THE DEVELOPMENT OF A SHELLER FOR BAMBARA GROUNDNUTS

SN Nkambule

(213504320)

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Supervisor: Professor TS Workneh

Co-Supervisor (s): Dr G Lagerwall

: Dr A Kassim

ABSTRACT

Bambara groundnut (*Vigna subterranean (L) Verdc*) is an indigenous African crop. This crop is classified as a drought resistant crop that can produce good yields even in poor soil conditions. The Bambara groundnut crop is currently grown by rural or subsistence farmers in South Africa. Current research is focused on the agronomic and growing aspect relating to this crop. Data on the physical properties and processing equipment for the Bambara groundnuts are limited. The main objective of this research project was to determine the physical properties of Bambara groundnuts at different moisture contents. The physical properties of both shelled and unshelled Bambara groundnuts consisting of axial dimensions, geometric mean diameter, volume, surface area, static coeffient of friction, sphericity, cracking force, porosity, bulk and true density were determined at different moisture contents (i.e. 6, 15, and 20 %). The physical properties of the whole ushelled nuts were mesured first. The Bambara groundnt pods were subjected to manually shelling. Then finally, the physical properties of shelled Bambara groundnuts were measured. The physical properties were then used to design a portable shelling machine. The results from this study show that that axial dimensions, geometric mean diameter, sphericity, volume, and weight increased with increases in moisture content. The static coefficient of friction of shelled and unshelled groundnuts increased from 0.15 to 0.19 and 0.29 to 0.31, respectively. Similarly, the bulk density of shelled and unshelled groundnuts increased from 500 to 955 $kg.m^{-3}$ and 355 to 422 $kg.m^{-3}$, respectively. The results also show that the true density of shelled nuts increased from 994 to 1832 $kg.m^{-3}$ while for the unshelled groundnuts it increased linearly from 532 to 655 $kg.m^{-3}$. However, the cracking force of both shelled and unshelled groundnuts showed a declining trend as moisture increased from 6 to 20 %. The shelling machine was then designed based on the physical properties of Bambara groundnuts at a 6 % moisture content. The shelling machine consisted of a hopper, shelling shaft, shelling chamber, transmission system, blower, and a motor. The machine was designed to shell atleast 100 $kg.hr^{-1}$ of bambara groundnuts. Subsequently, the machine was evaluated based on the shelling efficiency, mechanical damage, capacity, and cleaning efficiencies. The shelling efficiency, mechanical damage, and machine capacity decreased as the moisture content increased from 6 to 20 %. The shelling effficiency declined from 72 to 22 %. It was, therefore, recommended to shell Bambara groundnuts at a 6 % moisture content.

DECLARATION ON PLAGIARISM

I, Siboniso Nhlanhla Nkambule, declare that:

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This section is outlining the work submitted and presented in a conference or symposium. The submission of abstract to a symposium was checked and approved by Supervisors. Chapter 3 was presented in a symposium on September 2018. The * indicates the corresponding author. The details and the author's name of symposium submission are outline as follow:

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SUPERVISOR'S APPROVAL

Subject to the regulations of the school of engineering, we the Supervisors of the candidate, consent to the submission of this dissertation for examination.

Supervisor: Prof Tilahun Workneh Date ________________________

Co-supervisor: Dr G Lagerwall Date ________________________

Co-supervisor: Dr A Kassim Date ________________________

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1. INTRODUCTION

In the past, a combination of fertiliser application, pest control, and irrigation systems resulted in an increase in yield production. However, due to water shortages and water pollution, crops that require less agricultural management such as application of fertiliser and irrigation are required to sustain food security (Aydin, 2002; Dordas, 2009). Introducing crops that are drought resistant will reduce water usage in the agricultural sector and also reduce the level of poverty, especially in the African Continent.

The Bambara groundnut crop (*Vigna subterranean (L) Verdc*) is an indigenous crop that originated from West Africa, and it was widely distributed to the rest of Africa by indigenous people (Department of Agriculture and Fisheries (DAFF), 2011). This crop is primarily cultivated by small-scale and subsistence farmers for both human and animal consumption (Koné *et al.*, 2009). The groundnut crop can also be classified as a drought resistances plant, as it produces good yields on poor soil conditions (Berchie *et al.*, 2012; Hillocks *et al.*, 2012).

Bambara groundnuts are legumes which have compact and well-developed tap roots. The leaves are approximately 15 cm long, stiff, and green in colour (DAFF, 2011). The pods of these groundnuts are grown below the soil, with a round shape, and wrinkled with one or two seeds, while the seed inside the pods are brown, yellow or purple when matured (DAFF, 2011). According to DAFF (2011), these types of plants take 7 to 15 days to germinate, the seeds should be stored for approximately 12 months before planting. The flowering takes place after 30 days from planting (Atiku *et al.*, 2004; DAFF, 2011). These groundnuts grow during the summer season. The soil pH must range between 5.0 and 6.5, at the temperature between 20 to 28 ˚C, and these crops can be grown in poor soils (DAFF, 2011). In rural farming, commercial fertilisers are not used. Instead, animal manure is used to provide nutrients for these plants (Nigam *et al.*, 2004).

Bambara groundnuts contribute to increased food production, especially in West African countries. This crop is also grown for its high protein (Massawe *et al.*, 2005). Primarily, this crop is grown for human consumption, the pods or seeds are usually consumed while they are still green, immature or when are dry (DAFF, 2011; Hillocks *et al.*, 2012; Khan *et al.*, 2017). According to Massawe *et al.* (2005), these groundnuts can also be used to produce milk similar to soya bean milk which is rich in proteins. In other African countries, such as Nigeria and Burkina Faso, Bambara groundnuts are used in production of cosmetics, pharmaceutical products. Farmers also use groundnut kernels, leaves, and nuts in animal feed (DAFF, 2011; Hillocks *et al.*, 2012). In Botswana and Ghana, people use these groundnuts to produce flour for baking. Studies have also shown that Bambara groundnuts have potential to produce oil (Brough *et al.*, 1993; Mkandawire, 2007; Mpotokwane *et al.*, 2008). According to Massawe *et al.* (2005), Bambara groundnuts are consumed in Asia during special occasions, and usually this nuts are served as snacks.

Recent research on Bambara groundnut has focused on agronomic and breeding aspects (Khan *et al.*, 2017). Bambara groundnuts are shelled manually. However, the shells are hard to break, which makes shelling tedious (Atiku *et al.*, 2004; Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). Thus, it is clear that the development of a sheller for Bambara groundnuts is required to assist in the promotion of bambara as a potential industrial crop (Mkandawire, 2007).

There is limited literature on the physical properties of unshelled Bambara groundnuts. The only literature encounter was of the physical properties of shelled Bambara groundnuts (seeds) (Mpotokwane *et al.*, 2008)**.** However, during the design process of Bambara groundnuts processing equipment, such as a sheller, dusking equipment and harvesters, the physical properties the whole unshelled nut are required. Pliestic *et al.* (2006) used the universal testing machine to determine the cracking force required to crack filbert nut and kernel. This method can also be adopted to find the maximum cracking force required to break the kernels and nuts of bambara groundnuts. The cracking force can be used to find the maximum power required to shell these types of groundnuts.

The available bambara shelling machine consists of several main components including a hopper, blower, cracking chamber, and power transmission system (Atiku *et al.*, 2004; Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). The available machine uses huge electrical motors to operate, whereas in rural areas most people do not have access to electricity on their farms. Therefore, these machines cannot be adopted to be used in rural farms. A low power consumption machine is required to suit rural farms. To commercilase the production of Bambara groundnuts, a portable sheller that will use low energy during operating is required to accommodate rural farmers. In rural farms, the separation of the kernels and nuts during shelling is done manually, which is labour intensive and time consuming (Mkandawire, 2007; DAFF, 2011). Development of a Bambara groundnut sheller that has a pneumatic cleaner still needs to be designed in South Africa. This system should be cheap and affordable to South Africa scale farms with aid of using local materials.

The study focus on the determination of the physical properties for both shelled and unshelled Bambara groundnuts at the different moisture content. The physical properties include axial dimensions, weight, volume, sphericity, area, and static efficiency of friction, porosity, cracking forces, bulk and true density.

The primary objective of this study was to design a Bambara groundnuts sheller which will assist South Africa Farms during shelling season. The sheller had to be portable and affordable to rural farmer in South Africa. The used of local material in the design of shelling machine was also prioritised.

1.1 The Dissertation Structure

The dissertation structure is outline as follow:

Chapter 1 This chapter is the general introduction of the research that provides the rational and overview of the study. The primary objectives are also outlined.

Chapter 2 This chapter provides an overview of a critical literature review of the Bambara groundnuts, in term of production, harvesting, processing and storages. Also the methods used to determine physical properties are reviewed from different types of groundnuts.

Chapter 3 This is an experimental chapter where the physical properties both of shelled and unshelled Bambara groundnuts were determined at different moisture contents.

Chapter 4 This chapter is where a full design of a Bambara groundnuts shelling machine is outliner. The physical properties of Bambara groundnuts obtained on Chapter 3 are used to design a portable shelling machine.

Chapter 5 The chapter presents general conclusion and recommendations of the study and its findings.

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2. A REVIEW ON THE PHYSICAL PROPERTIES, PRODUCTION AND PROCESSING OF BAMBARA GROUNDNUTS

Abstract

In this chapter, a review of the local (South Africa and Africa) and international Bambara production is presented. Production includes planting, harvesting, storing, and the postharvest processing of Bambara groundnuts. This crop is classified as a drought resistance and nutritious crop that produces yields in less fertile fields. The global Bambara production yield is approximately 330 000 tons.year^{-1}. West Africa produces about 45 to 50 % of the global production. Bambara groundnuts are typically produced for human consumption and the leaves are used for animal feeding. The Bambara groundnut yield production shows a declining trend since 2012. This is due to limited research focusing on postharvest technology. Planting, weeding and harvesting in Bambara groundnuts is done manually which slows down the production. The shelling of the kernel is also done manually and is time consuming. The literature shows that the manual shelling results in high damage and is a tedious task. This creates a stumbling block during the industrialisation of this nutritious crop. Therefore, an efficient way to shell Bambara is required. The lack of data on physical properties of Bambara groundnuts also results in challenges when designing processing equipment. The available physical properties in Bambara groundnuts only focus on the seeds. However, during the design of post-harvest processing equipment, the physical properties of whole groundnut is required. The existing shelling machines can be improved to accommodate the Bambara groundnuts for better processing. This will improve the availability of post-harvesting processing equipment. Therefore more small scale farmers will be attracting in growing this type of groundnuts. As results this crop will be industrialised.

2.1 Global Production of Bambara Groundnut

The world's production of Bambara groundnuts is approximately 330 000 tons per year. However, West Africa's production is about 45 to 50 % of the world's production (Koné *et al.*, 2009; Ibrahin and Ogunwusi, 2016). Global demand for Bambara groundnuts is higher than current rates of production. That means there is potential for Bambara groundnut production to be industrialised (Brough *et al.*, 1993; Swanevelder, 1998; Hillocks *et al.*, 2012). In semi-arid zones, Bambara groundnuts can produce a yield between 450 to 850 kg ha^{-1} (Koné *et al.*, 2009; Ibrahin and Ogunwusi, 2016).

2.2 Bambara Groundnuts Production in Africa

The Food and Agriculture Organisation has statistical information about three African countries that grow Bambara groundnuts for human and animal consumption. However, six or more countries also grows Bambara groundnuts for human and animal consumption. (Swanevelder, 1998; Hillocks *et al.*, 2012; FAO, 2014). Production yields of Bambara groundnuts have declined since 2012, due to limited research focus on these crops (Ibrahin and Ogunwusi, 2016). There are no post-harvest technologies available for processing this crop. As a result, production yields and consumption tends to decline over time (FAO, 2014).

In Africa, Nigeria has the highest yield production of Bambara groundnuts and is approximately 10 000 tons per year, which is equivalent to the yield of 800 kg·ha^{-1} (Koné *et al.*, 2009; Adebowale *et al.*, 2011). In Zimbabwe, Bambara groundnuts are inter-cropped with maize during the rainy season, since the growers believe that intercropping improves soil conditions and fertility (Hillocks *et al.*, 2012).

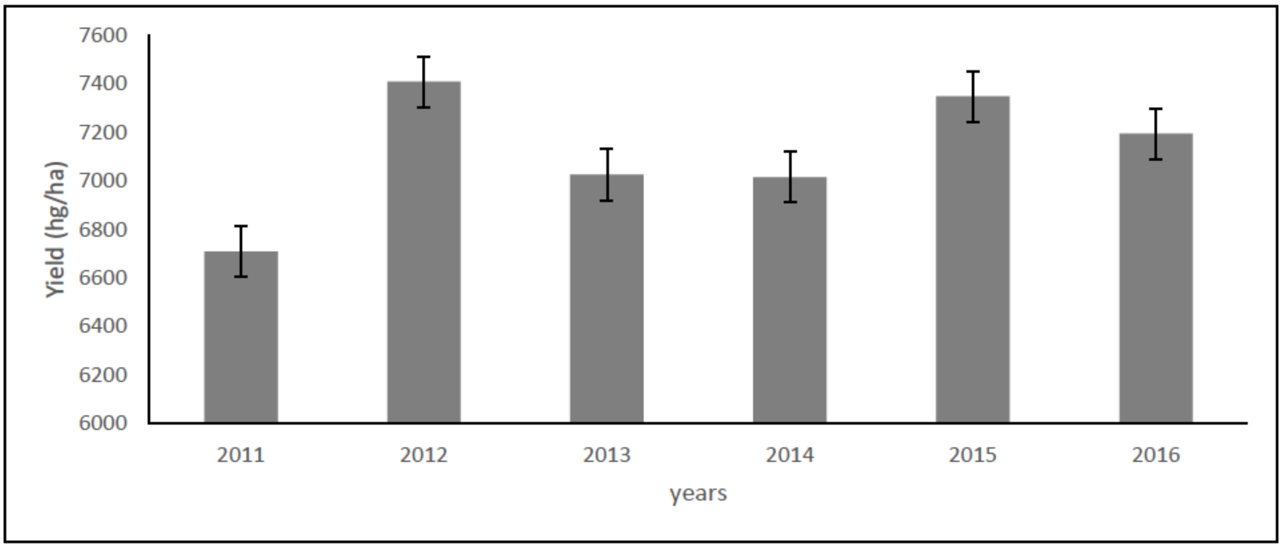

Figure 2.1 The summary of Bambara groundnut yield production in Africa (FAO, 2014)

2.3 Bambara Groundnut Production in South Africa

In South Africa, Bambara groundnut s are cultivated in the Mpumalanga, Limpopo, and KwaZulu-Natal provinces. The crop was migrated by indigenous people from West Africa to South Africa (Swanevelder, 1998; Department of Agriculture and Fisheries (DAFF), 2011; Mabhaudhi and Modi, 2013). The groundnut is currently grown by small-scale farmers in an area that ranges in between 300 to 2500 m^2 per farmer. Yield production is approximately 300 $kg \cdot ha^{-1}$ (Swanevelder, 1998).

2.4 Bambara Groundnut Consumption in Africa

Bambara groundnuts are consumed while they are still immature or when they are dry. Fresh seeds are boiled with or without shells and mixed with boiled maize (Swanevelder, 1998; DAFF, 2011; Abdualrahman *et al.*, 2016). In some countries, such as Ghana and Nigeria, a Bambara groundnut gravy is produced and sold to supermarkets (Abdulrahman *et al.*, 2016). In Burkina Faso, Botswana, and Nigeria, these groundnut are crushed to produce flour for making porridge and cakes (Hillocks *et al.*, 2012).

2.5 Physical Properties of Bambara Groundnuts

Physical properties are important for the design of planting, harvesting, sorting, processing, and transporting equipment (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008). During the design and fabrication of a shelling machine, physical properties are required for sizing the machine components including a hopper, cleaning system, shelling unit, transmission and power system (Mpotokwane *et al.*, 2008). Physical properties are required during the design of a specific component in the shelling machine. For example, when sizing the hopper, the designer needs to know the static coefficient, and volume of the Bambara groundnuts.

2.5.1 Dimensions

According to Oluwole *et al.* (2007b), the effective moisture content for the shelling process is 5 %. Therefore, it is important to measure the physical properties at this moisture content to obtain accurate results. To find the dimensions of the Bambara groundnut pods and nuts, a caliper is used to measure the length, width, and thickness (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Kibar and Ozturk, 2008). According to Mpotokwane *et al.* (2008), the average length, width, and thickness of shelled (nuts) Bambara groundnut were found to be 11.01 mm, 9.96 mm, and 9.48 mm at 5 % moisture content (Mpotokwane *et al.*, 2008). However, there is no available literature where the dimensions of the unshelled (pods) nuts and kernels were measured. During the design of the hopper and storage equipment, the size of the whole seeds are required. This is so that an effective hopper and storage can be sized to accommodate a certain number of groundnuts based on the design specifications (Kibar and Ozturk, 2008; Mpotokwane *et al.*, 2008).

2.5.2 Weight

The weight of the groundnuts requires important consideration during the design of the harvesting, planting, and shelling equipment (Pliestic *et al.*, 2006; Oluwole *et al.*, 2007b; Yalcin and Ersan, 2007). The weight is measured using the digital weighing scale. Based on literature, the average weight of the Bambara groundnut nuts was found to be 0.60 g at 7.17-8.99 % moisture content (Mpotokwane *et al.*, 2008). From the review of literature, only the average mass of the nuts without the shells is recorded. However, in the design of the shelling machine, the mass of the pods is also required to determine the required feed rate (Ogunlade *et al.*, 2014). The weight of the seed with the kernel still needs to be determined from experiments.

2.5.3 Volume

During the design of the hopper of the shelling machine, or any processing machine for seeds, the volume of the pods is required to size the holding capacity of the hopper. The volume of the seeds depends on their dimensions (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008).

Sphericity, surface area, and porosity are related to volume and dimensions, which are also required as design parameters. In addition, these parameters are also used for classifying the shape of the groundnuts (Yalcin and Ersan, 2007; Kibar and Ozturk, 2008; Mpotokwane *et al.*, 2008). The method of Asoegwu *et al.* (2006) is commonly used to measure the dimensions of the seeds. In this method, 100 seeds at different moisture contents are collected randomly from the bowl. The dimensions (length, width, and thickness) of the seeds are then measured using a Vernier caliper (Mpotokwane *et al.*, 2008).

Equation 2.1 is used to calculate the volume of a groundnut from the dimensions results (Bart-Plange and Baryeh, 2003; Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008).

$$V=\frac{\pi B^2L^2}{6(2L-B)} \tag{2.1}$$

where V=volume of the seeds,

L=length of the seed, and

B= parameter that relate to the width (W) and thickness (T).

$B=(WT)^{0.5}$

2.5.4 Sphericity

Sphericity measures how closely the shape of the seed approaches the perfect sphere (Jain and Bal, 1997; Bart-Plange and Baryeh, 2003; Yalcin and Ersan, 2007). This parameter can be related to the static efficiency of friction. The closer a seed is to a perfect sphere, the lower the static efficiency of friction. Mpotokwane *et al.*, (2008), found that the sphericity of shelled Bambara groundnuts ranges from 84.2 to 88.1 % from moisture contents of 7.17-8.99 %. However, to design the hopper and cleaning system, the sphericity of both the shelled and unshelled are required. Sphericity can be calculated by using the axial dimensions of the Bambara groundnuts (Gupta and Das, 1997; Bart-Plange and Baryeh, 2003; Pliestic *et al.*, 2006).

2.5.5 Seed porosity

Porosity can be defined as the free spaces between the packed seeds which are not occupied by the seeds, this parameter is used during the design of storage facilities of the seed (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007). The porosity can be calculated by using true density and bulky density of the seeds (Gupta and Das, 1997; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008). Equation 2.2 is used to determine the porosity for seeds and pods (Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008).

$$\varepsilon=\frac{\rho_t-\rho_b}{\rho_t}\times 100 \tag{2.2}$$

where ε= seed porosity (%),

ρ_t= true density (kg.m^{-3}), and

ρ_b= bulky density (kg.m^{-3}).

