MODIFICATION AND EVALUATION OF A GROUNDNUT CRACKER FOR CRACKING *JATROPHA CURCAS* SEEDS

by

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DECLARATION

I hereby declare that this submission is my own work towards the Master of Science in Agricultural Machinery Engineering and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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ABSTRACT

Jatropha curcas L. is a multipurpose drought-resistant plant with numerous attributes and considerable potentials. The most valuable aspect of the plant is the oil content of its seed kernel. In the extraction of the oil, the seeds are either cracked to obtain the kernels or used without cracking. Using uncracked nuts produce oil at low recovery and quality, whiles cracking manually involves so much labour and time. The objective of the study was to modify an existing motorised Groundnut Cracker with a winnower for cracking *Jatropha curcas* seeds and to evaluate its performance. The physical dimensions of seeds and kernels were determined for the design of the sieve of the cracker. The cracker was evaluated using 3 kg seed samples at cracking drum speeds of 140, 150, 160, 170 and 180 rpm and feed gate openings of 32, 48 and 64 mm. Chemical extraction of *Jatropha curcas* oil for kernel samples with 0 %, 20 %, 40 %, and 100 % husk contents was done. A sieve with hole diameter 10 mm was selected and designed for the cracker. At 140 rpm and 48 mm feed gate opening, the cracker had a capacity of 1037.90 kg/h, blower loss of 2.76 %, cleanliness of 88.65 %, uncracked seeds of 3.32 %, kernel recovery of 48.57 %, cracking efficiency of 96.68 % and machine efficiency of 90.84 %. Chemical oil extraction gave the lowest oil yield from the sample with 100 % husk at 66.7 % of oil extraction and highest oil yield from the sample with 0 % husk content at 93.5 % of oil extraction, an increase of 40.1 % in oil yield due to seed cracking.

Keywords: Jatropha curcas seeds, cracker-winnower, speed, feed gate opening, oil.

DEDICATION

This thesis is affectionately dedicated to my loving parents Mr. and Mrs. Amoah and siblings Cynthia, Lydia, Veronica and Tony, for their supports and encouragements throughout my study.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1. Background

Jatropha curcas L. commonly called physic nut or purging nut is a draught-resistant plant belonging to the tribe *Joannesieae* in the family *Euphorbiaceae*. It is grown in many countries in the tropical and sub-tropical regions of the globe including Ghana. It grows very well even on marginal lands, which are areas with unsuitable conditions for crop production due to soil and climate constraints (Jongschaap *et al*., 2007). The plant can be successfully cultivated both under irrigated and rainfed conditions. It is a multi-purpose plant with all the parts being useful for a wide range of products as described by Gubitz *et al*. (1999), Openshaw (2000), Sirisomboon *et al*. (2007), Kumar and Sharma (2008) and many others.

The plant itself can be used as living fence (especially to exclude farm animals), ornamental plant, erosion control or firewood (Sirisomboon *et al*., 2007). Various parts of the plant are of medicinal value, its bark contains tannin, the flowers attract bees and thus the plant has a honey production potential (Kumar and Sharma, 2008). Its wood and fruit can be used for numerous purposes including fuel (Openshaw, 2000; Kumar and Sharma, 2008). It also provides a meal that serves as a highly nutritious and economic protein supplement in animal feed, if the toxins are removed or non-toxic varieties are used (Gubitz *et al*., 1999; Kumar and Sharma, 2008). The seed or press cake after oil extraction has potential as a fertilizer or biogas production if available in large quantities (Kumar and Sharma, 2008). Notable among these benefits from *J. curcas* is the oil content of the seed kernels which after extraction can be used for fuel (especially biodiesel), soap, insecticide and medicinal purposes (Gubitz *et al*., 1999; Sirisomboon *et al*., 2007). These benefits from the plant when explored can be of great advantage for human and industrial use.

Dry *J. curcas* fruit contains about 37.5 % shell and 62.5 % seed and the seed contains about 42 % hull/husk and 58 % kernel (Singh *et al*., 2008). The seed kernel contains about 40-60 % (w/w) of oil (Openshaw, 2000; Kumar and Sharma, 2008). Extraction of oil from the seeds can be done by mechanical means with a press (ram, hydraulic or screw), using solvents like chemicals/water or enzymatically (Gubitz *et al*., 1999; Forson *et al*., 2004; Shah *et al*., 2004; Pradhan *et al*., 2011). In order to acquire the seed kernels for the oil extraction, the fruits after they have been dried, need to be cracked to obtain the seeds after which the husk or hull can be removed from the seed for the seed kernel which contains the oil. This seed husk is sometimes removed manually using simple tools like pliers, stones and sticks (Sirisomboon *et al*., 2007; Henning, 2009) or not removed at all (Achten *et al*., 2008). When done manually, it is time-consuming, labour-intensive and involves a lot of drudgery (Bobobee, 2002). Again, when the seed husk is not removed, it implies the loss of energy in the form of retained oil in seed cake and the loss of seed husk, which is a source of fuel (Jongschaap *et al*., 2007).

1.2. Justification

Currently, there is no known mechanical means of cracking or dehulling *Jatropha curcas* seeds to obtain the seed kernels in Ghana. In order to acquire a mechanical method of cracking the seeds that will be faster and involve less labour, an already existing Groundnut Cracker designed by Bobobee (Bobobee, 2002) of the Department of Agricultural Engineering, KNUST, was modified. The modification was necessary because of the differences between the properties (mechanical and physical) of groundnut and *J. curcas*. In designing processing equipment (for agriculture), the properties of the material to be handled need to be considered. The physical and mechanical properties of *J. curcas* are important to design equipment for dehulling, nut shelling or cracking, drying and oil extraction, and also in other processes like, transportation and storage (Sirisomboon *et al.*, 2007). There was therefore the need for the modification of the existing groundnut cracker for effective cracking of the *J. curcas* seeds.

A mechanical means of cracking *J. curcas* seeds for the biofuel production sector was necessary to enhance mass production of the oil at a faster and easier rate with a higher recovery percentage. According to Shukla (2006), in the mechanical expelling of oil from whole (uncracked) seeds, the deoiled cake retains 9-10 % oil and if the seed coat is removed even by 50 %, oil recovery even with mechanical expellers will increase by 4-5 %. Hence, appropriate dehullers or crackers need to be developed.

Cracking will also make available the husk, which will be a very good source of energy for both domestic and industrial use. The seed husk as reported by Singh *et al*. (2008) and Vyas and Singh (2007) can be used in a gasifier or in briquetted form since it has thermal properties (ash, volatile matter, fixed carbon and calorific value) comparable to that of wood. Currently, growers are unable to achieve the optimum economic benefits from the plant, especially for its various uses (Kumar and Sharma, 2008) and the husk is one of them. Moreover, the energy value of the remaining portion of *J. curcas* fruit which includes the husk is twice that of the biofuel (Singh *et al*., 2008). Overall, the kernel has about 35 % less energy and the oil about 70 % less energy than the whole fruit, because of processing losses (Openshaw, 2000).

In recent times, the planting and use of *J. curcas* as biofuel is being promoted by governments, international organizations and NGOs (Brittaine, 2010). In 2008, *J. curcas* was planted on an estimated 900,000 ha globally – 760,000 ha (85 percent) in Asia, followed by Africa with 120,000 ha and Latin America with 20,000 ha. By 2015, forecasts suggest that *J. curcas* will be planted on 12.8 million ha (Brittaine, 2010). In Africa, Ghana and Madagascar will be the largest producers (Brittaine, 2010). In order that the full potential of the plant is realised, it is necessary that efficient means of operation are employed to reduce the level of losses in the use of *J. curcas*. This will also ensure efficient use of the scarce land put under *J. curcas* cultivation, thereby preventing adoption of cultivated farmlands for its production. Hence, there is the need to develop a mechanical cracker to dehull or crack *J. curcas* seeds for optimum extraction and utilisation of the energy content of the seed.

1.3. Objectives

The main objective of this study was to modify an existing groundnut cracker to crack *Jatropha curcas* seeds and to evaluate it.

The specific objectives were:

- To determine the physical properties (physical dimensions, arithmetic mean diameter, geometric mean diameter, sphericity, surface area, aspect ratio, 1000-unit mass, coefficient of static friction and angle of repose) of *Jatropha curcas* seeds and kernels necessary for the design of the cracker.
- To develop an appropriate sieve for cracking the *Jatropha curcas* seeds.
- To test and evaluate the performance of the *Jatropha curcas* seed cracker at different operational speeds and feed gate openings.
- To determine the oil recovery for cracked seeds, uncracked seeds and their mixtures at different percentages of seed husks.

CHAPTER TWO

LITERATURE REVIEW

2.1. The *Jatropha curcas* Plant

The botanical family of *Jatropha curcas* is composed of about 175 different species of plants (Henning, 2009). *J. curcas* L., also known as Physic, Barbados or Purging nut is a drought-resistant shrub or tree, widely distributed in the wild or semi-cultivated areas in Central and South America, Africa, India and South East Asia (Kumar and Sharma, 2008).

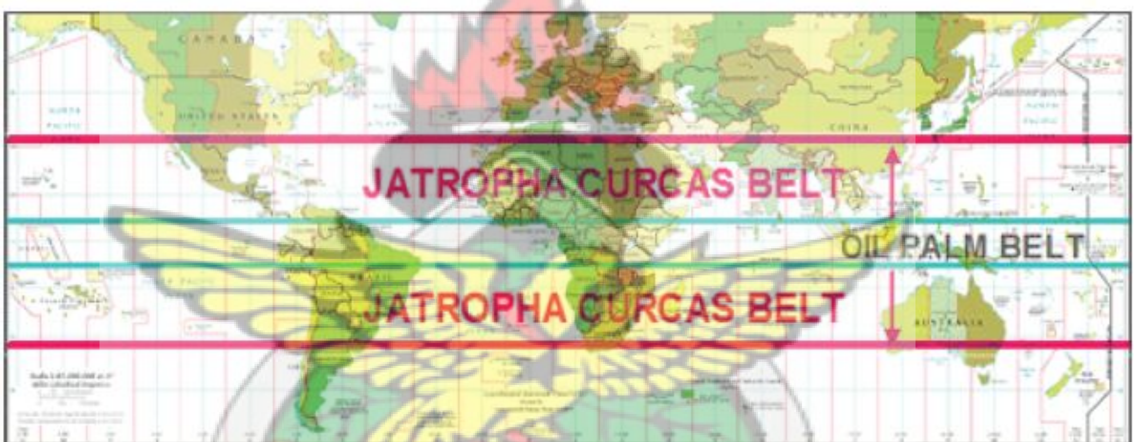

Figure 1: The most suitable climate conditions for the growth of *Jatropha curcas* L. lie within latitudes 30° N and 35° S and Oil palm lie within latitudes 4° N and 8° S (Source: Jongschaap *et al.*, 2007)

Figure 1 indicates the areas of the globe where *J. curcas* L. and oil palm (*Elaeis guineesis*) can survive. It can be seen that *J. curcas* L. grows within a very wide area (30° N, 35° S) compared to oil palm which grows within a smaller area of the globe (4°

N, 8° S). This gives *Jatropha curcas* the advantage of it being globally used for commercial or industrial purposes.

Jatropha curcas grows well in gravely, sandy, well drained soils. It does not survive in standing water hence heavy clay soils are less suitable and should be avoided. It is known for its ability to survive in very poor dry soils under conditions considered marginal for agriculture and can even root into rock crevices. However, survival ability does not mean that high productivity can be obtained from *J. curcas* under marginal agricultural environments. In some reports, it is said that *J. curcas* can grow in saline soils, but it is not known, to which extent irrigation by salty water can support it and the yield to be expected (Henning, 2009; Brittaine, 2010).

Jatropha curcas can be propagated reproductively through direct seeding or transplanting or vegetatively by the stem cutting (Heller, 1996; Jongschaap *et al*., 2007). *J. curcas* is easy to establish, grows relatively quickly and is hardy, being drought tolerant. It can grow up to a height of about 5 m but can attain a height of 8 or 10 m under favourable conditions (Divakara *et al*., 2010). It has a life expectancy of more than 50 years. It has few pests and diseases and will grow under a wide range of rainfall regimes from 200 to over 1500 mm per annum. During prolonged rainless periods, the plant sheds its leaves as a counter to drought (Openshaw, 2000).

Figure 2: *Jatropha curcas* plant (left) and branch with fresh and dried fruits (right)

2.2. Applications of *Jatropha curcas* L.

Jatropha curcas L. has several domestic and industrial applications. It is a plant with many attributes, multiple uses and considerable potential. It is therefore referred to as the "wonder plant" (Sayyar *et al.*, 2009; Jain and Sharma, 2010). These multiple applications of *J. curcas* have been reported by several researchers, notable among them are Gubitz *et al.* (1999), Openshaw (2000), Henning (2000 and 2003) Jongschaap *et al.* (2007) and Singh *et al.* (2008).

Jatropha curcas plant is not browsed by animals and has a long life which properties also make it a perfect plant for use as hedge or living fence and to demarcate boundaries. (Henning, 2000). Because of its drought tolerance and its lateral roots near the surface, *J. curcas* plant is often used for anti-erosion measures, either in the form of plantation together with other species, or in the form of hedges to reduce wind speed and protect small earth dams or stone walls against runoff (Henning, 2003). Together with Vetiver or Lemon grass, the *J. curcas* hedges can build up a filtering system that reduces the erosion of surface soil by run-off. After only a short time, terraces are formed (Henning, 2003). *J. curcas* also helps in the reclamation of marginal soils by exploring the soil with an adequate root system. It was demonstrated that soil structure increased significantly after *Jatropha curcas* was grown for 18 months under semi-arid conditions in India; macro-aggregate stability increased by 6-30 %, whereas soil bulk density was reduced by 20 % (Chaudharry *et al*., 2007 and Ogunwole *et al*., 2007).

Jatropha curcas is a woody plant, therefore, its twigs, branches and stems can be used for a number of purposes especially as fuel, sticks and poles (Openshaw, 2000; Jongschaap *et al*., 2007). Unfortunately, the twigs remain green for a long time and are difficult to dry out and burn. If used as poles, they have a tendency to sprout. However, in some countries, the live pole is used to support vines such as the vanillin plant. It flowers profusely in response to rainfall or irrigation and can flower up to three times a year. Bees pollinate these flowers; thus it is possible to have apiaries in association with *J. curcas* areas (Openshaw, 2000; Kumar and Sharma, 2008). Latex and oil from the plant have molluscicidal, medicinal and pesticidal properties (Gubitz *et al*., 1999). Tannin can be extracted from the bark and nutshell and used to treat leather. A varnish can be made from the oil and the leaves are a feedstock for silk worms (Openshaw, 2000). Table 1 summarises the medicinal uses of the various parts of the *Jatropha curcas* plant.

