Faculty of Health, Science and Technology
Environmental and energy systems

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Evaluation of five hardwood species from Zambia to produce fuel pellets for cooking purposes

Study with a single pellet press including pellet production, post production testing and X-ray examinations

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Utvärdering av fem lövträslag från Zambia för att producera bränslepellets för matlagningsändamål

Studie med en enpetarpress inklusive pelletstillverkning, efterproduktionsprovning och röntgenundersökningar

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Abstract

81% of the population in sub-Saharan Africa relies on charcoal and firewood to cover their energy needs for cooking. In Africa charcoal is usually produced by burning tree in a traditional kilns and then the food is cooked with a carbon-fired stoves indoors. All that links to three problems; deforestation, health issues and overpopulation, all of which can be reduced with a pellet cooking stove.

Zambia in sub-Saharan Africa consumes charcoal equivalent to 6,089,000 tons of firewood each year. The total consumption of firewood being 13,967,000 tons per year. That leads to harvesting rate between 250,000 and 300,000 hectares each year making Zambia having one of the world's fastest deforestation rates. Deforestation can be reduced by using the energy from the wood more efficient. In charcoal production and heating with charcoal about 72-86% of the produced energy is released to the atmosphere resulting the efficiency rate of only 14-28%. In comparison pellet production efficiency rate is 70-83%. Therefore if fuel pellets are used for cooking purposes energy instead of charcoal efficiency increases by 42-69% leading to lower need of wood material to cover equal energy demand.

In this study five hardwood species and a softwood reference material from Zambia has been evaluated for fuel pellet production purposes. Evaluated hardwood species are Umsafwa, Umupundu, Umusamba, Umwenge and Umutondo. Reference material is already in use for pellet production in Zambia. Evaluation includes pellet production in a single pellet press, post production testing and X-ray examinations for tree different moisture contents; 8%, 10% and 12%. Pellet production includes friction energy, maximal friction energy and compression energy measurements. Post production testing includes density and hardness testing as well as X-ray examinations that indicate the amount of produced ash in the combustion process.

High compression energy means higher energy cost in production so low compression energy is a desired property. Umupundu was the only wood species whose moisture content had no effect on the amount of compression energy. Umsamba and Umutondo gave the lowest and Umupundu and Umsafwa the highest compression energies of the tested hardwood pellets.

Almost all of the friction energies of the tested materials were close to one another. The biggest exception was Umsafwa with 8% moisture content which had 38% higher friction energy than the reference material on average in this study. The values of the friction energy are low compared with other studies but within the reasonable limits compared with the reference material. A clear linear relationship was found between the friction energy and F_{max}, so the friction energy directly implies the magnitude of the force of Fmax. A high hardness value is desirable because high hardness links directly to pellets high durability. All hardwood species tested were harder than the reference material.

Ash significantly shortens the service life of the pellet stove, therefore it is desirable to produce as little ash as possible. Umsafwa and Unwenge has the lowest amount of metals that indicates the smallest amount of ash formed when burning pellets. Umsafwa with MC of 12% and Umwenge with MC of 10% are the best mix based on this study.

Sammanfattning
81% av befolkningen i Afrika söder om Sahara är beroende av träkol och ved för att täcka sitt energibehov för matlagning. I Afrika produceras träkol vanligtvis genom att träden bränns i en traditionell ugn och sedan tillagas maten med en koleldad spis inomhus. Det leder till tre problem; avskogning, hälsoproblem och överbefolkning, allt detta kan minskas med en pellets spis.

I Zambia förbrukar träkol motsvarande 6 089 000 ton ved varje år, och den totala förbrukningen av ved är 13 967 000 ton per år. Det leder till en avverkningstakt på mellan 250 000 och 300 000 hektar varje år vilket gör att Zambia har en av världens snabbaste avskogningshastigheter. Avskogningen kan minskas genom att energin från veden används mer effektivt. Vid produktion och användning av träkol frigörs cirka 72-86% av den producerade energin till atmosfären, vilket resulterar i en användningsgrad på endast 14-28%. Vid pelletstillverkning är motsvarande värde mycket högre, 70-83%. Om bränslepellets används istället för kol för matlagningsändamål ökar därför energieffektiviteten med 42-69%, vilket leder till lägre behov av trämaterial för att täcka lika energibehov.

I denna studie har fem lövträslag och ett referensmaterial av barrträd från Zambia utvärderats för produktion av bränslepellets. De utvärderade lövträslag är Umsafwa, Umupundu, Umusamba, Umwenge och Umutondo. Referensmaterialet används redan för pelletstillverkning i Zambia. Utvärderingen inkluderar pelletsproduktion i enpetarpress, efterproduktionstestning och röntgenundersökningar för trädens olika fukthalter; 8%, 10% och 12%. Pelletsproduktion omfattar friktionsenergi, maximal friktionsenergi och mätningar av kompressionsenergi. Testning efter produktion inkluderar densitets- och hårdhetstestning samt röntgenundersökningar som indikerar mängden producerad aska i förbränningsprocessen.

Hög kompressionsenergi innebär högre energikostnad i produktionen alltså låg kompressionsenergi är en önskad egenskap. Umupundu var det enda träslag vars fukthalt inte hade någon effekt på mängden kompressionsenergi. Umsamba och Umutondo gav de lägsta och Umupundu och Umsafwa de högsta kompressionsenergierna av de testade lövträpellets.

Nästan alla friktionsenergier för de testade materialen låg nära varandra. Det största undantaget var Umsafwa med 8% fukthalt som hade 38% högre friktionsenergi än referensmaterialet i genomsnitt i denna studie. Värdena på friktionsenergierna är låga jämfört med andra studier men inom de tillåtna gränserna jämfört med referensmaterialet. Ett tydligt linjärt beroende hittades mellan friktionsenergin och F_{max}, således friktionsenergin antyder direkt storleken på kraften hos F_{max}. Ett högt hårdhetsvärde är önskvärt eftersom det kopplas direkt positivt till pellets hållbarhet. Alla lövträslag som testades var hårdare än referensmaterialet.

Ask förkortar pelletskaminens livslängd avsevärt, därför är det önskvärt att producera så lite aska som möjligt. Umsafwa och Unwenge har den lägsta mängden metaller som anger den minsta mängd aska som bildas vid förbränning av pellets. Umsafwa med MC på 12% och Umwenge med MC på 10% är den bästa mixen baserat på denna studie.

Preface

This thesis has presented orally to an audience familiar with the subject. The work has then discussed at a special seminar. The author of this work has actively participated in the seminar as an opponent to another degree project.

As an author, I would firstly like to thank my amazing thesis advisor Jonas Berghel for the outstanding support and guidance through the thesis project. Thanks for helping me with both experimental laboratory work and literature side of the project. I am also thankful for Lars Pettersson for providing guidance with the single pellet press. Thanks also to Emerging Cooking Solutions for initiating the topic of this thesis and enlightening me all the way from Zambia about the pellet industry and the given materials. Final thanks to my nearest; Max, family and friends for being there for me.

Karlstad, 25.5.2021

Annika Silvennoinen

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1. Introduction

1.1 Climate

Zambia is located in southern, sub-Saharan Africa where the capital and largest city is Lusaka (see **Figure 1**). The climate in Zambia is tropical with three distinct seasons; dry-cold, dry-warm and wet. Dry-cold season lasts from May to August when the temperature is approximately 14 - 26°C. Dry-warm season begins after a dry-cold season lasting until October. During the dry-warm season temperatures are round 26 - 32°C and the air is dry. Rainy season is the longest of seasons lasting from October to April and during that time temperature is high, between 26 – 32°C. Having these climate seasons in Zambia is mostly explained by the altitude and geography of a high plateau with few hills and mountains. (CIA, 2022) However, the global warming effect is increasing average temperature nationwide that might be affecting which species thrive in the country in the future.

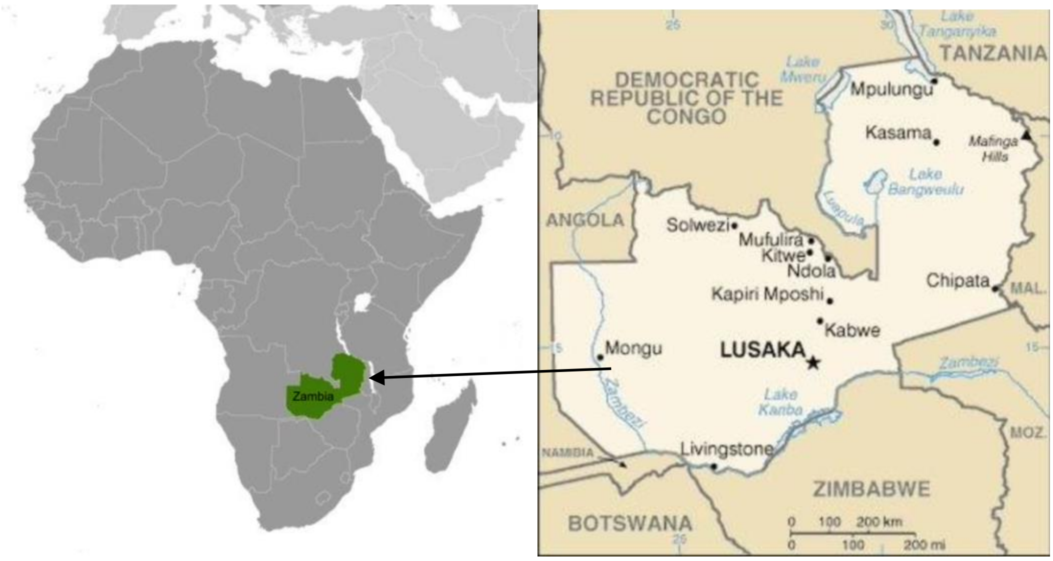


Figure 1. Map over Africa and location of Zambia (CIA, 2022).

There are several lakes, rivers, dams and waterways in Zambia making it one of the best water recourse owning country in Africa (Shane et al., 2016). The biggest lakes are Lake Tanganyika, Lake Mweru and Lake Banweulu, the size of which varies according to the season (CIA, 2022). A concern with rainfalls and droughts is the extreme seasons that are threatening crop yields and livelihood (Silimina, 06.2020). According to donor organizations severe drought in the western and southern provinces combined with the floods in the north made more that 2.3 million Zambians dependent on food aid during the years 2017 and 2018 (Silimina, 06.2020). This means that the farming conditions in Zambia can vary depending on the time and place.

Zambia is one of the most forested land in sub-Saharan Africa, roughly 67% is covered by forests (FAO, 2011). Forest is dominated by an open savannah, Miombo, that is covering three quarters of the total land area (Henriksson, 2018). The main species of the Wet Miombo is Brachystegia floribunda, B. graberrima, B. taxifolia, B. wangerrmeana and Marquesia macroura (FAO, 2003). The main spieces of wood in Dry Miombo is instead Brachystegia spiciformis, B. boehmii and Julbernadia globiflora (FAO, 2003). Additionally about 30-32% of the land area is nature reserves (Kisiangani & Masters 2011). However, the deforestation rate in Zambia is one of the world's fastest and the state haven't been able to stop illegal deforestation (Kauda, 2018). Forest binds carbon dioxide from the atmosphere, so trees should be protected. One way to reduce deforestation is to use the energy of the cut wood more efficiently.