The bulk density is the ratio of mass of the sample to its total volume and this parameter can be determined by filling beaker with seeds and measures the weight (Aydin, 2002; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008). True density is the density of the groundnuts without space in between the pods, and the standard methods used to measure true density is called toluene displacement (Aydin, 2002; Bart-Plange and Baryeh, 2003; Zewdu, 2011). The groundnuts are filled in beaker and toluene chemical is used to measure the volume of the free space in the container. The porosity, true density and bulk density of shelled Bambara groundnuts ranges from 22.22 -24.24 %, 100.2 – 1004.7 kg.m^{-3}, and 757.8 – 780.1 kg.cm^{-3}, respectively (Mpotokwane *et al.*, 2008). For sizing hopper, cleaning system and storage facilities, the porosity, bulky and true density of the whole grounguts is required.

2.5.6 Static coefficient of friction

The static of coefficient of friction can be determined on different surfaces of materials, including rubber, galvanised steel, stainless steel and plywood (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007). The nuts and kernels should be placed on adjustable tilting plates. The plate is raised until the material on top starts to slide, and at that point, the angle is recorded (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Mpotokwane *et al.*, 2008). This method is repeated on different materials that are used for transporting, processing and harvesting equipment. In shelling machines, the static coefficient can used to determine the inclination angle of hopper and cleaning systems (Aydin, 2002; Mpotokwane *et al.*, 2008). Several literature of different groundnuts shows that as moisture content rises the coefficient of friction also increase linearly (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007).

2.5.7 Maximum cracking force

The force required to crack the nuts and kernels can be measured with laboratory Texture universal testing machine. This machine compresses the seed and records the maximum force that induced to the groundnut before cracking it (Pliestic *et al.*, 2006). There is no available literature on measuring the cracking force for Bambara groundnuts. However, there was an available method was adopted to an available literature were (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007) measuring cracking force for filbert nuts.

2.6 Processing Involve During Post Harvesting

The post-harvesting process in different types of groundnuts will be outlined in this section including harvesting, drying, shelling and cleaning.

2.6.1 Harvesting

Bambara groundnuts are harvested manually when the plant leaves start to turn yellow (Swanevelder, 1998; Zewdu, 2011). During harvesting, the whole plant is pulled out from the ground gently to avoid pod loss (Aydin, 2002; Oluwole *et al.*, 2007a). In small scale-farming, there is no available equipment to harvest these type of groundnuts, so harvesting is done manually

The pods can also be harvested while green to be boiled and served as snacks, during this time the harvester should pull off the plant to avoid pod loss and the remaining pods are removed by hoe (DAFF, 2011). Commercially, other types of groundnuts are harvested using a conventional combine equipment. This equipment combines activities including harvest, threshing, and shelling at the same time (Butts *et al.*, 2009; Torres *et al.*, 2014). According to Torres *et al.* (2014), the groundnuts harvested with a conventional combine harvester have 11% of foreign material.

2.6.2 Drying

After the groundnuts have been harvested, the rural farmers leave the pods on the ground for sun drying for one or two days (Mkandawire, 2007; DAFF, 2011). However, this practice could lead to post-harvest loss. Proper drying and storage facilities are required to avoid food loss (Aydin, 2002; Mkandawire, 2007). The required moisture content of the groundnuts before shelling ranges between 5 to 8 % dry basis, which can be achieved by leaving the pods in the sun to dry for approximately 6-7 days (Oluwole *et al.*, 2007a).

2.6.3 Shelling

Rural farmers use manual shelling where sticks and stones are used to remove the groundnut kernels. However, this traditional method was found to be inefficient, time-consuming, and laborious with low output (Nigam *et al.*, 2004; Mohammed and Hassan, 2012). On shelling machine, the manual machine was found to have low machine capacity with high mechanical compared to engine drive machine (Atiku *et al.*, 2004; Mohammed and Hassan, 2012).

Conventional combine harvesters that are used in large-scale farming are not suitable for harvesting Bambara groundnuts. There, therefore, exists a need to modify the conventional combine harvester so it can accommodate Bambara groundnut harvesting (Hillocks *et al.*, 2012; Torres *et al.*, 2014). The physical properties of Bambara groundnuts will be required to adequately modify the conventional combine harvester. The combine harvester can achieve up to 62 % shelling efficiency while outfield shelling machine achieved up to 80 % (Atiku *et al.*, 2004; Mohammed and Hassan, 2012; Ugwuoke *et al.*, 2014).

Shelling machines suitable for Bambara groundnuts are not yet available in South African. This is due to limited research focus on the physical properties of Bambara groundnuts. This challenge is a constraint to the large-scale production of Bambara groundnuts. (Atiku *et al.*, 2004; Butts *et al.*, 2009).

2.6.4 Cleaning

There are two cleaning systems that are commonly used to remove chaff and foreign material namely, manual and mechanical systems. These two systems are outlined in this section.

(a) Manual cleaning

After manual shelling, the groundnut seed, chaff, and kernel are mixed together, so a cleaning system is required to separate the nuts from the rest of the material. In rural farming, a winnowing process is used to remove the chaff and foreign material from the groundnuts (Nigam *et al.*, 2004). This method can also be classified as density separation because wind is used to separate the chaff and foreign material from nuts. According to Atiku *et al.*, (2004), the winnowing process can be done by vigorously moving a container with shelled materials up and down. As the material fall by gravity, the air passes through the groundnuts removing the chaff from the nuts. This method is the basic-indigenous cleaning system.

(b) Mechanical cleaning

Mechanical cleaning of groundnuts can be achieved either by blowing or sieving, depending on the process at which this system had been installed (Nigam *et al.*, 2004; Ugwuoke *et al.*, 2014). This system can either be combine or work separated.

Vibrating sieves are commonly used to eliminate chaff, sand and broken pods. However, this system cannot remove empty or large kernels. The blowing process uses an airflow fan which removes the empty pods based on density. The combination of vibration sieves and blowing is a more efficient process for cleaning groundnuts after shelling (Atiku *et al.*, 2004; Ugwuoke *et al.*, 2014).

During sizing of a blow fan, the terminal velocities of the kernels and nuts are required, these parameters are important to prevent the nuts from being blown out during the cleaning process (Atiku *et al.*, 2004; Özgüven and Vursavuş, 2005; Oluwole *et al.*, 2007a). The terminal velocity of the kernels is usually low compared to the terminal velocity of the nuts, and this parameter is also dependent on the density of the materials (McHale *et al.*, 2009). Özgüven and Vursavuş (2005) used a theoretical equation to find the terminal velocity of pine nuts. The average terminal velocities of the nuts and kernels was found to 8.23 and 6.98 $m.s^{-1}$ respectively. Equation 2.4 is used to calculated terminal velocity of any groundnuts (Özgüven and Vursavuş, 2005).

$$V_t=\frac{R_e*\mu_f}{D\rho_f} \tag{2.4}$$

where V_t= terminal velocity ($m.s^{-1}$),

R_e= Reynold's number,

D= geometric mean diameter (m),

μ_f= absolute vascosity, and

ρ_f= mass density of air ($kg.m^{-3}$).

2.7 Machinery used for Processing Groundnuts

The unavailability of groundnut processing machines, especially those for shelling, has had a negative impact on the commercialisation of Bambara groundnut production (DAFF, 2011; Raghtate and Handa, 2014). The lack of shelling machines and other processing equipment has caused a decline in the production of Bambara groundnuts over the years (Aydin, 2002; DAFF, 2011; Hillocks *et al.*, 2012). There are post-harvest processing machines that are used in industry to process groundnuts. These include threshing and shelling machines.

2.7.1 Threshing machines

Commercially, groundnuts are harvested using a combine conventional threshing machine, these types of machines are usually mounted onto a tractor (Butts *et al.*, 2009). Small scale farmers use threshing machines that are use electric, human and fuel power. Threshing machines have six major components including the frame, threshing drum, cleaning, and transmission system (Maduako *et al.*, 2006). The threshing drum is the most important component. This component includes hollow pipes, shaft and rubber flaps, which separate the kernel from nuts (Maduako *et al.*, 2006; Ali, 2007; Ogunlade *et al.*, 2014). Figure 2.2 illustrates the structure of a threshing drum.

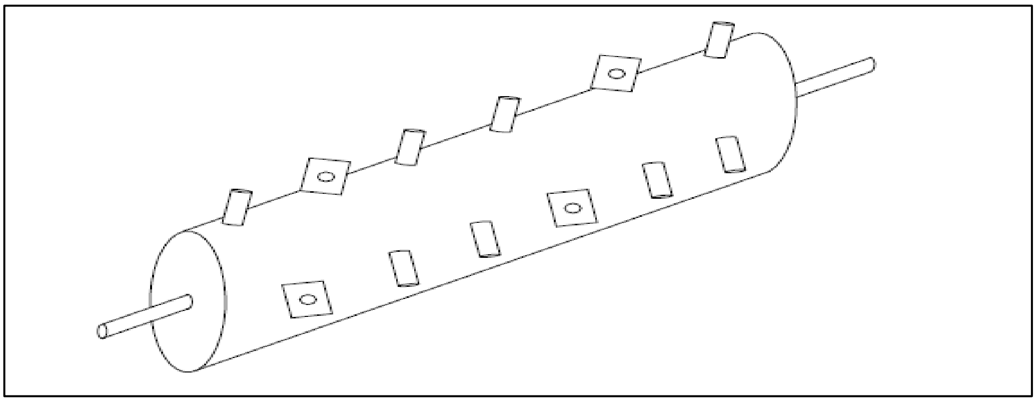

Figure 2.2 Threshing drum (Ogunlade *et al.*, 2014)

The pods are primarily stored in the hopper, and then the groundnuts are released from the hopper to the threshing chamber where the kernels are broken down by the threshing drum. The threshed material is transported to the cleaning system which removes chaff and foreign material (Ogunlade *et al.*, 2014). The cleaning system includes a sieve, blowing fan and transmission system (Ali, 2007; Ogunlade *et al.*, 2014). Table 2.1 shows a summary of specifications and machine performances of available threshing machines for small scale farmers (Ali, 2007; Ogunlade *et al.*, 2014). The performance of the threshing machines depends on the moisture content. Increasing moisture content has direct proportionality with mechanical damage and reduces the threshing efficiency (Ali, 2007; Butts *et al.*, 2009; Ogunlade *et al.*, 2014).

Table 2.1 A summary of the available threshing machines performance at an average moisture content of 8% (Ali, 2007; Ogunlade *et al.*, 2014)

Parameters	Threshing Machines Performance
Operational speed	290 rpm to 300rpm
Capacity	345.5 to 3532 $kg.hr^{-1}$
Cleaning efficiency	46-64 %
Mechanical loss	Up to 30 %
Power consumption	4.5 kW
Threshing efficiency	65-89 %

2.7.2 Shelling machines

There are two types of shelling machines that are commonly used to shell Bambara groundnuts, namely roller and centrifugal crackers (Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b; Mohammed and Hassan, 2012). The roller cracker mechanism consists of a hopper, shelling units (rollers), winnowing system and power system (Atiku *et al.*, 2004). The hopper inclination depends on the angle of repose for the groundnut pods. The shelling units consist of two rollers: one stationary and the other driven by a pulley and belt (Atiku *et al.*, 2004). Furthermore, the winnowing system consists of a sieve and blowing fan which remove the chaff from the nuts. The roller cracker uses electrical motor.

A centrifugal shelling machine for Bambara groundnuts consists of a hopper, shelling unit (impeller), separation units and the power system (Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b; Mohammed and Hassan, 2012). The working principles of the centrifugal and roller crackers are the same but the difference is that the centrifugal machines use impellers in the shelling units instead of rollers. Mohammed and Hassan (2012), investigated both manual and electrically powered centrifugal shelling machines, concluding that the manual machine had higher mechanical loss and less capacity compared to electrically powered machine.

Atiku *et al.* (2004) developed a shelling machine for Bambara groundnuts which used the roller cracker. This machine caused 20 % mechanical damage. In Nigeria, a centrifugal shelling machine was also developed. The performances of this machine was better compared to the roller cracker technique that was developed by Atiku *et al.* (2004). Oluwole *et al.* (2007b) concluded that the centrifugal was the best method to be used for shelling groundnuts. The summary of performance evaluation was represented in Table 2.2.

Table 2.2 Summary of shelling machine performances (Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b; Mohammed and Hassan, 2012)

Parameters	Shelling Machines Performances
Operation speed	1000-1300 rpm
Capacity	96.3 to 215.8 $kg.hr^{-1}$
Cleaning efficiency	79.5 to 85 %
Shelling efficiency	65 to 89 %
Mechanical loss	Up to 20%
Power consumption	2.6 Kw

2.8 Energy used During the Processing of Groundnuts

During the processing of groundnuts, various types of energy are used such as manual, petroleum, renewable energy, and electrical power. These types of power will be outlined in the following section.

2.8.1 Manual power

Manual power can be used in machines in different ways, such as pedalling and hand cracking. Pedal power has become the most reliable power system that can be used to power machines for rural farmers or small-scale farmers. Human beings can produce 50 to 250 watts during pedalling (Farina *et al.*, 2004; Megalingam *et al.*, 2012). Pedalling can power a machine either by mechanical power or converting mechanical power to electrical power using a dynamo (Farina *et al.*, 2004). According to Megalingam *et al.* (2012), the maximum pedalling speed was found to be 120 rpm. However, available shelling machines operate at speeds of 1000 to 1300 rpm, so using pedalling power will require excess transmission system to increase the pedalling speed. In addition, this can increase initial and operating costs of the machine.

Hand cracking machines can be operated by turning wheels. This type of power can produce either mechanical power or electric power (Wu *et al.*, 2007). Hand cranking mechanism can produce power ranging from 50 to 70 W at a speed of 60 to 95 rpm, these machines were mostly used during maize shelling (Nkakini *et al.*, 2007; Wu *et al.*, 2007). According to Wu *et al.* (2007), pedalling is the most suitable power compared to manual power, and also hand cranking cause muscle discomfort which result in muscle injuries. Mohammed and Hassan (2012), developed a hand cracking machine that was used for shelling groundnuts, and the machine capacity, mechanical loss, and shelling efficiency were 65 %, 2.8 % and 118.9 $kghr^{-1}$ respectively. There is no available manual powered-machine which is used to processing Bambara groundnuts.

2.8.2 Petroleum energy

There are two petroleum engines that can be used in agricultural machines, namely diesel and petrol engines. Diesel engines are more efficient compared to petrol engines, so most small agricultural machines use diesel engines during operation (Chintala *et al.*, 2017). Ogunlade *et al.* (2014), developed a groundnut threshing machine that uses fuel engines. The machine was found have a threshing efficiency of 80 % and a machine capacity of 3.5 tonnes per hour. These machine is portable, that means rural farmers can share them during shelling and will be able to increase their production.

2.8.3 Renewable energy

Agricultural machines usually use power from photovoltaic systems which generate energy from solar radiation. These renewable systems include solar panels, batteries, charge controls and electrical cables (Boxwell, 2010; Jacobson and Delucchi, 2011). The solar energy is used to power electrical motor from the transmission system of shelling machines.

2.8.4 Electrical power

The current shelling machines for Bambara groundnuts use electrical motors to power the transmission system, so this machine can be used on farms where electricity or solar power is available (Atiku *et al.*, 2004; Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). However, Bambara groundnuts are currently grown by small-scale or rural famers in areas where grid electricity is limited (Nigam *et al.*, 2004). To increase the production of Bambara groundnuts on rural farmers, manually or fuel powered equipment is required to be developed. Currently, Bambara groundnuts are processed manually which results in low production, resulting in failure to meet market demand (Nigam *et al.*, 2004; Hillocks *et al.*, 2012).

2.9 Engineering Challenges Related to Processing Bambara Groundnuts

Bambara groundnuts are grown by rural families. Therefore, the planting, weeding, harvesting, and shelling are done manually (Nigam *et al.*, 2004; DAFF, 2011). During the design of processing equipment for agricultural material, the physical properties need to be considered (Atiku *et al.*, 2004; Mpotokwane *et al.*, 2008). The lack of Bambara groundnut processing equipment is caused by limited availability of physical properties in literature. As result, the production of these groundnuts became slowly and time consuming (Atiku *et al.*, 2004). In order to develop a shelling machine, the physical properties for whole nuts are required to size the hopper, shelling units, transmission and cleaning systems (Mpotokwane *et al.*, 2008).

The existing shelling machine for Bambara groundnuts uses electrical power during operation. However, these types of groundnuts are grown by rural farmers where access of electrical power is limited. As a result, the production of Bambara groundnuts remains low as compared to other types of groundnuts (Atiku *et al.*, 2004; Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). To industrialise Bambara groundnut production, engineers are required to develop processing machines that will accommodate the rural farmers and these machines should be affordable, low maintenances, portable, and uses manual, petroleum or renewable power.

2.10 Performance Evaluation for Shelling Machine

Shelling machines are tested at different pod moisture contents. Machine performance evaluation includes shelling efficiency, mechanical damages, winnowing efficiency, percentage of unshelled pods and power transmission (Atiku *et al.*, 2004; Maduako *et al.*, 2006; Butts *et al.*, 2009; Mohammed and Hassan, 2012). The shelling efficiency can be calculated using Equation 2.5 (Atiku *et al.*, 2004; Mohammed and Hassan, 2012).

$$\eta=\left(\frac{N_1}{N_T}\right)\times 100 \tag{2.5}$$

where η=shelling efficiency,

N_1=the number or mass of fully shelled nuts without breaking, and

N_T=the total number or mass of the groundnuts.

During the shelling process some of the groundnuts are damaged by the shelling drums or impellers, and these mechanical damages can be calculated using Equation 2.6 (Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b; Mohammed and Hassan, 2012).

$$\text{mechanical damage (\%)}=\frac{Q_B}{Q_T}\times 100 \tag{2.6}$$

where Q_B= mass of damaged groundnuts (kg), and

Q_T= mass of the total groundnuts sample (kg).

After shelling, the groundnuts go to the cleaning system or winnowing system so that the chaff and kernels can be removed from the nuts, performance evaluation of this system can be calculated using Equation 2.7 (Oluwole *et al.*, 2007b; Mohammed and Hassan, 2012).

$$\eta_s=\frac{Q_G}{W_c}\times 100 \tag{2.7}$$

where η_s=mechanical efficiency (%),

Q_B=mass of shelled groundnuts (kg),and

W_c=mass of chaff recorded in the groundnuts (kg).

The percentage of unshelled pods can be calculated from Equation 2.8 (Oluwole *et al.*, 2007a).

$$\cap_u = \frac{N_4}{N_T} \times 100 \qquad (2.8)$$

where $\cap_U$= percentage of unshelled pods (%),

N_4= number of unshelled pods, and

N_T= total number of groundnuts samples pods.

Power transmission can be evaluated using a PCE-AT-5 instrument which measures the rotational speed of the pulleys and belts, this data can be used to calculate the power transmitted to the shelling and cleaning systems to verify if is sufficient or insufficient.

2.11 Discussion and Conclusions

Recent literature focused on the agronomical aspect of the Bambara groundnuts, which has contributed to the slow growth in the production of these groundnuts. The research also shows that these groundnuts are grown by rural farmers, and the product is consumed by their families or sold in local areas (Swanevelder, 1998a; DAFF, 2011). According to Mkandawire (2007), Bambara groundnut production is lower than the world's demand. This could be caused by the slow production or insufficient equipment for Bambara groundnuts.

In Africa, Bambara groundnut planting, harvesting, and shelling processes are done manually which has resulted in decreased production over the years. This challenge has slowed down the process of industrialisation of groundnut production (Oluwole *et al.*, 2007b; FAO, 2014). Literature shows that the shortage of information about Bambara groundnut physical properties has slowed down the development of processing, harvesting, shelling, and planting equipment (Atiku *et al.*, 2004; Oluwole *et al.*, 2007b). The available literature on physical properties can improve the current yield production of this crop and enable more businesses to invest in this crop. That result significantly mitigating poverty in African continent.

In Nigeria, the current shelling machines that are available use large electrical motors during operation. However, in rural farms, electricity is usually not available, as a result these machines are not feasible for use by rural or subsistence farmers (Aydin, 2002; Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). The power required to shell the Bambara groundnuts is determined from theoretical formulas that were developed for other types of groundnuts. As a result, the force and power required to shell these types of groundnuts are relatively higher (Atiku *et al.*, 2004;

Oluwole *et al.*, 2007a). The forces can be determined using the universal testing machine, and this force can be used to find the accurate power needed to crack the shell or kernel of this groundnuts.