Table 1: Uses of the different parts of *Jatropha curcas* L. in medicines

Plant part used	**Disease**	**Source**
Seed	Treat arthritis, gout and jaundice	Heller(1996)
Tender twig/stem	Toothache, gum inflammation, gum bleeding, pyorrhoea	Kaushik and Kumar(2004)
Plant sap	Dermatomucosal diseases	Kumar and Sharma(2008)
Plant extract	Allergies, burns, cuts and wounds, inflammation, leprosy, leucoderma, scabies and small pox	Heller(1996), Kaushik and Kumar(2004)
Water extract of branches	HIV, tumor	Kumar and Sharma(2008)

The *Jatropha curcas* plant starts producing fruits after about six months of planting but adequate yield is obtained after about one to three years (Pradhan *et al.*, 2011). This is actually dependent on a number of factors some of which are rainfall amount and soil fertility (Traoré, 2006; Openshaw, 2000). The fruits produced by the *J. curcas* plant have a number of applications and uses. Each dried fruit mostly consists of three black seeds enclosed in the fruit coat or hull. The seed is also made up of the kernel and the seed husk or hull. Each component of the fruit is useful for one thing or the other. The fruit coat or hull which forms about 37.5 % of the fruit can be used as fuel, feed stock in a biogas plant and green manure (Gubitz *et al.*, 1999; Singh *et al.,* 2008). The energy content of the fruit coat is about 11.1 MJ/kg, ash content of 13 % of dry weight at a moisture content of 15 % (Jongschaap *et al*., 2007).

The fraction of the seeds in the fruit is 62.5 % and they form the most important component of the *J. curcas* plant. Each seed is made up of about 58 % kernel and 42 % seed husk/hull (Gubitz *et al.*, 1999; Singh *et al.*, 2008). The seed husk can also be used as organic fertilizer as well as fuel, either in briquetted forms or in their ordinary forms for industrial or domestic purposes. The seed husk has energy content of 17.2 MJ/kg, ash content of 5 % of dry weight at a moisture content of 10 % (Openshaw, 2000; Jongschaap *et al.*, 2007). The kernel contains about 40-60 % (w/w) of oil and has great advantage and application both domestically and industrially especially for countries with developing economies (Kumar and Sharma, 2008).

The seed cake obtained after pressing out oil from the kernel can be used as feedstock for biogas plants and as organic fertilizer in agricultural fields. It contains about 6 % N, 3 % P and 1 % K as well as traces of Ca and Mg. One tonne of seed cake applied to the soil is equivalent to applying 0.15 tonne of NPK (40:20:10) mineral fertilizer (Lieth, 1975). A German Technical Cooperation (GTZ) project in Mali carried out a fertilizer trial with pearl millet and the results is presented in Table 2. However, phytotoxicity expressed as reduced germination, was reported when high rates of up to 5 t/ha were applied (Heller, 1996). Phytotoxicity to tomatoes seeded in the field was reduced by increasing the time difference between application and seeding (Moreira, 1970).

Table 2: Fertilizer trial with pearl millet in Mali

Parameter	Manure	*Jatropha curcas* press cake	Mineral fertilizer	Control
Amount applied /ha	5 tonnes	5 tonnes	100 kg of $(NH_4)_2PO_4$ and 50 kg of urea	0
Yield, kg/ ha	815	1366	1135	630

Source: Heller (1996)

If non-toxic varieties as in Mexico are used, the seed cake can also be used as feedstock. The oil can be used for the production of soap, both by traditional and improved or industrial methods as can be experienced within some communities in Mali and India (Figure 3). This is the most interesting and economically viable application of the *J. curcas* oil (Henning, 2003 and 2009).

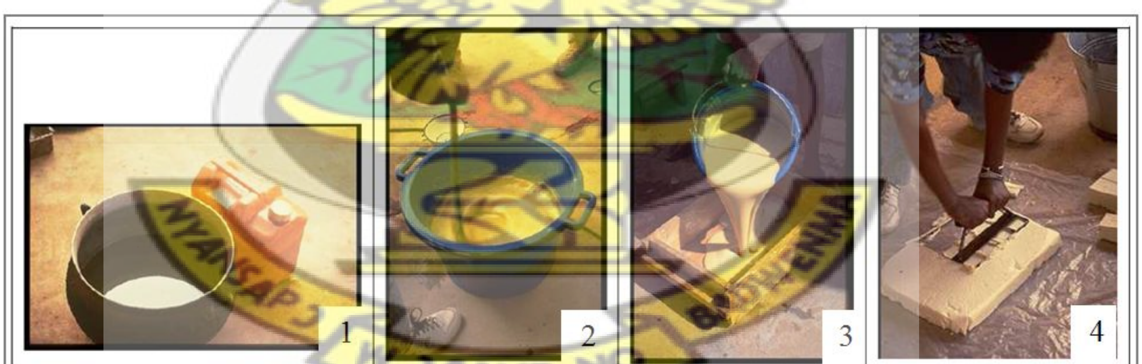

Figure 3: Procedure for local soap production in Mali: 1 – *Jatropha curcas* oil, 2 – Mixing oil, water and caustic soda, 3 – Pouring liquid soup into mould to solidify, 4 – Cutting soap pieces out (Source: Henning, 2009)

The oil can also be used as insecticides and for medicinal purposes. Another major application of the oil is its use as fuel, either as straight vegetable oil (SVO) for lighting, cooking and electricity or in the form of biofuel (Gubitz *et al.*, 1999; Jongschaap *et al.*, 2007). A summary of the applications of the different components of *Jatropha curcas* L. have been presented in Figure 4.

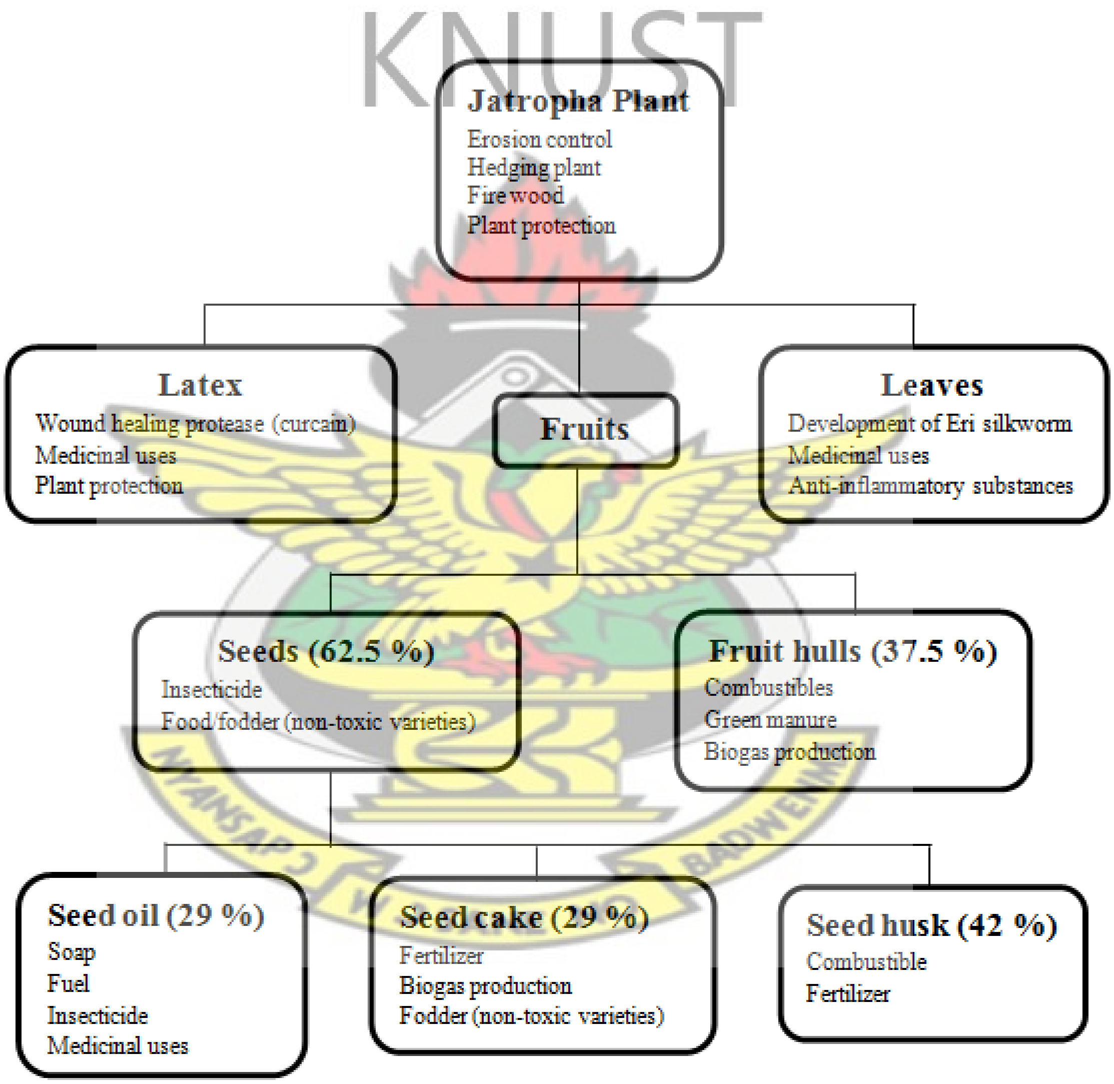

Figure 4: Application of the various components of *Jatropha curcas* L. (Sources: Gubitz *et al*., 1999; Singh *et al*., 2008)

2.3. *Jatropha curcas* oil and biodiesel

There has been renewed interest in the use of vegetable oils for the manufacture of biodiesel due to their less polluting and renewable nature compared to conventional diesel (Pradhan *et al.*, 2011). *Jatropha curcas* L. is very popular worldwide because of the oil content of its seed kernels. The seed kernel is rich in non-edible oil (40-60 % w/w) which can be used for numerous purposes as outlined in Section 2.2. There are different methods of *J. curcas* oil extraction.

2.3.1. Oil Extraction Methods

During the extraction of *Jatropha curcas* oil and its products, the *J. curcas* seeds undergo a sequence of post harvest operations, such as dehulling, expression or extraction, to remove the oil. Expression is the process of mechanically pressing liquid out of liquid-containing solids whereas extraction refers to the process of separating a liquid from a liquid-solid system (Khan and Hanaa, 1983; Brennan *et al.*, 1990; Pradhan *et al.*, 2011). The mechanical and solvent methods are two common methods of *J. curcas* oil extraction. Additional methods like the enzyme assisted three phase partitioning method and others have been reported by different researchers (Shah *et al.*, 2005).

2.3.1.1. Mechanical Oil Extraction Method

Mechanical expression of oil from the seeds by means of a screw press is considered one of the oldest and most popular methods of the oil production in the world (Pradhan *et al.*, 2011). This is because (Mrema and McNulty, 1985; Pradhan *et al.*, 2011):

i. The equipment is simple and sturdy in construction.
ii. The equipment can easily be maintained and operated by semi-skilled supervisors.
iii. It can also be adapted quickly for processing of different kinds of oilseeds.
iv. The oil expulsion process is continuous with product obtained within a few minutes of start of the processing operation.

It involves the application of pressure by mechanical means on oil bearing materials to press out the oil. The screw press, ram press and hydraulic press are commonly used to apply pressure in the expression of oil as shown in Figures 5 and 6 (Forson *et al*., 2004; Willems *et al.*, 2008; Henning, 2009).

Figure 5: Sundhara (left) and Sayari (right) screw expellers (Source: Henning, 2009)

Figure 6: Manually operated Bielenberg Ram Press produced in Madagascar (Source: Henning, 2009)

Mechanical press performance with a given oilseed depends on the preparation method of the raw material and the settings of the press (Singh *et al*., 2002; Beerens, 2007). Mechanical screw presses typically recover 86-92 % of oil from oilseeds (Singh & Bargale, 2000; Pradhan *et al*., 2011). Adjusting pressing parameters like internal pressure and temperature, press cylinder size, nozzle size and rotational speed of press shaft can improve oil recovery and decrease residual oil in the cake (Beerens, 2007; Karaj and Müller, 2011). Oil recovery can also be enhanced by suitable pre-treatment of the oilseed, such as cleaning, conditioning, decorticating, cracking, optimum hull content, flaking, cooking or preheating, extruding, and drying to optimal moisture content (Zheng *et al*., 2003; Pradhan *et al*., 2011).

Cracking or dehulling *Jatropha curcas* seeds for mechanical pressing increases oil recovery as can be seen in Figure 7 and reduces the wear rate of the press due to high level of friction caused by the seed husk. However, a certain percentage of husk or hull is required in the kernels to provide the needed consistency and friction for the press cake to flow through the press (Shukla, 2006; Wim *et al.*, 2007).

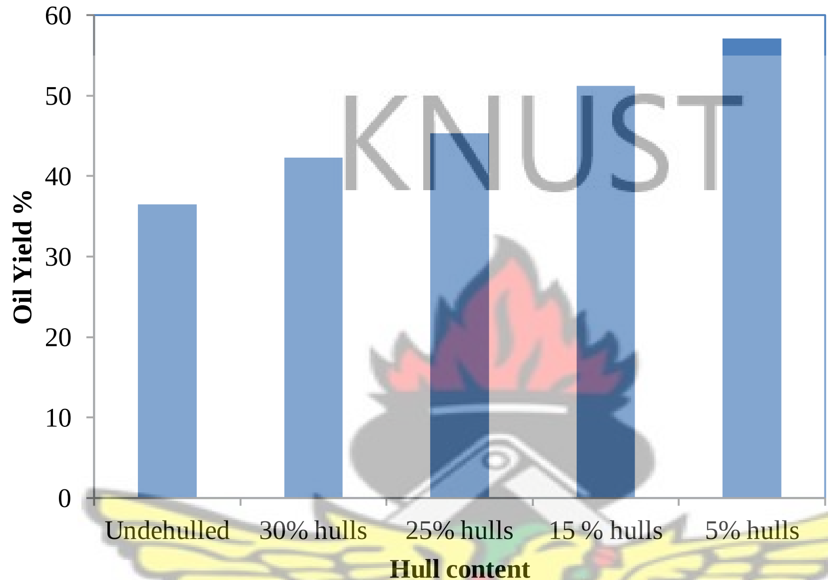

Figure 7: Graph of oil extracted from samples with different fractions of hull or husk (Source: Wim *et al.*, 2007)

Although some oilseeds are cold-pressed, that is, there is no thermal treatment before or during pressing, cooking before pressing generally improves oil yield. The heating or cooking of oilseeds increases oil yield as a result of the breakdown of oil cells, coagulation of protein, adjustment of moisture content to the optimal value for pressing, and decreased oil viscosity, which allows the oil to flow more readily (Ward, 1976; Wim *et al.*, 2007). According to Pradhan *et al.* (2011), oil recovery from *J. curcas* seeds was highest at an optimum moisture content of 9.69 % dry basis after cooking the sample for

10 min at a temperature of 110°C. It was realized that, the amount of oil that could be recovered was generally low at higher moisture contents. Singh *et al.* (2002) also reported that oil recovery increased whiles residual oil content decreased as moisture content of crambe (*Crambe abyssinica*) seeds decreased. This make moisture content a very critical parameter in the extraction or expression of oil from oil bearing seeds.

