	2.8 ± 0.3	1.187 ± 0.01	25 ± 0
	8.9	55 ± 1.6	33 ± 1.6	2.6 ± 0.3	1.157 ± 0.01	26 ± 2
Pige	4.0	65 ± 2.5	43 ± 5.3	1.6 ± 0.2	1.239 ± 0.01	41 ± 5
	5.7	57 ± 1.1	48 ± 2.8	1.9 ± 0.2	1.239 ± 0.01	46 ± 4
	7.7	53 ± 3.7	64 ± 4.3	1.7 ± 0.2	1.221 ± 0.01	41 ± 1
Pine	6.7	136 ± 17.2	68 ± 6.5	2.8 ± 0.3	1.172 ± 0.01	17 ± 3
	8.1	115 ± 11.5	63 ± 4.0	2.6 ± 0.1	1.185 ± 0.01	18 ± 3
	10.1	62 ± 17.5	60 ± 2.4	2.6 ± 0.1	1.152 ± 0.01	15 ± 0
Sicklebush	4.5	75 ± 1.3	42 ± 2.2	1.7 ± 0.1	1.214 ± 0.01	16 ± 1
	6.1	54 ± 1.3	40 ± 1.2	1.7 ± 0.0	1.228 ± 0.01	26 ± 1
	8.6	49 ± 1.4	45 ± 3.7	1.8 ± 0.2	1.193 ± 0.00	31 ± 1
Teph	4.9	78 ± 4.0	48 ± 7.7	2.0 ± 0.2	1.266 ± 0.01	67 ± 5
	6.7	77 ± 1.7	60 ± 5.3	2.7 ± 0.4	1.270 ± 0.01	70 ± 0
	9.5	80 ± 2.6	72 ± 6.1	3.3 ± 0.6	1.254 ± 0.00	70 ± 0

Unlike hardwoods with high amounts of xylan, pine hemicellulose is mainly glucomannan, which has been shown to generate a low W_{comp} (Frodeson *et al.* 2018). As shown in Table 1, pine has the highest level of lignin, and lignin has been shown to generate a high W_{comp} (Frodeson *et al.* 2018). In the same study, pine was distinguished as being the wood that had the lowest value of W_{comp} . Although it is likely that there is a difference between pelletizing African pine and Scots pine from Scandinavia, more studies have to be conducted to support this statement.