1.2 Charcoal for cooking

Ascetic living conditions in developing countries put pressure on the inhabitants to cut down the forest among other things for cooking purposes. 81% of the population in sub-Saharan Africa relies on charcoal and firewood to cover their energy needs for cooking (AFREA, 2011). Zambia consumes charcoal equivalent to 6,089,000 tons of firewood each year, and the total consumption of firewood is 13,967,000 tons per year (Kisiangani & Masters 2015). Firewood is harvested from the forest and Zambia is in the top 10 most deforesting countries in the world. Amount of forest harvested is between 250,00 and 300,000 hectares each year, according to Zambia's Forest Department. Additionally according to Zambia's government and forest experts most harvesters have been cutting down the forests without a license and exporting them illegally to Asia because of ever-growing international demand for timber, together with high wood prices (Kauda, 2018). There is thus a great demand for cutting down the trees for domestic needs and foreign trade (Kauda, 2018).

In addition to deforestation, production and use of charcoal can have a cause-and-effect link to overpopulation and health issues. Wood collection is a major source of income for many households, charcoal production alone employs about 500,000 people in Zambia (Ryan et al., 2016). Traditionally it is women and children who are tasked with the collection which in some cases can take up to 30 hours a week. This working time could be used in more productive ways such as education, playing or income generation (WHO, 2016). For every missed year of secondary education, a risk of girls marrying as a child and having a child before age 18 rises by 6 percent (Wodon, 2018). It has been stated that the population is predicted to double in sub-Saharan Africa from 1.1 billion in 2012 to 2.3 billion in 2050 (Haub, 2012). As a result, the population will grow as will the need for energy and it leads to rising inefficient and unsustainable use of biomass (Kisiangani & Masters, 2011; Shane et al., 2016).

Poor ventilation and incomplete combustion generates harmful substances in indoor air causing single most important environmental health risk factor worldwide. Smoke from fireplaces and basic cooking stoves is estimated to cause 4.3 million premature deaths every year. This indicates that more deaths are caused every year by indoor air pollution than malaria, HIV/AIDS and tuberculosis combined. It is an issue even more important than the lack of clean water and sanitation. (WHO, 2016)

The amount of energy needed for cooking purposes could be reduced if the energy utilization rate were higher and the amount of energy wasted in the process were lower. According to Smeets (2012) conversion of wood into charcoal is usually done in small traditional kilns which efficiency is only about 8-12% and cooking stoves used in Africa have efficiency about 7-12% (see **Figure 2 (1)**). This results in the loss of 72-86% of the energy produced. Therefore most of the energy in wood and charcoal is released into the atmosphere in the process which is clearly not sustainable usage of energy. If carbon-fired stoves were replaced by EPA certificated pellet cooking stoves, then up to 70-83% of the produced energy would be used resulting in the loss of only 17-30% (see **Figure 2 (2)**) (U.S. Department of Energy, n.d.). Therefore pellet stoves sold by Emerging Cooking Solutions can be one solution to releasing fewer particles to the indoor air while cooking and to using energy more efficient.

Figure 2. 1. Carbon-fired stove, 2. Emerging Cooking Solution's pellet cooking stove.

1.3 Emerging Cooking Solutions Ltd

Emerging Cooking Solutions (ECS) is pellet producing company founded 2012 in Zambia. Their main products are fuel pellets and cooking stoves nonetheless the company also sells solar panels. Nowadays pellets are produced of waste wood (pine sawdust) but the goal is to find new biomasses to replace the current material. The reasons for the need of new raw material are the reduction of waste wood due to increased demand and competition. One of the company's missions is to stop the deforestation of Africa, starting in Zambia. Therefore new biomaterials could possibly be cultivated funded by the company, so there would be no need to harvest new forest. Fast-growing trees would be most suitable for this purpose.

1.4 New biomaterials for pellets

Low amount of ash produced during the combustion process of the pellets is a desired property from pellet biomaterials. High ash content can reduce the life length of a cooking stove from 1000 hours to 100 hours due to blocking the ventilation holes in the stoves (Ohlsson, 2022). The ash content of different biomaterial can be predicted with a wavelength-dispersive X-ray spectroscopy that measures the content of elements in raw materials. One of the most influential factors on the concentration of different elements in wood ash is the amount of charcoal which varies due to incomplete combustion (SLU, n.d.). Addition to charcoal, wood ash contains mainly of calcium, potassium, magnesium, silicon, phosphorus and oxygen (SLU, n.d.). If these metals are found in abundance in the hardwood species studied compared to the reference tree which are softwood species, then the ash formed in the combustion process may interfere in the burning of the pellets on the pellet stove. Generally more ash is produced from the burning of soft trees compared with hard trees (Millati, 2019).

Amount of cellulose, hemicelluloses, lignin and extractives in the biomaterial determines the properties of biomaterial. For pellet production today, wood is by far the most widely used material (Henriksson, 2018). According to Yang and Jaakkola (2011) wood in a living tree contains 40-50% water and the remaining dry substance can be divided into structural substances and non-structural substances. The structural substances in wood constitute about 95% of the dry substance containing cellulose, hemicelluloses, lignin and extractives (Yang and Jaakkola, 2011). The mass proportion of chemical substances is depending on the morphological region, kind of the tree, and age of the wood (Yang and Jaakkola, 2011). Generally softwood contains more glucan composition and less xylan compared with hardwood that consist mostly of glucan and xylan (Millati, 2019).

1.5 Zambia's national goals towards sustainable development

Companies are not the only ones trying to find replacement for charcoal production and burning charcoal. Zambia's government decided 2009 to participate Reduce Emissions from Tropical Deforestation and Degradation in developing countries [REDD +]. This project is arranged by UNFCCC and the aim is to take action against deforestation. One of the set goals is to improve the utilization and regulate the production of charcoal and wood by 2030 (Matakala et al. 2015).

Year 2015 Paris Agreement was signed for United Nations Framework Convention on Climate Change (UNFCC) issuing to limit global warming to below 2 grades with 17 sustainable development goals. Total 196 parties adopted this legally binding international treaty on climate change agreeing to reduce their greenhouse gas emissions to reach the set goals. (United Nations, 2015) Zambia's Intended Nationally Determined Contribution (INDC) to the 2015 Agreement is to improve sustainable forest management, sustainable agriculture and usage of renewable energy as well as energy efficiency by the year 2030. Among these goals is to improve cooking devices to include improved biomass stoves and to replace charcoal with biomass. (UNFCCC 2015)

1.6 Fuel pellets for cooking

Fuel pellets are compressed biomass which can be used for several purposes, among others for cooking purposes. Energy for cooking is obtained by burning pellets in a stove or a burner that heats cooking utensils. Fuel pellets has normally a diameter between 6-12mm and a length of about 20mm. These properties are obtained in the production process where biomass is compressed in about 100℃ temperature through a metal matrix that has a specific hole diameter and press channel length. The properties of the matrix and compressing process affect not only the dimensions but also the density and hardness of the produced pellets. Influencing factors include biomaterial composition, how much ash is produced when the pellets are combusted and how well the pellets withstand transport without crumbling. As well as the production process and the material, the environment can also affect the properties of the pellets, such as moisture content. Tropical climates have higher humidity than, for example, southern Europe. Therefore the moisture that is transferred from the air to the pellets in Sweden after the pelleting can be less than what is transferred in Zambia. Also dirt that has accumulated during transport have effect on the content of pellets and these should be taken into account in the manufacture of pellets (Berghel, 2022). According to Andersson (2017) studies show that the moisture content plays a key role in durability of pellets. For pellets made of spruce mixed with pine, moisture content increased durability, but for pellets made of beech and pine moisture content in a range 6-16% instead decreased durability of pellets (Andersson, 2017). Thus, the importance of moisture content to the durability of pellets depends on other properties of the biomass used.

1.7 Single pellet press

In this study pelleting is done in a single pellet press where one pellet is made at a time. This single pellet press is presented in **Figure 3**. A single pellet press is useful on studying trends in changes in pellet quality of different material (Mišljenović et al., 2016). It is also proven to enable a simple prediction of the behavior of materials during pelleting (Holm et al., 2011). With greater amounts of biomass, full-scale continuous press is needed but this study is a pilot study which focuses on a fewer masses for quality research.

In a single pellet press, the pellets are produced in two steps. In the first step, the material is placed in a matrix press channel in the matrix and pressed against the metal piece with a piston. In the next step, the bottom piece and the metal piece is removed and the compressed pellet is pushed out of the matrix press channel. During the second stage, frictional force between pellet and channel is measured. Friction force is causing back pressure in the matrix press channel. The maximum value of the friction force (Fmax) is reached when the force of the piston reaches the value of the static friction. After that the pellet starts to move in the matrix press channel and that movement is resisted by kinetic friction until the pellet comes out of the channel.

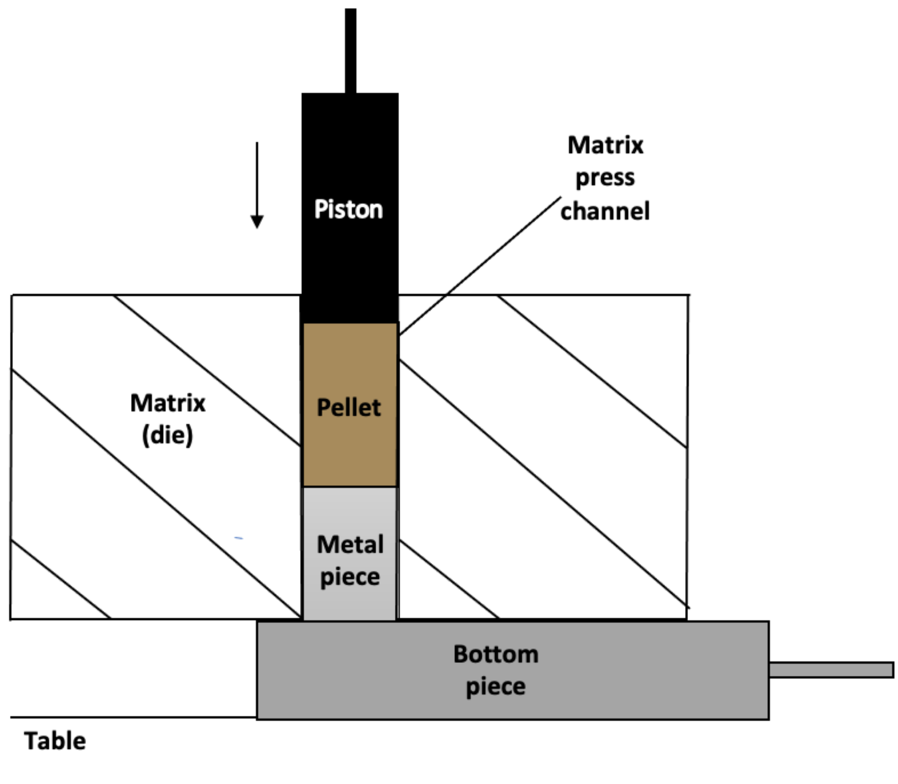


Figure 3. Pelletizing in a single pellet press. The arrow indicates the direction of the piston force.

Measuring the force needed to compress pellets and corresponding friction force are important for production purposes. Energy needed affects the profitability of production, contribution to saving the environment and choosing the right matrix. The more energy used in the production of pellets, the more expensive the production because it costs to buy electricity. In addition to the cost, the production of electricity pollutes the environment, so the ideal biomaterial in this sense would require as little energy as possible. Furthermore, production is affected by the temperature of the matrix. In a single pellet press, temperature of about $100°C$ is reached by heating the matrix with electricity. However, in large-scale pellet production several different biomaterials are used in the same machines and the thermal energy can be obtained for free if the frictional energy of different biomaterials is about equal. The frictional force resists the movement of the pellet in the matrix press channel and releases thermal energy needed in the pellet compressing process. Too low friction energy equals to too low matrix temperatures (Nielsen Holm et al., 2009).