2.3.1.2. Solvent Oil Extraction Method

Solid liquid extraction, sometimes called leaching, involves the transfer of a soluble fraction (the solute or leachant) from a solid material to a liquid solvent. The solute diffuses from the solid into the surrounding solvent (Sayyar *et al.*, 2009). This method of extraction is considered as the most efficient among all the known methods even though it requires a very long period for its completion. Depending on the solvent used and other factors, it has the ability to extract up to 99 % of the oil content of oilseeds, hence it is usually used as the standard (that is, 100 % oil recovery) with which the other methods are compared (Shah *et al.*, 2004; Shah *et al.*, 2005; Beerens, 2007; Wim *et al.*, 2007). Some of the solvents identified and commonly used in this extraction process are hexane and petroleum ether. Other solvents like heptane and pentane can be used for extraction of oil in other seeds like castor (Adriaans, 2006).

Parameters such as solvent type, temperature range, solvent to solid ratio, processing time and particle size have been identified to influence the oil yield in solvent extraction. (Winkler *et al.*, 1997; Shah *et al.*, 2004, 2005; Hawash *et al.*, 2008; Sayyar *et al.*, 2009;

Karaj and Müller, 2011). Sayyar *et al.* (2009) reported that for the solvent type, hexane gave better oil recovery compared to petroleum ether under the same conditions. Again, for both solvents (hexane and petroleum ether), oil recovered increased with increasing temperature up to around boiling point after which the oil yield reduced because most of the solvent vaporised. Increasing solvent to solid ratio up to a specific limit will increase the yield because of greater concentration gradient between the solid and liquid phase which favours good mass transfer. A solvent to solid ratio of 6:1 gave the best yield in oil recovery for both hexane and petroleum ether in the investigation done by Sayyar *et al.* (2009). Considering the processing time, it was reported that most of the oil was extracted after six (6) hours even though the maximum yield was after a period of eight (8) hours for both solvents (Sayyar *et al.*, 2009). For particle size, larger particles (more than 0.75 mm) gave the lower oil yields compared to the smaller particles since the former has smaller contact surface area and are more resistant to solvent entrance and oil diffusion. However, very fine particles (below 0.5 mm) gave lower oil yields compared to particles between 0.5 and 0.75 mm and this could be due to the clustering together of the finer particles resulting in a reduction in the effective surface area (Sayyar *et al.*, 2009).

2.3.1.3. Other Methods

One other method of extraction of *Jatropha curcas* oil which is usually applied traditionally or locally especially in a country like Madagascar is the use of water (Henning, 2009). In this method (Figure 8), the *J. curcas* seeds are dehulled to obtain the kernels which are roasted and pounded. The resulting paste is then mixed with water and boiled over fire for about 20 minutes. After this period, the oil which floats over the water is then skimmed off into another container. Surplus water can subsequently be removed by heating the oil over fire. The oil is then filtered to remove solid particles. This method is however labour intensive and time-consuming as it takes about 12 h to produce a litre of the *J. curcas* oil (Henning, 2009).

Figure 8: Traditional method of *Jatropha curcas* oil extraction in Madagascar: 1 – Roasting of *Jatropha curcas* kernels, 2 – Pounding of roasted kernels into paste, 3 – Boiling of *Jatropha curcas* slurry, 4 – Skimming of floating *Jatropha curcas* oil (Source: Henning, 2009).

2.3.2. *Jatropha curcas* Biodiesel

After extraction, the *Jatropha curcas* oil can be used for several purposes as outlined in Section 2.2 above. One of the major applications of the oil is for the production of biodiesel. Currently due to gradual depletion of world petroleum reserves and the impact of environmental pollution by increasing exhaust emissions, there is an urgent need to develop alternative energy resources, such as biodiesel fuel. Biofuel is a non-polluting, locally available, accessible, sustainable, and reliable fuel obtained from renewable sources (Jain and Sharma, 2010). Malaysia, USA and Europe obtain their biodiesel from palm oil, soybean and rapeseed/sunflower, respectively, which are edible whiles India produces its biodiesel from non-edible seeds like *Jatropha curcas* and Karanjia (Tuli, 2006). The kind of oil used is based on a number of factors including its availability, technological knowledge, cost and ease of production (Tuli, 2006). There are four methods commonly used to modify straight vegetable oil (SVO) into biodiesel. These are (Ma and Hanna, 1999; Jain and Sharma, 2010):

i. Blending with diesel
ii. Micro-emulsification
iii. Thermal cracking (pyrolysis)
iv. Transesterification – the most commonly used method

Biodiesel consist of mono or simple alkyl esters of fatty acids derived from vegetable oils or animal fats. It is also known as a clean and renewable fuel. It is usually produced by the transesterification of the vegetable oils or animal fats with methanol or ethanol and alkali catalysts (Berchmans and Hirata, 2008; Akbar *et al*., 2009). For the transesterification process to be successful, the free fatty acid (FFA) content of the feedstock should be below 1 %. This is because high FFA content (>1 %) reacts with the alkali catalyst to form soaps, resulting in serious emulsification, separation problems and low biodiesel yield. *Jatropha curcas* L. oil has high FFA contents (about 14 %), which is far beyond the limit, hence cannot be directly used in an alkali catalysed transesterification process (Lu *et al*., 2009). Therefore, a pre-esterification process catalysed by homogeneous acids, such as sulphuric acid, phosphorous acid or sulfonic acid, is used to reduce the FFA content. This turns the raw oils transesterificable by the alkali catalyst and converts FFAs to valuable fatty acid methyl esters (Tiwari *et al*., 2007; Berchmans and Hirata, 2008; Lu *et al*., 2009). The transesterification reaction is influenced by factors such as reaction temperature, alcohol to oil ratio, type of catalyst, catalyst to oil ratio, mixing intensity, moisture content of oil and purity of the reactants (Ma and Hanna, 1999; Tuli, 2006; Berchmans and Hirata, 2008; Jain and Sharma, 2010).

2.3.2.1. Advantages and Disadvantages of Biodiesel

The following are the advantages of using biodiesel as substitute for diesel (Jain and Sharma, 2010; Juan *et al*., 2011):

a) Biodiesel is a sustainable and renewable form of fuel.
b) Biodiesel is a green liquid fuel free from environmental problems as it produces better emissions (visible smoke and noxious fumes and odours) compared to diesel. From Table 3, reported reductions in emissions by 100 % biodiesel (B_{100}) are far higher than that by a blend of 20 % biodiesel and 80 % diesel except for NO_x. The higher emission of NO_X could be reduced either by slight retardation of injection timing (1–5°) or by use of a catalytic converter. The life cycle analysis of biodiesel shows that the reduction in CO_2 emission is about 16 % with B_{20} and 72 % with B_{100} use on per litre combustion basis (Labeckas and Salvinskas, 2006; Jain and Sharma, 2010).

Table 3: Comparison of emission reductions in biodiesel and its blend with diesel

Emission type	**B_{100} (%)**	**B_{20} (%)**
Hydrocarbon	- 67	- 20
CO	- 48	- 12
Particulate matter (PM)	- 47	- 2
NO_x	+ 10	+ 2
SO_2	- 100	-20
Polycyclic Aromatic Hydrocarbon (PAH)	- 80	- 13

Sources: Labeckas and Salvinskas (2006), Jain and Sharma (2010)

c) It can make the vehicle perform better as it has a cetane number of over 100 which is a measure of the quality of the fuel's ignition properties.

d) It is safe for use in all conventional diesel engines.

e) Owing to the clarity and the purity of biodiesel it can be used without adding additional lubricant unlike diesel engine.

f) Biodiesel is a non-flammable and non-toxic form of fuel.

g) It reduces the environmental effect of waste products. Because biodiesel is made out of waste products itself, it does not contribute to nature's garbage at all. Biodiesel can be made out of used cooking oils and lards. So instead of throwing these substances away, the ability to turn them into biodiesel becomes more than welcome.

h) Biodiesel can be produced locally. A locally produced fuel can be more cost efficient. There is no need to pay tariffs or similar taxes to the countries from which oil and petroleum diesel is sourced. Every country has the ability to produce biodiesel.

i) It is energy efficient. If the production of biodiesel is compared with the production of the petroleum diesel, producing the latter consumes more energy. Biodiesel does not need to be drilled, transported, or refined like petroleum diesel. Producing biodiesel is easier and less time consuming.

Despite the numerous benefits outlined above, there are some negative aspects involved in the use of biodiesel as fuel. Below are the disadvantages in using biodiesel (Jain and Sharma, 2010):

a) Biodiesel has a lower calorific value of 39-40 MJ/kg compared to 43 MJ/kg for diesel.
b) It has higher pour and cloud points of -15 to 10°C and -3 to 12° C respectively compared to -35 to -15°C and -15 to 5°C for diesel.
c) It produces 10 % higher NO_x emissions.
d) Biodiesel is also corrosive in nature against copper and brass.
e) It has low volatility compared to diesel.

2.4. Physical Properties of Seeds and their Application

Agricultural and food processing equipment are often designed and constructed without sufficient prior knowledge of the physical properties of the plant materials (Mieszkalski, 1997). Before rational work can be done on the design of dehulling or cracking machines, it is necessary to first study the process of dehulling taking into consideration the morphological, physical and mechanical features of the seeds to be cracked

(Sirisomboon *et al.*, 2007; Karaj and Müller, 2010). The working elements of the equipment will come into direct contact with the seeds hence knowledge of the seed properties is very vital in design. Information on whether the seed cover is actually connected with the endosperm or only encapsulates it will be the basis for selecting the method for removing the seed cover (Mieszkalski, 1997). Physical properties aid in solving many of the problems associated with machine design and also in analysis of the behaviour of products during agricultural processing (Akaaimo and Raji, 2006).

Some of the physical properties of *Jatropha curcas* seeds applied in the design of processing equipment are moisture content, physical dimensions (length, width and breadth), geometric mean diameter, sphericity, bulk density, solid density, 1000-unit mass, porosity, coefficient of friction on various surfaces and angle of repose (Sirisomboon *et al.*, 2007; Karaj and Müller, 2010). A very good knowledge of these physical properties are necessary in the design of agricultural equipment for dehulling, separating fruit hulls from seeds, seed cracking, separating seed husks from kernels, drying, cleaning and oil extraction (Garnayak *et al.*, 2008; Olalusi and Bolaji, 2010).

2.4.1. Moisture Content

Moisture content of the seed refers to the amount of water contained in the seed. It is determined either on wet basis or on dry basis. It is a very useful physical property of biological materials, because it affects almost all the other physical properties of the materials which in turn influence the performance of processing equipment (Garnayak *et al.*, 2008; Gupta and Das, 1999). For example, Sudajan *et al*. (2002) determined some of the physical properties of sunflower seeds and heads at different moisture contents which was used in the design of a prototype sunflower thresher. Many other researchers like Gupta and Das (1997), Bart-Plange and Baryeh (2003), Garnayak *et al*. (2008), Davies (2010), Olalusi and Bolaji (2010) and Balakrishnan *et al*. (2011) have confirmed the influence of moisture content on the physical properties of *J. curcas* and other seeds. It is therefore necessary to state the moisture content at which any physical property is being investigated.

2.4.2. Physical Dimensions

The physical dimensions are the length, equatorial diameter (width) and breadth (thickness). The length refers to the major diameter whiles the breadth is the minor diameter of the seed. The intermediate diameter is the equatorial diameter or width. Knowledge of these dimensions is useful in determining aperture sizes in the design of seed handling equipment (Omobuwajo *et al*., 1999). Again, these dimensions, together with other parameters like the geometric mean diameter, arithmetic mean diameter, aspect ratio and sphericity describe the size and shape of the seed which influence its behaviour. For example, the flowability characteristic of the seed is influenced by the sphericity, such that movement of non-spherical seeds under gravity is mostly slow and on their flat surfaces (Omobuwajo *et al*., 1999; Jayan and Kumar, 2004). A fruit or seed is considered spherical if its sphericity value is greater than 0.8 or 0.7, respectively (Pradhan *et al*., 2009; Davies, 2010).

2.4.3. Bulk Density

Bulk density is the density of the material when packed or stacked in bulk whiles solid density is the density of the material, excluding any interior pores that are filled with air (Sahin and Sumnu, 2006). Materials with large pore spaces among them have lower bulk densities compared with those having small pore spaces. A 1000-unit mass refers to the mass of thousand seeds. The mass and density characteristics of the seeds are quite useful in estimating product yield and machine throughput of equipment (Omobuwajo *et al*., 1999). Also, seed weight affects seed flow and in turn, influences the design of hoppers for seeds in processing equipment (Jayan and Kumar, 2004).

2.4.4. Porosity

According to Mohsenin (1986), porosity is defined as the ratio of the inter-granular void space volume and the volume of the bulk grain. The porosity can be determined through the direct method by measuring the quantity of added liquid that fill the void space in a bulk seed sample or through the indirect method by using an air comparison pycnometer (Correa *et al*., 2007). Porosity is usually needed in air flow and heat flow situations like winnowing, cleaning, drying, storage, etc. (Garnayak *et al*., 2008; Pradhan *et al*., 2009).

2.4.5. Angle of Repose

Angle of repose is also a very important physical property of seed, useful for the design of processing, storage and conveying systems of agricultural materials. When grains or seeds are piled on a flat surface, the sides of the pile are at a definite reproducible angle with the horizontal. This angle is called the angle of repose of the material (Sahin and

Sumnu, 2006). When the grains or seeds are smooth and rounded, the angle of repose is low. Very fine and sticky materials have high angle of repose due to high friction among them (Sahin and Sumnu, 2006; Sirisomboon *et al.,* 2007).