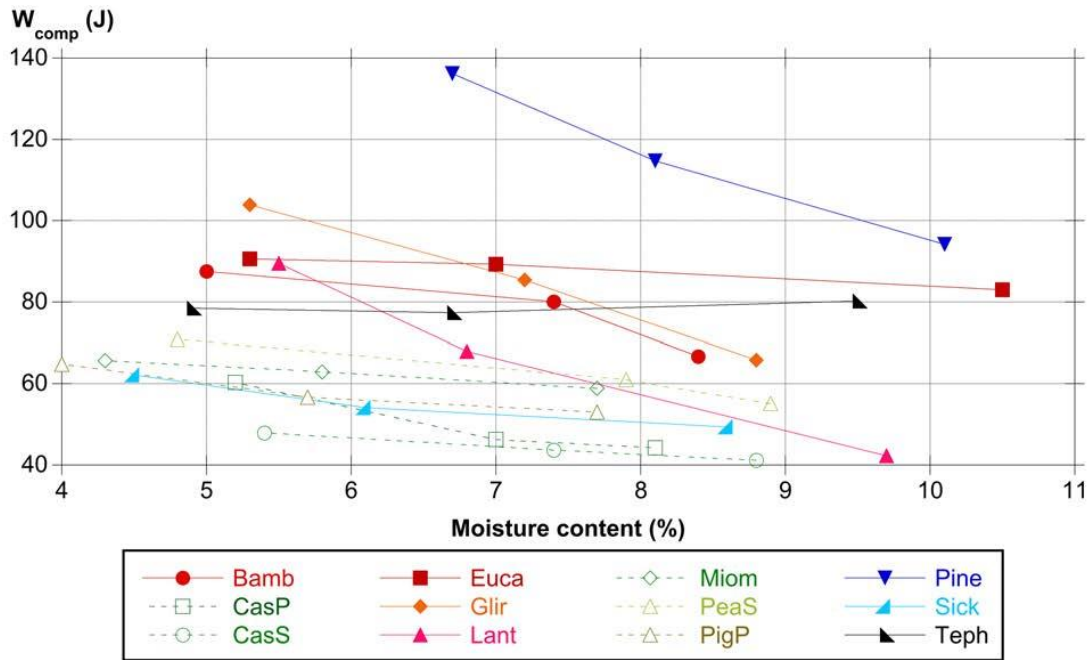


Fig. 2. Compression work, W_{comp} from 1 kN to 14 kN for all tested materials at different MC. The lines between the dots do not describe the regression or the inclination, the lines should be seen as help for the reader to follow the materials trends.

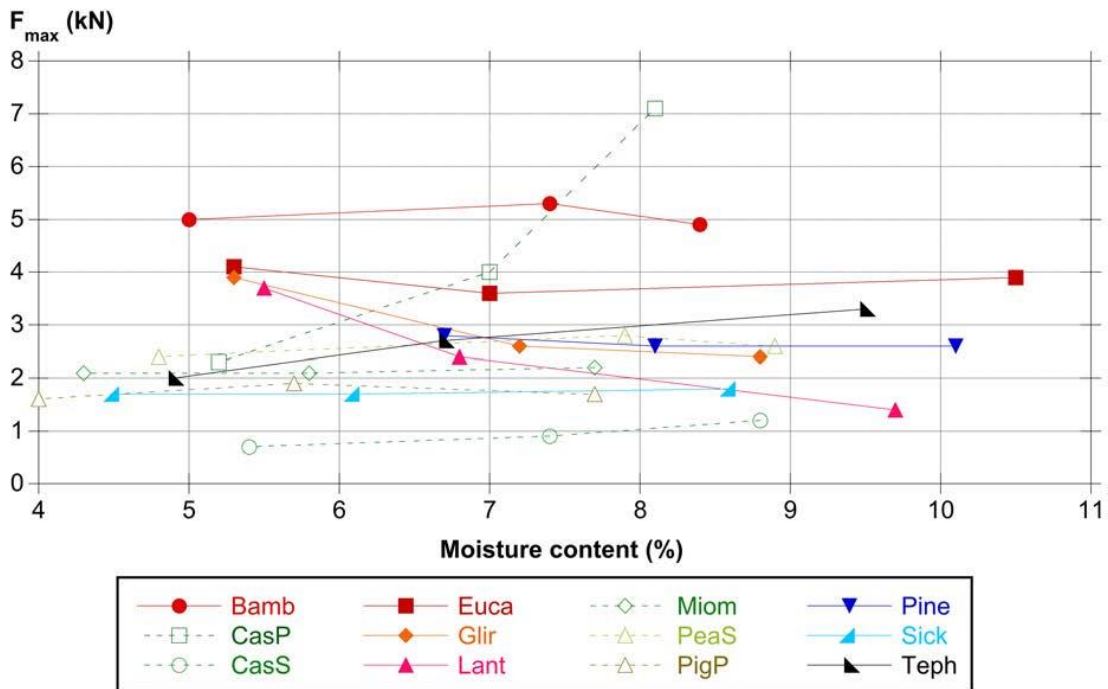


Fig. 3. Maximal backpressure, F_{max} at different MCs, for all tested materials. The lines between the dots do not describe the regression or the inclination, the lines should be seen as help for the reader to follow the materials trends.

To generate P_{roller} , the material has to cause a F_{max} , which is the static friction that can hold against P_{roller} in the active part of the die channel. As shown in Fig. 3, the highest generated F_{max} in this study was generated by CasP at 8% MC, with Bamb as the second highest followed by Euca. However, Bamb and Euca both had a high F_{max} for all tested MCs and seemed rather independent of increased levels of moisture in comparison to CasP, which increased greatly with an increased MC (Fig. 3). Furthermore, CasS and Teph slightly increased in F_{max} with increased MC, while Glir and Lant slightly decreased. The F_{max} of the other materials seemed unaffected by the increased MC (Fig. 3). As shown in Fig. 3, all of the woody biomasses had a high F_{max} at a low MC in comparison with the herbaceous biomasses. When the MC increased, this difference between woody-based and herbaceous biomaterials levelled out in Glir and Lant. The CasP had a higher MC and, therefore, Bamb and Euca should be pelletized with shorter press lengths. The independent behavior in F_{max} versus MC for Eucalyptus, miombo, peanut shell, pigeon pea, and sicklebush meant that they could be combined in raw material mixtures for pellet production. This, due to the rather wide optimum for MC for such a mix, will simplify the production properties.