Mohammed and Hassan (2012) developed a manual groundnut shelling machine which was operated by hand cracking. These machines can be modified to accommodate the Bambara groundnuts, and also these machines can be feasible to be used in rural farms. There is also potential for renewable energy or manually powered machine instead of the electrical power, but the problem with this type of energy is that it requires large capital investment and these machines' setup is not easy to be moved from one place to another (Boxwell, 2010; Mohammed and Hassan, 2012). Diesel engine shelling machines can also be developed, this engine can allows the machine to be portable, and easily to be transported from one farmer to the other (Maduako *et al.*, 2006).

The literature reveals that the limit in physical properties of Bambara groundnuts result in lacking of processing equipment. There are several methods that can be adopted in literature that can be used to find the physical properties of Bambara groundnuts. These physical properties will used to develop processing, planting, harvesting, and shelling equipment for this type of groundnuts. By doing this, groundnut production can be industrialised easily. The design of a shelling machine that will use either manual power or low power consumption motor powered. Machines will also increase the production of these groundnuts, because the rural farmers will able to increases the rate of production after harvesting and avoid postharvest losses.

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3. THE EFFECT OF MOISTURE CONTENT ON THE PHYSICAL PROPERTIES OF BAMBARA GROUNDNUTS

Abstract

This study aimed at investigating the effect of moisture content on both shelled (nuts) and whole unshelled (pods) Bambara groundnuts. The physical properties were mesured at three moisture content levels. The properties measured includes axial dimension, geametric mean diameter, volume, sphericity, static coefficiency of friction, cracking, true and bulky density. The finding shows that axial dimensions, geometric mean diameter, sphericity, volume, and weight increases as moisture content increases. The static coefficient of friction of shelled and unshelled groundnuts increased from 0.15 to 0.19 and 0.29 to 0.31, respectively. Simirlarly, the bulk density of shelled and unshelled groundnuts increased from 500 to 955, and 355 to 422 kg.m^{-3}, respectively. The results also shows that the true density of shelled nuts rose from 994 to 1832 kg.m^{-3} while for the unshelled groundnuts it increased linearly from 532 to 655 kg.m^{-3}. However, cracking force of both shelled and unshelled groundnuts showed a declining trend as moisture increased from 6 to 20 %. In terms of designing a crushing or shelling machine, the data from the lower moisture content is recommended during the design process.

3.1 Introduction

Bambara groundnuts are subject to yearly yield reduction. These groundnuts are consumed mostly by human beings and domestic animals (DAFF, 2011; Ugwuoke *et al.*, 2014). This crop is also known to produce reasonable yields in low fertile soils (Unigwe *et al.*, 2016). As a result of high yields, the Bambara nut crop can potentially help reduce hunger in the African continent. In Africa, Bambara groundnuts are produced by subsistence farmers mainly for household consumption and for sale to the local market (DAFF, 2011; Oyeyinka *et al.*, 2017). In recent years, available literature has focused on industrialising Bambara groundnuts (Mkandawire, 2007; Mpotokwane *et al.*, 2008; DAFF, 2011). In South Africa, Bambara groundnuts are mainly produced in Mpumalanga, Limpopo, and KwaZulu-Natal province (DAFF, 2011).

The lack of knowledge about the physical properties of crops such as Bambara nuts results in inefficient processing, harvesting, handling and storage of the nuts (Atiku *et al.*,2004: Oluwole *et al.*,2007). This leads to reduction of yield in each harvest. In South Africa, production of Bambara groundnuts is labour intensive as it is done manually by local people (DAFF, 2011). Consequently, the production of this type of crop, lose value from potential investors during industrialisation.

Mpotokwane *et al.* (2008) determined the physical properties of Bambara groundnuts seeds at a moisture content of 7.17 to 8.99 %. In addition, a study by Baryeh (2009) investigated the physical properties of shelled Bambara groundnuts (seed) at different moisture content. During the design of processing, harvesting, shelling, and storage equipment, the properties of the whole groundnuts (shelled and unshelled) is required. This limitation could be solved by determining the physical properties of the both shelled (nuts) and unshelled (pods) Bambara groundnut. This data would help designers to design or manufacture equipment to process Bambara groundnuts.

The objective of this chapter was to determine the physical properties of both shelled and unshelled Bambara groundnuts at the different moisture contents.

3.2 Materials and Methods

A 5 kg bag of Bambara groundnuts was obtained from a local market in Malelane, Mpumalanga Province. The groundnuts were subjected to sun drying for a week, thereafter the samples were stored in the Food Engineering lab at room temperature (23 °C). All foreign materials and soil were removed from the samples before storage.

3.2.1 Experimental design

The experiments were divided into two parts. In the first part, the physical properties of unshelled Bambara groundnut were determined at three different moisture contents of 6, 15, and 20 %. In the second part, groundnuts were manually shelled, and the physical properties of the shelled nuts were measured. The physical properties that were measured include axial dimensions, weight, volume, true density, static coefficient of friction, porosity, bulky density, and cracking force. The experimental design flow diagram is shown in

Figure 3.1.

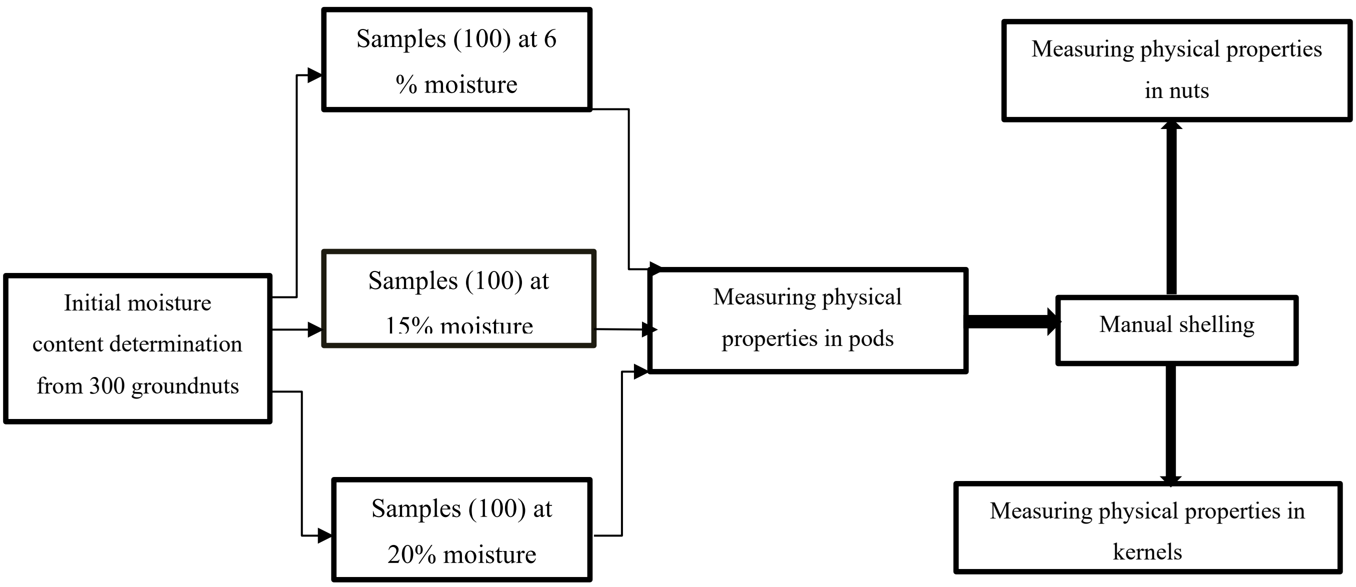


Figure 3.1 Experimental design flow chart

3.2.2 Materials

In this study the following materials were used; a digital vernier caliper, texture analyser machine, digital mass balance, steel sheet, oven drier, ruler, beaker and groundnuts samples.

3.2.3 Data collection

Groundnut samples of 300 pods were selected using a simple random method, and all foreign materials were removed. The initial moisture content of the samples were determined using the standard oven dry method (AOAC, 2002; Asoegwu *et al.*, 2006; Raghtate and Handa, 2014).The samples were oven dried for a period of 24 hours and Equation 3.1 was used to calculate the initial moisture content.

$$MC_{wd}=\frac{W_i-W_d}{W_i}\times 100 \tag{3.1}$$

where MC_{wd}=moisture content (%w.b),

W_i=initial mass (kg), and

W_d=mass of the groundnuts after drying (kg).

The initial moisture of samples was calculated to be 6 %. The samples were then divided into three groups of 100 pods each. The samples were set at three different moisture content levels of 6 (initial moisture content), 15 and 20 %. To obtain the higher moisture content, the samples were prepared by adding a calculated amount of distilled water (Q) which was determined by using Equation 3.2 (Koocheki *et al.*, 2007). The samples were stored in the freezer at 4 ± 1 ^{0}C for a week to allow a uniform distribution of moisture within groundnuts (Adejumo *et al.*, 2005; Prosper and Uguru, 2018).

$$Q=\frac{W_i(M_f-M_i)}{100-M_f} \tag{3.2}$$

where W_i = initial mass (Kg),

M_i = initial moisture (%), and

M_f = required moisture (%).

The following parameters were determined from the samples.

3.2.3.1 Dimension, sphericity, volume, and surface area

During experiments, samples were taken out from the refrigerator and allowed to warm up for a period of an hours (Koocheki *et al.*, 2007). The dimensions were measured in three different axis (x, y, and z), which are the length (L), width (W), and thickness (T). The geometric mean diameter (D_g), which is a function of average dimensions of length, width, and thickness were calculated using Equation 3.3 (Pliestic *et al.*, 2006; Mpotokwane *et al.*, 2008).

$$D_g = (LWT)^{\frac{1}{3}} \qquad (3.3)$$

where D_g = Geometric mean diameter (mm),

L = length (mm),

W = width (mm), and

T = thickness (mm).

Sphericity (∅) which is a parameter that describes how close the groundnuts are to a perfect sphere was calculated using Equation 3.4 (Mpotokwane *et al.*, 2008).

$$\emptyset = \frac{(LWT)^{\frac{1}{3}}}{L} \qquad (3.4)$$

The volume (V) and surface area (S) of pods and nuts were calculated using Equation 3.5 and 3.6, respectively (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007).

$$V = \frac{\pi B^2 L^2}{2(2L - B)} \qquad (3.5)$$

$$S = \frac{\pi B^2 L^2}{2L - B} \qquad (3.6)$$

where $B = (WT)^{0.5}$

3.2.3.2 Weight

The weight of each groundnut was measured using a digital weighing balance calibrated to a 0.001 accuracy (Mpotokwane *et al.*, 2008: Baryeh, 2001). The weight of each pod, nut, and kernel was measured in grams.

3.2.3.3 Coefficient of static friction

The static coefficient of friction was measured at three different moisture contents (6, 15 and 20 %). A galvanised steel sheet was used to measure this parameter. A galvanised steel was used because this material is commonly used in a small scale agricultural hoppers and storage facilities. The shelled and unshelled nuts were placed on an adjustable tilting surface and the height at which nuts begin to move was recorded. Equation 3.7 was used to calculate the coefficient of static friction (Pliestic *et al.*, 2006). **Error! Reference source not found.** illustrates the experimental procedure for measuring the coefficient of static friction.

$$\propto = \tan^{-1}\left(\frac{h}{l}\right) \tag{3.7}$$

where $\propto =$ the angle of repose (mm),

$h =$ a hight at which the pods or nuts starts to slide (mm), and

$l =$ lenght of the plates (300mm).

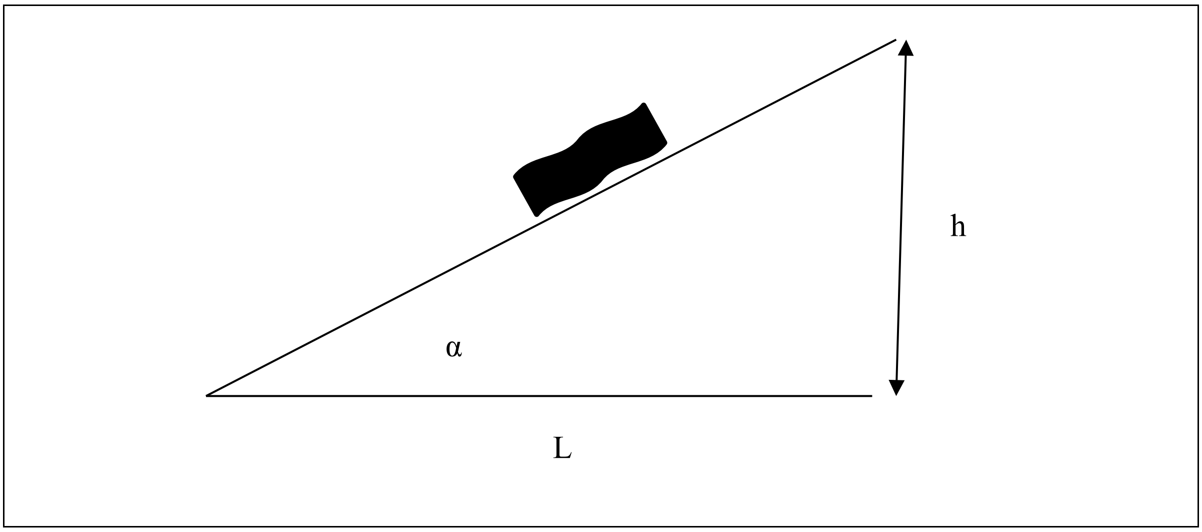


Figure 3.2 Experimental set up of coefficient of static of friction (Pliestic *et al.*, 2006)

3.2.3.4 Porosity

Bulky density is the ratio of mass to volume. This parameter was determined by filling a 500 ml beaker with groundnuts and the weight of the sample was measured (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Muhammad *et al.*, 2018). The bulk density was calculated as ratio of the weight and volume of the beaker. True density was determined using the toluene displacement method, where a 500 ml beaker was filled with groundnuts and toluene chemical. The toluene was used because it has a lower surface tension and specific mass compared to water (Muhammad *et al.*, 2018). As the result the groundnuts in the solution would not absorb this chemical. The mass of the toluene present in container was used to calculate the true density (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007; Muhammad *et al.*, 2018). Porosity was calculated by using Equation 3.8 (Mpotokwane *et al.*, 2008).

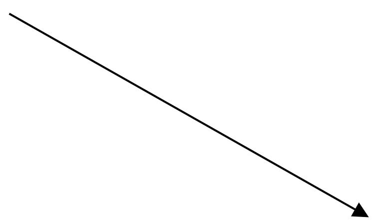
$$P=(1-\frac{\rho_b}{\rho_t})\times 100 \qquad (3.8)$$

where ρ_b=bulky density (kg.m^{-3}), and

ρ_t=true density (kg.m^{-3}).

3.2.3.5 Cracking force

The force required to crack the groundnuts was measured using the Universal Texture Analyser INSTRON 3340 equipment, which compresses the kernels and nuts until they start cracking (Pliestic *et al.*, 2006). A fixed plate was used to place the groundnuts during the cracking experiments. The results were recorded in the form of line graph, which shows the maximum cracking force. Figure 3.3 demonstrates on how the equipment works.



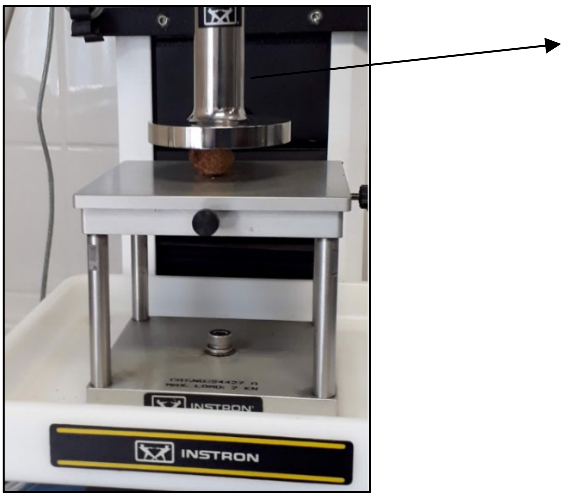


Figure 3.3 Texture analyser equipment which demonstrate how the cracking force was measured experimentally

3.3 Statistical Analysis

The data was analysed using a 2013 Microsoft Excel tool, where descriptive statics were determined from summary of the data analysis option. The statistics were analysed at a 95 % confidence level from the mean. In addition, graphs and tables were used to present the findings of the study.

3.4 Results and Discussion

3.4.1 Dimensions, geometric mean diameter, sphericity, volume and surface area

Table 3.1 shows the results for the average and standard error of axial dimensions. The length of unshelled nuts ranged from 19.7 to 21.1 mm as moisture content rose from 6 to 20 %. The width and thickness ranged from 14.9 to 15.6 mm, and 13.5 to 13.7 mm respectively. The results show that there is a positive linear relationship between the moisture content and dimensions. During the measurement of axial dimensions, it was observed that some of the unshelled nuts had double seed inside which only affected the length (L) of nuts. Therefore, the standard error on the length was found to be higher than that of the width (W) and thickness (T) of unshelled nuts. The relationship between axial dimensions (L, W and T) and moisture contents (M_C) are represented by linear regression Equation 3.9 to 3.11. The dimensions of Bambara groundnuts are lower compare to filbert nuts. The length, width, and thickness of filbert nuts ranges from

25 – 27 mm, 19- 21 mm, and 17 – 21 mm, respectively (Pliestic *et al.*, 2006). Some of groundnuts had double seed inside, which caused design challenges during the design of a processing machine such as shelling machine.

$$L = 0.099M_C + 19.27 \quad (R^2 = 0.92) \tag{3.9}$$

$$W = 0.05M_C + 14.70 \quad (R^2 = 0.89) \tag{3.10}$$

$$T = 0.013M_C + 13.40 \quad (R^2 = 0.96) \tag{3.11}$$

The geometric mean diameter also increased as the moisture content increased as shown in Table 3.1. As moisture content rose, as the groundnuts expand. This expansion affects the length of the groundnuts. A similar trend was also reported in a study where the relationship between moisture content and coriander seeds were investigated (Yalcin and Ersan, 2007).

Table 3.1 Axial dimensions of unshelled Bambara groundnuts (standard error)

Moisture content (%)	**Dimensions of shelled groundnuts (mm)**			**Geometric mean diameter (mm)**
	length	width	thickness	
6	19.7 (±0.47)	14.9 (±0.38)	13.5 (±0.30)	15.8
15	21.0 (±0.38)	15.6 (±0.31)	13.6 (±0.28)	16.4
20	21.1 (±0.49)	15.6 (±0.34)	13.7 (±0.27)	16.5

The average length of the shelled groundnuts increased from 11.3 to 11.8 mm (4.2 %), the width increased from 9.3 to 9.7 mm (3.7 %), and the thickness increased from 8.6 to 8.9 mm (3.4 %). A similar trend was also reported by Baryeh (2001) where physical properties of shelled Bambara groundnuts were determined at different moisture contents levels (5 to 35 %). However, the geometric mean diameter slightly increased from 9.66 to 10.4 mm. This is because the groundnuts seed absorb less moisture compare to groundnuts kernels.

Table 3.2 Axial dimensions (standard deviation) of the shelled Bambara groundnuts

Moisture content (%)	**Dimensions of shelled groundnuts (mm)**			**Geometric mean diameter (mm)**
	Length	width	thickness	
6	11,2 (±1.56)	9,34 (±0.87)	8,58 (±0.81)	9,66

15	11,6 (±1.40)	9,58 (±0.93)	8,76 (±0.83)	9,91
20	11,8 (±1.50)	9,72 (±1.20)	9,02 (±0.74)	10,4

The linear regression equations describes the relationship between axial dimensions and moisture contents can be seen from Equation 3.12 to 3.14.The regression (R^2) shows that there was closed relation between axial dimensions and moisture contents.

$$L = 0.0354M_C + 11.2 \qquad (R^2 = 0.99) \qquad (3.12)$$

$$W = 0.0261M_C + 9.34 \qquad (R^2 = 0.099) \qquad (3.13)$$

$$T = 0.0215M_C + 13.4 \qquad (R^2 = 0.99) \qquad (3.14)$$

The sphericity of unshelled Bambara groundnuts decreased from 80 to 78%, while for the shelled nuts the sphericity declined from 85 to 86% as seen in Figure 3.4. The findings show that shelled nuts are more spherical than unshelled nuts. Baryeh, (2001) and Mpotokwane *et al.*, (2008) reported that the sphericity of shelled Bambara groundnuts increased as moisture content increases, which follows a similar trend with the findings obtained from the experiments conducted in this study. In this study, the sphericity of unshelled groundnuts showed a declining trend as the moisture increased. The sphericity declined because as moisture content rose, the kernels did not expand equally in all directions. Therefore, the shape of the groundnuts become less round. A similar trend was also reported in a study where the relationship between moisture content and the sphericity of soya beans were investigated (Kibar and Ozturk, 2008). In terms of design considerations, at lower moisture contents the unshelled groundnuts tends to roller faster.