2.4.6. Coefficient of Friction

The coefficient of friction is defined as the ratio between the frictional force and the normal force on the surface of the material used in the wall (Correa *et al.*, 2007). For biological products, according to Mohsenin (1986), two types of friction coefficients are considered, the static coefficient determined by the force capable to initiate the movement and the dynamic coefficient determined by the force needed to maintain the movement of the grains or seeds in contact with the wall surface. These depend on the type and nature of the materials or surfaces in contact. Rough and viscous surfaces usually have high coefficients of friction while smooth and hard surfaces have lower coefficients of friction (Sirisomboon *et al.,* 2007). All these properties influence the performance of processing equipment hence must be investigated and applied in equipment design.

2.5. Shellers, Crackers, Decorticators and Dehullers

Jatropha curcas oil, as discussed above has numerous applications and therefore needs to be efficiently extracted for maximum benefits. Shukla (2006) stated that crackers or dehullers need to be developed for *J. curcas* seeds in order to increase the amount of oil mechanically extracted from the kernels since using undehulled or uncracked seeds increases the amount of oil retained in the seed cake. Pradhan *et al*. (2010) also indicated that, *J. curcas* production and processing must be mechanized and properly improved to aid profits and reduce losses, considering all the benefits associated with it.

Decortication or dehulling of *Jatropha curcas* seeds refers to the action of separating the shell/seed coat from the seed or kernel, prior to milling and extracting the oil from the kernel (Prandhan *et al*., 2010). Dehulling or decortication of fruit may be achieved using one of several methods (mechanics): impact, rubbing (shearing), squeezing (compression) or a combination of any of the three. In these three, the rubbing action would produce seed with minimal damage. To achieve minimal seed damage it is essential to apply least impact with rubbing action (Prandhan *et al*., 2010). There are different types of crackers, decorticators or dehullers. Some of these are discussed below.

2.5.1. Universal Nut Sheller

The Universal Nut Sheller (UNS) is shown in Figure 9. It was developed by Jock Brandis of the Full Belly Project, a non-profit organization based in Wilmington, North Carolina, which designs labour-saving devices to improve the lives of people in developing communities (Harrell *et al.*, 2010; Wikipedia, 2011). The UNS was introduced into Ghana by Dr. Rick Brandenburg (Professor of entomology) and Dr. David Jordan (specialist in crop science) from North Carolina State University (Hampton, 2010). It is a simple hand-operated machine capable of shelling 50 kg/h of raw, sun-dried groundnuts. It requires less than US$ 50 in materials to make and is made of concrete poured into two fibreglass moulds, some metal parts, one wrench and any piece of rock or wood that might serve as a hammer (Wikipedia, 2011).

Figure 9: Universal Nut Sheller: 1 – Longitudinal-section view, 2 – Pictorial view (Source: http://en.wikipedia.org/wiki/Universal_Nut_Sheller)

The Universal Nut Sheller accepts a wide range of nut sizes without adjustment. If adjustment is necessary, it can be done quickly and easily. In other countries, it can be used to shell other fruits like *Jatropha curcas*, coffee, neem, and sometimes shea (that is in Uganda but not Ghana). Although the cost for the materials needed to build this sheller is low, there is also a onetime cost for the fibreglass mould that is used to make the two pieces of moulded concrete, which makes the technology expensive (Ramli, 2003). Again, since it is manually operated, it involves manual labour and also has a low capacity. This makes it not very suitable for large scale production or processing of the nuts/seeds. Moreover, the sheller does not include a winnower or separator hence separation of husk from the kernel which takes more time and presents more difficulties than the actual shelling is done manually making the process labour-intensive (Hopfen, 1981).

2.5.2. Hand-operated *Jatropha curcas* Fruit Decorticator

Another manually operated cracker or decorticator is the Hand-operated *Jatropha curcas* fruit decorticator with a separator shown in Figure 10. It was developed by Pradhan *et al*. (2010) in India. The major components of the machine are the frame, hopper, decorticating chamber, concave sieve, rotating blades, discharge outlet and a vibrating separator with sieve to separate seed and shell. Decortication is achieved by the shearing action of the rotating blades on the *J. curcas* fruits working against the concave sieve. The machine has a maximum capacity of 40 kg/h of *J. curcas* fruit which means the machine is not meant for commercial production but for small scale farmers and micro-industries (Pradhan *et al*., 2010).

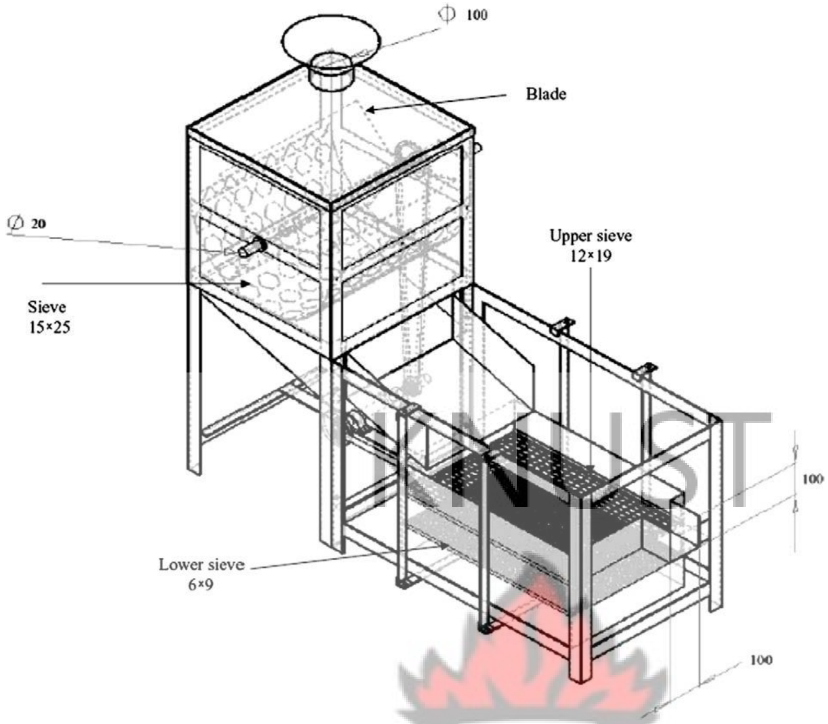

Figure 10: Hand-operated *Jatropha curcas* fruits decorticator (Source: Pradhan *et al*., 2010)

Crackers or dehullers operated by mechanical sources of power are usually of higher capacities compared to the manually operated ones; hence they are suitable for commercial processing or production (Rijssenbeek and Galema, 2010). Presently in Ghana, there is no known locally manufactured motorised cracker or decorticator for *J. curcas* seeds which will aid commercial processing. This presented the need for the development of a mechanically powered *J. curcas* seed cracker, which would have a blower to separate the kernels from the seed husk to aid in the commercial processing of the seeds.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Description of the *Jatropha curcas* Cracker

The *Jatropha curcas* Cracker as shown in Figure 11 is the modified version of the existing groundnut cracker. It consists of a frame, hopper, neck, feed control gate, shelling drum cover, cracking shaft with bearings and a pneumatic tyre as shelling drum, concave sieve, blower shaft with bearings and blower blades, blower cover, belt guard, three pulleys and two spouts (one for husks and the other for the kernels). The hopper is connected to the shelling drum cover by the neck. Between the neck and the shelling drum cover is the feed control gate which regulates the amount of material entering the cracking or shelling unit. This prevents the shelling unit from getting overloaded and clogged. The shelling drum cover shields the cracking mechanisms.

The concave sieve dimension was determined by the sizes of the *Jatropha curcas* seeds and kernels. The cracking unit and all the other components are mounted on the frame. Attached to one end of the frame is the blower with its cover. The spout for the kernels is mounted below the blower. The spout for the husks is also located at other end of the frame. The cracking or shelling drum is driven by an electric motor, through a flat belt connected to the pulley on the cracking shaft. Another pulley which connects the cracking unit shaft to drive the blower shaft through a relatively smaller pulley by means of a belt is fixed at the other end of the cracking shaft. A guard shields the two pulleys and belts to prevent accident during operation.

The feed control gate regulates the flow of materials or seeds from the hopper into the cracking unit. The cracked materials pass through the sieve and are cleaned by an air stream from the blower. This air blows the lighter chaff or *J. curcas* seed husk out of the equipment through the husk delivery spout leaving the heavier kernels to fall and exit through the kernel delivery spout. In order for the groundnut cracker to be modified for cracking *J. curcas* seeds, a new sieve for the machine needed to be developed. Therefore, physical properties of *J. curcas* seeds and kernels were determined to enable the development of the sieve.

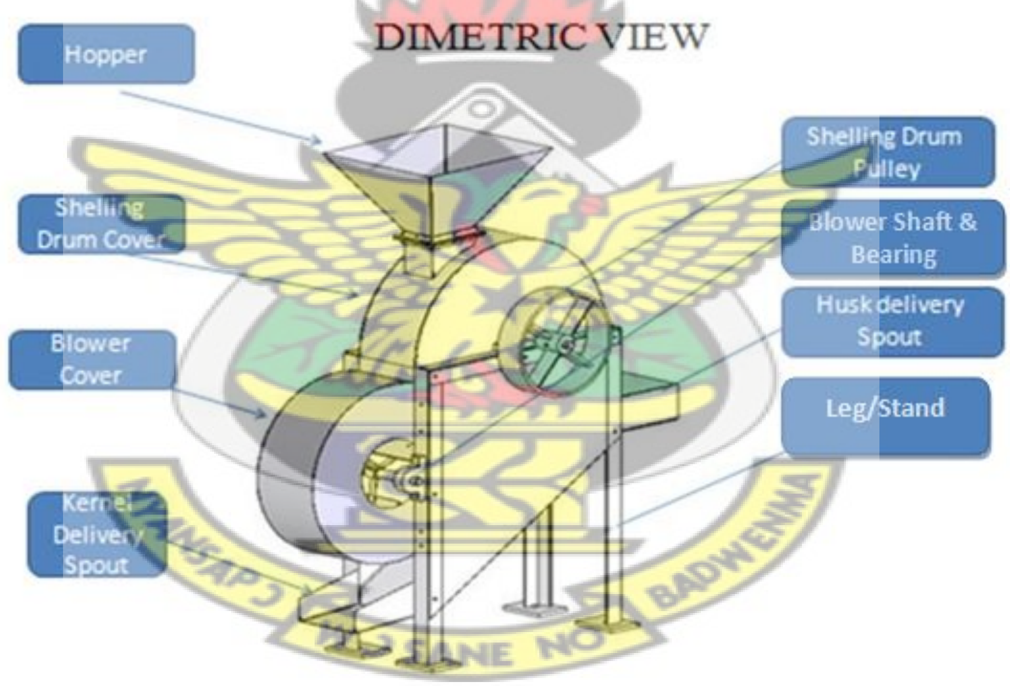

Figure 11: Dimetric view of the *Jatropha curcas* seed cracker

3.2. Determination of physical properties of seeds

For the construction of the *Jatropha curcas* seed cracker, some physical properties of the *J. curcas* seeds and kernel were determined. The physical properties determined were physical dimensions (length, equatorial diameter and breadth), arithmetic mean diameter, geometric mean diameter, sphericity, aspect ratio, 1000-unit mass, coefficient of friction on three different surfaces (plywood, galvanised steel and mild steel) and angle of repose.

3.2.1. Physical dimensions of seeds and kernels

Samples of 100 seeds and kernels were randomly taken. Each seed was measured for its length (a), equatorial diameter (b, also known as width) and breadth (c, also known as thickness) as shown in Figure 12, using a digital vernier calliper reading to 0.01mm. Each seed was placed between the outside jaws of the calliper to measure the length along the major axis of the seed. The equatorial diameter (b) was measured such that it was perpendicular to the length of the seed whiles the breadth (c) was measured to be perpendicular to both the length and the equatorial diameter. The physical dimensions of 100 kernels were also measured in a similar manner as described for the seeds.

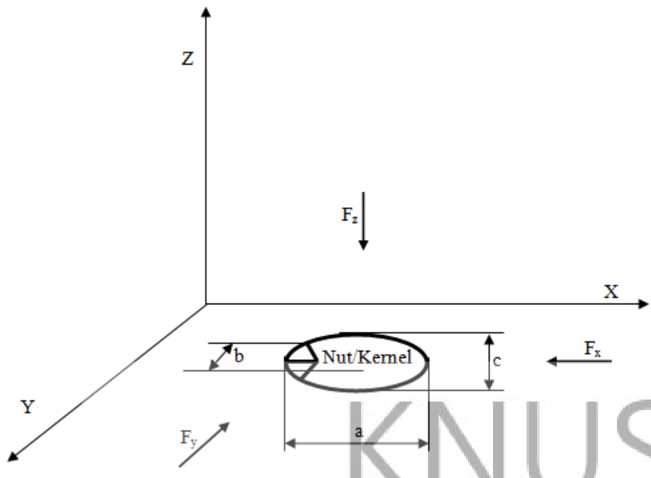

Figure 12: Measurement of the dimensions of *Jatropha curcas* seeds/kernels

3.2.2. Arithmetic mean diameter

The arithmetic mean diameter of the *Jatropha curcas* seeds and kernels were determined after Mohsenin (1986), Sirisomboon *et al.* (2007) and Prandhan *et al.* (2009) by the relation:

$$\text{Arithmetic mean diameter } (D_a) = \frac{a+b+c}{3} \tag{1}$$

where a is the length, b is equatorial diameter and c is breadth of the seed or kernel.

3.2.3. Geometric mean diameter

The geometric mean diameter was also determined from the physical dimensions (length (a), equatorial diameter (b) and width (c)) of the seeds and kernels. It was obtained from the relation (Sirisomboon *et al.*, 2007; Prandhan *et al.*, 2009):

$$\text{Geometric mean diameter } (D_g) = (abc)^{\frac{1}{3}} \tag{2}$$

3.2.4. Sphericity

Sphericity of the seeds and kernels were determined from the equation given below, which has been used by other researchers (Mohsenin, 1986, Sirisomboon *et al.*, 2007; Prandhan *et al.*, 2009). It is defined as:

$$\text{Sphericity}\ (\phi) = \frac{(a+b+c)^{\frac{1}{3}}}{a} \qquad (3)$$

where a is length, b is equatorial diameter and c is breadth of the seed or kernel

3.2.5. Surface area

Surface area of the seeds and kernels was calculated using the following equations (Jain and Bal, 1997; Bart-Plange and Baryeh, 2003):

$$\text{Surface area} = \frac{\pi\, d\, a^2}{(2a - d)} \qquad (4)$$

where $d = (bc)^{0.5}$

3.2.6. Aspect Ratio

The aspect ratio, R_a, was computed using the following relationship (Altuntas *et al.*, 2005; Sharma *et al.*, 2011):

$$\text{Aspect ratio} = \frac{b}{a} \qquad (5)$$

where a is the length and b is the equatorial diameter

3.2.7. 100-unit mass of seeds and kernel

Three samples of 100 seeds and kernels were weighed and their average weights determined. The average was then multiplied by 10 to obtain the 1000-unit mass for the seeds and kernel (Sirisomboon *et al.,* 2007).