The energy required to overcome friction, W_{fric} , is shown in Fig. 4, where Bamb and Euca presented the highest W_{fric} . The lowest W_{fric} was registered when pelletizing CasS and PeaS (Fig. 4).

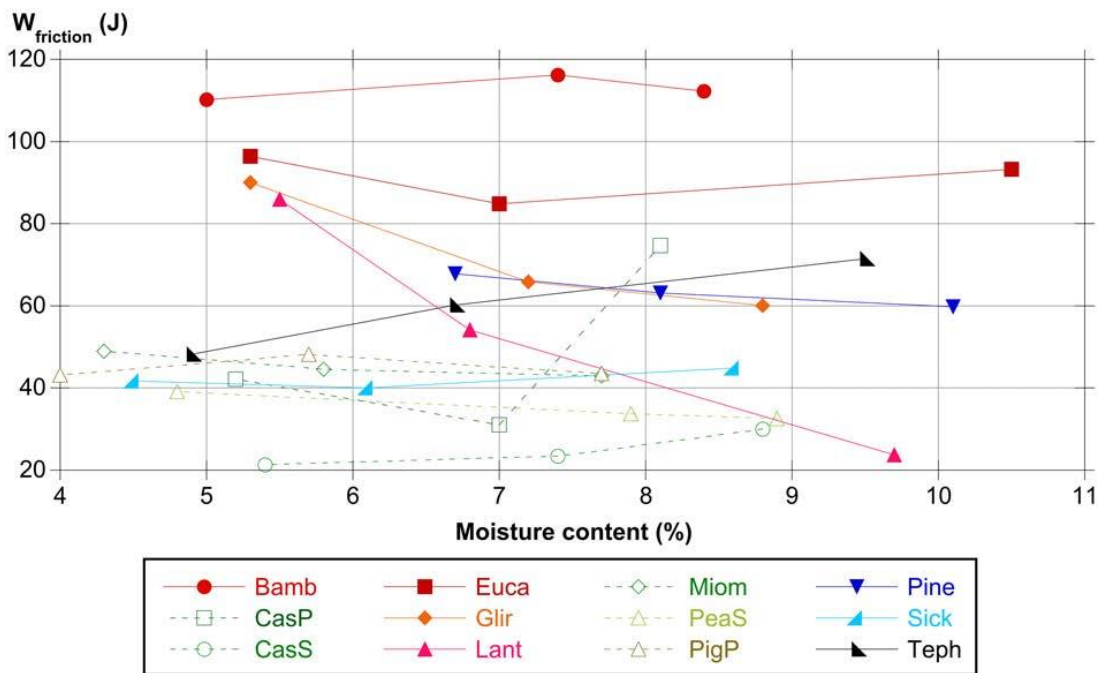


Fig. 4. Friction work, W_{fric} for all materials at different MCs. The lines between the dots do not describe the regression or the inclination, the lines should be seen as help for the reader to follow the materials trends.

Herbaceous biomass generally had a lower W_{fric} . Lower W_{fric} for herbaceous biomass compared to wood has been reported in other studies (Castellano *et al.* 2015). One explanation is that woody biomasses consist of a relatively low proportion of extractives compared to herbaceous biomass (Castellano *et al.* 2015). Another explanation is that

herbaceous biomass contains more proteins that can have a lubricating effect on the active part of the die channel (Stelte *et al.* 2011; Castellano *et al.* 2015; Frodeson *et al.* 2018). If W_{fric} and F_{max} are low, then the backpressure is also low, and if a high P_{roller} is sought, then a longer press length must be chosen to compensate for the lower friction. Bamb and Euca generated a larger need for friction work, and therefore should be pelletized with shorter die press lengths.