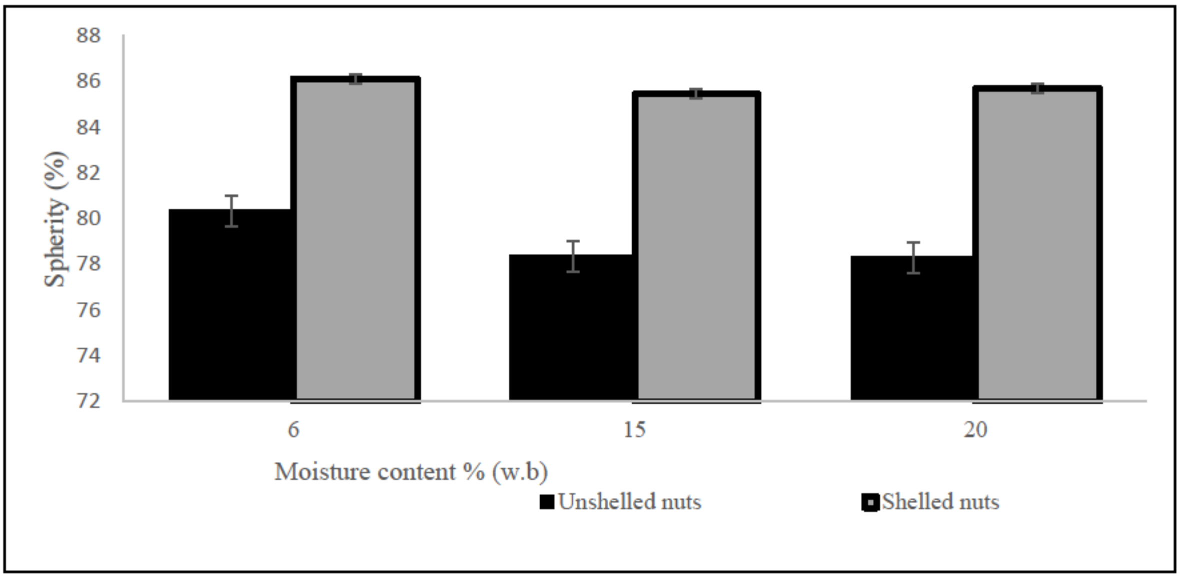


Figure 3.4 The sphericity of both unshelled and shelled groundnuts at different moisture contents

In this experiment, the volume was found to increase from 1615 to 1806 mm^3 and from 392 to 510 mm^3 for the unshelled and shelled groundnuts respectively. The projected area of the unshelled Bambara groundnuts rose from 9691 to 10835 mm^2. A similar trend was observed on the nuts as reported by (Pliestic *et al.*, 2006; Mpotokwane *et al.*, 2008). As the size of Bambara groundnuts increases, the volume and surface area also increase linearly. Such a trend relating to the surface area was also reported in filbert nuts and coriander (Pliestic *et al.*, 2006; Yalcin and Ersan, 2007). In conclusion, as the size of Bambara groundnuts increase, the volume and surface area also increase linearly. Therefore, the Bambara groundnuts will need a smaller hopper or storage facilities at lower moisture contents.

3.4.2 Weight

The findings show that as moisture content increases from 6 to 20 %, the average weight of each shelled and unshelled groundnut also increased linearly from 0.54 to 0.673 g, and 0.81 to 0.96 g, respectively. As moisture content rises, the standard deviation of unshelled groundnuts also rose. This shows that the kernels had a higher water holding capacity, consequently the weight of unshelled nuts increased significantly with moisture content (Kibar and Oz Turk, 2008)). Similar findings were reported by Baryeh, (2001) where physical properties of Bambara groundnuts were determined. In this study, it was found that the deviation from mean was smaller in lower moisture content as seen in Table 3.3. In terms of the design of a shelling or crushing machine, at lower moisture content, the machine will have a low capacity because the groundnuts have a lower weight at lower moisture content.

Table 3.3 The weight of both shelled and unshelled groundnut at different moisture contents

Moisture content (% w.b)± SD	Unshelled nuts (g) ± SD	Shelled nuts (g) ± SD
6	0.81(±0.28)	0.54 (±0.17)
15	0.85 (±0.26)	0.58 (±0.19)
20	0.96 (±0.38)	0.67 (±0.17)

3.4.3 Static coefficient of friction

During the experiments, it was found that as moisture content increased in both shelled and unshelled Bambara groundnuts, the static coefficient of friction also increased. The shelled Bambara groundnut static coefficient of friction increased from 0.29 to 0.31, while the nut's static coefficient of friction increased from 0.15 to 0.19 in galvanised steel sheeting. A similar trend was observed by Pliestic *et al.* (2006), where the physical properties of filbert nuts and kernels were determined at different moisture content. Baryeh (2001), reported that the static coefficient of friction of shelled Bambara groundnuts (seed) increase from 0.29 to 0.58 at moisture content ranges from 5 to 35% (w.b) in galvanised iron sheeting. The results were higher compare to results obtained in this experiment. This is because Baryeh, (2001) conducted the friction experiment on iron sheeting while in this study, a galvanised sheet was used during experiments.

The increase of the static coefficient of friction in both shelled and unshelled nuts is caused by the moisture present, which offers the cohesive force on the contact surface (Pliestic *et al.* 2006). As a result, the groundnuts experience more friction at higher moisture content. The regression analysis (R^2) for both shelled and unshelled nuts are close and equal to 1 as seen in Figure 3.5. This shows that there was strong relation between the moisture content and the static coefficient of friction.

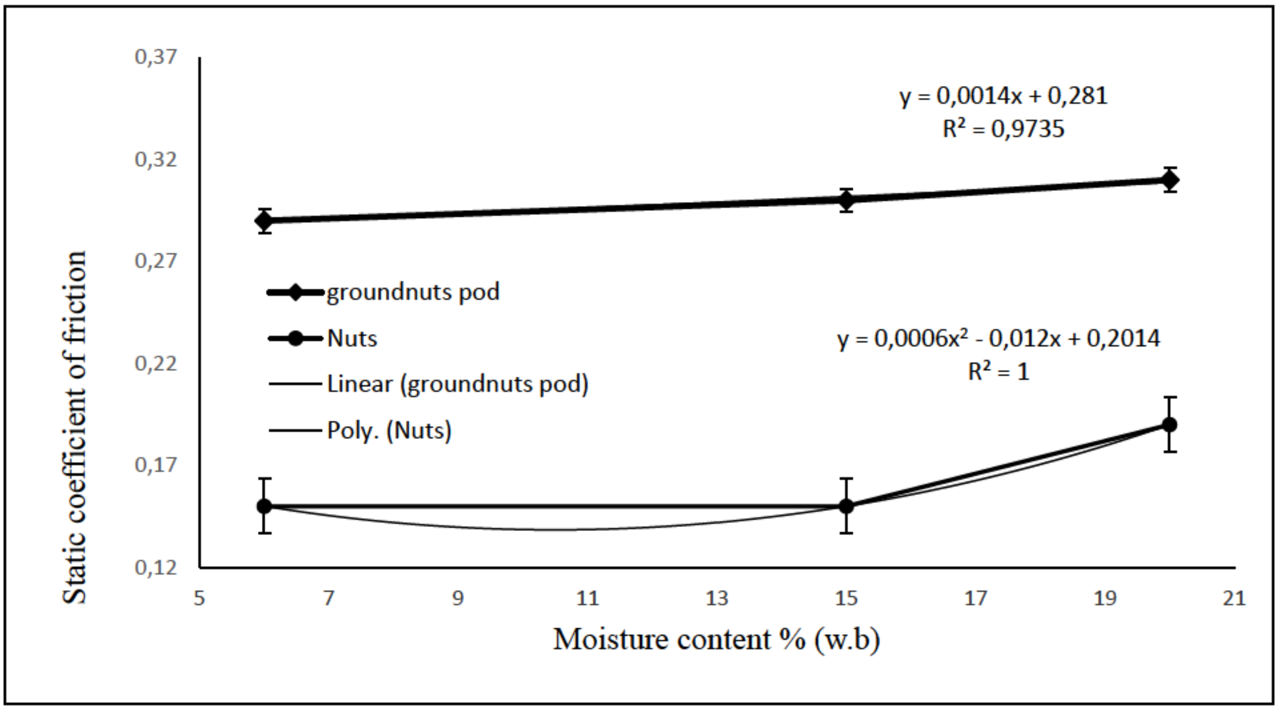


Figure 3.5 The static coefficient of friction at different moisture content levels

3.4.4 Porosity

In this study, the values of bulk and true density were obtained from the experiments. Thereafter Equation 3.8 was used to calculate porosity. The porosity of both shelled and unshelled ground ranged from 49 to 47 %, and 35 to 32 %, respectively. It was found that the porosity of groundnuts decrease linearly as moisture content increase from 6 to 20 % as seen in Figure 3.6. Baryeh, (2000), reported that the porosity of Bambara groundnuts seeds decreases non-linearly as moisture content increases. However, Pliestic *et al.* (2006) reported that the porosity of Filbert nuts increases as moisture content rises. Therefore, based on the findings of this study, it was observed that the groundnuts expand as moisture content rise. Consequently, the space between the groundnuts was reduced. A similar trend was also reported by Kibar and Oz Turk (2008), where physical and mechanical properties of soya beans were determined. Kibar and Oz Turk (2008) reported that the porosity of soya beans decreased from 22.58 to 20.61 % from moisture contents ranging from 8 to 16 %. The porosity of this beans is lower compared to Bambara groundnuts and filbert nuts (Pliestic *et al.* 2006 : Baryeh, 2000).

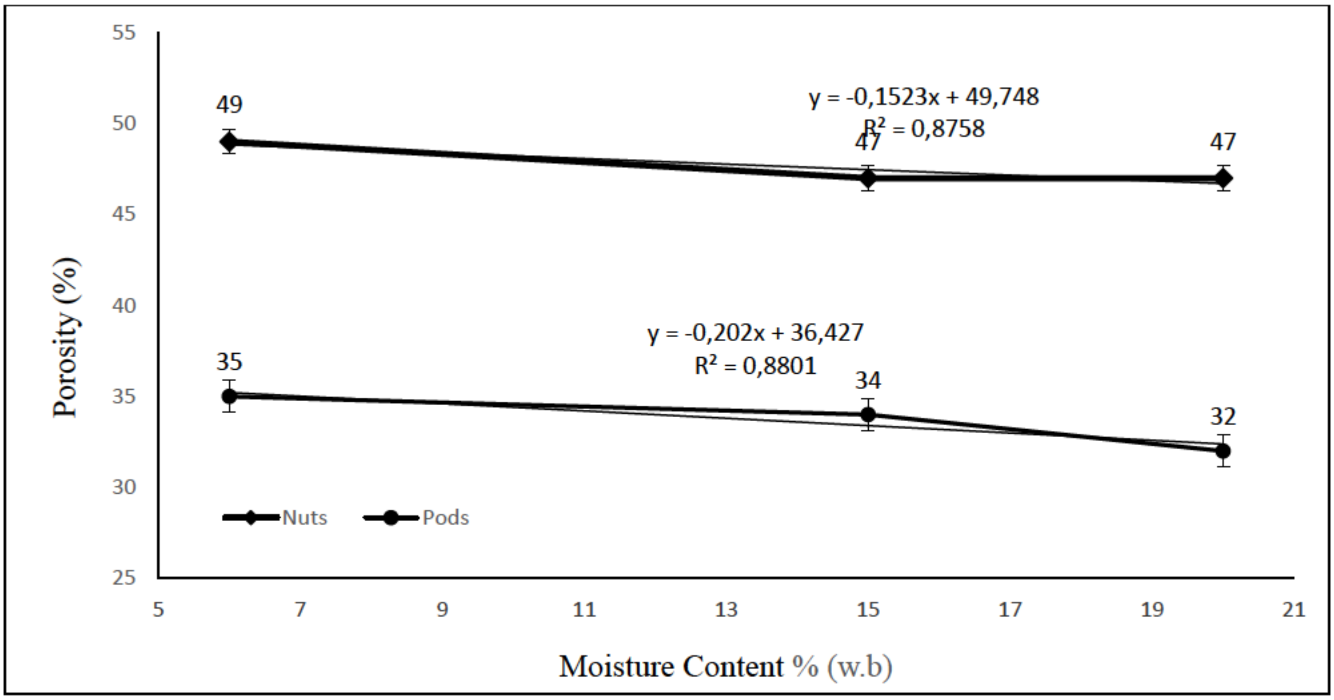


Figure 3.6 Porosity of Bambara groundnuts at different levels of moisture contents

(a) Bulky density

The bulk density of shelled Bambara groundnuts nuts increased exponentially while the bulk density on unshelled nuts increased linearly as moisture content rose from 6 to 20%. The bulk density for shelled and unshelled groundnuts increased from 500 to 955 $kg.m^{-3}$, and 355 to 422 $kg.m^{-3}$, respectively. However, Baryeh (200) reported that the bulk density of Bambara groundnuts seeds declined from 795 $kg.m^{-3}$ to 696 $kg.m^{-3}$ as moisture content increase from 5% to 35% w.b. Baryeh (2001) used a pycnometer to measure the bulky density, and in this research, a different methods was used. The groundnuts were filled in a beaker to measure the mass the groundnuts (Pliestic *et al.*, 2006; Mpotokwane *et al.*, 2008). Then, the bulk density was calculated as ration of the weight of groundnuts and volume of the beaker (Pliestic *et al.*, 2006; Mpotokwane *et al.*, 2008). Therefore, in this experiment it was found that as the moisture increase the weight of the groundnuts also increase. The bulk denisty was increasing in both shelled and unshelled groundnuts as shown in Figure 3.7.

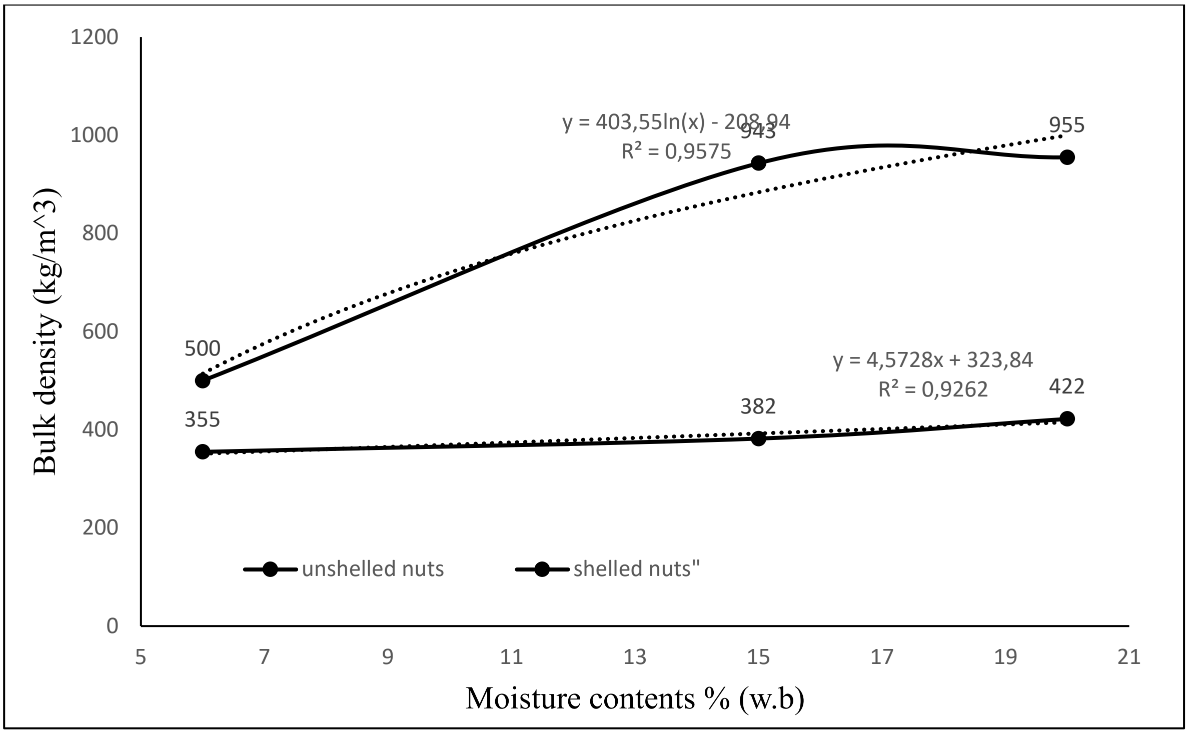


Figure 3.7 The bulk density of Bambara groundnuts at different moisture content

(b) True density

The true density of both shelled and unshelled nuts increased from 994 to 1832 kg.m^{-3}, and 994 to 1832 kg.m^{-3}, respectively. The true density of shelled nuts increases non-linearly while the true density for unshelled nuts increased linearly. A similar trend was found by Muhammad *et al.* (2018) during the determination of physical properties of groundnuts (*Manipintar* and *Ex-Dakar*). The findings in this study shows that there is strong correlation between moisture content and true density because as moisture increased the true density increased as shown in Figure 3.8. However, the findings of true density of Bambara groundnuts seed reported by Baryeh (2001) showed a declining trend.

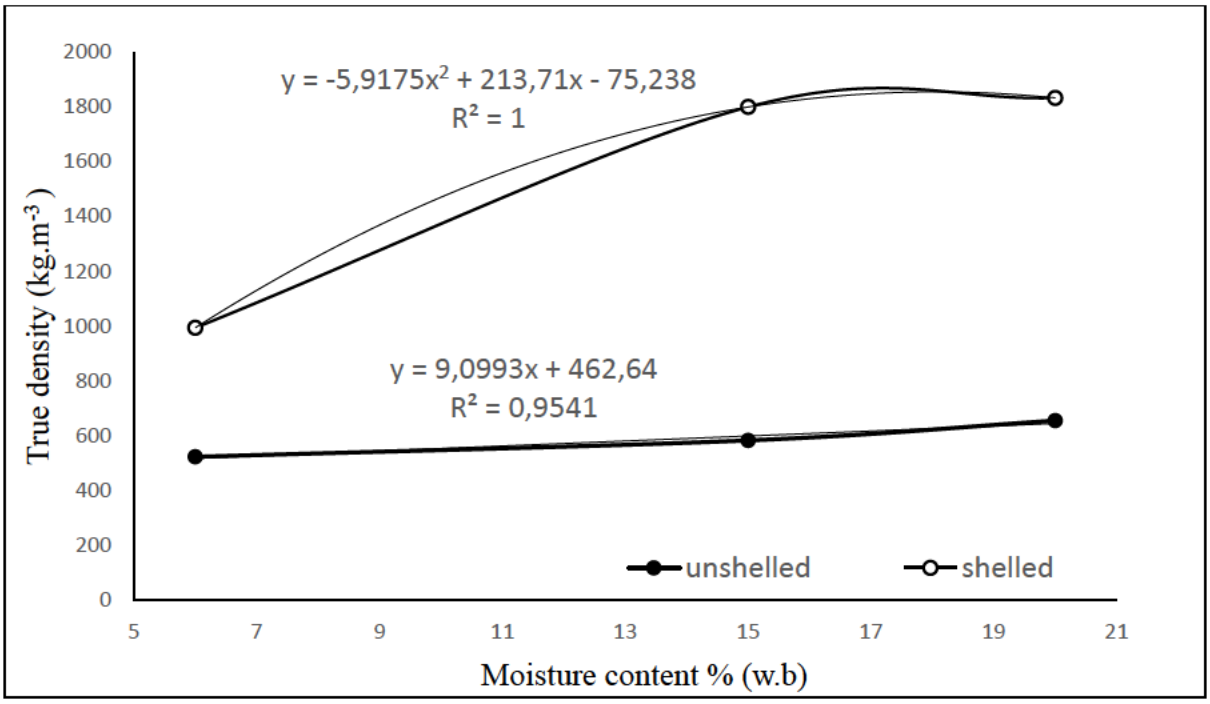


Figure 3.8 True density of Bambara groundnuts at moisture content ranges from 6 to 20 %

3.4.5 Cracking force

The average cracking forces required for cracking the Bambara groundnuts kernels at 6, 15, and 20 % are 32.5 ±12, 29.9 ±15.3, and 28.9 ±9 N, respectively. It was observed that as moisture content increases, the kernels became softer. As result the cracking force required for cracking kernels declines as shown in Figure 3.9 . Similar trend were also observed by Pliestic *et al.* (2006), where the forces required for cracking filbert nuts declined as the moisture content increased. Pliestic *et al.* (2006) reported that the required force for cracking filbert nuts declined from 690 to 580 N as moisture increase from 6.19 to 28.71 %.