3.2.8. Coefficient of Static Friction

Coefficients of static friction against plywood, galvanized steel and mild steel were determined for five (5) samples of seeds and kernels. An open (at both ends) PVC cylindrical pipe of diameter 100 mm and height 50 mm was placed on the inclined surface (plywood, galvanised steel or mild steel) whose angle of inclination was adjustable by means of a screw thread mechanism (Figure 13). The sample was then placed in the pipe and the pipe raised about 5 mm from the surface in order for the sample to be in contact with the surface. The angle of inclination of the surface was increased gradually by turning a nut until the cylinder with the sample just started to slide down. This angle between the surface and the horizontal was then measured, the tangent of which gave the coefficient of friction as stated in Equation 6. Similar methods have been used by other researchers including Gupta and Das (1997), Baryeh (2002) and Bart-Plange and Baryeh (2003).

$$\text{Coefficient of static friction } (\mu) = \tan\theta \qquad (6)$$

where θ = angle between the surface and the horizontal at which samples just start to slide down

Figure 13: Setup for coefficient of static friction determination (left) indicating measurement of the angle, θ (right)

3.2.9. Angle of repose

The angle of repose is the characteristic of the bulk material which indicates the cohesion among the individual units of the material (Sirisomboon *et al*, 2007). The higher the cohesion, the higher the angle of repose. It was determined using two methods; filling and emptying methods. An apparatus consisting of a circular plate of 200 mm diameter and a hollow cylinder of 150 mm diameter and 250 mm height were used. For the emptying angle of repose (Figure 14), seed or kernel samples were put in the cylinder which was placed on the plate. The cylinder was then lifted slowly allowing the samples to form a cone on the circular plate. The height of the cone was then measured and the angle of repose calculated from Equation (8) given below. In determining the filling angle of repose (Bart-Plange and Baryeh, 2003), the seed or kernel samples were poured from a height of 150 mm unto the circular plate. The height of the heap or cone formed was measured and the angle of repose calculated using Equation (8) given below:

$$\tan\gamma = \frac{h}{r} \tag{7}$$

$$\text{Angle of repose}(\gamma) = \tan^{-1}\left(\frac{h}{r}\right) \tag{8}$$

where h is the height of the cone or heap formed and r is the radius of circular plate

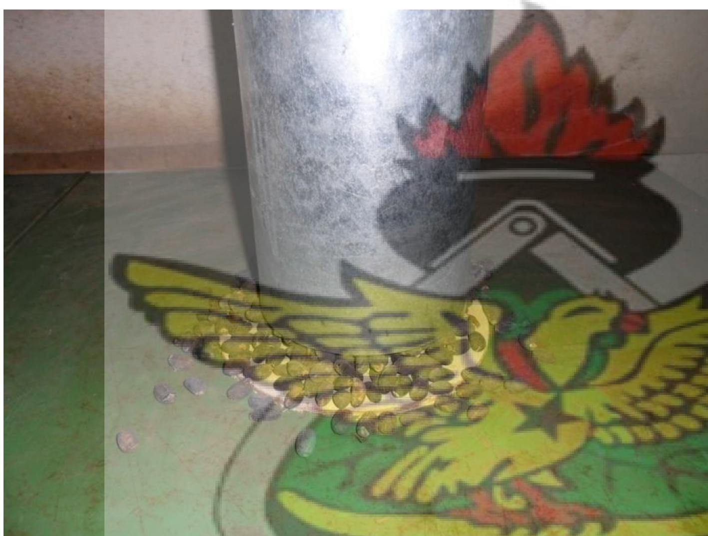

Figure 14: Setup for determining emptying angle of repose

3.3. Experimental Design

The equipment was tested using a completely randomised factorial design. The factors varied were the speed of the shelling drum and feed gate opening. Drum speeds of 140 rpm, 150 rpm, 160 rpm, 170 rpm and 180 rpm were used. The feed gate openings used were 32 mm, 48 mm and 64 mm. Samples of weight 3 kg were used in each experimental unit. The initial moisture content of the seeds before cracking was determined by the standard hot air oven method at 105 ± 1 °C for 24 hours as described by Garnayak *et al.* (2008) and Pradhan *et al.* (2011). Three samples of seeds were weighed and dried at 105 °C for 24 hours after which the weights of the samples were taken again. The result is represented in Appendix 1.

The performance evaluation factors measured were capacity, blower losses, cleanliness, percentage of uncracked seeds, kernel recovery, cracking efficiency and machine efficiency. Each experiment was replicated three times. Table 4 indicates the plan or design used in the data collection. The data was analysed using Microsoft Office Excel 2007 and General Linear Model in Minitab 15 Statistical Software.

Table 4: Experimental design for the data collection

Feed Gate opening	**32 mm**			**48 mm**			**64 mm**		
Replications / **Speed (rpm)**	1	2	3	1	2	3	1	2	3
140	×	×	×	×	×	×	×	×	×
150	×	×	×	×	×	×	×	×	×
160	×	×	×	×	×	×	×	×	×
170	×	×	×	×	×	×	×	×	×
180	×	×	×	×	×	×	×	×	×

× - represents one experimental unit

3.4. Determination of the machine evaluation parameters

The parameters for evaluating the machine were determined with the equations explained below (Audu *et al*., 2004; Pradhan *et al*., 2010):

3.4.1. Machine Capacity

The capacity of the machine was calculated using the equation:

$$\text{Capacity} = \frac{\text{Total mass of sample (kg)}}{\text{Total time to crack sample (h)}} \qquad (9)$$

3.4.2. Blower losses

During separation of the kernel from the husk by the blower after cracking, some of the kernels which were lighter or broken were blown along with the husk through the husk delivery spout. This constituted the blower losses and was computed by:

$$\text{Blower losses (\%)} = \frac{\text{Mass of kernels (broken + whole) in husk}}{\text{Total mass of sample}} \times 100 \qquad (10)$$

3.4.3. Cleanliness

Cleanliness is the ability of the blower to effectively separate the husks from the kernels without leaving any husk in the kernels. Cleanliness was determined as follows:

$$\text{Cleanliness (\%)} = \left(1 - \frac{\text{Total mass of impurities}}{\text{Total mass of clean kernels}}\right) \times 100 \qquad (11)$$

where impurities refer to seed husk found among the kernels.

3.4.4. Percentage of Uncracked seeds

During cracking, some of the seeds go through the cracking unit without being cracked. These were usually seeds smaller than the size of holes in the sieve. It was computed using the relation:

$$\text{Uncracked (\%)} = \left(\frac{\text{Mass of uncracked seeds}}{\text{Total mass of seeds}} \right) \times 100 \qquad (12)$$

3.4.5. Kernel Recovery

Kernel recovery is the mass of the kernels recovered from the seeds after cracking. It is the ratio of the weight of the kernels to that of the seeds. It was computed using the relation:

$$\text{Kernel Recovery (\%)} = \frac{\text{Total mass of clean kernels}}{\text{Total mass of sample (seeds)}} \times 100 \qquad (13)$$

3.4.6. Cracking Efficiency

Cracking efficiency is the ability of the machine to effectively crack the *Jatropha curcas* seeds. It was calculated using the relation:

$$\text{Cracking Efficiency (\%)} = \left(1 - \frac{\text{Mass of uncracked seeds}}{\text{Total mass of sample}} \right) \times 100 \qquad (14)$$

3.4.7. Machine Efficiency

Machine Efficiency is the ability to crack the seeds and separate the kernels and shells through the kernel delivery spout. In other words, it means the ability of the machine to do what it is expected to do. It was computed using the relation:

$$\text{Machine Efficiency (\%)} = \frac{\text{Percentage of kernels recovered}}{53.47\ (\%)} \times 100 \qquad (15)$$

where, 53.47 % (Appendix 7) represents the mass of kernels in 100 g of seeds at the time of cracking

3.5. Extraction of oil

Samples of decorticated seeds were taken to the Department of Chemistry of KNUST for the extraction of oil by chemical method using petroleum ether as solvent. Four different samples having different weights of seed husk, each replicated three times were used. The percentages of husk used in the experiment were 0 %, 20 %, 40 %, and 100 % husk contents (Wim *et al*., 2007). Before this experiment, determination was made for the percentages of kernel and husk in three (3) samples of 100 g seeds (Appendix 5).

According to the mean results of this preliminary experiment, 58.2 % by weight (58.2 g) of the 100 g sample of seed was kernels while the other 41.8 % weight (41.8 g) was husks. These percentages agreed with the 58 % kernel and 42 % husk reported by Singh *et al.* (2008). Based on this result, the percentages of the husk in the samples were adjusted from 100 % (being 41.8 g) to 0 % (no amount of husk added to sample). The samples with 100 % husk represented uncracked seeds used in oil extraction while the 0 % husk represented the fully cracked and cleaned (of husk) kernels. The composition of kernels was maintained at the constant weight of 58.2 g since for a given 100 g sample of seeds, the average weight of kernel is constant (whether cracked or uncracked).

In the preparation of samples, clean *Jatropha curcas* kernels were ground with a Kitchen blender for 2 min. Grinding was done for a short period in order to prevent the samples from heating up to cause the oil in the kernels to drain out. The ground sample was then screened with a 2 mm sieve to remove large particles. The same grinding and sieving procedures were used for samples of the husk.

Figure 15 shows the Soxhlet extraction apparatus used in the extraction of the oil. The apparatus consist of the soxhlet unit, a round bottom flask, a water bath and a condensation unit which is connected by a tube to a source of water. It is held in an upright position by a retort stand. The temperature of the water contained in the water bath was set to 70°C since the boiling point of the solvent (petroleum ether) was 40-60°C (Sayyar *et al.,* 2009). Each sample was weighed into a thimble (a small bag made from calico).

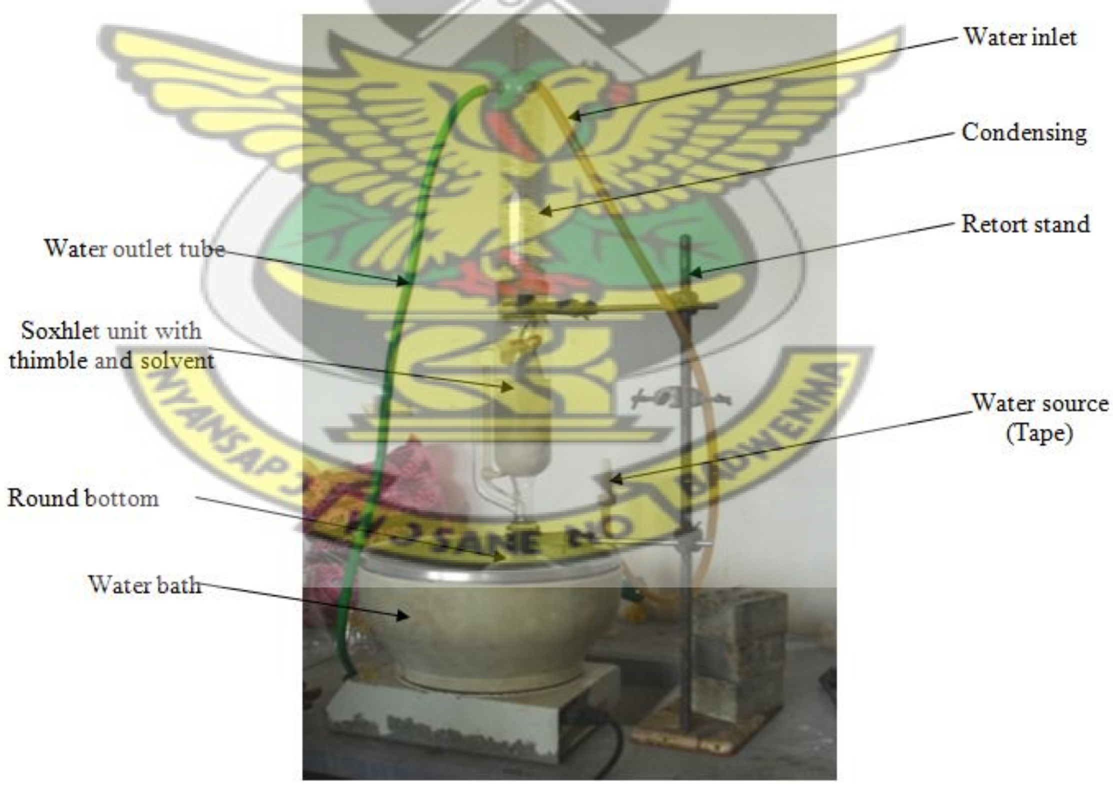

Figure 15: A complete set-up for chemical extraction of *Jatropha curcas* oil

The water bath was filled with water and the round bottom flask was clamped onto the retort stand and suspended in the water. The soxhlet unit was then fixed unto the round bottom flask at the lower end and clamped by the retort at the upper end. The solvent was then poured in the soxhlet unit until it started to reflux into the round bottom flask. The thimble containing the sample was then placed in the soxhlet unit after which the condensation unit, which was connected to the source of water, was fixed on top of the soxhlet unit. The tap or water source was opened to allow water to flow through the condensation unit. The water bath, connected to an electric power source was then switched on to heat up and maintain the temperature of the water at 70°C.

Petroleum ether evaporated from the round bottom flask rises through the soxhlet extractor and cooled by the water flowing through the condensation unit. The condensed petroleum ether flows into the extraction unit of the soxhlet containing the ground *Jatropha curcas* sample in the thimble. As the solvent collects around the sample, it dissolves the oil in the ground material. With increase in the amount of solvent that condenses, its level in the extraction unit and siphon tube rises until the siphon tube is completely filled. When this happens, the solvent with the dissolved oil is siphoned back into the round bottom flask. The solvent evaporates, leaving the oil in the flask and the process is repeated all over again.