One important parameter for pellet production in Zambia is to find a mix of raw materials that has rather constant pelletizing properties. Materials with similar compression and friction energies ought to have a related behavior in the pellet press and therefore result in analogous press lengths. This means that pelletizing should be able to be performed without changing pellet dies. According to this study, Miom, PeaS, PigP, and Sicklebush, at certain MCs, had similar compression and friction energies (see Figs. 2, 3, and 4). Thus, these materials should be an effective starting point for a raw material mix; this means that a producer can probably use these materials as single raw materials, or in a mixture, without changing the process parameters. This knowledge of suitable press length in pellet production allows for an economic, time effective production when using these types of biomasses.

Pellet Properties

Pellet solid density

The density, hardness, and moisture uptake were chosen as the tested pellet properties. High-density pellets are important for those using pellet cooking stoves, as there is a requirement that a load of fuel pellets should give an expected amount of energy when burned. Pellets with the highest density were produced with CasP (Fig. 5).

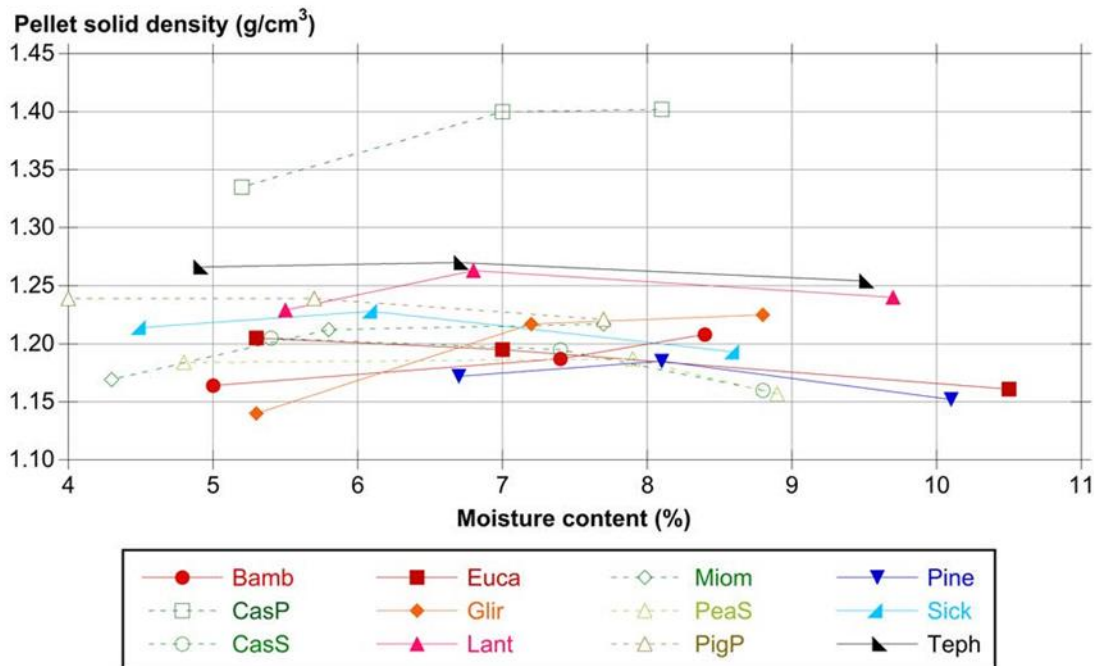


Fig. 5. Pellet solid density for all tested materials at varied pellet MCs. The lines between the dots do not describe the regression or the inclination; the lines should be regarded as help for the reader to follow the materials trends.

This could have been due to the high content of starch (Table 1). Cassava has been investigated as an additive and showed a similar effect on pellets (Lockenus 2014). The remaining biomasses, as shown in Fig. 5, did not differ considerably in density between each other or with different moisture contents. This was a desirable result because a similarity in density between the materials means that a pellet producer can switch between materials without risking a variation in bulk density. Additionally, it is important knowledge if a broad raw material base is to be used.