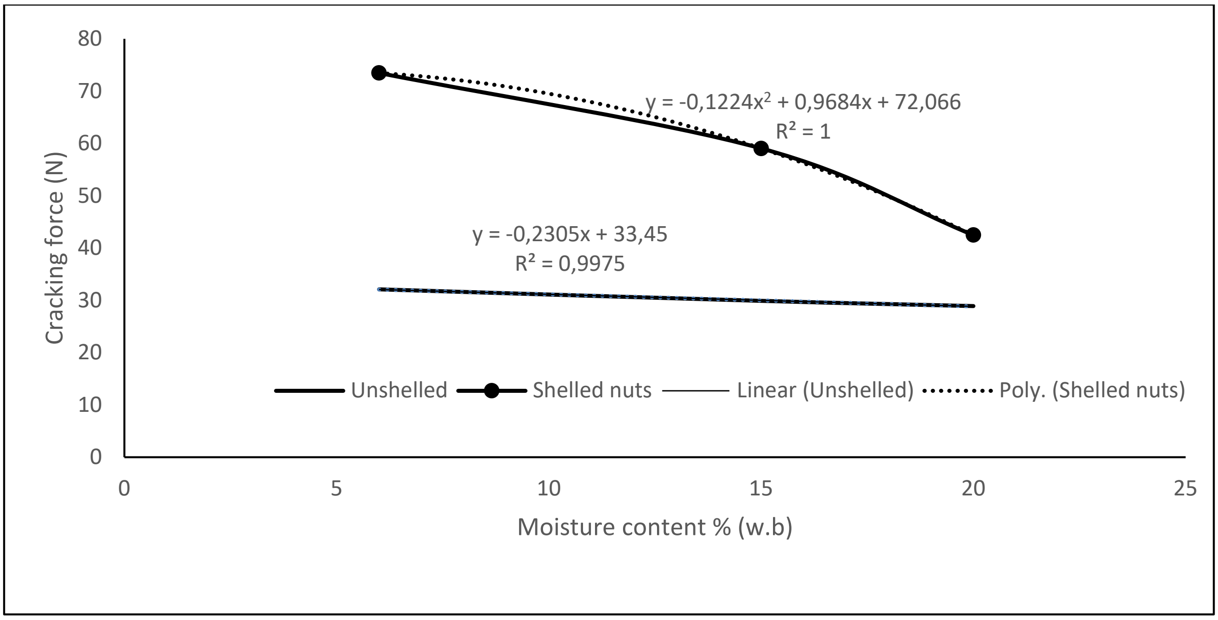


Figure 3.9. The required cracking force at different moisture content

The average forces for cracking Bambara shelled nuts at 6, 15, and 20 % are 73.5 ± 16.3, 59 ±15.6, and 42 ± 10.1 N, respectively. As the moisture increases, the data deviation from the mean decreased from 16.30 to 10.1 N. Figure 3.9 showed the relationship between moisture content and cracking force. The linear regression analysis (R^2) of both shelled, and unshelled nuts are closed to one. This indicates that there was a close relation between moisture content and cracking force.

3.5 Conclusion and Recommendations

The physical properties were measured at three different moisture contents levels which are 6, 15, and 20 %. The different moisture content levels were set by adding calculated amount water. The physical properties measured includes dimensions (length, width and thickness), geometric mean diameter, volume, sphericity, and static coefficient of friction, porosity, cracking force, bulk and true density. The axial dimensions, geometric diameter, and volume increased with increased moisture content. The sphericity of the groundnuts was found to decline as moisture content increased. It was observed that as the moisture content increased, the nuts did not expand equally in all directions. Therefore, the nuts became less round as the moisture content increased. The static coefficient of friction was found to be higher for unshelled groundnuts, because as moisture increased, the kernel gained more water and increased contact time on the galvanised steel. In this study, the results show that the porosity between both shelled and unshelled nuts decline linearly as moisture content increased. The bulk density of both shelled and unshelled nuts were found to decline as moisture content rose while true density increased with moisture content. The cracking force of both kernel and shelled nuts declined as moisture content rose. It was also observed that as the moisture content increased, the skin of both shelled and unshelled nuts became weaker. As a result, the cracking force declined with increased moisture content. The findings of this study can be used to design post-harvesting processing equipment include shelling and grinding machines. For future research, it is recommended to determine the physical and chemical properties in wide range of moisture content levels to accommodate other food processing such as canning.

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4. DESIGN OF PORTABLE BAMBARA GROUNDNUTS SHELLING MACHINE

Abstract

Shelling is the process whereby the kernel is separated from the nut manually or mechanically. The aim of this chapter was to design a portable Bambara groundnut shelling machine. A potable Bambara groundnuts shelling machine was developed. This prototype consists of a hopper, shelling chamber, frame, collector, fan blower, and transmission system. The hopper shape is a triangular prism that had been welded on semi-circular drum which covers the shelling chamber. The machine shelling mechanism is a shelling shaft with spikes on it. The machine is powered with a 1.1 kW motor operating at a speed of 1390 rpm. The power is transmitted by belt and two pulleys while the pneumatic system consists of a fan blower that separates the nuts from the kernels. The machine was evaluated for shelling efficiency, mechanical damage capacity and cleaning efficiency. The samples used for evaluation were set at different moisture content levels of 6, 15, and 20 %. The shelling efficiency of the machine declines from 71.8 to 21.89 % as moisture content increases from 6 to 20 %. The mechanical damages also decrease from 3.66 to 1.46 % as the moisture contents increases. The capacity of the machine therefore depends on moisture content. The findings from this study show that as the moisture content increase, the machine capacity decrease from 145.6 to 80.1 $kg.hr^{-1}$. Overall, the machine was found to perform better with groundnuts with lower moisture content. It is recommended that the farmers shell the groundnuts at lower moisture content to avoid poor performance during shelling.

4.1 Introduction

Bambara groundnuts are harvested manually by lifting or pulling the plant out of the soil (Atiku *et al.*, 2004; DAFF, 2011). The groundnuts are left on the ground to dry in the sun, and the recommended moisture content is between 8 to 12 % (Oluwole *et al.*, 2007a; Oluwole *et al.*, 2007b). There Bambara groundnuts are used for various applications such as human consumption, industrial products, and animal feeds (DAFF, 2011). After harvesting, Bambara groundnuts require agro-processing such as drying and shelling to improve the storage of the nuts.

Shelling is a process at which kernels are separated from nuts by means of mechanical or manually process. In South Africa, the local farmers use manual shelling, where sticks and stones are used to remove the groundnut kernels (DAFF, 2011). However, this traditional method was found to be inefficient, time-consuming, and laborious with low output (Jambhulkar *et al.*, 2019). According to Atiku *et al.* (2004), the traditional ways of shelling results in high damage of nuts which causes profits loss. This challenge creates a stumbling block during the industrialisation of Bambara groundnuts in South Africa and Africa as whole.

Atiku *et al.* (2004) develop a Bambara groundnut sheller in Nigeria which used a roller to shell the kernels and a pneumatic system to for the removal of chaff. During performance evaluations, the machine had a shelling efficiency and mechanical of 80 %, and 38 %, respectively. The feed rate or machine capacity was 93.6 $kg.hr^{-1}$ (Atiku *et al.*, 2004). However, this machine is not available in markets, so there is a need to develop a Bambara groundnuts machine that will be affordable small-scale SA farmers. The machine should result in minimum mechanical damage with a sufficient cleaning efficiency in order to maximise production.

The main of objective of this research project was to design, construct, and evaluates a Bambara groundnut shelling machine. The machine should have a cleaning system which separates the foreign objects and kernels from the nuts. The machine should be constructed from local material and be easy to operate at a minimum cost.

4.1.1 Project specifications

The project specifications are to design:

(c) a portable and affordable shelling machine for Bambara groundnuts,
(d) a machine capacity of at least 100 $kg.hr^{-1}$,
(e) a machine with less than 10 % mechanical damages,
(f) a machine with at shelling efficiency of at least 80 %, and
(g) a machine with a cleaning efficiency of at least 60 %.

4.2 Material and Methods

The material and methods for the design of sheller is outlined in the following sections.

4.2.1 Description of the shelling machine

The shelling machine consist of a hopper, shelling shaft with spike, blower, collecting system, transmission system, and a small electric motor. The hopper is a triangle prism shape that was mounted on a semi-drum. During operation, groundnuts are poured from the inclined hopper. The groundnuts fall under gravity to the shelling shaft where spikes create impact forces which breaks the pods of the groundnuts. The collection system is fitted with a blower that removes chaff from the nuts, and the nuts are collected using open container. Figure 4.1 illustrates a concept drawing of Bambara groundnuts shelling machine that was planned to be designed. The theoretical design is outlined in on the sub-sections below. The full assembly prototype can be also seen in Appendix, Figure 6.7.

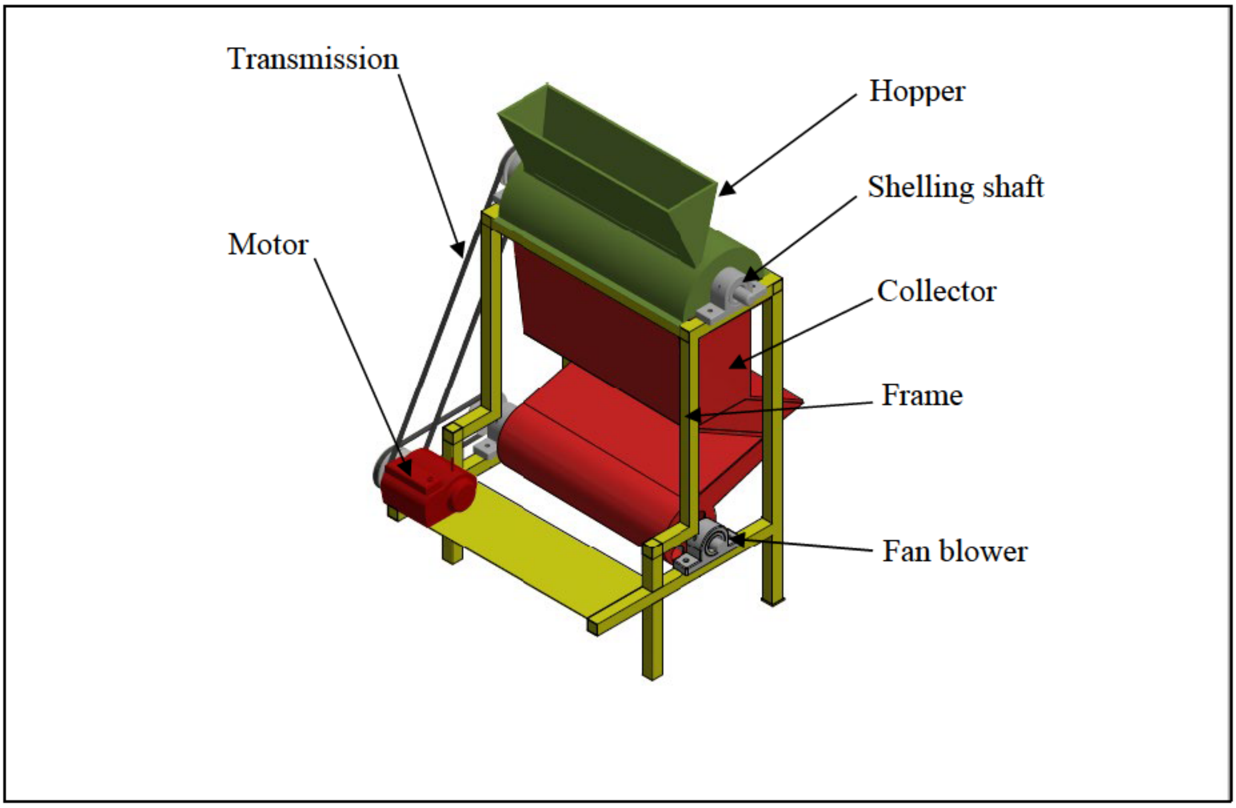

Figure 4.1 Concept drawing of a Bambara groundnuts shelling machine

4.2.2 Theoretical design and construction

During the design of a sheller for Bambara groundnuts, the important criteria that were taken into consideration include the strength required to crack the Bambara kernels, safety, and environmental health. Material selection were based on safety, availability, durability, strength, and cost. The design includes a hopper, shelling chamber, cleaning and power transmission system. The power transmission system includes shaft, belts drive, pulleys, bearings, and an electric motor. The design and sizing of the individual components are outlined in this section. The physical properties of Bambara groundnuts at 6 % were using during the design process.

4.2.2.1 Hopper design

Based on design specification, the shelling machine was designed to shell at least 100 $kg.hr^{-1}$of Bambara groundnuts. The total volume required was calculated to be 0.28 m^3 from using the density of Bambara groundnuts pods at a 6 % MC. This volume required a large hopper. Therefore, the machine was set to be refilled 28 times to achieve the machine capacity. The hopper shape was selected to be a triangle prism that will hold a volume of 0.02 m^3 per fill. The length (l) and breadth (b) of the hopper were set to be 420 and 130 mm respectively. The volume required per refill was known to be 0.02 m^3, so a formula to calculate the volume of triangular prism was used to calculate the unknown height (h) of the prism. The height of the prism was calculated to be 200 mm from Equation 4.1.

$$v = \frac{1}{2} \times l \times b \times h \tag{4.1}$$

$$0.02 = \frac{1}{2} \times 0.420 \times 0.2 \times h$$

$$h = 0.02 \text{ m}$$

Where v = volume (m^3),

l = length (m),

b= breadth (m), and

h= height (m).

The half drum cylinder and the triangle prism hopper were welded together. Both the cylinder and hopper were constructed from 1 mm steel sheet which was available and cheap in the market. **Error! Reference source not found.** shows a detail drawing of the hopper that was mounted on semi-secular drum.

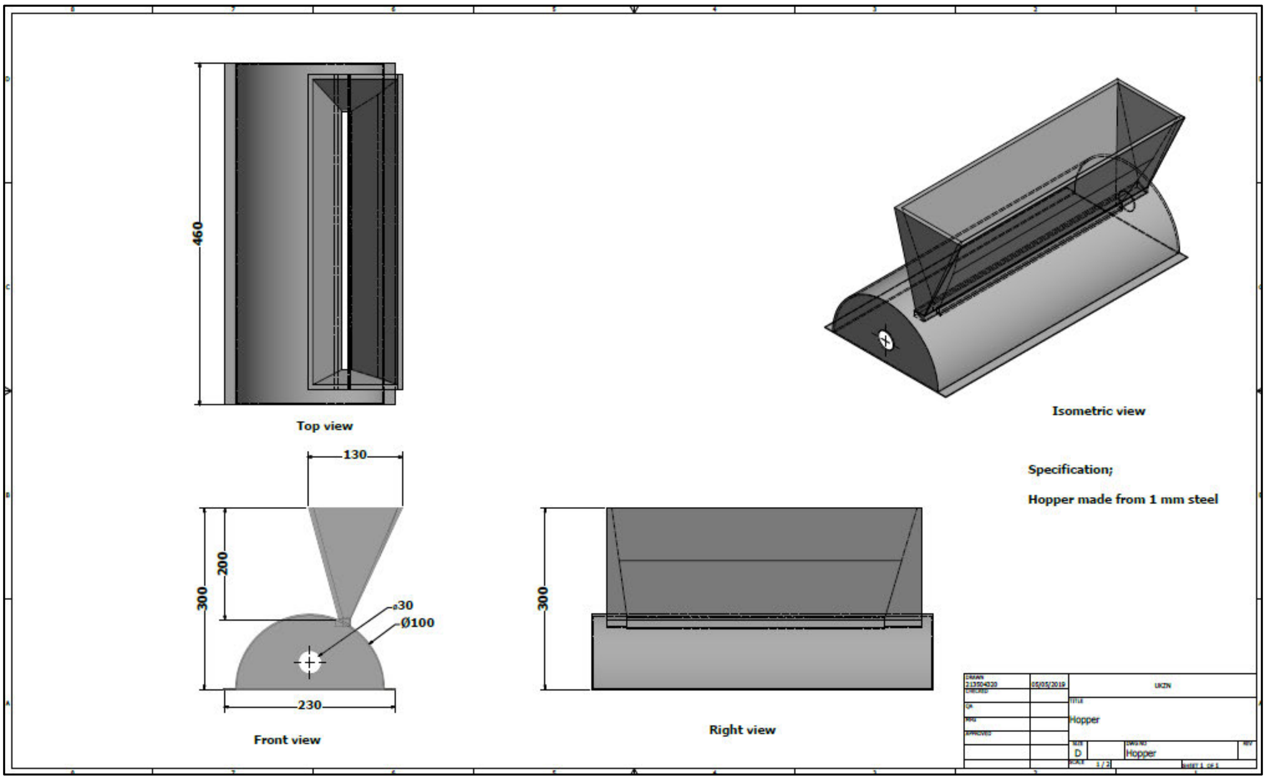

Figure 4.2 The detailed illustration of a hopper

4.2.2.2 Determination of the required power

The total power for shelling Bambara groundnuts was a sum of the required shelling power (Ps) and the power to drive the shelling shaft (P_D).

(a) Required shelling power (Ps)

Based on experiment in Chapter 3, it was found that the average force required for cracking Bambara groundnut pods and nuts at 6 % moisture content was 32 ±12 N, and 73.74 ± 16.3 N, respectively. The power required was calculated based on the average force required for cracking the Bambara groundnut pods at 6 % moisture contents. The diameter of the shelling shaft was assumed to be a 25 mm diameter. According to Atiku *et al.* (2004), the speed 250 rpm was found to be an effective shelling speed for Bambara groundnuts at 6%. So, in this prototype design, 250 rpm was selected to be the shelling speed. To minimise groundnut damages, spikes and wires were used as a shelling component. Equation 4.2 was used to calculate the angular velocity of the shaft (Ogunlade *et al.*, 2014; Raghtate and Handa, 2014). The angular velocity (w) was calculated to be 26.19 rad.s^{-1} from Equation 4.2 (Ogunlade *et al.*, 2014; Raghtate and Handa, 2014).

$$w = \frac{2\times\pi\times N}{60} \quad (4.2)$$

$$= \frac{2\pi\times 250}{60}$$

$$= 26.19 \text{ rad.s}^{-1}$$

where ω = angular velocity (m.s^{-1}), and

N= speed of the shaft (rpm).

The torque (T) of the shaft was calculated to be 7.6 Nm from Equation 4.3 (Ogunlade *et al.*, 2014). The radius (r) of the shaft was assumed to be 12.5 mm (25 mm diameter). The required shelling power was calculated to be 300.92 W from Equation 4.4 (Ogunlade *et al.*, 2014). Where a safety factor (SF) of 1.5 was used (Ogunlade *et al.*, 2014).

$$T = F\times r\times ns\times na \quad (4.3)$$

$$= 32.25\times 0.0125\times 19\times 1$$

$$= 7.66 \text{ Nm}$$

where T = shaft torque (Nm),

F_{av} =average crack force (N),

n_a =number of active row per time,

n_s =number of active spikes, and

r =radius of the shaft (m).

$$P_s = TW(SF) \quad (4.4)$$

$$= 26.19\times 13.52\times 1.5$$

$$= 300.92 \text{ W}$$

where Ps = power required to shelling Bambara groundnuts (W),

T = shaft torque (Nm), and

SF = safety factor.