The experiment was done for a period of 6 h for each sample (Sayyar *et al.*, 2009). After the 6 h, the thimble containing the sample was removed from the extraction unit and the solvent was allowed to condense into the extraction unit leaving the oil in the round bottom flask. This continued till all the solvent was evaporated, which was determined by the absence of any bubble from the oil, after which the oil was allowed to cool and settle. The oil was then poured into a container and allowed to stand for about a week for the glycerine to settle below the container. The oil was then decanted and its volume determined.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Physical properties

The physical properties for the *Jatropha curcas* seeds and kernels were determined and the mean values presented in Table 5. Moisture content of the seeds and kernels were 10.42 % and 7.61 % dry basis, respectively. The detailed values can be found in Appendices 2.

Table 5: Physical properties of *Jatropha curcas* seeds and kernels

Properties	**n**	**Seed**	**Kernel**
Length, mm	100	18.11 (±0.88)	15.05 (±0.68)
Equatorial diameter, mm	100	11.47 (±0.49)	9.05 (±0.60)
Breadth, mm	100	8.89 (±0.41)	7.34 (±0.46)
Arithmetic mean diameter, mm	100	12.84 (±0.47)	10.48 (±0.46)
Geometric mean diameter, mm	100	12.26 (±0.44)	9.99 (±0.46)
Sphericity	100	0.68 (±0.02)	0.66 (±0.02)
Surface area, mm^2	100	398.46 (±27.84)	264.74 (±24.12)
Aspect ratio	100	0.63 (±0.03)	0.60 (±0.04)
1000-unit mass, g	3	541.33 (±0.49)	402.00 (±0.26)
Coefficient of static friction on various surfaces			
Ply wood	3	0.39 (±0.02)	0.42 (±0.01)
Galvanised steel	3	0.32 (±0.01)	0.41 (±0.03)
Mild steel	3	0.48 (±0.04)	0.53 (±0.01)
Angle of repose (°)			
Filling method	3	38.61 (±2.52)	42.38 (±1.52)
Emptying method	3	37.71 (±0.90)	38.64 (±1.51)

n = number of samples.

The physical dimensions being the length, equatorial diameter and breadth of the seeds and kernels gave the results shown in Table 5. These dimensions were important in the design of the cracking sieve, clearance between the sieve and the tyre in the cracking unit and other apertures of the cracker (Omobuwajo *et al.*, 1999). The length, equatorial diameter and breadth of the seeds were 20.3 %, 26.7 % and 21.1 %, respectively greater than those of the kernels. Sirisomboon *et al.* (2007) reported differences of 36 %, 29 % and 17 % for the length, equatorial diameter and breadth, respectively between the seeds and the kernels. The differences among the two results may be due to differences in the varieties of *Jatropha curcas*. Other parameters applied were the arithmetic mean diameter, geometric mean diameter, surface area, sphericity, aspect ratio and 1000-unit mass. The results for sphericity indicated that the seeds were 2 % more spherical than the kernels. The *Jatropha curcas* seeds and kernels cannot be considered as spherical since their sphericity values were below 0.7 (Pradhan *et al.*, 2009; Davies, 2010).

The coefficients of static friction for the kernels were higher than that for the seeds by 7.7 %, 28.1 % and 10.4 % on the ply wood, galvanised steel and mild steel surfaces, respectively, which agreed with the results reported by Sirisomboon *et al.* (2007) and Karaj and Müller (2010). This was because of the low hardness and viscous nature of the surfaces of kernels, making it difficult for them to slide. It also shows that surfaces for the gravitational flow of kernels need to be inclined at greater angles compared to that for seeds. Considering the three surfaces, coefficient of static friction was highest on mild steel, followed by plywood with galvanised steel as the lowest. This also agreed with the results of Sirisomboon *et al.* (2007) for *Jatropha curcas* kernels. Angle of repose was also higher for kernels than for the seeds, which can be attributed to the reason given above for the coefficient of static friction. The viscous nature of the kernel surfaces created higher friction among the kernels leading to higher angle of repose (Sahin and Sumnu, 2006; Sirisomboon *et al.*, 2007). Results for the filling methods of determination were higher than those for the emptying methods for both seeds and kernels. This agreed with the results of Sirisomboon *et al.* (2007).

In the design of the sieve for the *Jatropha curcas* seed cracker, the physical dimensions measured for the seeds and kernels were used (Omobuwajo *et al*., 1999; Pradhan *et al*., 2010). The equatorial diameter and breadth for the seeds and kernels were applied in the design. In the cracking of the seeds, the principle is that the seeds need to be retained on the sieve for them to be cracked while the kernels must pass through the sieve after cracking to avoid being crushed. Hence, a sieve with circular holes was needed to provide this condition for cracking.

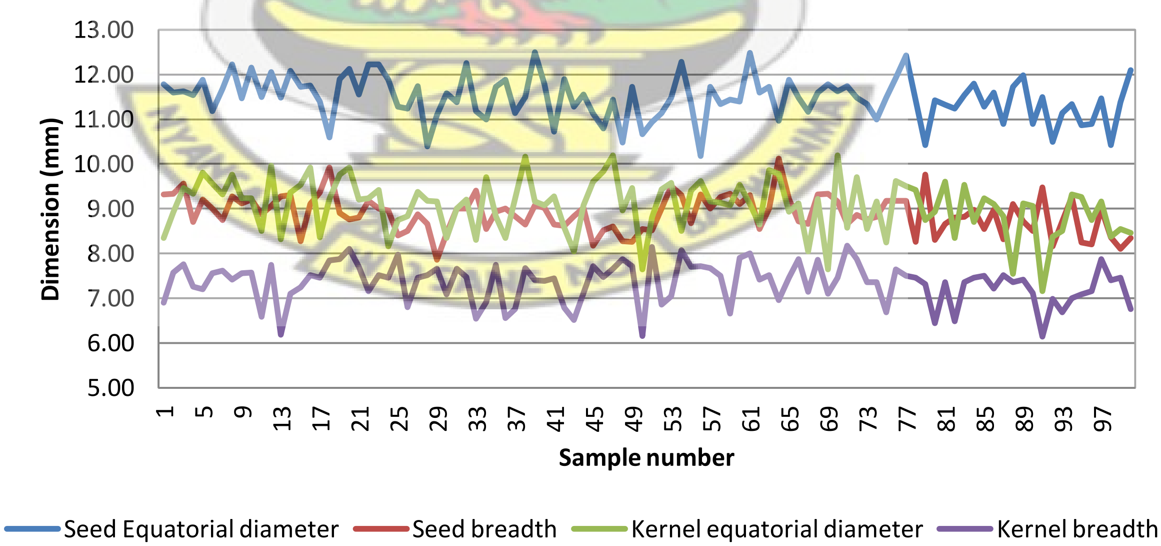

Figure 16: Graph of dimensions for *Jatropha curcas* seeds and kernels

From the results shown in Figure 16, the 10 mm dimension was identified as unique to satisfy the condition stated above. This was because, the equatorial diameters of all the seeds were above 10 mm, implying that the seeds cannot drop through the holes in the sieve even though the dimensions of the breadth were all below 10 mm except one. Also, equatorial diameter dimensions for the kernels were below 10 mm except three samples whiles the breadth dimensions were below 10 mm. This means kernels could pass through a sieve with size 10 mm in diameter except the three kernels that could possibly be crushed. Based on these results and analysis, a sieve with holes 10 mm in diameter (Figure 17) was designed for the cracking of the *Jatropha curcas* seeds.

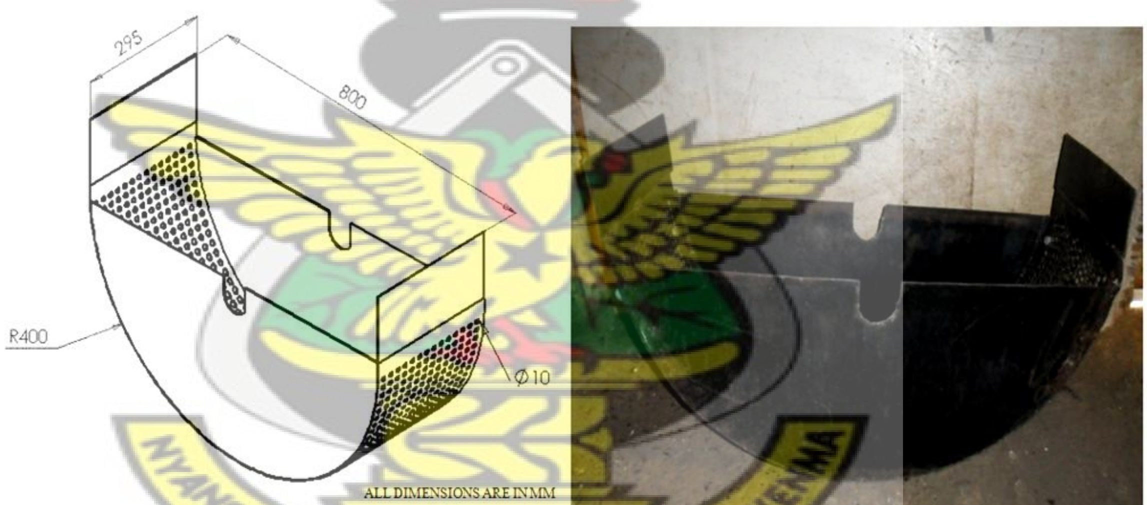

Figure 17: Sieve for cracking *Jatropha curcas* seeds - isometric view (left) and picture (right)

The semi-circular sieve was constructed from a 2 mm mild steel metal plate of dimensions 295 x 1560 mm. The plate was then rolled into the semi-circular shape with radius 400 mm. Two side plates also of radius 400 mm and semi-circular in shape with allowance cut for the cracking shaft to pass through were welded to it. The sieve was installed in the *Jatropha curcas* cracker. Clearance between the sieve and the pneumatic tyre for cracking was set to be 14.08 (±1.56), 18.25 (±1.22) and 18.50 (±1.31), respectively for the centre and the two sides of the tyre (Appendix 3).

Comparing these figures with the clearance quoted by Bobobee (2002) as best for cracking groundnut (16-18 mm), it could be realised that the variation was due to the differences in physical properties between groundnut pods and *Jatropha curcas* seeds. Groundnut pods had physical dimensions of 20.69 (±0.04) length, 10.91 (±0.08) equatorial diameter and 9.11 (±0.04) breadth for the Chinese variety and 32.88 (±0.25) length, 13.75 (±0.06) equatorial diameter and 10.92 (±0.10) breadth for the Manipinta variety. The Chinese variety was 14.25 % and 3.04 % greater in length and breadth, respectively than *Jatropha curcas* seeds but 5.13 % smaller in equatorial diameter than the *Jatropha curcas* seed. The Manipinta variety was also 81.56 %, 19.88 % and 22.83 % in length, equatorial diameter and breadth, respectively greater than the *J. curcas* seeds.

4.2 Evaluation of the *Jatropha curcas* Cracker

The *Jatropha curcas* seed cracker was evaluated to ascertain its performance under different operational speeds and feed gate openings. The initial moisture content of the *J. curcas* seeds was determined to be 10.42 % dry basis (Appendix 1). Figure 18 shows the output from the machine at different operational speeds. The results have been presented and discussed below. Detailed statistical analyses with Minitab have been presented in Appendix 4.

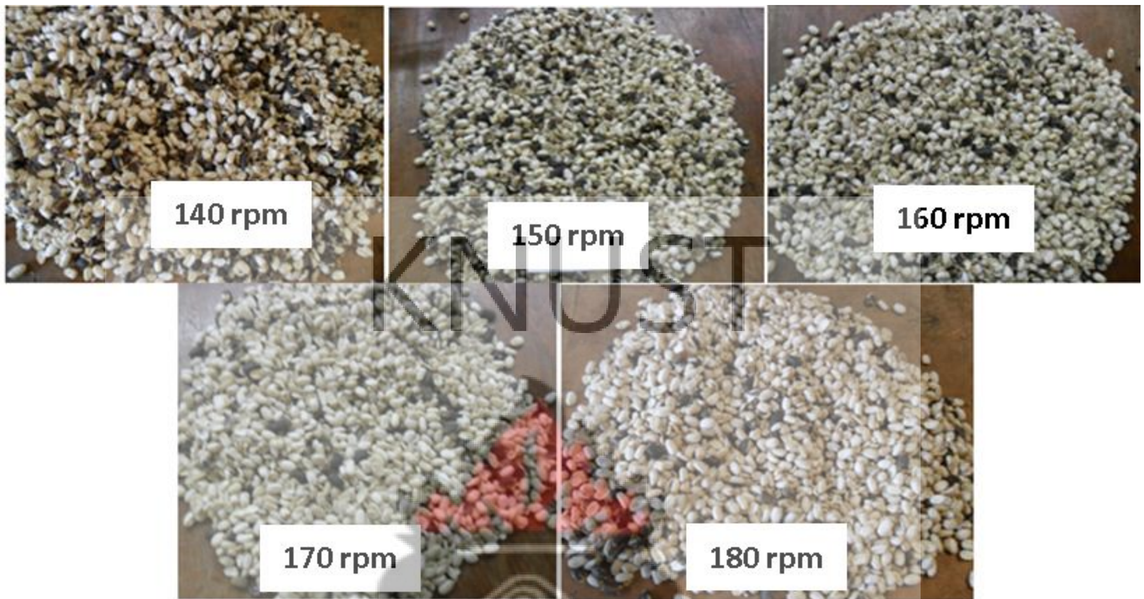

Figure 18: Samples from the machine after cracking at different speeds

4.2.1 Machine Capacity

Capacities of the machine at different speeds and feed gate openings have been shown in Figure 19. Machine capacity was highest at the 140 rpm speed for both the 48 mm and 64 mm openings, while for the 32 mm opening the highest capacity was achieved at 180 rpm. Lowest capacities were recorded at the 160 rpm speed for the 64 mm opening, 180 rpm for the 48 mm opening and 140 rpm for the 32 mm opening. From Figure 19, it is evident that the feed gate opening influenced the capacity of the machine. The capacity was highest at 64 mm feed gate opening and lowest for the 32 mm opening for all the speeds. The highest capacity at the 64 mm opening was 81 % and 713 % higher than that for the 48 mm and 32 mm openings, respectively. At 48 mm feed gate opening, the capacity was 348 % higher than that for the 32 mm opening. The reason was that at higher feed gate openings, more seeds were allowed into the cracking unit which increased the quantity of seeds cracked within a period of time by the machine. Feed gate opening has high significant effect ($p < 0.001$) on capacity, while speed has no significant effect on capacity at a given feed gate opening (Appendix 4a). There were no significant differences ($p < 0.05$) among the capacities with respect to speed of operation (Table 6). On the other hand, differences among the capacities for the feed gate openings were significant ($p < 0.05$) as seen from Table 7.