For the friction energy between materials to be equal, raw materials with naturally low frictional force require a matrix with a long press channel. Therefore the pushed distance is longer and the total frictional force is higher. In turn, those raw materials that naturally have higher frictional force need a shorter matrix press channel. Short press channel makes the thrust distance shorter, resulting in a lower total frictional force. Thus, pellets can be made from different raw materials with the same friction force resulting to equal heating energy when using different matrices.

1.8 Purpose and goal of the study

The purpose of this study is to increase knowledge about five hardwood species grown in Zambia and their ability to be pelleted to expand the possibilities to produce fuel pellets from different biomasses and help Emerging Cooking Solutions' business expand in a sustainable way.

The goal is to recommend the most suitable hardwood species, or a mixture of a few hardwood species studied for the manufacturing of cooking fuel pellets. The recommendation is based on a comparison with reference material already in use in Zambia. The recommendation is based on 3 factors: pellet production, post production testing and X-ray examinations. Pellet production includes compression energy, friction energy and Fmax testing to find out the characteristics of the production of raw material pellets. Post production testing includes density, hardness and moisture measurements to determine pellets sustainability. X-ray examinations goal is to find the relationship between the materials and their ash content.

2. Methods

The materials are presented and described based on literature in chapter 2.1. Then preparing material, pelletizing and measuring are introduced and explained in chapters 2.2 - 2.7. Every part of the study is executed in a laboratory in the Karlstad University.

2.1 Materials

The tested materials were 1) reference material (*Pine Kesiya, Merkusii and Oocarp*), 2) Umsafwa (*Syzygium Guineense*), 3) Umupundu (*Parinari Curatellifolia*), 4) Umusamba (*Brachystegia Boehmii*), 5) Umwenge (*Diplorhynchus Condylocarpon),* 6) Umutondo (*Julbernardia Paniculata*) (see **Figure 4**). All wood species were shipped from Zambia by Emerging Cooking Solutions Ltd. Of the tree species, Umsafwa, Umupundu, Umusamba, Umwenge, and Umutondo were sent as wooden blocks approximately 6cm high and 3,5cm wide in diameter (see **Figure 4**). The reference material used in the study was pre-chopped into sawdust in Zambia (see **Figure 4)**.

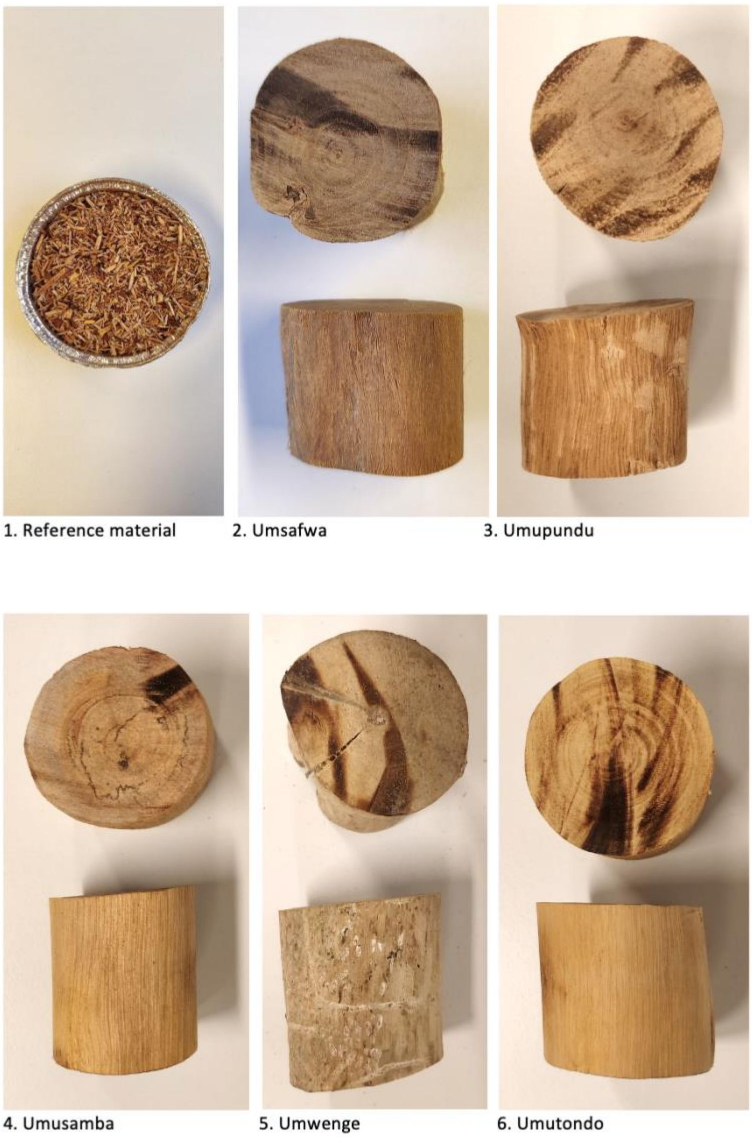


Figure 4. Materials used in the study.

In this study the wood materials used for the production of fuel pellets were obtained from EMC. The wood species were selected for the study because they have not been previously studied for fuel pellet purpose and according to Mattias (2022) they are local species in Zambia that might be good for pelletizing. Common for all of the studied hardwood species is that they are not fast-growing trees (Siwale, 2022).

1. **Reference material**

Reference material is a mixture of three species of wood*; Pine Kesiya, Markusii* and *Oocarpa* (Matthias, 2018). Reference species are softwood species. All three wood species are pine plants that belong to the pine genus and the family pine (Matthias, 2018). According to Matthias (2018) species occur on plantations around Zambia. The exact amounts of the species in the wood mixture are not known.

2. **Umsafwa**

Umsafwa grows in dry evergreen forests and more specifically in the Parinari forest or the Marquesia forest (FAO, 2002). It is a hardwood species and also a fruit tree.

3. **Umupundu**

Umupundu is also a traditional food plant (Siwale, 2022). The wood is very hard and heavy containing silica crystals that are making it difficult to work with (Drummond R. 1972). Umupundu is a hardwood tree.

4. **Umusamba**

Umusamba is one of the three domain species of the floristically poorer Dry Miombo woodland (FAO, 2003). The tree can grow 15 meter tall and the wood is heavy, tough and strong making it hard to work with. Umsamba is also a hardwood species.

5. **Umwenge**

Umwenge is a sub-canopy species that belongs to the Burkea-Diplorhynchus species (FAO, 2007; FAO, 2005). The tree can grow up to 4.5-6 meter tall, occurring on the highest ground in the river valleys (FAO, 2005). Umwenge is a hardwood species.

6. **Umutondo**

Umutondo is also growing on the high altitudes specially over the warmer parts of Africa. Therefore it’s a common species in plateau woodland in central Zambia. (Storrs, 1979). The tree has a grey bark and can grow up to 20-30 meters (Coates, 1961). Umutondo is a hardwood species.

2.2 Chopping and milling

All wood species used in the study were chopped into sawdust with particle size no larger than 1 mm. The process of chopping and milling was carried out in the following stages:

- Raw materials is chopped by sawing wood blocks into small cubes with a side length of about 2cm.

- Wood pieces are fed into a IKA Pilotina MU cutting mill with 3 teeth (see **Figure 5**). The sieve hole size is 1 mm preventing the passage of larger sawdust particles.
- The sawdust is sieved into a container from which the sawdust is carefully collected by tree species into glass containers.

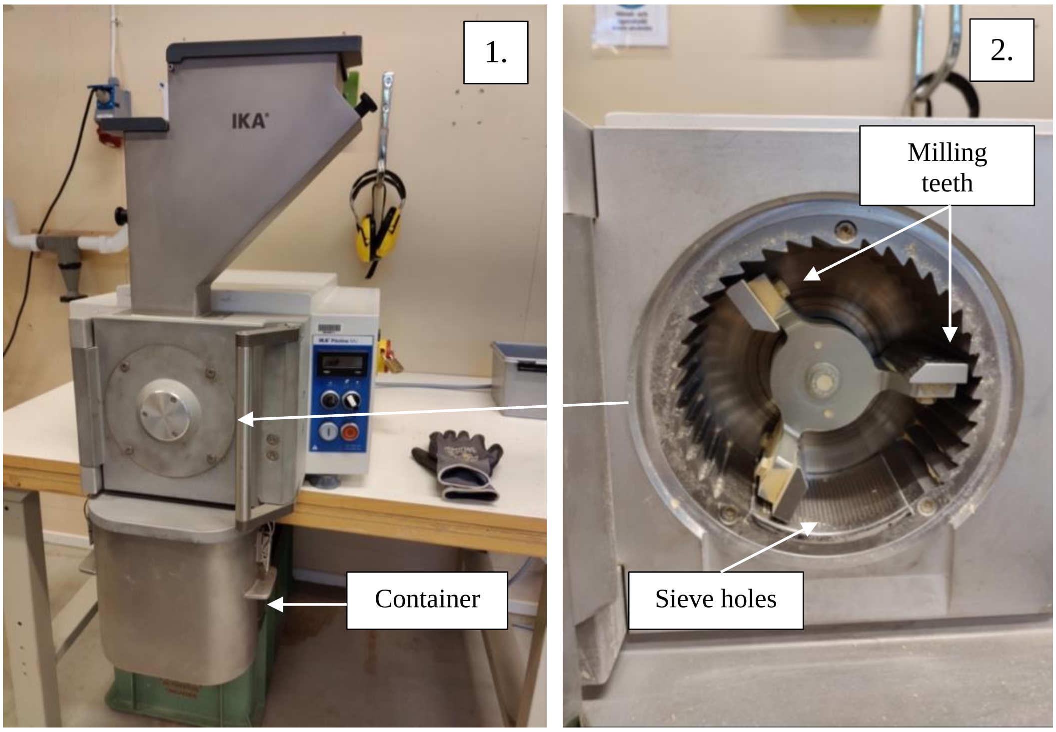


Figure 5. 1. IKA Pilotina MU, universal cutting dry mill. 2. Inside of the cutting mill.

2.3 Drying and moistening

After shredding all samples are dried in the drying chamber at 103°C for at least 24 hours to make sure that the moisture content were 0%. Oven used is presented in **Figure 6**.

Figure 6. 1. WTC-binder FD53, drying chamber. 2. RADWAG moisture analyzer, series MAC 50.

After drying, the samples are divided into plastic bags. Each of 6 studied tree species is divided into 3 plastic bags each containing about 15g raw material. Then moistening is carried out in following stages:

- The closed plastic bags with sawdust are weighed on a scale.
- The amount of water required is calculated according to (1).

$$MC = \frac{H_2O}{DS+H_2O} \quad (\%)\ (1)$$

There MC = Moisture Content, H_2O = amount of water and DS = dry substance.

- Finally the amount of water is sprayed into the plastic bags with a spray bottle. After each spray, the weight is read from the scale so that the amount of water in the plastic bags will not exceed the desired limit value.
- The aim in moistening is to obtain moisture contents 8%, 10% and 12% to study the effect of moisture on the palletization of materials.
- The plastic bags are sealed for 24 hours to distribute moisture throughout the bag.
- Moisture contents are then measured with a moisture analyzer presented in **Figure 6.** A margin of error in the moisture contents is within -0.5% to +1.0% before pelletizing.

2.4 Pelletizing

The layout of the pelletizing station in Karlstad University is showed in **Figure 7**. 6 pellets are made for each series. There are a total of 18 series and the series consist of 6 different wood materials. For each wood material 3 series are made with different moisture contents (8%, 10% and 12%).