(b) Power required to drive the shelling shaft (P_D)

The shelling mechanism includes a shelling shaft and spikes. This combination was chosen because Oluwole *et al.* (2007a) found that using an impact force in shelling was better than using rollers and a drum. Due to the variation of dimensions, some of the groundnut pods were damaged or un-shelled when a roller mechanism is used. To calculate the power required to drive the shelling shaft, the total weight of shaft and spikes were calculated. There are three rows of the spike on the shelling mechanism. The mass of each spike was calculated using Equation 4.5 to 4.7 (Ogunlade *et al.*, 2014). The total weight found to be 2.3 kg. The density of steel used was 7860 kg.m^{-3}. The radius, and height of a spike was set to be 5 mm, and 50 mm, respectively.

$$V_s = \pi r^2 h \qquad (4.5)$$
$$= \pi \times (0.005^2) \times (0.055)$$
$$= 4.319 \times 10^{-6}\ m^3$$

where V_s = volume of each spike (m^3),

r = radius of the Shaft (m), and

h= spikes height (m).

The total mass of the spike was calculated from density formula

$$\rho = \frac{m}{v} \qquad (4.6)$$
$$m = \rho \times v$$
$$= 7860 \times 4.19 \times 10^{-6}$$
$$= 0.034\ kg$$

$$\text{Total weight} = \text{mass of each} \times \text{number of spikes} \qquad (4.7)$$
$$= 0.034 \times 57$$
$$= 2\ Kg$$

The total weight of both shaft and spikes were calculated to be 45 N by using the gravity formula. The sum of spikes and shaft mass in kg was multiplied by gravitational acceleration (9.81 ms^{-2}). The torque was calculated to be 0.56 Nm from Equation 4.8 (Hassan *et al.*, 2009).

The power to drive the shelling mechanism was calculated to be 22 W from Equation 4.98 (Hassan *et al.*, 2009).

$$T_D = W_D \times R_D \tag{4.8}$$
$$= 45 \times 0.0125$$
$$= 0.56 \text{ Nm}$$

where T_D= torque (Nm),

W_D = mass of shaft and spikes (N), and

R_D = radius of shaft and spikes (m).

$$P_D = \omega_D \times T_D \times FS \tag{4.9}$$
$$P_D = 26.18 \times 0.56 \times 1.5$$
$$= 22\ W$$

where P_D = power required to drive shaft (W), and

ω_D = angular velocity (rad.s^{-1}).

The total power required was the sum of required shelling power and the powered to drive shelling shaft. From Equation 4.10, the total power for shelling the groundnuts was calculated to be 625.02 W 8 (Hassan *et al.*, 2009). The smallest motor available was a 1.1 Kw motor at 1390 rpm motor speed. For the reduction of rotation speed and power a transmission system (belts, chain, sprocket, and pulleys) can be used. The rotation of the selected motor selected was 1390 rpm and required was 250 rpm. Therefore, the transmission system was required for speed reduction.

$$P = P_S + P_D \tag{4.10}$$
$$= 603.02 + 22$$
$$= 625.02 \text{ W}$$

4.2.2.3 Design of transmission system

The power is transmitted from motor to the shelling shaft by means of belt and pulleys. There are two pulleys in the transmission, namely the driver (small) and driven (large). The driver pulley was selected to be a V-pulley with a diameter of 56 mm. The specifications of the driver pulley is highlighted in the Figure 6.1, of the Appendix (Catalogue, 2012). The diameter of the driven pulley was then calculated to be 311 mm from Equation 4.11 (Olaoye and Adekanye, 2018: Muhammand and Isiak, 2019). The driven pulley specification can be seen in Figure 6.2 , Appendix (Catalogue, 2012). Motor speed was assumed to be 1390 rpm.

$$D2 = \frac{D1 \times N2}{N1} \tag{4.11}$$

$$= \frac{56 \times 1390}{250}$$

$$= 311 \text{ mm}$$

where D2= diameter of large pulley (mm),

D1= diameter of small pulley (mm)

N2= speed of large pulley (rpm), and

N1= speed of the small pulley (rpm).

The two pulleys were connected by a V-belts which transmits rotational power from the motor to a shelling shaft. The distance between the driver and driven pulleys was calculated to be 383 mm from equation 4.12 (Olaoye and Adekanye, 2018). Using a centre to centre distance, the length of the belt was calculated to be 1384 mm from equation 4.13 (Olaoye and Adekanye, 2018). The selected belts was a SPZ V-belts of 1380 mm length and it was purchased at the local shop. The detailed specifications of the belt can be seen in Figure 6.3, Appendix (Catalogue, 2012).

$$C = 2D1 + D2 \tag{4.12}$$

$$= (2 \times 56) + 311$$

$$= 383 \text{ mm}$$

where C= centre to centre distance (mm).

$$L = 2C + \frac{(D1-D2)^2}{4C} + \frac{\pi(D1+D2)}{2} \tag{4.13}$$

$$= 2(383) + \frac{(311-56)^2}{4(383)} + \frac{\pi(311+56)}{2}$$

$$= 1384 \text{ mm}$$

where L= length of the belts (mm).

4.2.2.4 Shaft design

Atiku *et al.*, (2004), designed a groundnut shelling machine that used rollers to shell the groundnut kernel. The machine had a shelling efficiency and mechanical damages of 80%, and 38 %, respectively. This significant damage could be caused by the variation of the axial dimensions of Bambara groundnuts. Some of the Bambara groundnuts contain double nuts inside, which affect the unshelled length. Due to variation of the axial dimensions, spikes were used as the cracking mechanism. The spike will be welded 11 mm apart to allow only the shelled groundnuts to pass through. The average axial dimensions (length) of shelled groundnuts was found to be 11.2 ± 1.56 mm, as seen in Table 3.2.

Shaft sizing depends on axial loads, torsion and bending (Hassan *et al.*, 2009). These parameters also had an impact on the life expectancy of the bearings. The axial loads in this shaft include the shelling spikes and pulley weight. The force acting on the shaft are presented in Figure 6.4, where a static force diagram was shown. From the static force diagram, the maximum vertical moment was found to be 4.30 Nm. The horizontal moment was set to be zero because there was no force on the horizontal direction. Therefore, the resultant moment (M_{mx}) was calculated to 4.30 N.m from Equation 4.14 (Ogunlade *et al.*, 2014). The horizontal moments diagram can be seen Figure 6.5 of the Appendix. The torsional moment (M_t) was calculated to be 23.03 Nm from Equation 4.15 (Ogunlade *et al.*, 2014).

$$M_{max}=\sqrt{M_x^2+M_y^2} \tag{4.14}$$

$$=\sqrt{(4.30)^2+(0)^2}$$

$$= 4.30 \text{ N.m}$$

where M_{max}=resultant bending moments,

M_x= maximum horizontal bending moments diagram (Nm), and

M_y= maximum vertical bending moments (Nm).

$$M_t = \frac{P_s \times 60}{2\pi N_1} \quad (4.15)$$

$$= \frac{603.02 \times 60}{2\pi \times 250}$$

$$= 23.03 \text{ N.m}$$

where M_t=Torsional moments (Nm),

P_s=power required for shelling bambara groundnuts (W), and

N1=speed of small pulley (rpm).

The shaft was set to be supported by two pillow bearings at the end. Therefore, this shaft will experience minor vibration, so the combined shock and fatigue factor for bending and torsional moments were set to be 2.0 and 1.5, respectively (Hassan *et al.*, 2009). The allowed bending stress (γ_d), and safety factor (SF) for shaft with keyways were 40 Nm.m^{-2}, and 1.5, respectively (Hassan *et al.*, 2009). The shaft diameter was calculated to be 24 mm from Equation 4.16 (Ogunlade *et al.*, 2014; Olaoye and Adekanye, 2018). The standard available shaft size was a 25 mm diameter which was selected in this project. During the power calculations in Chapter 4.2.2.3, the assumption made was that the shelling shaft had a 25 mm diameter which also achieved in this study. Therefore, the assumption made was correct.

The shaft was purchased at local shop and a rectangular key was milled on the shaft. This was done to protect the driving pulley from slippage. The spikes were welded on the shelling shaft. The detail drawing of the shelling shaft can be seen in Figure 4.3.

$$d_{shaft} = \left(\frac{16}{\pi \tau_d} \left((K_b M_{max})^2 + (K_t M_t)^2 \right)^{0.5} \right)^{\frac{1}{3}} \times SF \quad (4.16)$$

$$= \left(\frac{16}{\pi \times (40 \times 10^6} \left((2.0 \times 4.30)^2 + (1.5 \times 23.03)^2 \right)^{0.5} \right)^{\frac{1}{3}}) \times 1.5$$

$$= 0.024 \text{ m}$$

where d_{shaft} = diameter of the shelling shaft (m),

k_b = combine shock and fatigue factor applied in bending moment,

k_t= combine shock and fatigue factor applied on torsional moment,

M_{max}= resultants bending moments (Nm),

M_t= maximum torsional moment(Nm),

γ_d = allowable stress for steel shaft , and

FS =safety factor.

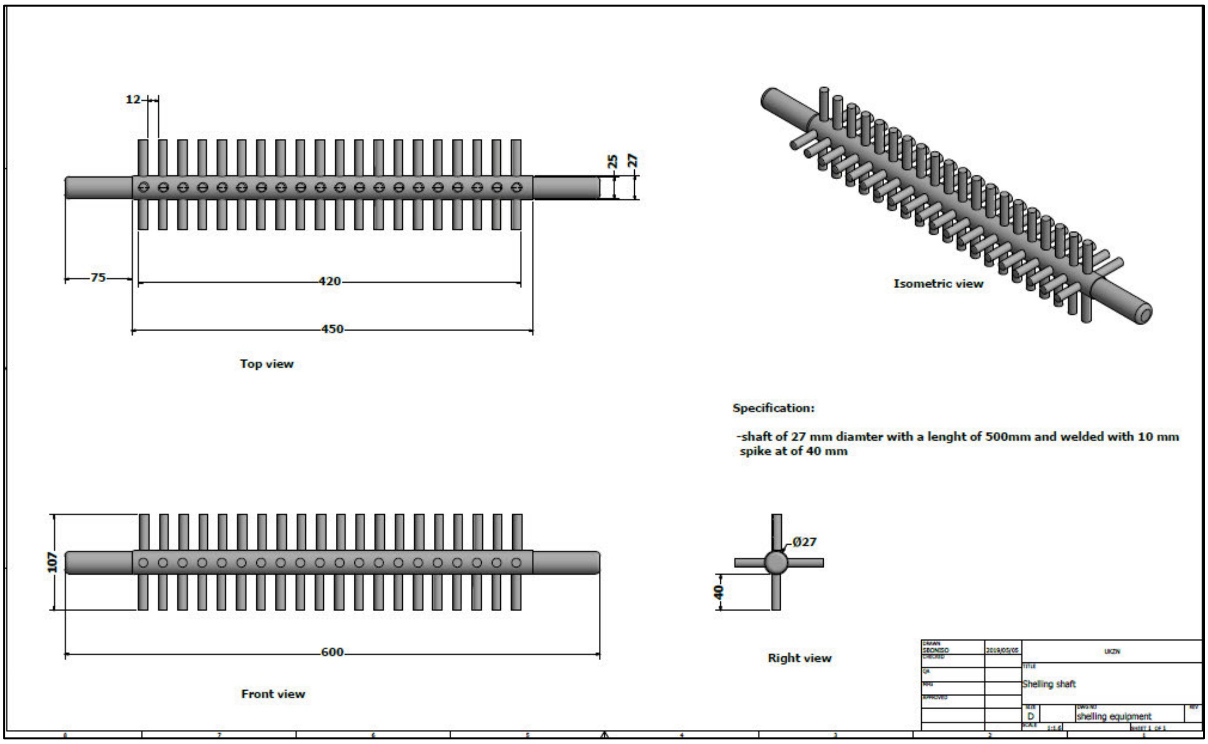

Figure 4.3 Shelling shaft with welded spikes at 11 mm apart

4.2.2.5 Collecting system design

The collector allows Bambara groundnuts to move from a hopper to fan blower. A fan was mounted at the bottom of the collector. These parts was manufactured from steel sheeting which was 1 mm thick. The collecting part was manufacture at Troy Manufacturing Company due to the complexity of the design. The detailed drawing is shown in Figure 4.4.

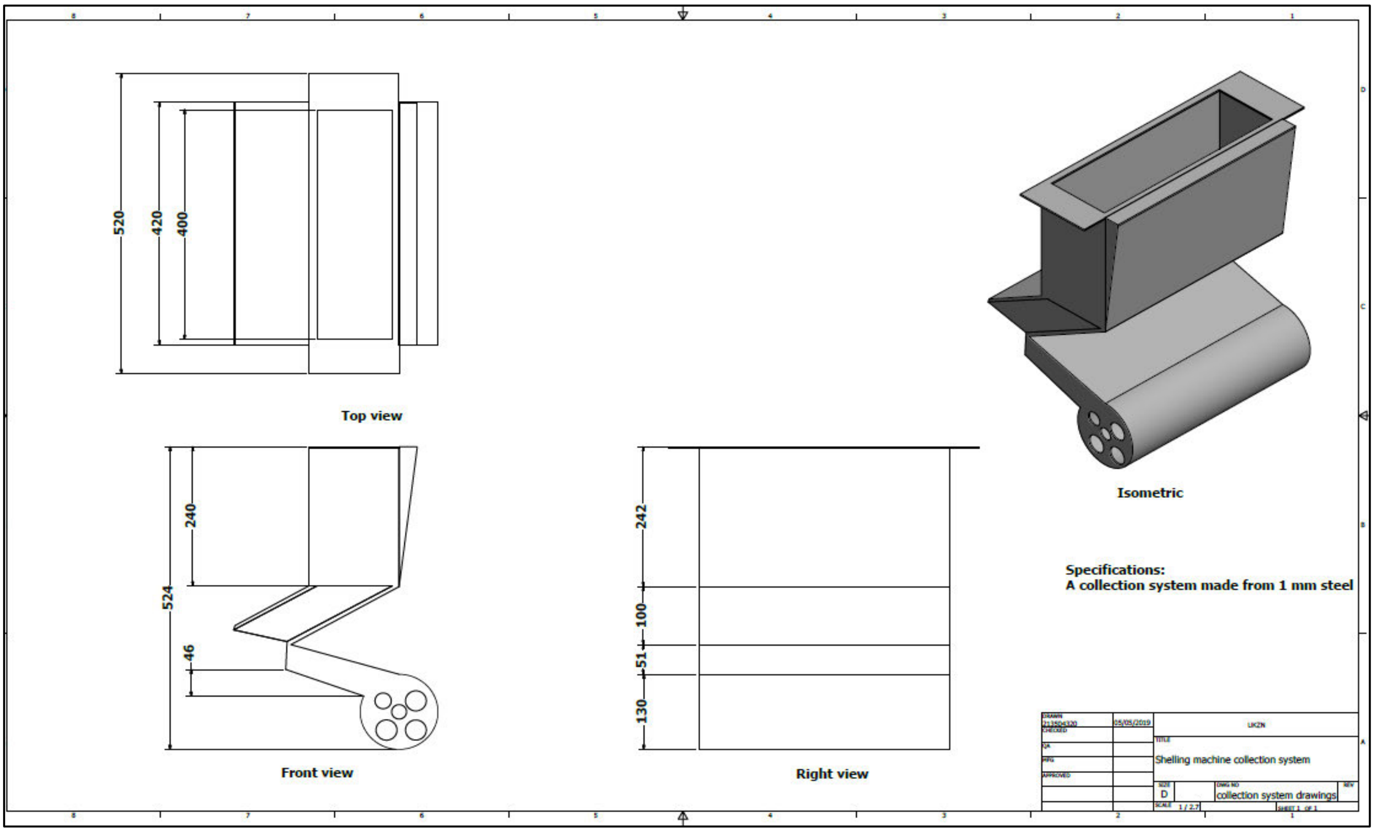

Figure 4.4 The detailed drawing of a collecting part

4.2.2.6 Fan capacity sizing

The fan was sized based on the terminal velocity and targeted fan efficiency. The terminal velocity is used in the sizing of a pneumatic system for a food processing machine (Ogunlade *et al.*, 2014). The terminal velocity of Bambara groundnuts was calculated to be 5.21 m.s^{-1} from Equation 4.18 (Nwigbo *et al.*, 2008).

$$v = \sqrt{\frac{2wP_pP_f}{CP_pP_fA_n}} \quad (4.18)$$

$$v = \sqrt{\frac{2(\frac{0.808}{1000}\times 355\times 1.17}{0.5\times(1.19\times 10^{-4})\times 355\times 1.17}}$$

$$= 5.21\ m.s^{-1}$$

where v=terminal velocity (m.s^{-1}),

w=mass of bambara groundnuts kernel (Kg),

c=dragging efficiency,

P_f=air density ($kg.m^{-3}$), and

P_p=density of groundnuts kernels($kg.m^{-3}$).

The required air volume to blow the chaff of Bambara groundnuts kernel was calculated to be calculated 0.167 $m^3.s^{-1}$ from Equation 4.19 (Ogunlade *et al.*, 2014). While the required power to drive the fan was calculated to be 81.63 W from Equations 4.20 (Ogunlade *et al.*, 2014). The fan efficiency was assumed to be 75 % at the static pressure of 366 $N^2.m^{-1}$ (Ogunlade *et al.*, 2014). The length and width of the fan blower housing were 320, and 100 mm, respectively. A 12 v double fan blower type CY125M was selected with a speed of 6 $m.s^{-1}$.

$$Q_A = vlw \tag{4.19}$$
$$= 5.21 \times 0.1 \times 0.32$$
$$= 0.167 \ m^3.s^{-1}$$

where Q_A = volume of required (m^3s^{-1}),

v = terminal velocity ($m.s^{-1}$),

l = length of fan opening (m), and

w = width of the fan opening(m).

$$P = \frac{Q_A P_s}{n} \tag{4.20}$$
$$= \frac{0.167 \times 366}{0.75}$$
$$= 81.36 \text{ W}$$

where P = power to drive fan (W),

Ps = static pressure of the fan ($N^2.m^{-1}$), and

Q_A= volume required ($m^3.s^{-1}$).

4.2.2.7 Design of frame structure

A frame supports the entire machine parts which includes the hopper, bearings, collector, motor, blower, and shelling shaft. During the design of the frame, the 38 × 38 × 2 mm square steel tube was selected as material for the frame support. The material for frame constructing was checked against buckling due to the load (SAISC, 2013). The frame structure can be seen in Figure 4.5. The total weight of the hopper was calculated to be 1.66 kg while the shelling shaft and spikes weighed 12.49 kg. The centrifugal blower and collection system weighed 4.4 kg. The total weight on the frame was therefore368 N including pulleys and the 1.1 Kw motor. The buckling calculations were based on the South African Steel Construction Handbook (SAISC, 2013). Equation 4.21 to 4.26 was using to check the stability of the frame (SAISC, 2013).

In these calculations the frame stability was checked. The sectional area on a 38×38×2 mm square tube was calculated to be 148 mm^2 from Equation 4.21.

$$A = t(2a-t) \quad (4.21)$$
$$= 2(2(38)-2)$$
$$= 148 \text{ mm}$$

where A= area of the section (mm^2),

t= thickness (mm). and

a= width (mm).