Hardness

The hardest pellets were made from Teph, followed by Glir. Pine was the biomass with the lowest hardness value over all of the tested MCs. This result was deviant from European pine, which is known to produce pellets with high quality and constitutes a considerable amount of the pellet production in Scandinavia. In previous studies, African pine has shown discrepant results compared to European pine (Andersson 2017). Low hardness pellets were also produced from CasP, Sicklebush, Euca, and PeaS at a low MC. As shown in Table 1, Teph had low levels of lignin in its composition. Lignin has been depicted as the most important factor in the production of high quality pellets, which is followed by the MC (Whittaker and Shield 2017). However, this study showed that other chemical substances in the raw material may be of greater importance for high quality, at least for hardness, than previously demonstrated. The high hardness of Teph is probably explained by its high amounts of cellulose and proteins. Cellulose has been found to result in durable pellets, despite the lack of lignin (Frodeson *et al.* 2018). Furthermore, proteins have been shown to improve durability in beech pellets (Holm *et al.* 2006).

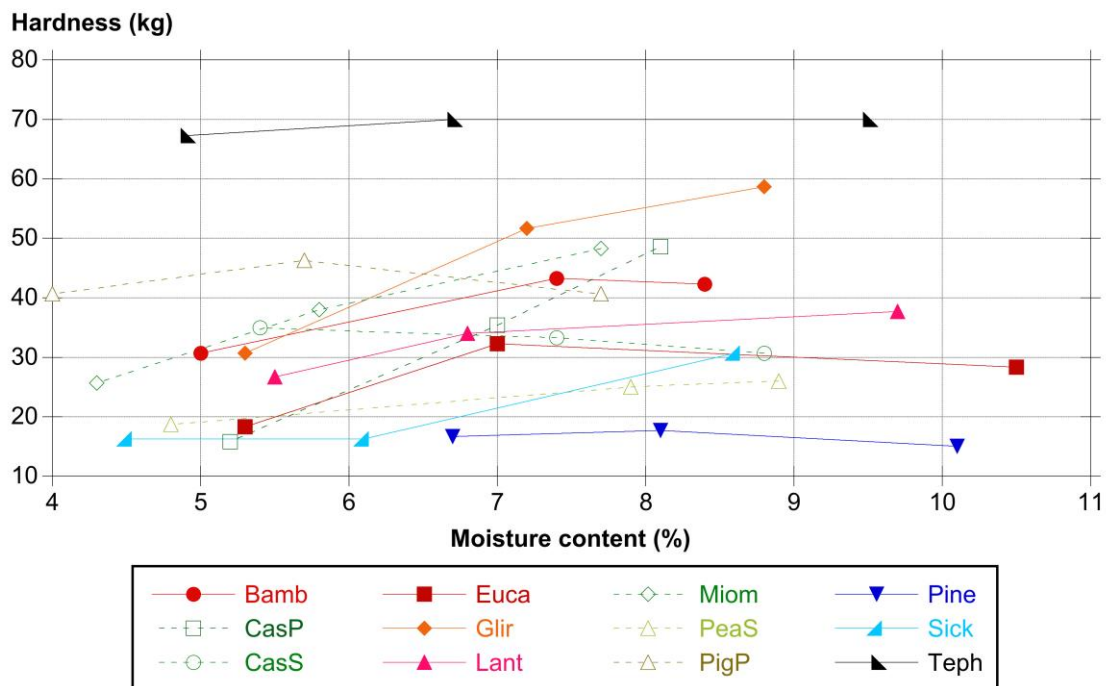


Fig. 6. Hardness for all tested materials at different pellet MCs. The lines between the dots do not describe the regression or the inclination; the lines should be regarded as help for the reader to follow the materials trends.

The combination of high protein and cellulose was probably the most notable factor in generating the hardest pellets within this study. However, within this study, the amount of MC was 5%, 7.5%, and 10%. As shown in Fig. 6, although CasP, Glir, Sicklebush, and Miom increased in hardness, they did not reach optimal hardness in the range of MC within this study. As shown in several studies, an optimum MC is within the range of 5% to 10% for woody biomasses and 10% to 15% for grass (Stelte *et al.* 2012), but can be as high as 20% to 25% (Moon *et al.* 2014). Likely, some of these materials have an optimum MC outside the range of the MC tested within this study. However, the purpose of this study was not to find the optimum MC level, but to find feedstocks that work well together in a broad raw material base for pellet production in Zambia. Thus, further studies are required correlated to optimum MC.