Figure 7. Layout of the single pellet press at Karlstad University. 1. Single pellet press monitor, 2. Scale, 3. Single pellet press that is drawn in the Figure 3, 4. Equipment for the manufacture of pellets, 5. Display for monitoring, 6. Air pistol.

The pellets were produced by the following steps:

- 1g raw material are weighed on a scale with a fail marginal of 0,1g.
- Removable bottom piece is placed to the bottom of the matrix press channel in a single pellet press.
- 10mm long metal piece is dropped to the cylindric matrix press channel that is 137mm long and has 8.2mm cylindric diameter. The temperature in the steel made matrix is constant 103℃. The matrix has outer diameter of 120mm.
- Weighed raw material are poured to the matrix press channel using a little funnel.
- Compressing is started at set displacement rate. Piston with a diameter of 8.0mm is pressing the raw material with a displacement rate of 15mm/min.
- Compressing is stopped when the monitored force reaches value of 14kN. Pressure is hold for 10s and then lowered for making the removal of the bottom piece easier.
- Bottom piece is removed as well as the metal piece.
- Compressing is started again at set displacement rate. Displacement rate for friction measurement is 30mm/min.

- Constant displacement speed is maintained until pellets fall out of the single pellet press channel.
- Pellet is cooled by placing it to the table in the room temperature for 5 minutes before placing it to a closed plastic bag.
- The single pellet press is cleaned between tree species with an air pistol.

2.5 Measurement data

Measurement data (the force of the piston, the time, the displacement of the table) is collected during pelletizing and produced Excel file is then analyzed. Compression energy, Fmax as well as friction energy is calculated from the measurement data. An example curve of how the force of the piston is changing as a function of time during pelletizing is presented in **Figure 8**.

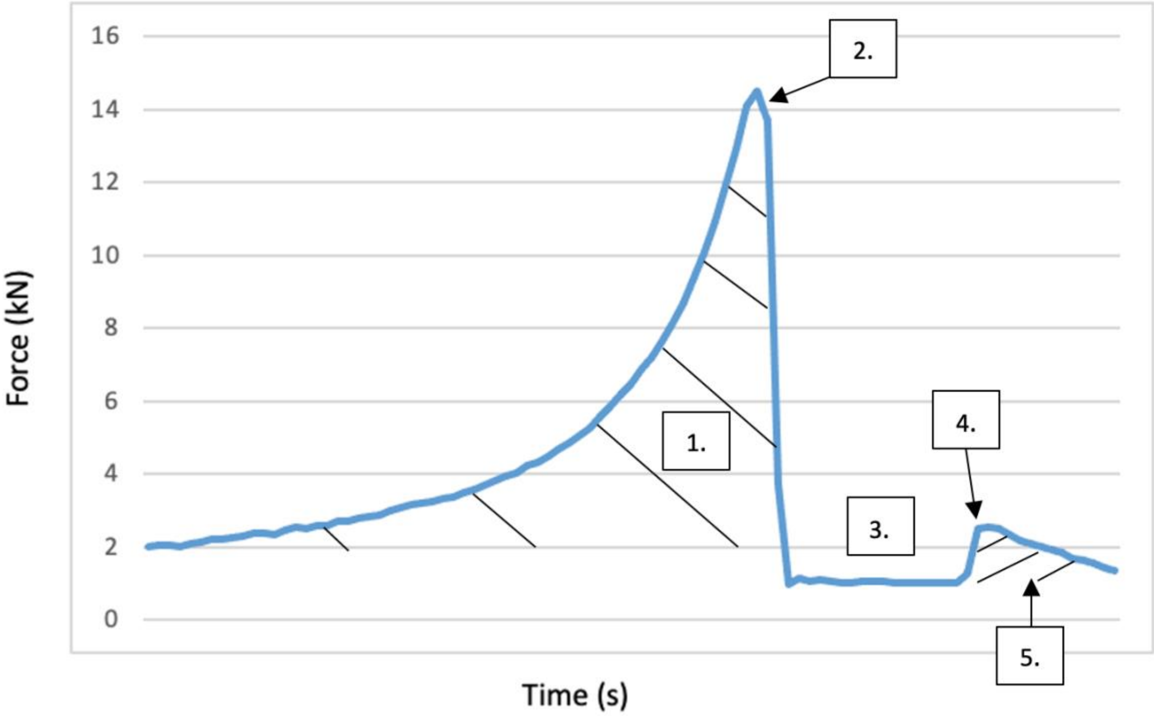


Figure 8. Example of a force curve during the pelletizing.

Compression energy (*Wcomp*) is calculated in step 1 where pistons force is rising from 2kN to 14kN. The table and all of the equipment are equal to 1kN force. This means that pellets are pressed with force interval from 1kN to 13kN. Once the desired value is reached, the pressure is dropped a little which leads to the decreasing values in **Figure 8** at step 2. In step 3 the bottom piece and the metal piece is removed and pistons force is constant low. Fmax is reached at step 4 just before the pellet starts to move in the matrix press channel. Fmax is equal to the value of the static friction. After pellet starts to move in the matrix press channel, force is decreasing and pellet comes out of the matrix. The friction energy (*Wfric*) is measured in step 5 for 10mm displacement starting from when the pellet starts to move in the matrix press channel. Friction energy is measured for 10mm because it is the length of the metal piece in the channel (see **Figure 3**). When the pellet passes 10mm, the area between the matrix and pellet starts to decrease as the pellet comes out of the matrix press channel. That's why only the first 10mm displacement is counted to the friction energy. W_{comp} as well as W_{fric} is calculated according to (2).

$$W = \int_0^t F \cdot (x)\, dx \qquad \text{(J) (2)}$$

There t= time (s), F = the force of the piston (kN), x = displacement (mm).

2.6 Quality measurements

Density (ρ) is calculated as an average value of six pellets for each series. Density for each pellet is calculated by measuring the length and diameter by electronic calipers and weighing pellets on an electronic scale. The measuring data is then used in equation (3).

$$\rho = \frac{m}{l \cdot r^2 \cdot \pi} \qquad \text{(g/cm}^3\text{) (3)}$$

There m = mass (g), l = length (cm) and r = radius (cm).

Hardness is measured with KAHL Pellet-Harnesstester (K3175-0011, Reinbek, Germany) which is presented in **Figure 9**. The tester measures radial pressure by pushing pellet with rising load one at a time until the pellet cracks. The load is presented in a scale from 0kg to 100kg and the maximal load is read from the scale when the pellet cracks. Hardness presented in the results is calculated as an average value of six pellets for each tree wood species and for each moisture content.

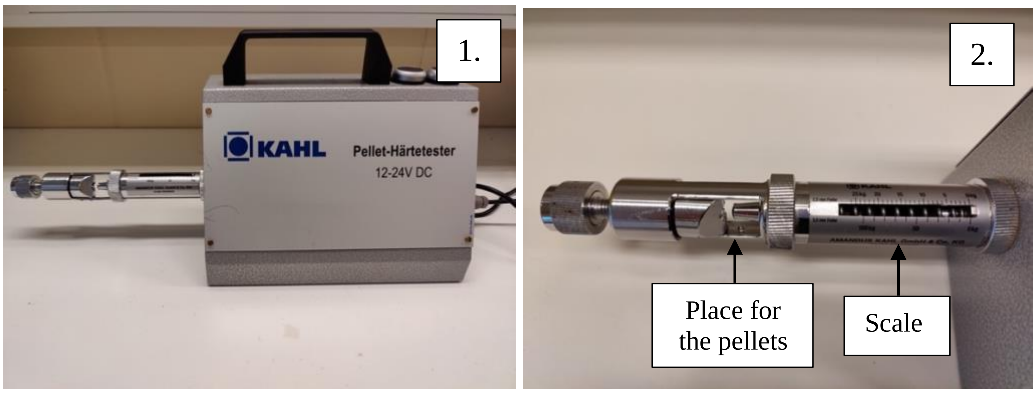


Figure 9. 1. Kahl Pellet-Hardnesstester. 2. The scale and a place where the sample is placed.

2.7 Sample content

X-ray spectroscopy is carried out with S1 TITAN model 800 which is presented in **Figure 10**. Device works by sending 50kV X-rays to the material and measuring the reflecting radiation and its' wave length. Based on the wave length and the amount of radiation, the device collects data of elements in the samples. Confidence interval for S1 TITAN is ±2 equivalent to 5% fail marginal. The device is dimensioned for geo exploration and calibrated for a soil sample. The soil sample consists of smaller particles in diameter than wood samples so the density of wood samples is lower than the soil samples. Because the unit of X-ray measurements is parts per million [ppm], the concentrations obtained from wood samples may be slightly lower than the actual ones. X-ray spectroscope interprets also magnesium as magnesium oxide, aluminium as aluminium oxide, silicon as silicon oxide and potassium as potassium oxide because those are common in soil samples.

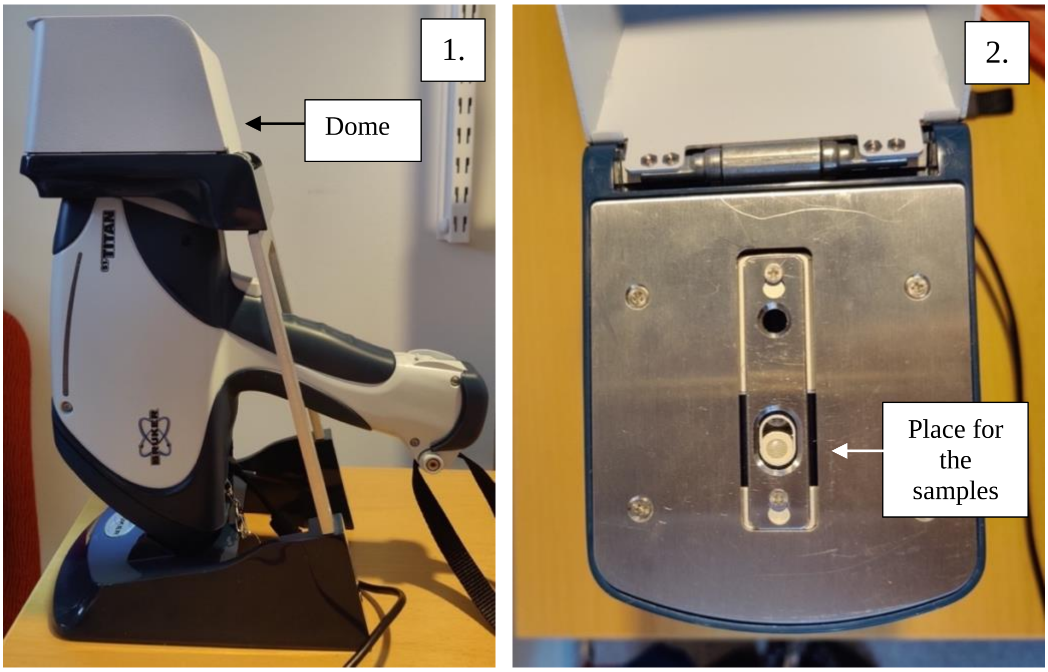


Figure 10. 1. Wavelength-dispersive X-ray spectroscope, S1 TITAN model 800, 2. An image of the inside of the spectroscope dome into which the sample is placed.

X-ray measurements were taken in three different phases:
1. Before any procedures.
2. After chopping and milling but before pelletizing.
3. After pelletizing and quality measurements.