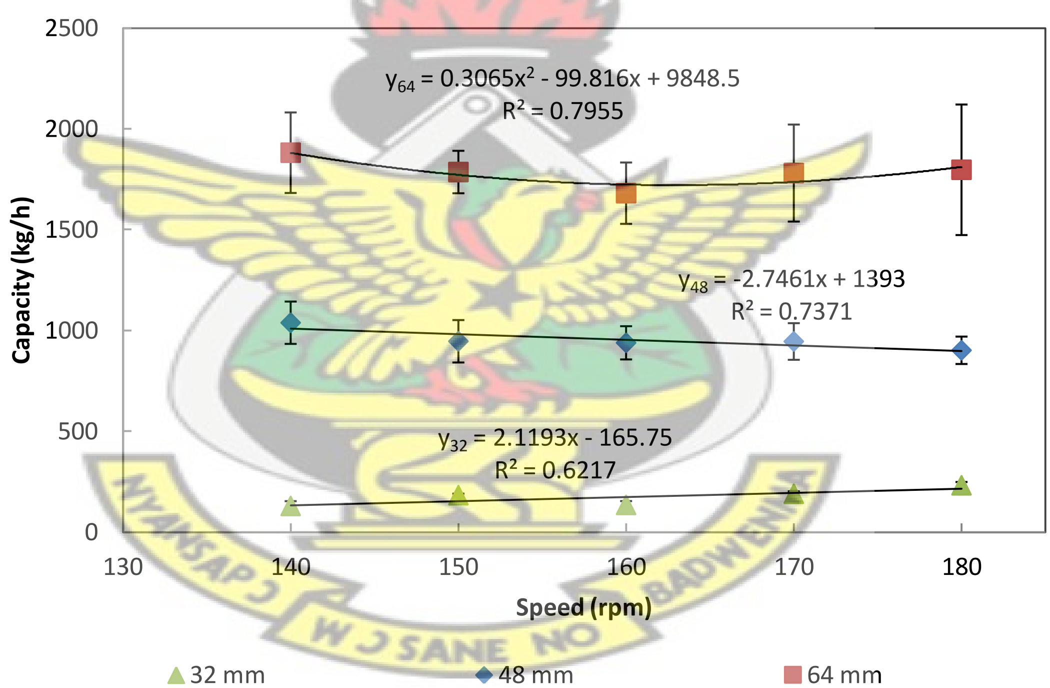

Figure 19: Machine capacity at different operational speeds and feed gate openings

The capacities decreased with increasing speed for both 48 mm and 64 mm openings. However, the capacity increased with increase in speed from 140 rpm to 180 rpm for the 32 mm opening, which agreed with the findings of Audu *et al.* (2004) that throughput of the concentric cylinder locust bean dehuller increased with increase in dehuller speed. The highest capacity was attained at a speed of 140 rpm, followed by the 180 rpm speed. However, the lowest capacity was recorded at 160 rpm. Feed gate opening 64 mm recorded the highest capacity, followed by the 48 mm then the 32 mm with the lowest as shown in Table 7. Even though a highest capacity of 1881.40 kg/h was obtained at 140 rpm speed for the 64 mm feed gate opening, 1037.90 kg/h at 140 rpm speed and 48 mm feed gate opening was chosen as best. This was because at the 64 mm opening, there could be the possibility of the machine becoming clogged when too much seed is introduced into the cracking chamber, considering the fact that only 3 kg of seeds was used in the evaluation.

Table 6: Effect of speed of operation on capacity and blower losses

Speed (rpm)	Capacity (kg/h)	Blower losses (%)
140	1016.1	3.098[a]
150	971.3	5.520[b]
160	917.7	8.514[c]
170	971.6	12.285[d]
180	976.4	16.627[e]

Means in the same column with different letters are significantly different at $p < 0.05$

Table 6 shows the statistical effect of speed of operation on the capacity and blower losses of the *Jatropha curcas* seed cracker. Also, Table 7 indicates the effect of feed gates opening on the capacity and blower losses of the cracker.

Table 7: Effect of feed gate opening on capacity and blower losses

Feed gate opening (mm)	Capacity (kg/h)	Blower losses (%)
32	173.3[a]	8.057[a]
48	953.6[b]	9.135[ab]
64	1784.9[c]	10.434[b]

Means in the same column with different letters are significantly different at $p < 0.05$

4.2.2 Blower losses

Figure 20 presents the trend in blower losses at different operational speeds and feed gate openings. Speed of operation had significant effect ($p < 0.001$) on blower loss. Feed gate opening also had significant effect ($p < 0.01$) on blower loss (Appendix 4b). There was an increase in the blower losses from 2.40 % to 14.01 %, 2.76 % to 17.81 % and 4.13 % to 18.06 % with increase in speed from 140 rpm to 180 rpm for the 32 mm, 48 mm and 64 mm openings, respectively. These increases were 484 %, 545 % and 337 % for the 32 mm, 48 mm and 64 mm openings, respectively. This was because at higher speeds, the blower speed was high hence lighter kernels were blown along with the husk out of the machine. This confirmed the findings of Gupta and Das (1999) that non-recoverable kernel fraction for sunflower seeds increased with increase in impeller speed of the centrifugal dehulling system. There were significant differences ($p < 0.05$) in blower loss among the five speeds (Table 6).

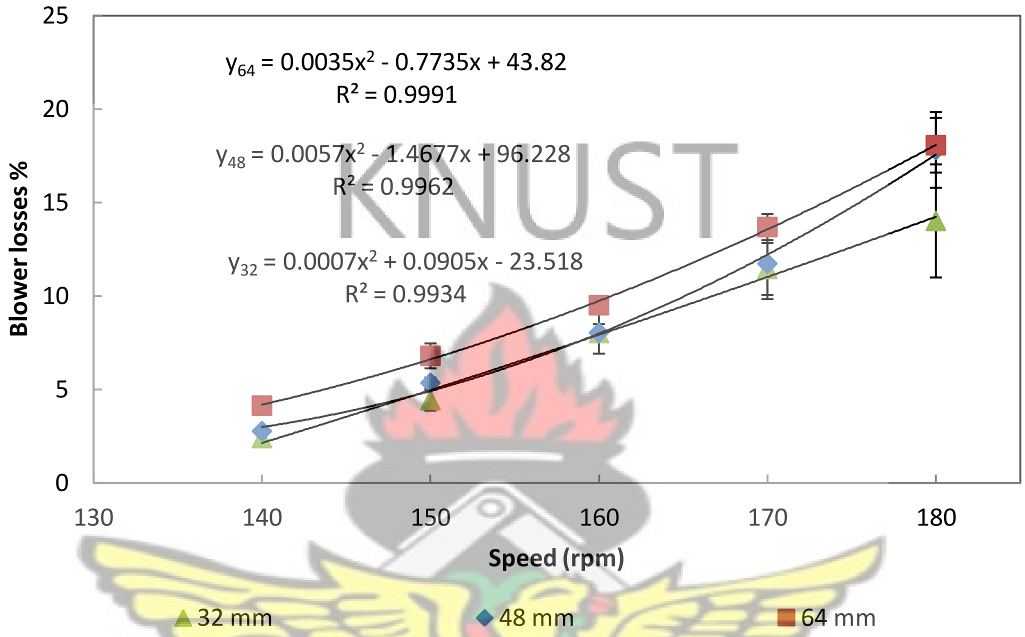

Figure 20: Blower losses at different operational speeds and feed gate openings

Blower loss was highest at the 64 mm feed gate opening and lowest at the 32 mm opening at every speed of operation, indicating blower loss increases with increase in feed gate opening. At the 140 rpm speed, blower loss at 32 mm opening was 15 % and 72 % lower than at the 48 mm and 64 mm openings, respectively. Also, at the 180 rpm speed, blower loss at the 32 mm opening was 27 % and 29 % lower than that at the 48 mm and 64 mm openings, respectively. This could be due to the high amount of materials going through the machine at a particular time at high feed gate openings, leading to many kernels being blown away.

There was significant difference ($p < 0.05$) in blower loss between the 32 and 64 mm feed gate openings but not between 32 and 48 mm and then 48 mm and 64 mm as shown in Table 7. It is also confirmed that blower loss at the 32 mm opening was the lowest compared to that at the 64 mm opening, which recorded the highest loss. Blower loss of 2.40 % was observed to be lowest at 140 rpm speed and 32 mm feed gate opening. However, comparing 2.76 % blower loss for the 140 rpm and 48 mm opening with the 129.05 kg/h lowest capacity that goes with 140 rpm and 32 mm opening, operating the cracker at 140 rpm and 48 mm opening will be more economical. Hence, 2.76 % blower loss at 140 rpm and 48 mm feed gate opening was chosen as best.

4.2.3 Cleanliness

Figure 21 shows the relationship among cleanliness, speed of operation and feed gate opening. Speed of operation has a very high significant effect ($p < 0.001$) on cleanliness (Appendix 4c). There was an increase in cleanliness with increase in the speed of operation, which produced clean kernels at higher speeds and kernels containing many husks at the lower speeds. There were sharp increases in cleanliness by 8.5 %, 5.6 % and 3.7 % for the 32 mm, 48 mm and 64 mm openings, respectively from 140 rpm to 150 rpm. These increases became gradual from 160 rpm to 180 rpm. The increases in cleanliness from the 140 to 180 rpm speed were 14.5 %, 11.4 % and 8.5 % for the 32 mm, 48 mm and 64 mm openings, respectively. This was because at higher speeds, the blower speed was great enough to blow much of the husk out of the samples, making it clean and vice versa. Table 8 confirms the trend of increase in cleanliness with speed. There were significant differences ($p < 0.05$) between cleanliness for the 140 rpm speed and that for all the other speeds. Also cleanliness at 150 rpm and 170 as well as cleanliness at 150 rpm and180 rpm speeds were significantly different. All the other results of cleanliness were not significantly different ($p < 0.05$).

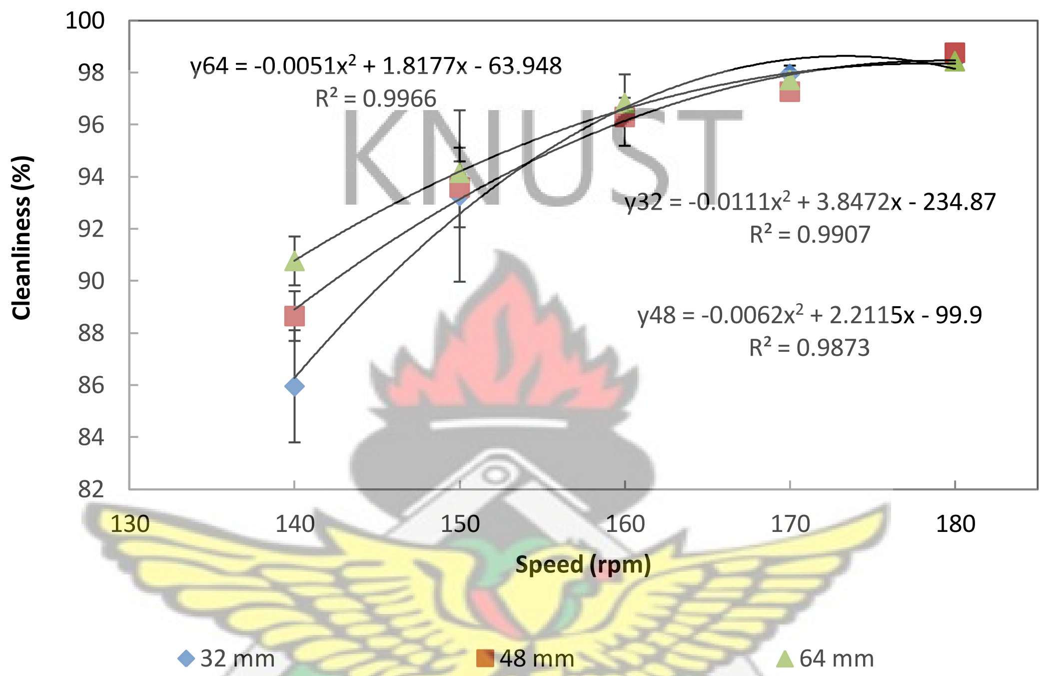

Figure 21: Cleanliness at different operational speeds and feed gate openings

Considering the feed gate opening, the 64 mm opening had the highest percentage of cleanliness while 32 mm had the lowest at the lower speeds but cleanliness became almost the same among the openings at higher speeds. Cleanliness at the140 rpm speed for the 32 mm opening was 5.6 % and 3.1 % lower than that for the 42 mm and 64 mm openings, respectively, while differences at higher speeds of 160 rpm and above were all below 1 %. Feed gate opening had no significant effect ($p < 0.05$) on cleanliness as indicated in Table 9 and from the ANOVA (Appendix 4c).

The highest result for cleanliness was 98.76 % obtained at 180 rpm speed and 48 mm feed gate opening. However, considering the high level of blower loss (17.81 %) associated with this speed, cleanliness at 140 rpm and 48 mm opening which was only 11.4 % less, was considered. This decision was also motivated by the fact that in the mechanical extraction of *Jatropha curcas* oil, some amount of husk is needed to provide consistency and friction for the press cake to flow through the press (Shukla, 2006; Wim *et al.*, 2007). Hence, cleanliness of 88.65 % (11.35 % husk content) at 140 rpm and 48 mm feed gate opening was recommended.

Table 8: Effect of speed of operation on cleanliness and uncracked seeds

Speed (rpm)	**Cleanliness (%)**	**Uncracked seeds (%)**
140	88.45[a]	3.456[a]
150	93.67[b]	3.022[b]
160	96.56[bc]	3.084[abc]
170	97.64[c]	2.855[bc]
180	98.55[c]	2.647[b]

Means in the same column with different letters are significantly different at $p < 0.05$

Table 8 indicates the statistical effect of speed of operation of the cracker on cleanliness and percentage of uncracked seeds. Statistical effect of the feed gate openings on the cleanliness of the *J. curcas* kernels and the percentage of uncracked seeds is shown in Table 9.