Moisture uptake

The climate in Africa can be challenging regarding the storage of biomass pellets. Therefore, moisture uptake is an important pellet quality parameter and should be low to better manage the challenging varied African climate with occasionally high humidity. As shown in Fig 7, all materials firstly rise quickly in moisture until a platform at equilibrium is reached, a profile that is consistent with other studies (Kong *et al.* 2016). Pellets of Euca had the lowest moisture uptake at equilibrium and Bamb, Glir, Pine, and Sicklebush also had lower moisture uptake. Lant and CasP resulted in the highest moisture uptake, as shown in Fig. 7. Using Lant and CasP for pellet production increased the risk of moisture uptake if pellets are exposed to, or stored in, humid areas. This can cause breakage and crumbs and affect the energy density (Telmo and Lousada 2011).

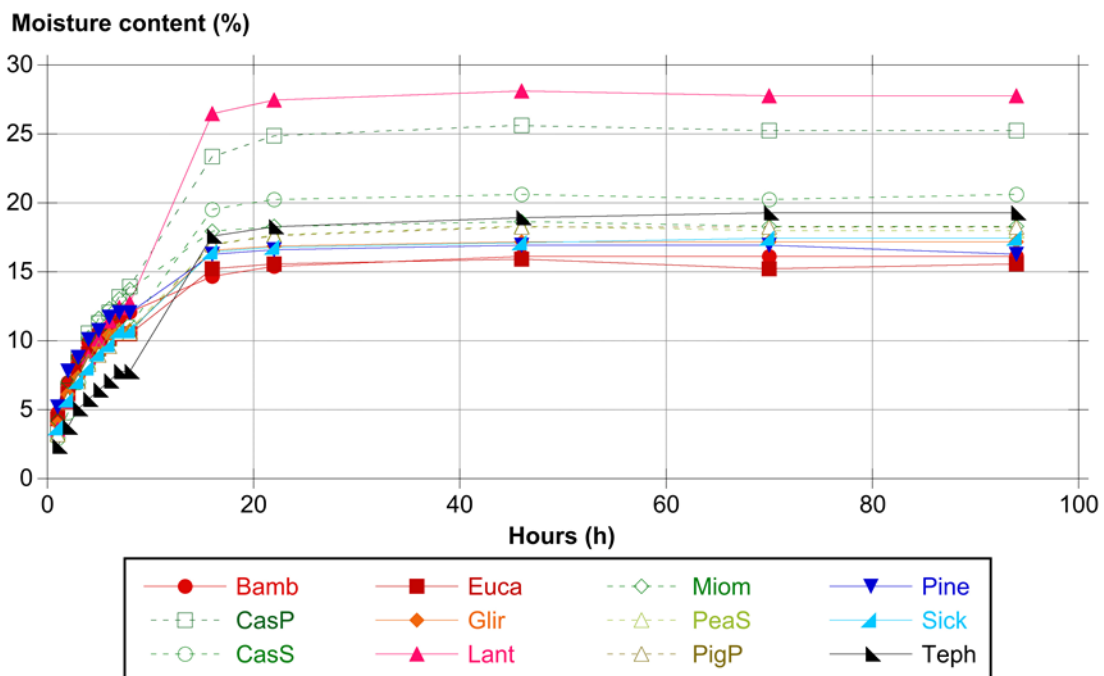


Fig. 7. Moisture uptake *versus* time for all materials tested in a climate chamber at 30 °C and 90% humidity. The lines between the dots do not describe the regression or the inclination, the lines should be regarded as help for the reader to follow the materials trends.

Sustainability Within Pellet Production

To solve the problems of deforestation and health risks related to food cooking in Zambia, pellet stoves and sustainable pellet production can be a solution. What distinguishes the logistical problem in Africa is long journeys in large trucks along inadequate roads that create problems; hence the importance of the raw material being regional and pellets being durable. Thus, it is necessary to find a sustainable utilization of the biomasses that simultaneously favors growth in the region. One way to achieve this is to collect a mix of locally available raw materials and produce pellets in a local pellet plant. In this study, 12 biomaterials were tested that are available in Zambia that could serve as feedstock in a pellet production facility. Of these, bamboo, *Lantana camara*, peanut shell, pigeon pea, pine, and sicklebush have potential as sustainable base raw materials for pellet production. Base raw material can be defined as a large available proportion of material that can be used in combination with other materials. However, there are some problems correlated to the logistics and availability for some of these six materials. Bamboo is spread out over vast areas and *Lantana camara* usually grows intertwined with other plants and trees making harvesting difficult. Therefore, the handling and logistics regarding these biomasses make it unlikely that they could be utilized as base raw materials. This means that peanut shell, pigeon pea, pine, and sicklebush have the greatest potential to be collected and exist in such large amounts that they could each act as the main part of a base raw material for pellet production in Zambia.