For the reference material there were no material before any procedures as the material were already chopped and milled. Therefore only phases 2 and 3 are measured for the reference material. For other materials X-ray measurements for phase 1 are done for the wooden blocks approximately 6cm high and 3,5cm wide in diameter presented in **Figure 3**. For phases 2 and 3 about 2g of each material is pressed tightly into the sample jar so that the surface is flat. Three measurements are taken from each sample and their average values are shown in **Tables I** and **II**.

3. Results

In line with study objectives, the results are divided into three sections: pellet production, post production testing and X-ray examinations. Pellet production includes a short introduction of the pellets as well as compression energy, friction energy and Fmax. Post production part includes density, hardness and moisture measurements. X-ray examinations include results for the X-ray spectroscopy. Collected data without the results of the X-ray examinations is presented in **Table I**. X-ray results are presented in section 3.3 in **Table II** and **Table III**.

Table I. Data collected in the study. MC fore and MC after is the moisture contents before and after pelletizing, W_{comp} is compression energy and W_{fric} is friction energy.

	MC fore [%]	MC after [%]	W_{comp} [J]	W_{fric} [J]	F_{max} [kN]	Density [kg/m^3]	Hardness [kg]
Reference material	7.6	5.9	51±13	14±2	1.4±0.2	1122±34	27±2
	10.1	7.7	46±12	14±2	1.4±0.2	1081±76	12±4
	11.7	9.7	28±12	13±0	1.3±0.1	963±12	9±1
Umsafwa *Syzygium Guineense*	8.6	5.6	63±11	22±5	2.7±0.7	1122±86	21±3
	10.2	7.8	50±4	17±1	2.1±0.2	1122±16	30 ±2
	12.1	8.5	54±8	16±1	2.1±0.2	1112±35	24±6
Umupundu *Parinari Curatellifolia*	8.4	6.6	65±14	18±1	2.2±0.1	1117±25	26±6
	10.8	8.2	52±16	16±1	2.0±0.2	1108±11	24±2
	12.1	9.2	68±5	18±1	2.2±0.1	1125±27	24±3
Umsamba *Brachystegia Boehmii*	8.3	6.9	43±5	16±2	1.8±0.2	1103±52	17±3
	10.4	7.2	42±5	15±1	1.8±0.2	1069±28	18±2
	12.3	8.1	43±11	16±3	1.8±0.3	1077±51	16±4
Umwenge *Diplorhynchus Condylocarpon*	8.0	5.3	55±14	16±1	1.9±0.2	1100±34	14±2
	9.9	6.7	52±4	16±1	1.8±0.2	1134±31	20±7
	12.0	7.7	47±9	19±1	2.1±0.1	1082±13	24±5
Umutondo *Julbernardia Paniculata*	8.8	5.8	45±10	15±2	1.7±0.1	1155±22	22±2
	10.1	7.0	46±9	18±3	2.3±0.5	1131±60	26±6
	12.3	7.8	38±6	16±2	1.9±0.6	1130±66	30±14

Density is not varying much between materials and moisture contents. Therefore pellets diameter are close to diameter of the matrix press channel and length of pellets is about the same.

3.1 Pellet production

All of the produced pellets are presented in **Figure 11** divided by materials and the moisture content (MC) before pelletizing. All of the studied materials were able to be pelletized without crushing immediately.

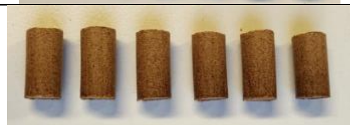
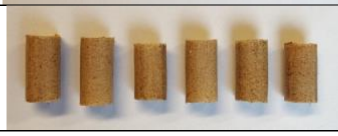
	MC 8%	MC 10%	MC 12%
Reference material			
Umsafwa *Syzygium Guineense*			
Umupundu *Parinari Curatellifolia*			
Umsamba *Brachystegia Boehmii*			
Umwenge *Diplorhynchus Condylocarpon*			
Umutondo *Julbernardia Paniculata*			

Figure 11. All of the produced pellets divided by raw material and moisture content.

Compression energy

The compression energy of all pellets are presented in **Figure 12**. *Wcomp* for Umupundu with moisture content of 12% was the highest, almost 70J. In general, *Wcomp* of Umupundu and Umsafwa were high compared to other materials. *Wcomp* of Umwenge was at the same level as that of the reference material, and *Wcomp* of Umsamba and Umutondo were somewhat lower than those of the reference material. *Wcomp* for Umsamba was independent of moisture content.

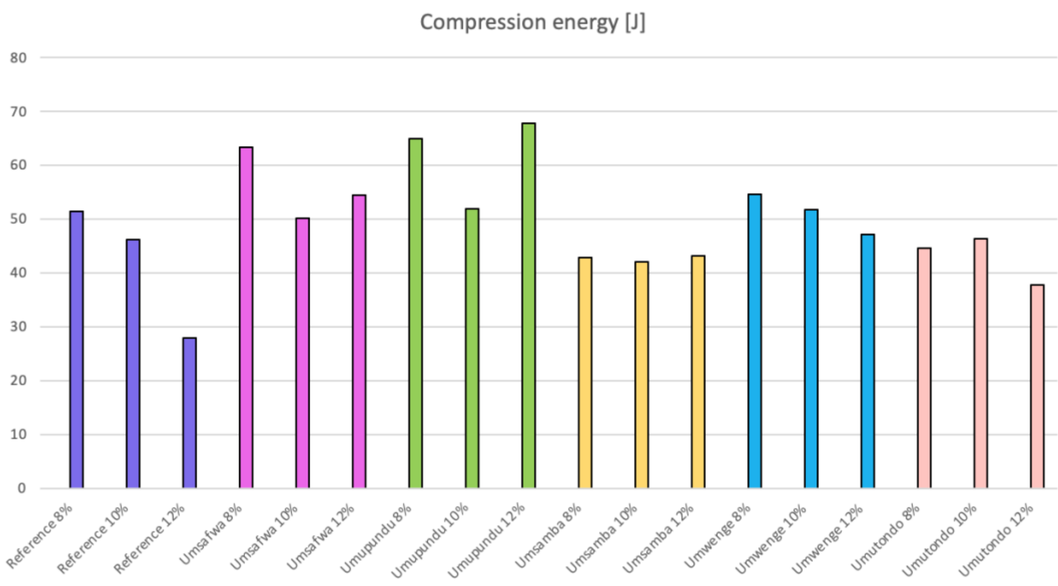


Figure 12. Compression energy for tested materials divided by moisture content. One colour represents one material.

Friction energy and Fmax

The friction energy are presented in **Figure 13**. *Wfric* of Umsafwa with MC of 8% was the highest, 22.25J. *Wfric* of Umsafwa with MC 8% was 38% higher than the reference material on average and 19% higher compared to the next highest friction energy of Umwenge with MC of 12%, 18.70J. Reference material had the lowest friction energy; 14.00J, 14.48J and 12.86J. The values of Umsafwa, Umwenge and Umutondo were most dependent on the moisture content compared to the other materials tested. Umsamba's *Wfric* was not dependent on moisture content.

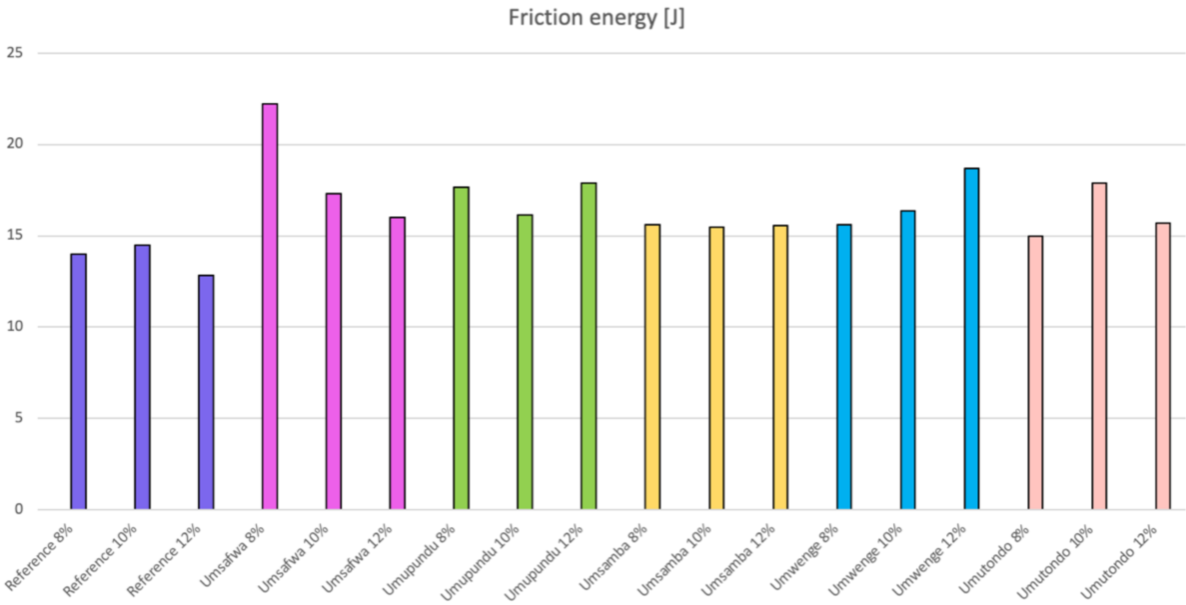


Figure 13. Friction energy for tested materials divided by moisture content. One colour represents one material.

Correlation between *Wfric* and Fmax is presented in **Figure 14**. *Wfric* and Fmax of Umsafwa with MC of 8% was the highest, 22.25J and 2.7kg. *Wfric* and Fmax of the reference material was the lowest, 12.86J and 1.27kg. The friction energy and Fmax of the Umutondo with MC 8% were the closest to it. The results between *Wfric* and Fmax are somewhat linear.

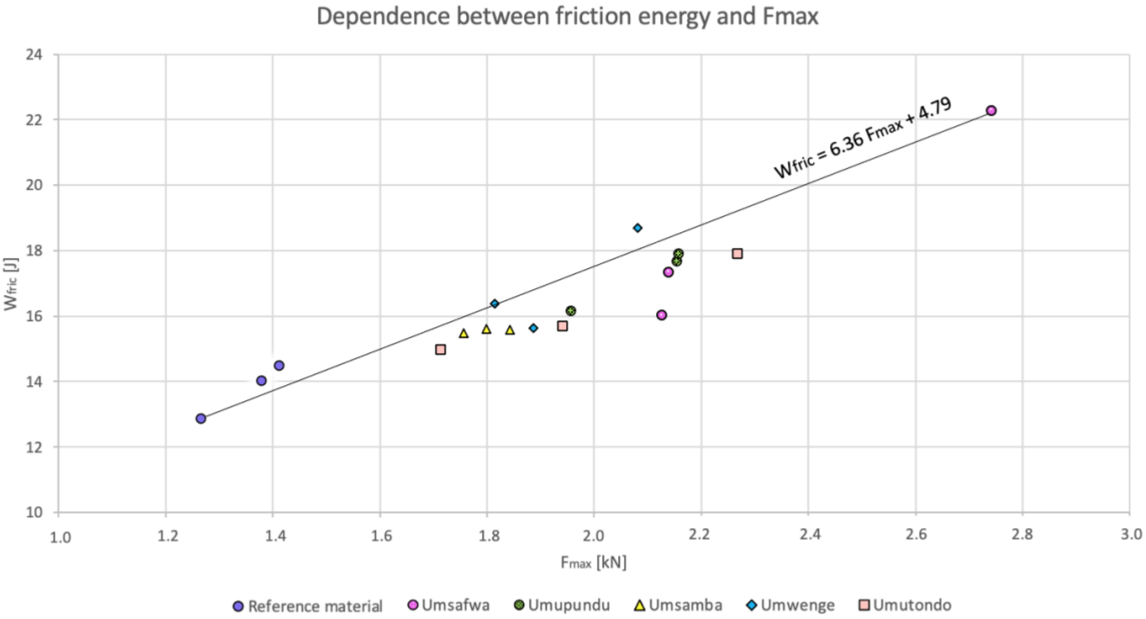


Figure 14. Y-axis describes friction energy for tested materials and X-axis describes Fmax for tested materials. One colour and form represents one material.