The natural axis was calculated to be 27.75 mm from the Equation 4.10.

$$y = a - \frac{a^2+at-t^2}{2(2a-t)} \quad (4.22)$$
$$= 38 - \frac{38^2+(38\times2)-2^2}{2(2(38)-2)}$$
$$= 27.75 \text{ mm}$$

Where y=neutral axis (mm),

Moment of inertia (I) for the square tube of 38×38×2 mm was calculated to be 21 149 mm^4.

$$I = \frac{1}{3}\left(ty^3 + a(a-y)^3 - (a-t)\left(a-y-t\right)^3\right) \quad (4.23)$$
$$= \frac{1}{3}\left(2\times27.75^3 + 38(38-27.75)^3 - (38-27.75)(38-27.75-2)^3\right)$$
$$= 21149 \text{ mm}^4$$

where I=moments of inertia (mm^4)

The section modulus (Z) and radius of gyration (k) was calculated to be 762 mm^3 and 12 mm.

$$z=\frac{I}{y} \tag{4.24}$$

$$=\frac{21149}{27.75}$$

$$=762\ mm^3$$

$$k=\sqrt{\frac{I}{A}} \tag{4.25}$$

$$=\sqrt{\frac{21149}{148}}$$

$$=12\ mm$$

The total load that creates buckling or crippling was calculated to be 35 456 N from Equation 4.11. The crippling or buckling was found to be greater than the total load acting on the frame which is 3 800N (SAISC, 2013). Therefore, the frame will not fail during operation.

$$W_{cr}=\frac{c\pi^2 EAK^2}{L^2} \tag{4.26}$$

$$=\frac{0.25\times\pi^2\times(210000)\times210\times12^2}{662^2}$$

$$= 35\ 456\ N$$

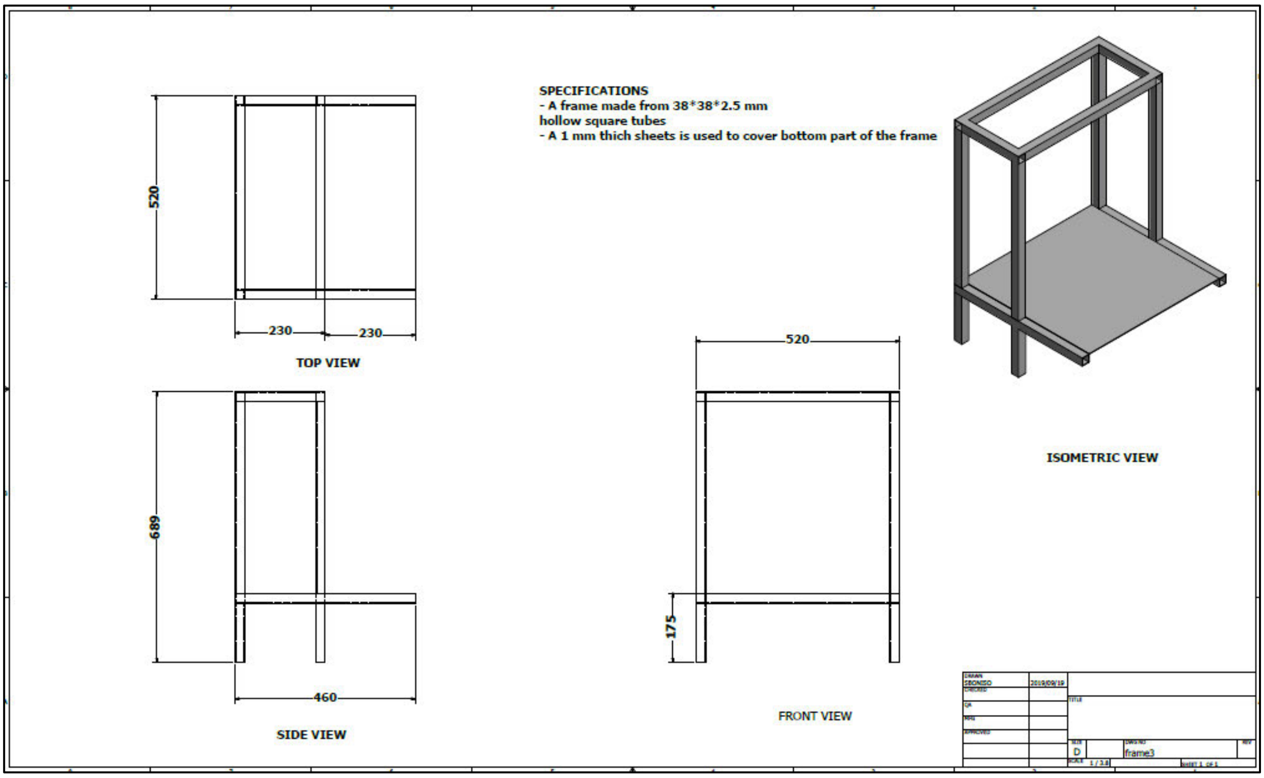

Figure 4.5 A detail drawing of a steel frame which was constructed with square tube

4.2.2.8 Fabrication and assembly of the prototype

During construction, the frame, and shelling shaft were manufactured at the UKZN Ukulinga workshop. While the hopper and collector were outsourced at the Troy manufacturing company. The parts were assembled at the Ukulinga farm workshop with the help of the technicians and undergraduate students.

4.2.2.9 Sheller performance evaluations

A 10 kg Bambara groundnuts samples was purchased from a subsistence farmer at Mpumalanga province. The initial moisture content of the samples were determined using the standard oven dry method (Raghtate and Handa, 2014).The samples were oven dried for a period of 24 hours and Equation 3.1 was used to calculated the moisture content. Then, the samples were set at three different moistures levels (6, 15 and 20 %) by adding calculated amount of distilled water using Equation 3.2.

The different performance evaluations that are carried out on agricultural machinery include shelling efficiency, mechanical damage, cleaning efficiency, and machine capacity (Atiku *et al.*, 2004; Nwigbo *et al.*, 2008; Raghtate and Handa, 2014). Shelling efficiency is the ration of the number of groundnuts that were shelled including broken seed to total number of groundnuts fed into shelling machine (Atiku *et al.*, 2004). Equation 4.27 was used to calculate the shelling efficiency of the prototype (Atiku *et al.*, 2004).

$$\eta_s = \left(\frac{N_1 + N_2}{N_T}\right) \times 100 \qquad (4.27)$$

where n_s= Shelling efficiency (%),

N_1= number of pods that were shelled and unbroken (g),

N_2= number of broken seed (g), and

N_T= total number of groundnuts fed to shelling chamber(g).

During the shelling process, some of the groundnuts can break due to the high impact forces induced into individual nuts. Mechanical damage can be calculated by the ratio of the number of broken nuts to the number of groundnuts fed onto the system machine (Atiku *et al.*, 2004). Equation 4.28 is used to calculated mechanical damage (Oluwole *et al.*, 2007b).

$$\eta_p = \left(\frac{N_2}{N_T}\right) \times 100 \qquad (4.28)$$

where η_p= mechanical damage (%),

N_T= total number of groundnuts (g), and

N_2= number of pods fully with broken nuts (g).

During the design of the system, a blower was incorporated for separation chaff and nuts. The cleaning efficiency can be calculated by measuring the total mass of groundnuts fed to the system and the total mass of the cleaned groundnuts (Atiku *et al.*, 2004; Oluwole *et al.*, 2007b). Equation 4.29 is used to calculate the winnowing efficiency (Atiku *et al.*, 2004; Oluwole *et al.*, 2007b).

$$\eta_w = \left(\frac{M_{SW}}{M_{TS}}\right) \times 100 \qquad (4.29)$$

where η_w = winnowing efficiency (%),

M_{SW} = mass of shell winnowed out (g), and

M_{TS} = total mass shelled (g).

According to the design specifications, the machine capacity should be 100 kg.hr^{-1}. During performance evaluation, the machine performance was evaluated by measuring the amount of groundnuts shelled per minute. Equation 4.30 will be used to calculate the machine capacity (Olaoye and Adekanye, 2018).

$$\text{Capicity}\left(\frac{\text{kg}}{\text{s}}\right) = \frac{Q_s}{T_m} \tag{4.30}$$

where Q_s = weight of shelled groundnuts (kg), and

T_m = shelling time (s).

4.3 Results and Discussions

The samples were tested at three different moisture content (6, 15, and 20 %). For each moisture content set up, three run were conducted and the average was calculated. The findings from the three moisture contents are outlined below. Figure 6.6 illustrates the samples used during the evaluation of the prototype.

4.3.1 Shelling efficiency

The shelling efficiency results are presented in Figure 4.6. The findings show that as moisture content increased the shelling efficiency of the machine decrease linearly. The groundnuts are shelled by impact force created between the nuts and spikes. As moisture content increase the contact time between the spikes and the pods increase which reduces the impact force. Therefore, the shelling efficiency declines as moisture content rises from 6 to 20 % (w.b). A similar finding was also reported by Atiku *et al.* (2004), where a Bambara groundnuts sheller was designed. The Bambara groundnuts machine achieved a maximum shelling efficiency of 80 % and a maxium mechanical damage of 38 % at moisture content ranges from 5 to 10 %

(w.b). it was also oberseved that as moisture increases, the number of unshelled pods also increased.

The design spcification was not achieved in this prototype. the target on shelling efficiency was atleast 80 % and the maximum achievable efficiency at 6 % MC was 72 %. This was because, during milling and drilling of the shelling shaft, the 12 mm spaces in between spike was not accurately achieved due to less experince of using the letha machine. The recommedation, is that a skilled techinian is required to mill and drill the shaft. The addition of horizontal wires on the spike can improve the shelling efficency.

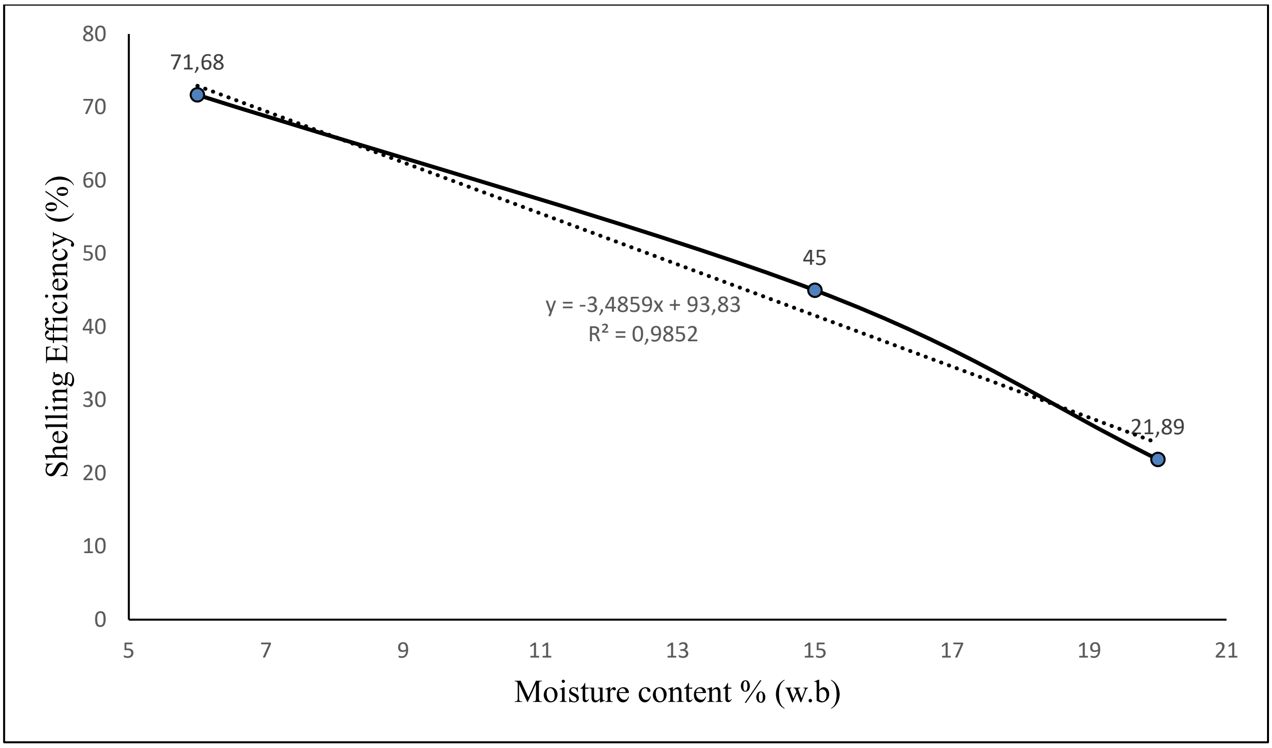

Figure 4.6 The shelling efficiency of a Bambara groundnuts sheller

4.3.2 Mechanical damage

The mechanical damage results are presented in Figure 4.7. The mechanical damage decreases from 3.66 to 1.46 % at moisture content ranges from 6 to 20 %. The expectation was that as moisture content rises, more seed will break due to soft skin at high moisture content. However, in this study, the results show that as moisture increase, the pods became more resistance to the impact force due to high contact time between spikes and nuts. As moisture increase the kernel became more sponges like, which prevent the seed from mechanical damage. A similar trend was also reported by (Atiku *et al.* 2004).

In this project mechanical damage was suppose to less than 10% according to the project specification. This specifaction was achieved as the maximun achieved mechanical damage was 3.66 %. Form this combined findings of mechancal damage and shelling efficiency, it shows that Bambara should be shelled at 6 % moisture content.

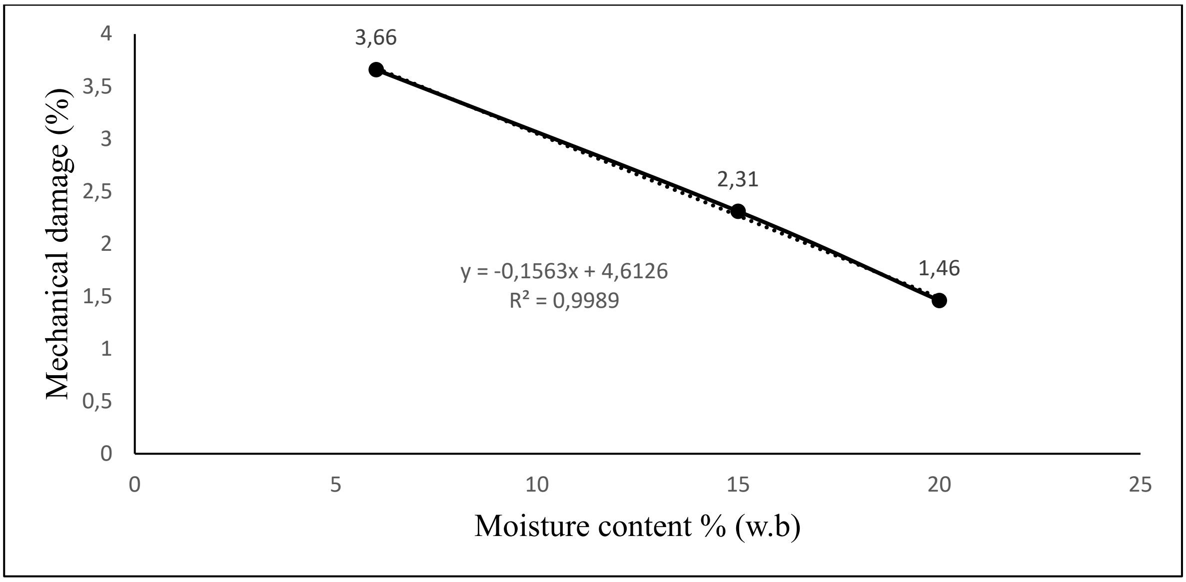

Figure 4.7 The mechanical damage at the different

4.3.3 Winnowing efficiency

The winnowing/cleaning efficiency was not evaluated due to damage of the fan blower during testing. During the initial running of the machine after assembly, the fan was working properly. However, during the testing, the fan was damaged. Due to delay encountered in this project, buying a new fan would cause a serious time-delay.

The winnowing efficiency of this prototype was expected to decrease as moisture content increases. As moisture content increases, the kernel gained more weight. Therefore, the air volume and the power required to separate the kernels from the nuts increases significate. Consequently, at high moisture content the fan would fail to blow chaff out grains. A similar finding was reported by (Atiku *et al.* 2004).

4.3.4 Machine capacity

The design machine capacity specification was at least 100kg.hr^{-1}. The machine was design for small scale farmers. During performance evaluation, the machine capacity declines from 145.6 to 80.1 kg. hr^{-1} from moisture content ranges from 6 to 20 % as seen in Figure 4.8. The decline in machine capacity was caused by friction between nuts and the hopper surface at high moisture content. In Chapter 3.4.3, the findings show that the friction increase as moisture content rises. As moisture content rose, the groundnuts experienced more friction as it rolled down the hopper. As a result, the machine had a lower machine capacity for the high moisture content scenarios. A similar trend was also reported by (Atiku *et al.* (2004).

The maximum machine capacity was 145.6 kg.hr^{-1} at 6 % moisture content. While the design specification was to shell at least 100 kg.hr^{-1}. Therefore this prototpye met the design specification. Dururing the shelling process, it is recommended that farmers shell the groundnuts at 6 % moisture.

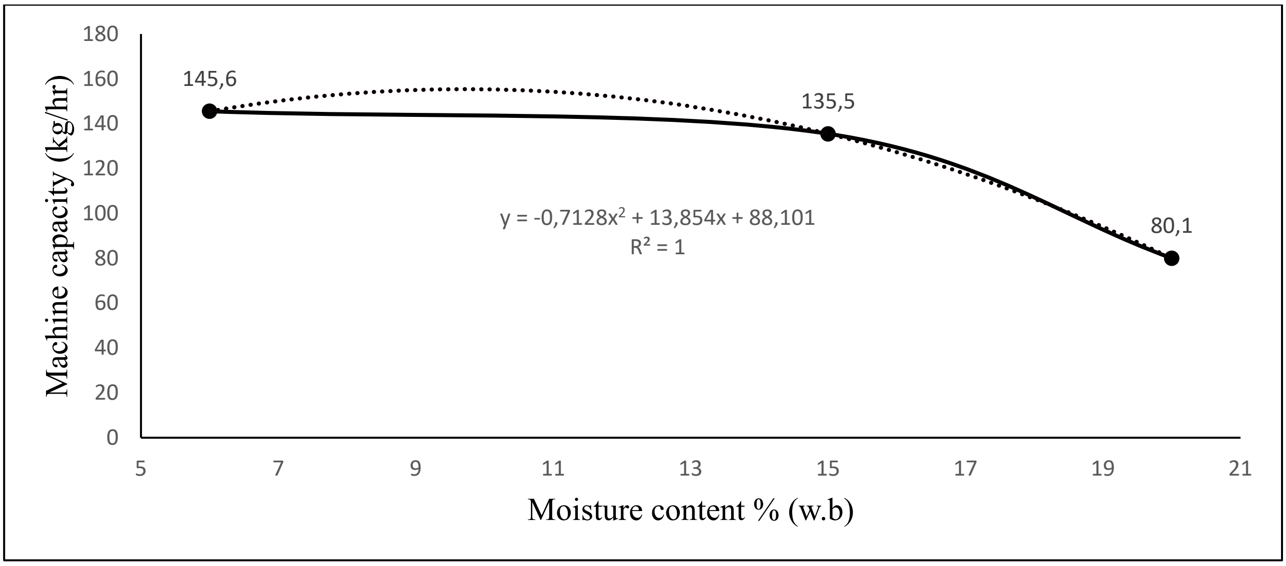

Figure 4.8 Machine capacity at different moisture content

4.4 Conclusion and Recommendations

The engineering properties of Bambara groundnuts obtained from Chapter 3 were used to design a shelling machine. The shelling machine components included a hopper, collector, transmission system, fan blower, and motor. The hopper was design to be a rectangular prism with a half cylinder welder on the bottom. The shelling mechanism includes the shelling shaft and spikes that are welded together. The prototype was constructed and tested at the Ukulinga workshop farm with the assistance of technicians and undergraduate students.

The performance evaluation was done at three different moisture content levels of 6, 15, and 20 %. The prototype was tested in for four performance types which include shelling efficiency, mechanical damage, winnowing efficiency, and machine capacity. The shelling efficiency of the prototype decreased as moisture content increased from 6 to 20 %. On the other hand, the mechanical damage and machine capacity also decrease from 3.66 to 1.45 %, and 145.6 to 80.1 $kg.hr^{-1}$, respectively. Due to fan blower damage, the winnowing efficiency was not tested. The performance of the prototype was found to be best at a 6 % moisture content. It is recommended that mechanical fan should be used instead of fan blower. A mechanical fan uses only rotational force while a fan blower requires electrical energy. The mechanical fan and shelling shaft can be employed since both uses the same rotational force from the motor.