For cassava peel, cassava stem, and eucalyptus, there are large enough amounts to supply pellet production as a quality improving additive. *Gliricidia* and *Tephrosia* are not harvested in quantities sufficient enough to assist as additives in a larger scale and there are also difficulties regarding their logistic chains. However, both *Gliricidia* and *Tephrosia* should have potential as additives especially in order to strengthen the bonds within the pellet. As shown in Fig. 6, the hardest pellets were from *Gliricidia* and *Tephrosia*, which may be due to high content of xylan in *Gliricidia* and high content of protein in *Tephrosia*. Thus, these materials should have good conditions to generate strong bonding's through "solid bridges", especially if they are added as fibers, instead of small particles. Kong *et al.* (2013, 2016) have shown that adding fibers instead of powder increases the intertwining actions and "solid bridges" within the pellets and more durable pellets are generated (Kong *et al.* 2013; Kong *et al.* 2016). This could benefit a pellet production that has a more varied raw material base. However, this has not been tested in this study and further work is needed.

Accordingly, this means that four of the tested materials in this study are found in such great amounts that they can be used as base materials: peanut shell, pigeon pea, pine, and sicklebush. Of these four potential base materials, pine was distinguished as a material with a high compression energy (Fig. 2) and a high compression energy (Fig. 4). No other tested material showed the same behavior correlated with compression and friction. The addition of pine with some of the other biomasses could generate quality and production problems.

Furthermore, there are two interesting groups of materials that this study can point out to function as combinations of raw material bases to broaden the availability of raw material and create sustainable pellet production. These groups are as follows: Group 1, the equal pellet abilities, and Group 2: low impact of varied moisture content group. Within Group 1, it was found that the materials that had equal pellet properties correlated with W_{comp} , F_{max} , and W_{fric} . Materials, such as miombo, peanut shell, pigeon pea, and sicklebush, belong in this group. All of these materials should be able to be used in a varied

raw material stream, independent of the amount of each material if particle sizes are equal. The advantage is also that this group would have the same die press length. Group 2 requires more control of the mixtures of raw materials. These materials were rather independent of MC, within the range used in this study, correlated with W_{comp} , F_{max} , and W_{fric} . They are materials such as eucalyptus, miombo, peanut shell, pigeon pea, and sicklebush. If these materials are mixed with a specific fixed share split, this mixture should have a rather wide optimum MC, which will simplify the production properties.

However, this research and these mixtures have not yet been tested, and it is important to keep in mind that the single pellet press does not produce pellets with quality parameters that can be applied directly to a pilot- or full-scale press (Holm *et al.* 2007; Mišljenović *et al.* 2016). The results should be considered as a way to predict trends in the changes in pellet quality and to evaluate different biomasses (Holm *et al.* 2011; Mišljenović *et al.* 2016). Ultimately, the environmental impact and health problems associated with current energy system based on charcoal are unsustainable, and the results of this study demonstrated promising prospects for creating a sustainable energy system for cooking in Zambia.

CONCLUSIONS

1. Pellets from sicklebush and pigeon pea have low W_{comp} , F_{max} , and W_{friction} with low moisture uptake. Both materials are accessible and abundant enough to supply a large-scale pellet plant. Sicklebush and pigeon pea had the same F_{max} and W_{friction} and should be able to be pressed with the same die press length.
2. Both types of cassava showed desirable qualities for an additive and increased the hardness of the pellets with increased moisture levels. The study also showed that the proportion of cassava must not be too high, if the pellet is to be stored in humid environments. Both cassava varieties, along with *Lantana camara*, were the materials that had the highest moisture uptake.
3. The results on W_{comp} , F_{max} , and W_{friction} when pressing pine sawdust from Zambia differed clearly from tests on *Pinus sylvestris* and the reason for this must be further investigated. Sawdust from pine is a cheap and easily accessible raw material in Zambia. To solve the problem of low hardness and the high W_{comp} , cassava can be used as an additive.

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