3.2 Post production

Hardness

The minimal, average and maximal values of hardness of all pellets are presented in **Figure 15**. The lower line of each post represents the minimal hardness value for one series and the highest point of the post represents the maximal value. The range was greatest for Umutondo with MC of 12% which also had the highest value for hardness, 44kg. The smallest range was measured for reference material with MC of 12% which also had the lowest hardness, 8kg. The average value for hardness varied irregularly between series and materials.

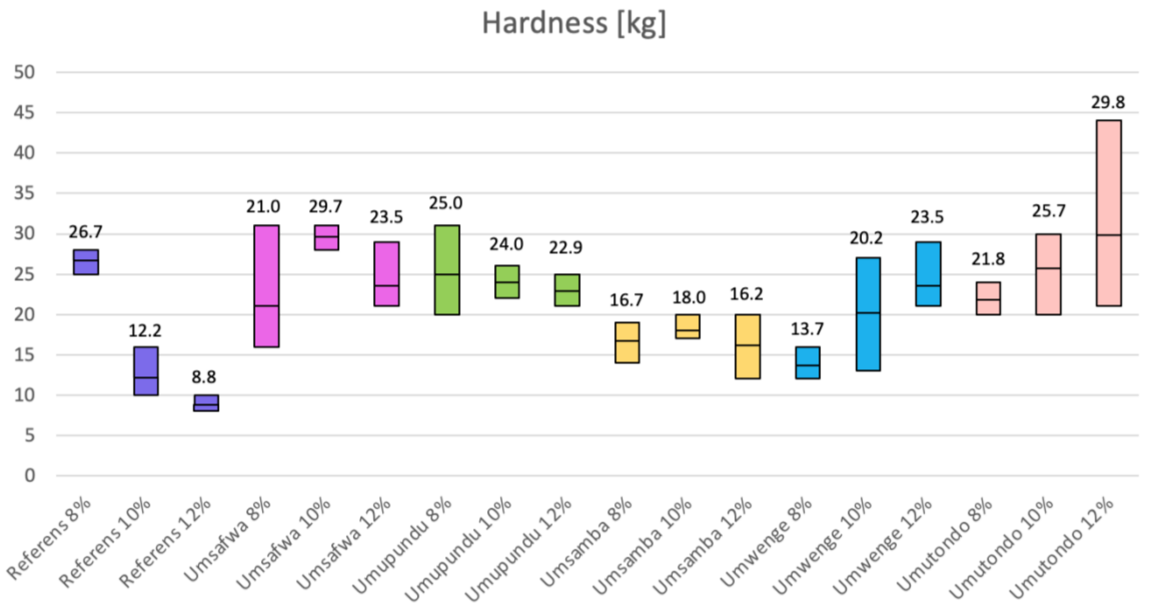


Figure 15. The maximal, average and minimal values of hardness for tested materials divided by moisture content. Line in the middle and the number above presents the average values. (One colour represents one material.

Moisture content

The moisture contents before and after pelletizing are presented in **Figure 16**. The lower and higher lines of each post represents the MC after respective before pelletizing. Moisture contents before to pelleting were measured to be about 8%, 10%, and 12%. Moisture evaporated the most in average in the process from samples containing 12 mass percent water in the beginning of pelletizing. The moisture contents after pelleting were about 6% to 10%.

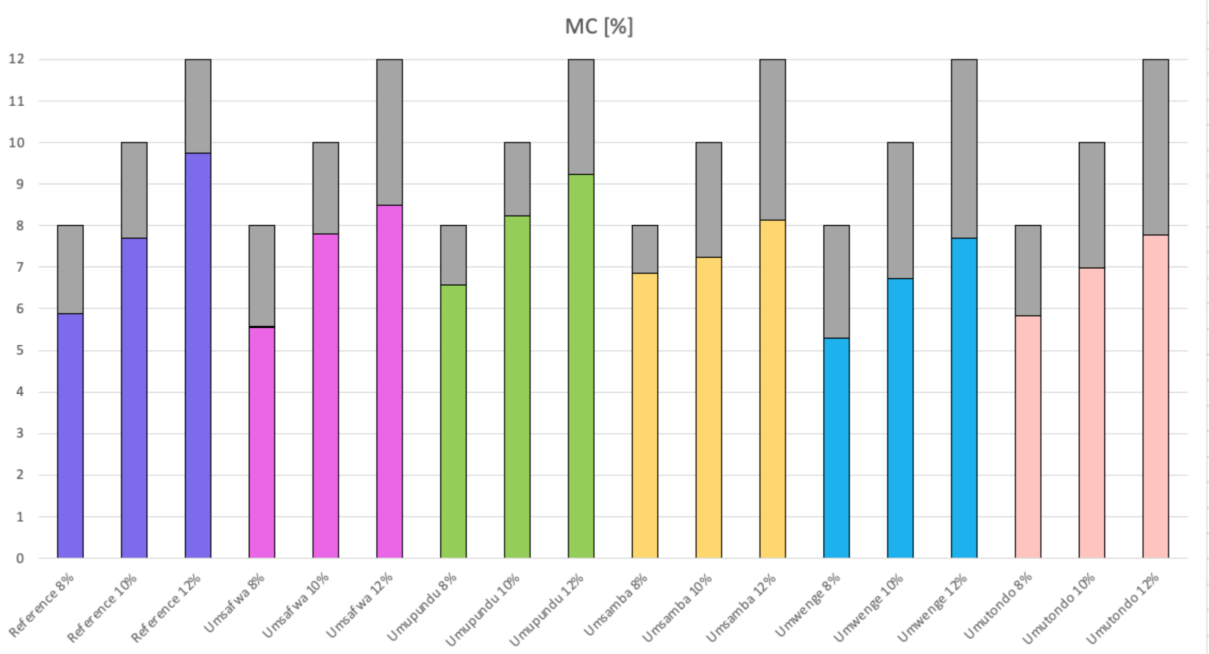


Figure 16. Moisture content before and after pelletizing. The lower and higher lines of each post represents the MC after respective before pelletizing (grey on the top of each post representing the evaporated water from the samples during pelletizing).

3.3 X-ray examinations

The X-ray results are presented in **Table II** and **Table III**. The metal oxides found in measurements are equal to the amount of found metals. Amount of magnesium, chromium and platinum grows during the pellet producing process. In turn, amount of aluminum, potassium, chlorine and manganese decreases during process. Amount of calcium and strontium is significant high in Umsamba and Umutondo compared with the reference material. Reference material has low contents of magnesium compared with all of the other samples where Umusamba has significant high content compared with reference material and Umupundu has the highest content of all results. Umupundu has also high content of zinc, silicon and chlorine compared with reference material. Contents of aluminium and copper are relatively low in all of the samples compared to reference material.

Table II. Metals that links to building ash, found in tested materials in X-ray spectroscopy [ppm]. Number 1 stands for samples before any procedures. Number 2 stands for samples after chopping and milling but before pelletizing. Number 3 stands for samples after pelletizing and quality measurements. Empty spaces are equal to zero. Reference means reference material. Reference 1 has no measured values.

	Ca	K2O	MgO	SiO2	P
Reference 1	-	-	-	-	-
Reference 2	0.371	0.189	0.732	2.032	
Reference 3	0.182	0.136	0.711	0.389	
Umsafwa 1	0.297	0.399	0.851	0.104	
Umsafwa 2		0.452	0.804		0.017
Umsafwa 3		0.452	0.921		0.022
Umupundu 1	0.482	0.165	1.589	3.017	0.016
Umupundu 2	0.352	0.227	1.078	2.746	0.068
Umupundu 3	0.255	0.248	0.996	1.234	0.069
Umsamba 1	2.261	0.311	1.119	1.001	0.125
Umsamba 2	1.896	0.202	1.051	0.751	0.036
Umsamba 3	1.772	0.179	0.826	0.025	0.033
Umwenge 1	1.280	0.453	0.979	0.153	0.279
Umwenge 2		0.399	0.783		0.021
Umwenge 3		0.393	0.727		0.010
Umutondo 1	1.221	0.429	0.813	0.291	0.084
Umutondo 2	1.115	0.257	0.732		0.033
Umutondo 3	0.887	0.253	0.787		0.022

Table III. Other metals found in tested materials in X-ray spectroscopy [ppm]. Number 1 stands for samples before any procedures. Number 2 stands for samples after chopping and milling but before pelletizing. Number 3 stands for samples after pelletizing and quality measurements. Empty spaces are equal to zero. Reference means reference material. Reference 1 has no measured value.

	Cu	Zn	Sr	S	Cl	Pd	Cr	Mn	Au	Al2O3
Reference 1	-	-	-	-	-	-	-	-	-	-
Reference 2	0.00230	0.00077	0.00160	0.00843	0.04507	0.00107	0.00253	0.04200	0.00073	0.44807
Reference 3	0.00130	0.00050	0.00173		0.03703	0.00367	0.00327	0.03603	0.00157	0.27977
Umsafwa 1	0.00067	0.00027	0.00247	0.01207	0.25193	0.00300	0.00567	0.01117	0.00090	0.25647
Umsafwa 2	0.00083	0.00040	0.00110	0.08370	0.29343	0.00107	0.00533	0.01700	0.00170	0.07090
Umsafwa 3	0.00073	0.00040	0.00197	0.06100	0.31163	0.00157	0.00370	0.01390	0.00203	0.11133
Umupundu 1	0.00043	0.00043	0.00233	0.05977	0.2111	0.00127	0.00600	0.00513	0.00077	0.40603
Umupundu 2	0.00033	0.00343	0.00140	0.08893	0.18863	0.00097	0.00363	0.00450	0.00140	
Umupundu 3	0.00043	0.00270	0.00173	0.07580	0.30053	0.00307	0.00483	0.00500	0.00187	
Umsamba 1	0.00073	0.00083	0.00827	0.43013	0.10117	0.00277	0.01280	0.04250	0.00187	0.44413
Umsamba 2	0.00103	0.00087	0.00467	0.30040	0.08470	0.00133	0.00537	0.02157	0.00197	0.07553
Umsamba 3	0.00057	0.00067	0.00733	0.22400	0.05077	0.00387	0.00683	0.002223	0.00263	0.05837
Umwenge 1	0.00097	0.00090	0.00470	0.45613	0.11643	0.00200	0.00633	0.03960	0.00253	0.29893
Umwenge 2	0.00097	0.00063	0.00083	0.11503	0.14160	0.00133	0.00270	0.03093	0.00097	0.08450
Umwenge 3	0.00100	0.00067	0.00130	0.08370	0.11523	0.00183	0.00287	0.02953	0.00253	0.07270
Umutondo 1	0.00047	0.00040	0.00547	0.28000	0.10077	0.00173	0.00563	0.02440	0.00250	0.30277
Umutondo 2	0.00083	0.00063	0.00323	0.21170	0.07700	0.00133	0.00127	0.01517	0.00110	0.07920
Umutondo 3	0.00080	0.00050	0.00430	0.13987	0.06157	0.00170	0.00573	0.01663	0.00213	0.11470