4.5 References

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5. CONCLUSION AND RECOMMENDATIONS

The conclusion and recommendations based on this study are outlined in this section

5.1 Conclusion

Bambara groundnuts yield production shows a decline both in Africa and the world since 2012. The available literature mostly focuses on the agronomy of Bambara groundnuts. Also, the literature reported that there is limited information on post-harvesting technology for processing Bambara groundnuts. Planting, weeding, and harvesting tasks are manual. In post-harvesting, Bambara groundnuts are manual shelled, which was reported to be time-consuming and tedious. The problems can be improved by developing efficient ways of shelling. In literature, the available physical properties are for only shelled nuts. Whereas during designing processing equipment, physical properties of the whole Bambara groundnuts (pods) are required for sizing the equipment. Therefore, determining the physical properties of Bambara groundnuts was needed to design a shelling machine.

The physical properties of Bambara were determined at three different moisture content levels. The axial dimensions, volume, and surface are increasing as moisture increases. The static coefficient of friction was tested in galvanised steel sheeting material. The findings show that the groundnuts experience more friction at higher moisture content. The static coefficient of friction of shelled and unshelled nuts shows an increasing trend from 0.15 to 0.19 and 0.29 to 0.31. The sphericity for both shelled and unshelled nuts decrease as moisture content increases. The porosity of shelled and unshelled nuts decrease from 49 to 47 and 35 to 32 %, respectively, as moisture content increases. The maximum cracking force for both shelled, and unshelled Bambara groundnuts occurred at 6 % moisture contents. As a result, the Bambara groundnuts at lower moisture content requires more power during the shelling. This study's findings can be applied during the design of processing equipment include shelling and milling machine for Bambara groundnuts.

The physical properties were used to design a shelling machine. The machine components include hopper, shelling spikes, collector, motor, fan blower, and transmission system. The machine was designed using local material. The hopper was designed to be a triangular prism that was welded on half a drum of 100 mm diameter. The shelling mechanism selected was a shelling shaft and spikes on it. The shaft sized was 25 mm in diameter. The transmission system is two pulleys and belts. The performance evaluation was done in terms of shelling efficiency, mechanical damage, winnowing efficiency and machine capacity. During the evaluation, the samples were set at different moisture content levels. As the moisture increase of the samples from 6 to 20 %, the findings show that shelling efficiency decrease from 71.9 to 21.9 %. The mechanical damage also decreases as moisture rose. The winnowing efficiency was not evaluated due to the damaged of the available fan blower. As moisture content increases, the machine capacity declines from 145.6 to 80 $kg.hr^{-1}$. The machine performed well at 6 % moisture content.

5.2 Recommendations

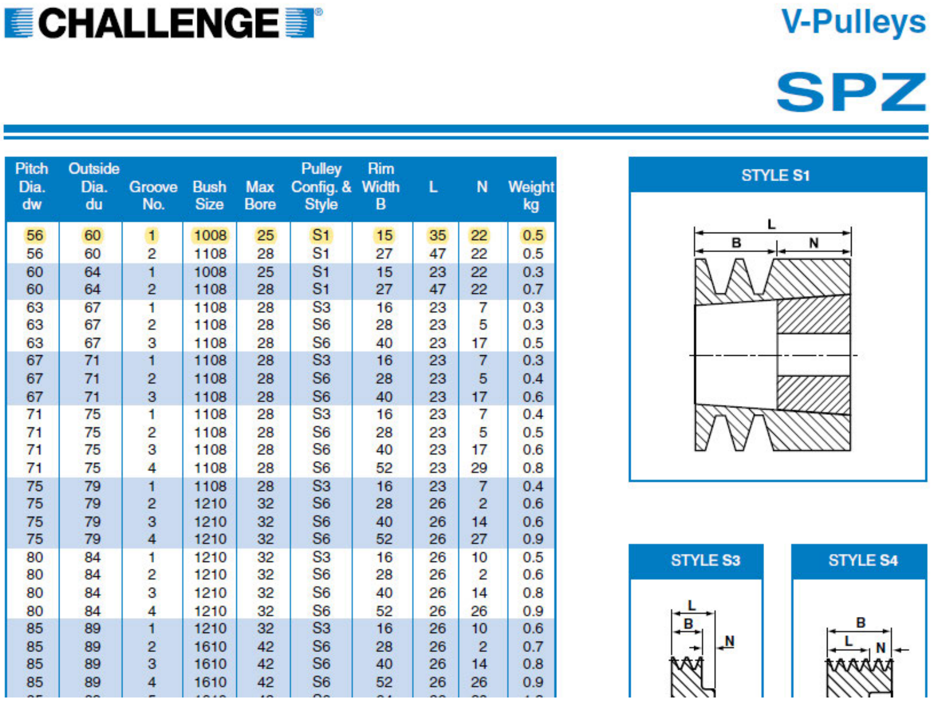
From this study, the recommendations are based on the determination of physical properties of Bambara groundnuts and the design of shelling machine. The following recommendations were made:

a) The physical properties were determined primarily for a sheller design in this study. For further improving this study, the physical of Bambara groundnuts must be determine from varies ranges of moisture content levels e.g. from 5 to 43 %. This will help designers to design different processing equipment such as planters, driers, harvesters, and wet storage facilities for the Bambara groundnuts.

b) The sheller requires modification especial on shelling mechanism. The machine can be design to have double shelling mechanism include shelling spikes and roller for better performance. The groundnuts will first pass the shelling shaft and then, the unshelled groundnuts will pass through the roller mechanism for further shelling process. However, these two mechanisms should use same transmission system to avoid high power consumption. The fan blower should be changed to mechanical fan instead of a blower to avoid sensibility and short life span of the blower. Mechanical fan should be constructed from shaft and steel sheeting.

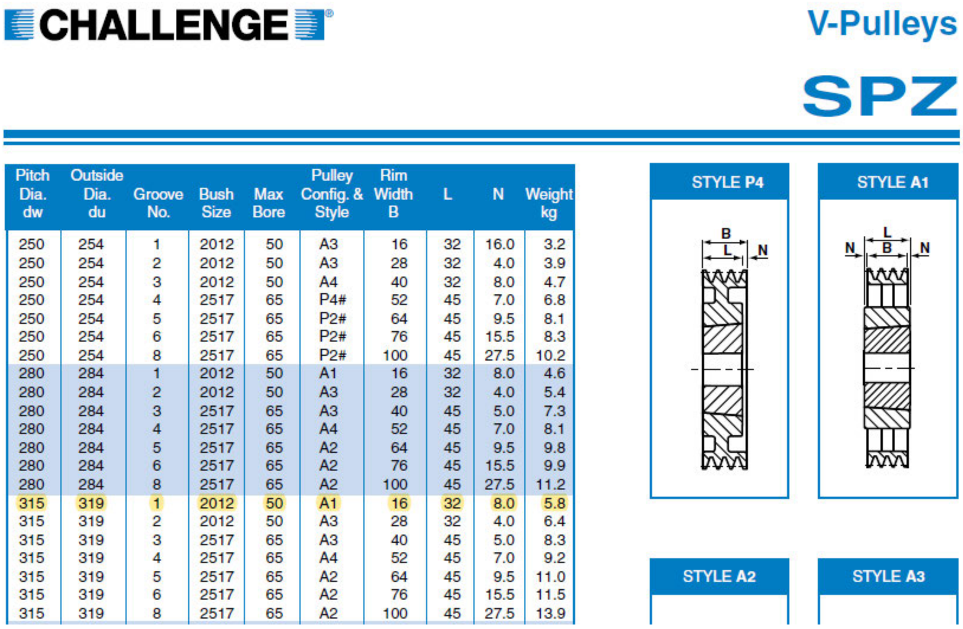
6. APPENDIX

The following figures are supplementary information



Pitch Dia. dw	Outside Dia. du	Groove No.	Bush Size	Max Bore	Pulley Config. & Style	Rim Width B	L	N	Weight kg
56	60	1	1008	25	S1	15	35	22	0.5
56	60	2	1108	28	S1	27	47	22	0.5
60	64	1	1008	25	S1	15	23	22	0.3
60	64	2	1108	28	S1	27	47	22	0.7
63	67	1	1108	28	S3	16	23	7	0.3
63	67	2	1108	28	S6	28	23	5	0.3
63	67	3	1108	28	S6	40	23	17	0.5
67	71	1	1108	28	S3	16	23	7	0.3
67	71	2	1108	28	S6	28	23	5	0.4
67	71	3	1108	28	S6	40	23	17	0.6
71	75	1	1108	28	S3	16	23	7	0.4
71	75	2	1108	28	S6	28	23	5	0.5
71	75	3	1108	28	S6	40	23	17	0.6
71	75	4	1108	28	S6	52	23	29	0.8
75	79	1	1108	28	S3	16	23	7	0.4
75	79	2	1210	32	S6	28	26	2	0.6
75	79	3	1210	32	S6	40	26	14	0.6
75	79	4	1210	32	S6	52	26	27	0.9
80	84	1	1210	32	S3	16	26	10	0.5
80	84	2	1210	32	S6	28	26	2	0.6
80	84	3	1210	32	S6	40	26	14	0.8
80	84	4	1210	32	S6	52	26	26	0.9
85	89	1	1210	32	S3	16	26	10	0.6
85	89	2	1610	42	S6	28	26	2	0.7
85	89	3	1610	42	S6	40	26	14	0.8
85	89	4	1610	42	S6	52	26	26	0.9

Figure 6.1 A figure show fully specification of the selected-highlighted driving pulley (Catalogue, 2012)



Pitch Dia. dw	Outside Dia. du	Groove No.	Bush Size	Max Bore	Pulley Config. & Style	Rim Width B	L	N	Weight kg
250	254	1	2012	50	A3	16	32	16.0	3.2
250	254	2	2012	50	A3	28	32	4.0	3.9
250	254	3	2012	50	A4	40	32	8.0	4.7
250	254	4	2517	65	P4#	52	45	7.0	6.8
250	254	5	2517	65	P2#	64	45	9.5	8.1
250	254	6	2517	65	P2#	76	45	15.5	8.3
250	254	8	2517	65	P2#	100	45	27.5	10.2
280	284	1	2012	50	A1	16	32	8.0	4.6
280	284	2	2012	50	A3	28	32	4.0	5.4
280	284	3	2517	65	A3	40	45	5.0	7.3
280	284	4	2517	65	A4	52	45	7.0	8.1
280	284	5	2517	65	A2	64	45	9.5	9.8
280	284	6	2517	65	A2	76	45	15.5	9.9
280	284	8	2517	65	A2	100	45	27.5	11.2
315	319	1	2012	50	A1	16	32	8.0	5.8
315	319	2	2012	50	A3	28	32	4.0	6.4
315	319	3	2517	65	A3	40	45	5.0	8.3
315	319	4	2517	65	A4	52	45	7.0	9.2
315	319	5	2517	65	A2	64	45	9.5	11.0
315	319	6	2517	65	A2	76	45	15.5	11.5
315	319	8	2517	65	A2	100	45	27.5	13.9

Figure 6.2 The specifications of highlighted driven pulley (Catalogue, 2012)

Z 10 x 6					
Imperial Li	Metric Lp	Metric Li	Imperial Li	Metric Lp	Metric Li
Z15	10 x 410	385	Z46.5	10 x 1210	1185
Z15.5	10 x 420	395	Z47	10 x 1220	1195
Z15.7	10 x 425	400	Z48	10 x 1240	1215
Z16.5	10 x 445	420	Z49	10 x 1270	1245
Z16.7	10 x 450	425	Z50	10 x 1290	1265
Z17.5	10 x 470	445	Z51	10 x 1320	1295
Z17.7	10 x 475	450	Z52	10 x 1340	1315
Z18	10 x 480	455	Z53	10 x 1370	1345
Z18.5	10 x 495	470	Z54	10 x 1390	1365
Z19	10 x 510	485	Z55	10 x 1420	1395
Z19.5	10 x 520	495	Z56	10 x 1450	1425
Z20	10 x 530	505	Z57	10 x 1470	1445
Z20.5	10 x 545	520	Z58	10 x 1500	1475
Z21	10 x 560	535	Z59	10 x 1520	1495
Z21.7	10 x 575	550	Z60	10 x 1550	1525
Z22	10 x 580	555	Z62	10 x 1600	1575
Z22.2	10 x 585	560	Z63	10 x 1620	1595
Z23	10 x 610	585	Z64	10 x 1650	1625
Z23.5	10 x 620	595	Z68	10 x 1750	1725
Z24	10 x 630	605	Z75	10 x 1920	1895
Z24.7	10 x 655	630	Z78	10 x 2000	1975
Z25	10 x 660	635			
Z25.7	10 x 675	655			
Z26	10 x 680	660			
Z26.5	10 x 700	675			
Z27	10 x 710	685			
Z28	10 x 730	705			
Z29	10 x 760	735			
Z29.5	10 x 770	745			
Z30	10 x 780	755			
Z30.7	10 x 805	780			
Z31	10 x 810	785			
Z31.5	10 x 820	795			
Z32	10 x 840	815			
Z33	10 x 860	835			
Z33.7	10 x 880	855			

A 13 x 8					
Imperial Li	Metric Lp	Metric Li	Imperial Li	Metric Lp	Metric Li
A18	13 x 490	460	A74	13 x 1920	1890
A19	13 x 520	490	A75	13 x 1940	1910
A20	13 x 540	510	A76	13 x 1960	1930
A21	13 x 570	540	A77	13 x 1990	1960
A22	13 x 590	560	A78	13 x 2020	1990
A23	13 x 620	590	A79	13 x 2050	2020
A24	13 x 650	620	A80	13 x 2070	2040
A25	13 x 670	640	A81	13 x 2090	2060
A26	13 x 700	670	A82	13 x 2120	2090
A27	13 x 720	690	A83	13 x 2140	2110
A28	13 x 750	720	A84	13 x 2170	2140
A29	13 x 770	740	A85	13 x 2190	2160
A30	13 x 800	770	A86	13 x 2220	2190
A31	13 x 820	790	A87	13 x 2240	2210
A32	13 x 850	820	A88	13 x 2270	2240
A33	13 x 870	840	A89	13 x 2300	2270
A34	13 x 900	870	A90	13 x 2320	2290
A35	13 x 920	890	A91	13 x 2350	2320
A36	13 x 950	920	A92	13 x 2370	2340
A37	13 x 980	950	A93	13 x 2400	2370
A38	13 x 1000	970	A94	13 x 2420	2390
A39	13 x 1030	1000	A95	13 x 2450	2420
A40	13 x 1050	1020	A96	13 x 2470	2440
A41	13 x 1080	1050	A97	13 x 2500	2470
A42	13 x 1100	1070	A98	13 x 2530	2500
A43	13 x 1130	1100	A99	13 x 2550	2520
A44	13 x 1150	1120	A100	13 x 2580	2550
A45	13 x 1180	1150	A102	13 x 2630	2600
A46	13 x 1200	1170	A103	13 x 2650	2620
A47	13 x 1230	1200	A104	13 x 2680	2650
A48	13 x 1250	1220	A105	13 x 2700	2670
A49	13 x 1280	1250	A106	13 x 2730	2700
A50	13 x 1310	1280	A107	13 x 2750	2720
A51	13 x 1330	1300	A108	13 x 2780	2750
A52	13 x 1360	1330	A109	13 x 2800	2770
A53	13 x 1380	1350	A110	13 x 2830	2800

Figure 6.3 A classical V-belt of 1380 mm length was selected (Catalogue, 2012)

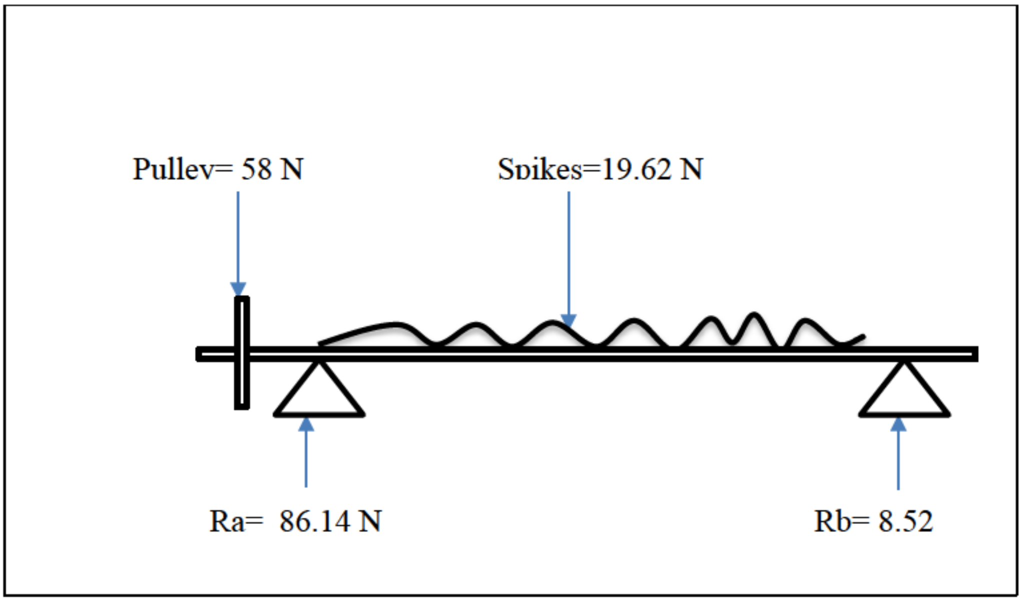


Figure 6.4. A force diagram of a shelling shaft

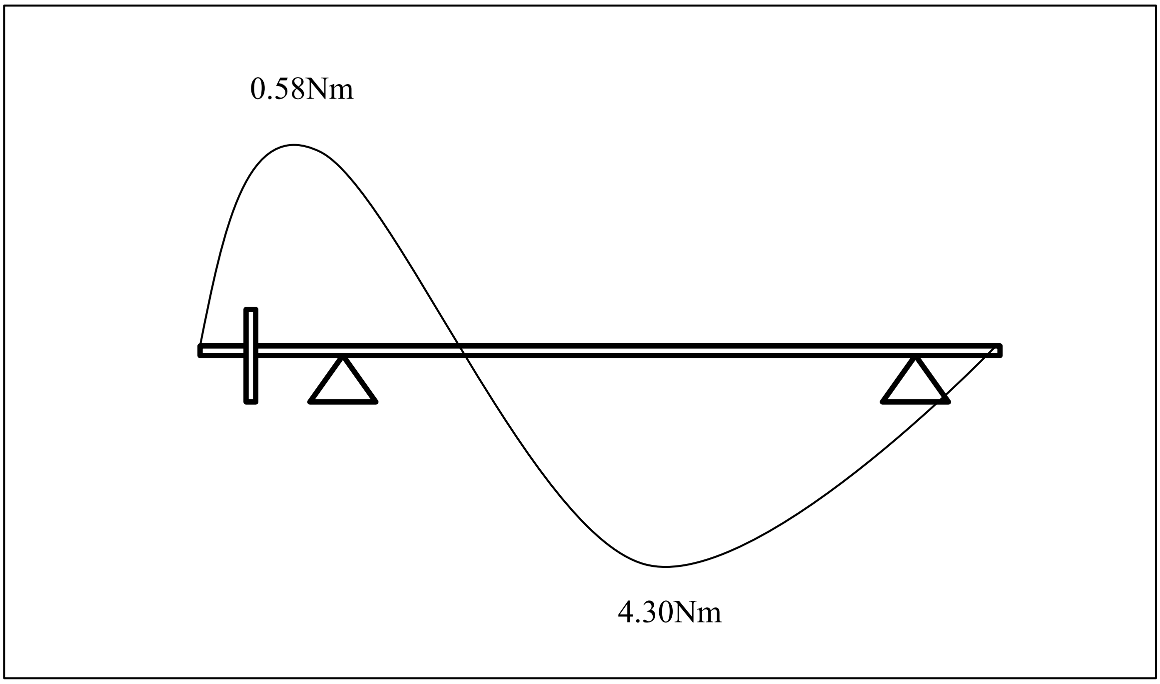


Figure 6.5 The shelling shaft's bending moment diagram

Figure 6.6 The samples used during evaluation

Figure 6.7 Full assembly prototype of Bambara groundnuts Sheller