	Pt	Mo	Rb	Ba	Ce	W	Y	Nb	Fe	Co	Ni
Reference 1	-	-	-	-	-	-	-	-	-	-	-
Reference 2	0.00150								0.00887		
Reference 3	0.00317	0.00073								0.00043	
Umsafwa 1	0.00070	0.00120	0.00033								
Umsafwa 2	0.00143				0.00347						
Umsafwa 3		0.00083	0.00013				0.00030	0.00040	0.00250		
Umupundu 1	0.00093	0.00087									
Umupundu 2	0.00167									0.00027	
Umupundu 3	0.00080	0.00063					0.00033				
Umsamba 1		0.00140	0.00020						0.01267		0.00070
Umsamba 2	0.00070										
Umsamba 3		0.00087	0.00007			0.00123					
Umwenge 1	0.00090	0.00070	0.00013	0.00213							
Umwenge 2										0.00040	
Umwenge 3	0.00207									0.00030	
Umutondo 1		0.00117	0.00017								
Umutondo 2	0.00083									0.00030	
Umutondo 3		0.00083					0.00030	0.00030			

Amount of magnesium in the samples is presented in **Figure 17**. Reference material had the lowest values between 0.59ppm to 0.71ppm depending on the stage of the process. Umsafwa, Umwenge and Umutondo had little higher values than reference material and Umupundu had highest content of all samples. Umsamba had high content of magnesium before pelletizing but values dropped below Umsafwa's values after pelletizing. All of the samples had values between 0.7ppm and 1.0ppm in the last stage, after pelletizing. The variation between the three measured values for each series was over 0.2ppm for reference 3, Umsafwa, Umupundu, Umsamba 1 and 2, Umwenge 3 and Umutondo 1 and 3. The largest differences between the lowest and highest values were for Umsamba 1, from 0.89ppm to 1.46ppm. The smallest variation was in turn for reference 2, from 0.53ppm to 0.65ppm.

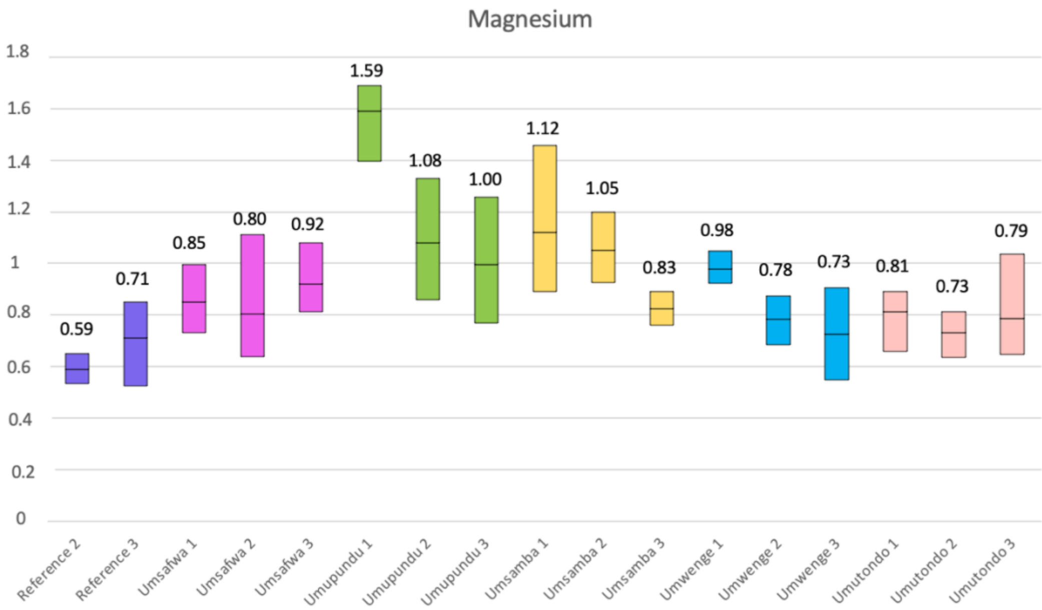


Figure 17. Magnesium in the samples in ppm. Numbers 1, 2 and 3 represents values before chopping and milling, before pelletizing respective after pelletizing and measuring. Each post represents the maximal, average and minimal values of magnesium for tested materials. Line in the middle and the number above presents the average values. Reference 1 has no measured values.

Amount of calcium in the samples is presented in **Figure 18**. The amount of calcium decreased during the process for reference material, Umupundu, Umsamba and Umutondo. Umsafwa and Umwenge had measured calcium only before chopping and milling and for this reason they are depicted by only one post. Reference material had the lowest values of calcium with Umsafwa and Umupundu. Umsamba had the highest values, over 90% higher values than reference material. Umutondo had also high amount calcium, about 50% higher than values for reference material. Umwenge had a lot of calcium before chopping and milling.

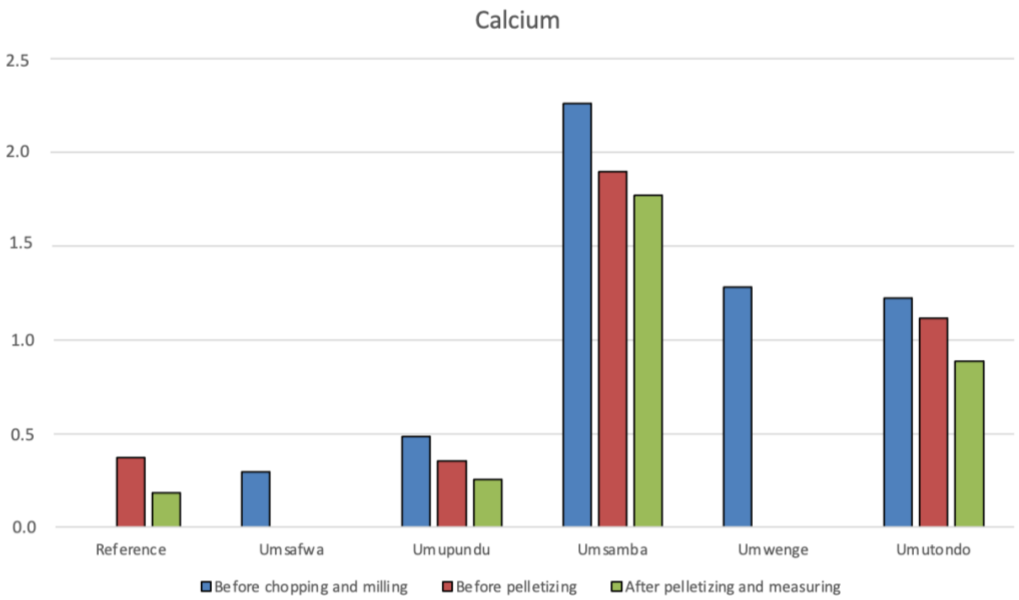


Figure 18. Calcium in the samples in ppm. Posts 1, 2 and 3 represents values before chopping and milling, before pelletizing respective after pelletizing and measuring (in that order from left to right). The absence of a post equals zero value. Reference material has no measured values before milling and chopping.

Amount of metals in the samples after pelletizing and measuring is presented in **Figure 19**. After pelletizing the pellets will be combusted so the amount of metals presented corresponds to the amount of metals in the ash. Umupundu and Umusamba had the highest values of metals. Umwenge had the lowest values. Umsafwa and reference material had almost identical amount of metals and Umwenge a bit less than those two. In all of the samples amount of metals listed in **Table III** is close to 0.35ppm except for Umsafwa which had 0.51ppm.

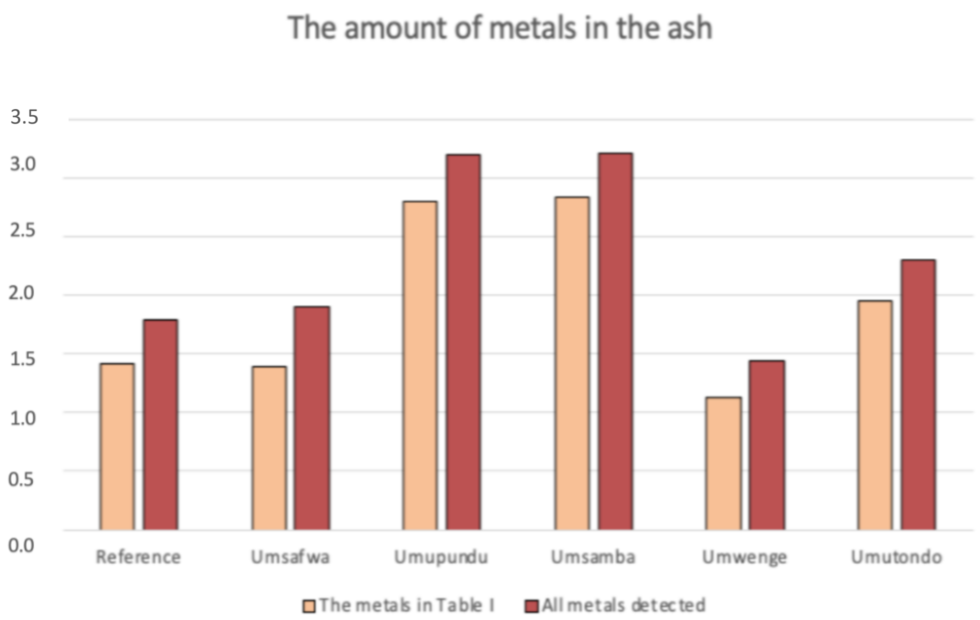


Figure 19. The amount of metals in the samples after pelletizing in ppm. Posts on the left (lighter color) presents the sum of the metals listed in Table II for each material after pelletizing and measuring. Posts on the right (darker color) presents the sum of all detected metals in Tables II and III. The difference in the values of the left and right posts reflects the amount of metals in Table III.

4. Discussion

In this study pellet production, post production testing and X-ray examinations were executed for 6 different materials: 1) reference material (*Pinus Kesiya/Merkusii/Oocarp*), 2) Umsafwa (*Syzygium Guineense*), 3) Umupundu (*Parinari Curatellifolia*), 4) Umusamba (*Brachystegia Boehmii*), 5) Umwenge (*Diplorhynchus Condylocarpon),* 6) Umutondo (*Julbernardia Paniculata*). The chemical composition of the hardwood species is not known, but the reliability of analyzing the results is increased by comparing the hardwood species with the reference material that is already in use in pellet production.

4.1 Compression energy

Umupundu was the only wood species whose moisture content had no effect on the compression energy. The energy required to compress the reference material decreases as the moisture content increases (see **Figure 12)**. Umwenge behaves in the same way. This means that the lowest value for the W_{comp} might be reached with even higher MC than 12%. For other materials, the relationship between W_{comp} and MC is more complex. According to the **Figure 12**, Umsafwa and Umupundu receive the lowest value of W_{comp} with MC of 10%. Therefore it could be guessed that MC values outside of the tested scale gives higher W_{comp} values. Though it is possible that even if MC is outside of the tested scale of 8% to 12%, these materials get even lower W_{comp} values. Umutondo, on the other hand, reaches its highest value of W_{comp} with MC 10% (see **Figure 12)**. However, not all materials are affected by moisture content. W_{comp} for Umsamba were measured to constant 42-43J with MC of 8%, 10 % and 12%. Based on the relation between MC and W_{comp} of the tested materials, Umsamba can be recommended for the production because even if MC increases or decreases there is no risk for unexpected changes in W_{comp} (see **Figure 12)**.

Umsamba and Umutondo gave the lowest values for compression energy of the tested hardwood pellets. High compression energy means higher energy cost (Henriksson, 2018). That's why low compression energy is wanted quality from pellets. W_{comp} for Umsamba and Umutondo is close to 40J which is relatively low compared with the reference material that had compression energy between 28J and 51J (see **Figure 12)**. On the basis of compression energy, I recommend Umsamba and Umutondo may be recommended for production of fuel pellets. Umsafwa and Umupundu had higher compression energy than other materials in the study. This means that considering the energy of compression, their manufacture consumes more energy. Both of these trees are also fruit trees according to Workson (2022) that might explain the high values and possible differences in their chemical structure compared with other studied tree species.

4.2 Friction energy and Fmax

Moisture content can affect the friction energy of the pellets. W_{fric} for Umsafwa decreases as the moisture content increases (see **Figure 13)**. Umwenge behaves the opposite, the highest W_{fric} is reached at the highest moisture content of the study, 12 %. *Wfric* of Umupundu, Umsamba and Umutondo depend on the moisture content in the same way as on W_{comp} (See **Figure 12**). The MC has no significant effect on the *Wfric* of the reference material and the friction energy are the lowest in the study. Considering the compression- and friction energy, Umasmba can be recommended for production as it is not dependent on moisture.

Friction energy for the studied materials are within the allowed limits. When the friction energy is too low, the resistance in the press channel becomes too low and a qualitative pellet cannot be produced (Nielsen Holm et al., 2009). According to Henriksson (2022) *Wfric* were low for Cashew nutshell which had *Wfric* of about 50J with MC of 7%. In light of this, all friction energy obtained in this study are low. However, the friction energy of the reference material is also between 12J and 15J, so in fact the values of the friction energy are within the allowed limits in this study.

There is a clear linear relationship between *Wfric* and Fmax. Fmax increases is proportion to the *Wfric* (see **Figure 14**). As a result, it is unnecessary to measure Fmax separately. Fmax can be deduced directly from the value of friction energy.

4.3 Hardness

All of the tested materials except for reference material with MC of 10% and 12% were acceptable for production based on the hardness of the materials. According to Andersson (2017) the moisture content plays a key role in durability of pellets. There is a positive linear relationship between mechanical strength and hardness (Said et. al., 2015). This means that the higher the hardness value, the better the pellets will withstand handling and transport. However, according to **Figure 15**, the hardness of the reference material was low at moisture contents of 10% and 12%, so the hardness of any other of the tested biomaterials was not significantly low. Of the tested hardwood species, Umwenge with MC of 8% broke down most easily and had an average hardness of 13kg. Umutondo had the greatest variation of hardness with MC of 12% where Umsafwa with MC of 8% and Umwenge with MC of 10% also had a large variations in hardness values. Large variations in hardness values can affect quality of the pellets. If a large proportion of the pellets receive a hardness value from the lower end of the scale, the produced batch is not so durable. However, even the smallest measured hardness values for highly variable materials are within acceptable limits compared with the reference material.

Moisture content affects hardness depending on the material. Increasing the moisture content of the reference material the hardness reduces (see **Figure 15)**. The same trend with smaller differences can be seen with the average values for Umupundu. For Umsafwa and Umsamba highest hardness value is achieved with MC of 10%. For Umwenge and Umutondo increasing MC, hardness increases. As the moisture content affects the hardness values, it should be taken into account in the production. However, even if the moisture content varies between 8% and 12%, there will not be concerns about the quality of the produced pellets because the pellets withstand wear and tear with measured hardness values based on this study.

4.4 Evaporation in the matrix

Compression of the pellets in the matrix significantly reduces the moisture content of the pellets. The MC of wood species decrease from 8-12% to 5.2-9.8% (see

Figure 16). MC of Umupundu is on average the highest in the study after pellet compression; 6.5-9.2%. The reference material and Umsafwa behave in the same way as Umupundu. The exception is that Umsafwa with MC of 12% dries more, resulting in a moisture content of 8.5%. Umwenge, in turn, evaporates the most water in the process resulting to MC between 5.2-7.8%. The moisture contents of Umutondo are very similar to those of Unwenge. The MC of Umsamba after compression is between 6.8-8.1% resulting the smallest scatter between the three tested moisture contents.

4.5 X-ray examinations

Umupundu and Umsamba builds a lot of ash when combusted based on the X-ray measurements. The amount of metals is the highest in Umupundu and Umsamba of the studied materials (see **Figure 19)**. This contradict Millat's (2019) who states that softwood species produce more ash compared with hardwood species. Reference material is the only softwood species studied and Umutondo, Umupundu and Umsamba has higher metal contents than the reference material. Both Umupundu and Umsamba consist high amount of magnesium before and after pelletizing (see **Figure 17)** and Umsamba consist high amount of calcium compared to all of the other tested materials (see **Figure 18)**. Amount of silicium in Umupundu is also high after pelletizing according to **Tabell II** compared with the reference material. Biomaterials that contain a lot of metals form more ash when combusted (SLU, n.d.). Because of the high metal content in Umupundu and Umsamba, compared with other tested materials, these two hardwood species builds more ash in combustion.

Umutondo has relatively high amount of metals compared with other tested materials and that is a risk for ash building during burning of pellets. The amount of metals in Umutondo is higher than in reference material but lower than in Umupundu and Umsamba (see **Figure 19**). Relatively high amounts of calcium in Umutondo is the main reason for the high metal concentrations of Unutondo compared with other studied materials (see **Table II** and **Table II**I). Amount of calcium is almost 1.0ppm while the amount for the reference material is around 0.2ppm. Because Umutondo contains more metals than reference material, more ash is formed in burning Umutondo than the reference material (SLU, n.d.). This can affect the attractiveness of Umutondo for pellet production, as the amount of ash formed shortens radically the life length of the stoves (Ohlsson, 2022).

The amount of metals listed in **Tabell II** predicts the amount of total metals in the biomaterial. According to **Figure 19** differences between the total amount of metals in tested materials is about 0.35ppm higher the amount of metals listed in **Tabell II**. Only exception were Umsafwa which had 0.51ppm other metals than those listed in **Tabell II**. The small difference between the total amount of metals and the amount of metals listed in **Tabell II** means that in order to determine the metal content, it is essential to measure the amount of calcium, kalium, magnesium, silicium and phosphate. In this study of the listed metals, the largest concentration differences between the hardwood species and reference material were observed for calcium, magnesium and silicium. However, the magnitude of the concentrations depends on the species of wood, so other species may have a higher concentration differences for other metals. Thus, in future studies, based on this study it is advisable to focus on measuring metals listed in **Tabell II**.

The concentration of metals increases during the pellet manufacturing process. The concentration of several metals increases when the wood species are processed into sawdust and again when the pellets are made in a matrix made of metal (see **Tables II** and **III)**. However, **Figure 18** claims otherwise because the amount of calcium decreases with the palletization process. This may be due to human factors such as measurement error or inaccuracy in metal measurement. It is logical that when wood species are machined with tools made of metal, the amount of metals in the samples increases.

4.6 Recommended material for pelletizing without mixing biomass

In this study all of the tested materials had high hardness compared with the reference material and the densities were about the same. All of the studied hardwood species are not fast-growing trees resulting that a lot of land needs to be used to grow these materials for pellet production purposes. Faster growing tree species could be a better choice for pelletizing from an environmental point of view because then smaller area can be used for growing the pellet material resulting lowering the deforestation rate. In addition to these properties Unsamba had low compression and friction energy but high amount of ash building when burning compared with other studied materials. Umwenge on the other hand had little higher compression and friction energy that varies with MC than Umsamba but low amount of metals that links to low ash building during combustion compared with other tested materials. Therefore, based on this research, Umwenge is best suited as a pellet material if desired to produce pellets from one material instead of a mixture of several materials.

4.7 Recommended materials for pelletizing with a mixture of biomasses

Umutondo and Umsamba has potential to be mixed but a lot of ash will be produced. Both had low compression- and friction energy in addition to higher hardness values than the reference material. However the X-ray results show that both includes a lot more metals than the reference material such as calcium and this links to high amount of ash during combustion, which can significantly shorten the lifetime of a stove (SLU, n.d.; Ohlsson, 2022). Because it can be suspected that the ash content is important, Umutondo and Umsamba can't be taken into consideration of larger industrial pellet production.

Umsafwa with MC of 12% and Umwenge with MC of 10% is the best mix based on this study. Friction energy are close to one another, 16J and 15.6J, meaning that heat produced in the matrix press channel is constant even if the amounts of the material in the mix varies. Compression energy are a bit higher than for most of the material, around 50J, but not the highest in the study. Therefore a bit more electricity are needed in production of this mix. Hardness is higher for both than for the reference material and even X-ray results state that not much ash is produced in the combustion process, which is desirable from the perspective of the life length of the cooking stove (Ohlsson, 2022). Therefore Umsafwa and Umwenge will make a good mix for pellet production based on this study.

4.8 Sources of error

The Zambian name of the wood species is probably correct, but there is no certainty about the names. The names are from Emerging Cooking Solutions and the names have been gone through with a PhD student who is originally from Zambia.

Pellets produced by a single pellet press may have different properties than pellets made by pressing biomaterial through a large matrix in a continuous pellet press used in large-scale production. As a result, the measured values with a continuous pellet press may differ from those measured in the study. However, the properties of the pellets should be predicted with a single pellet press (Mišljenović et al., 2016; Holm et al., 2011).

The reliability of the X-ray examination values is questionable because the device was calibrated for a soil sample analysis. The values obtained are probably lower than the actual ones because the wood could not be packed as tightly in the sample jar compared with soil samples. As a result, comparing values from this study to one another or to a reference material gives more information than to look at separate values.

4.9 Future work

Proposal for future research is to mix the recommended biomasses and pelletize them. It would also be useful to study the ratios of biomasses in the mixture of masses in order to find the best possible mixture for pelletizing.

To elucidate the more precise chemical composition (cellulose, hemicellulose, lignin, extractive) of the hardwood species studied in this study would certainly provide rationale for the results obtained. It could also lead to finding new uses for the tree species studied.

Another proposal for future research is to calculate the energy released in the combustion of the hardwood pellets studied in this study and to measure how much ash is formed. It would be rewarding to know whether the ash concentrations based on the amount of metals in the study match with actual ash measurements for the studied tree species.

Also one topic for future research could be testing of fast-growing and cultivated biomass as a new raw material for cooking fuel pellets. If the pellets produced from fast-growing tree species are as good as the pellets recommended in the study, then their cultivation and use could be started in Africa as a part of more environmentally friendly production. Also the use of a fruit trees for pellet production purposes could be reconsidered as the trees might give more value as a fruit producing trees.

5. Conclusion

This study increased the knowledge about pellet production, post production testing and X-ray examinations of five studied types of hardwood species grown in Zambia. In light of this study Unsafwa with MC of 12% and Umwenge with MC of 10% is the best mixture for the manufacturing of cooking fuel pellets. Other findings based on this study is listed below.

- There is a clear linear relationship between W_{fric} and F_{max}.
- Umupundu and Umsamba includes more metals than other studied materials meaning that combustion of Umupundu and Umsamba builds more ash compared with other tested materials. Therefore Umupundu and Umsamba can't be considered as good fuel pellet materials.
- Umutondo includes high amount of metals compared with the reference material but lower amounts than Umupundu and Umsamba. Therefore Umutondo might not be a good fuel pellet material.
- Umwenge is best suited as a pellet material if desired to produce fuel pellets from only one material instead of a mixture of several materials.

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