Table 9: Effect of feed gate opening on cleanliness and uncracked seeds

Feed gate opening (mm)	Cleanliness (%)	Uncracked seeds (%)
32	94.43	3.097
48	94.91	2.930
64	95.58	3.011

4.2.4 Percentage of uncracked seeds

Figure 22 represents the percentage of seeds that remained uncracked after the operation. From the ANOVA, speed had significant effect ($p < 0.01$) on uncracked seeds, while feed gate opening had no effect on uncracked seeds (Appendix 4d). There was a decrease in the percentage of uncracked seeds with increase in speed of operation for all the feed gate openings. The decrease was high from 140 rpm to 150 rpm and low from 160 rpm to 170 rpm and also from 170 rpm to 180 rpm. There was however an increase in the percentage of uncracked seeds from 150 rpm to 160 rpm for all the feed gate openings. The decreases in percentage values of uncracked seeds from the 140 rpm to the 180 rpm were 18.1 %, 30.2 % and 44.2 % for the 32 mm, 48 mm and 64 mm openings, respectively. The reason for this trend could be that at higher speeds, the machine had greater force to crack more of the seeds as compared to lower speeds. In Table 8, the highest and lowest percentages of uncracked seeds were obtained at 140 and 180 rpm speeds, respectively.

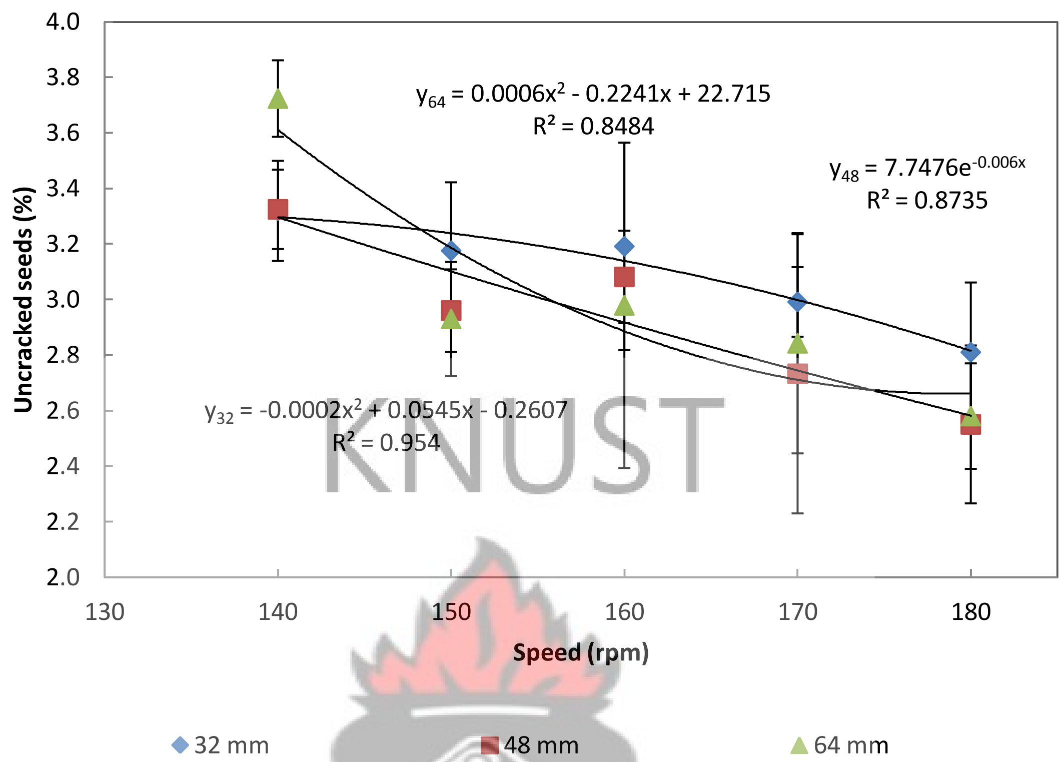

Figure 22: Percentage of uncracked seeds at different operational speeds and feed gate openings

The feed gate opening did not give any defined trend, except that the 32 mm had the highest results from the 150 to 180 rpm speeds. Results for the 48 mm and 64 mm openings swapped the second and third highest positions from 150 rpm to the 180 rpm speed. Table 9 also shows the 32 mm opening as having the highest percentage of the uncracked seeds, followed by the 64 mm with the 48 mm opening having the lowest percentage. There were no significant differences ($p < 0.05$) among the results at different feed gate openings as shown in Table 9. Oluwole *et al.* (2004) also found out that feed rate (amount of nut flowing through a gate opening per unit time) had no significant effect on the percentage of uncracked nuts in the sheanut cracker. The 180 rpm speed and 48 mm feed gate opening gave the lowest result of 2.55 % of uncracked seeds but considering the high level of blower loss at this speed, 3.32 % of uncracked seeds at 140 rpm and 48 mm feed gate opening was selected as best for the cracker's operation.

4.2.5 Kernel Recovery

Figure 23 shows the results for the percentage of kernels recovered from the seeds cracked at different operational speeds and feed gate openings. Speed had high significant effect ($p < 0.001$) on kernel recovery. However, feed gate opening had no significant effect in kernel recovery (Appendix 4e). There was a linear decrease in the percentage of kernels recovered as the speed of operation increased from 140 rpm to 180 rpm. The graph indicates a uniform decrease from one speed to the other as shown in the R^2 values of 0.9821, 0.9956 and 0.9747 for 32 mm, 48 mm and 64 mm feed gate openings, respectively. The decreases from 140 rpm to 180 rpm speeds were 35.6 %, 48.1 % and 44.7 % for the 32 mm, 48 mm and 64 mm feed gate openings, respectively. This decrease was due to the increase in the amount of kernels blown out of the machine as the speed of operation increased. Table 10 also shows the uniform decrease in kernel recovery from the 140 rpm speed to the 180 rpm speed.

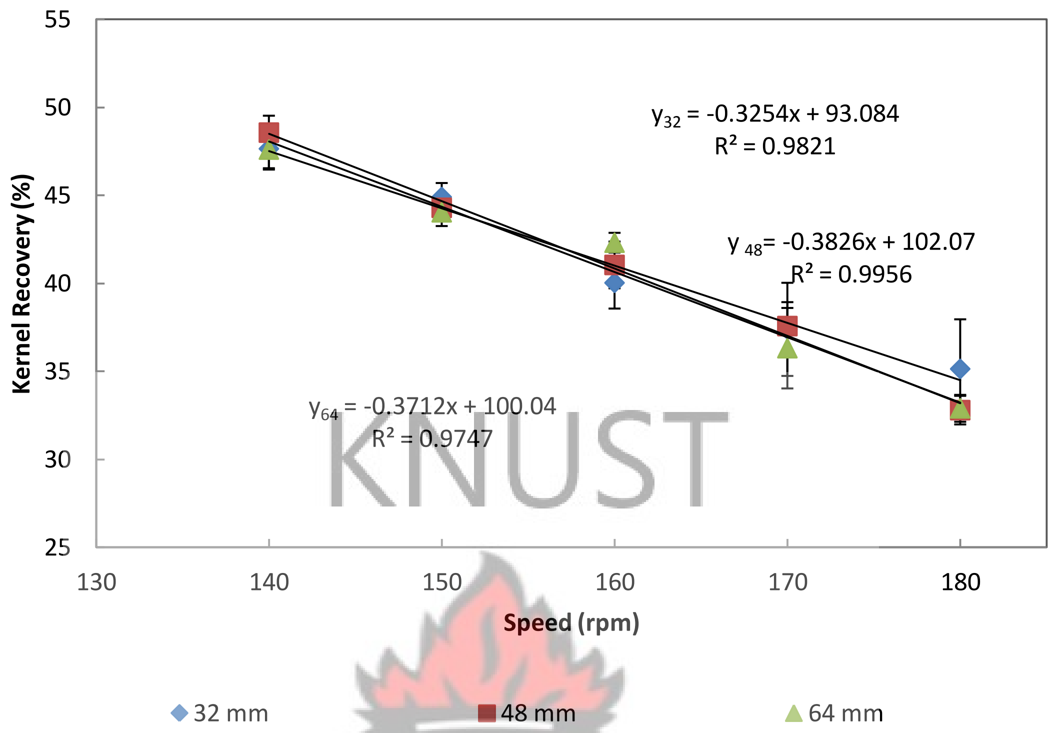

Figure 23: Kernel recovery at different operational speeds and feed gate openings

The feed gate openings gave results with no definite pattern (Figure 23). The results for different feed gate openings were very similar at each speed of operation. Table 11 also shows the 32 mm opening as having the highest percentage of kernels recovered, followed by the 48 mm, with the least at the 64 mm opening. At 140 rpm speed and 48 mm feed gate opening, the best result of 48.57 % for kernel recovery out of an average of 53.47 % (Appendix 7) of kernels that could be obtained from the seeds was recorded.

4.2.6 Cracking Efficiency

Figure 24 indicates the results for the efficiency of cracking the jatropha seeds at different speeds of operation and feed gate openings. Speed of operation had significant effect ($p < 0.01$) on cracking efficiency (Appendix 4f). There was an increase in the cracking efficiency as the speed increased from 140 rpm to 180 rpm even though these increases were not very great. However, the 150 rpm speed had cracking efficiencies higher than that of the 160 rpm speed for all the feed gate openings. The increase in cracking efficiency with speed was because the quantity of uncracked seeds decreased with increase in speed, making the efficiency of cracking higher at the higher speeds. This was in agreement with the result of Gupta and Das (1999) that dehulling efficiency of the centrifugal dehulling system for sunflower seeds increased with increase in impeller speed.

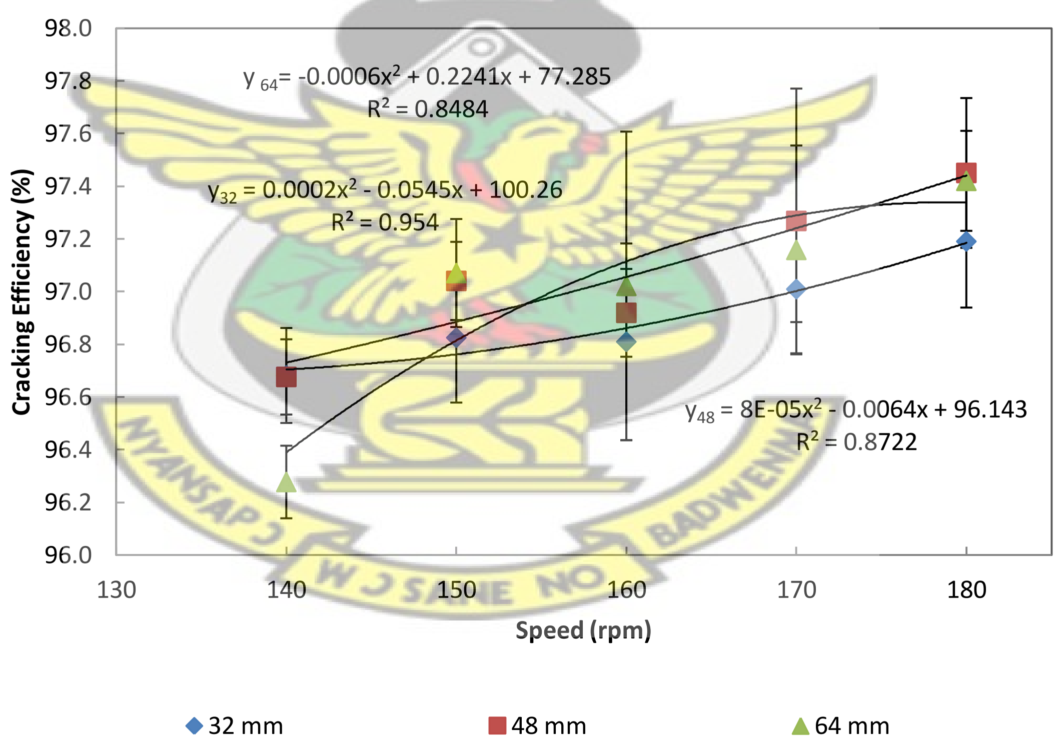

Figure 24: Cracking efficiency at different operational speeds and feed gate openings

Feed gate opening had no significant effect ($p < 0.05$) on cracking efficiencies as shown in Table 11. The 32 mm opening recorded the lowest efficiencies from the 150 rpm speed to the 180 rpm speed (Figure 24). Differences between the cracking efficiencies for the various feed gate openings were very small at all the speeds. However, Gupta and Das (1999) identified that, dehulling efficiency decreased as feed rate increased in the centrifugal dehulling system for sunflower seeds. Cracking efficiency in Table 11 is highest for the 48 mm opening and lowest for the 32 mm opening. The 180 rpm speed and 48 mm feed gate opening produced the highest cracking efficiency of 97.45 % but blower loss at this speed was very high (17.81 %). Hence, 96.68 % cracking efficiency at 140 rpm and 48 mm feed gate opening, which is only 0.80 % lower than the highest cracking efficiency (97.45 %) was chosen as the best for the operation of the cracker.

Table 10: Effect of speed of operation on cracking efficiency, kernel recovery and machine efficiency

Speed (rpm)	Kernel recovery (%)	Cracking Efficiency (%)	Machine Efficiency (%)
140	47.94^{a}	96.54^{a}	89.66^{a}
150	44.42^{b}	96.98^{b}	83.07^{b}
160	41.13^{c}	96.92^{abc}	76.93^{c}
170	37.10^{d}	97.14^{bc}	69.38^{d}
180	33.62^{e}	97.35^{b}	62.87^{e}

Means in the same column with different letters are significantly different at $p < 0.05$

Table 10 presents the statistical effect of speed of operation of the *Jatropha curcas* seed cracker on kernel recovery, cracking efficiency and machine efficiency. Also presented in Table 11 is the statistical effect of feed gate opening on the kernel recovery, cracking efficiency and machine efficiency of the cracker.

Table 11: Effect of feed gate opening on cracking efficiency, kernel recovery and machine efficiency

Feed gate opening (mm)	Kernel recovery (%)	Cracking Efficiency (%)	Machine Efficiency (%)
32	41.03	96.90	76.73
48	40.89	97.07	76.42
64	40.64	96.99	76.00

4.2.7 Machine Efficiency

The efficiency of the machine in cracking the *Jatropha curcas* seeds and recovering the kernels at different speeds and feed gate openings have been shown in Figure 25 and Tables 10 and 11. Speed of operation had very high significant effect ($p < 0.001$) on machine efficiency (Appendix 4g). There was a decrease in the machine efficiency as the speed of operation increased from 140 rpm to 180 rpm. The reductions in machine efficiency from 140 rpm to 180 rpm were 35.6 %, 48.1 % and 44.7 % for the 32 mm, 48 mm and 64 mm openings, respectively. This was because as the speed increased, the amount of kernels lost through blower losses increased leading to a reduction in the quantity of kernels recovered and hence the machine efficiency. Both Table 10 and Figure 25 show the reduction in machine efficiency with increase in speed of operation.

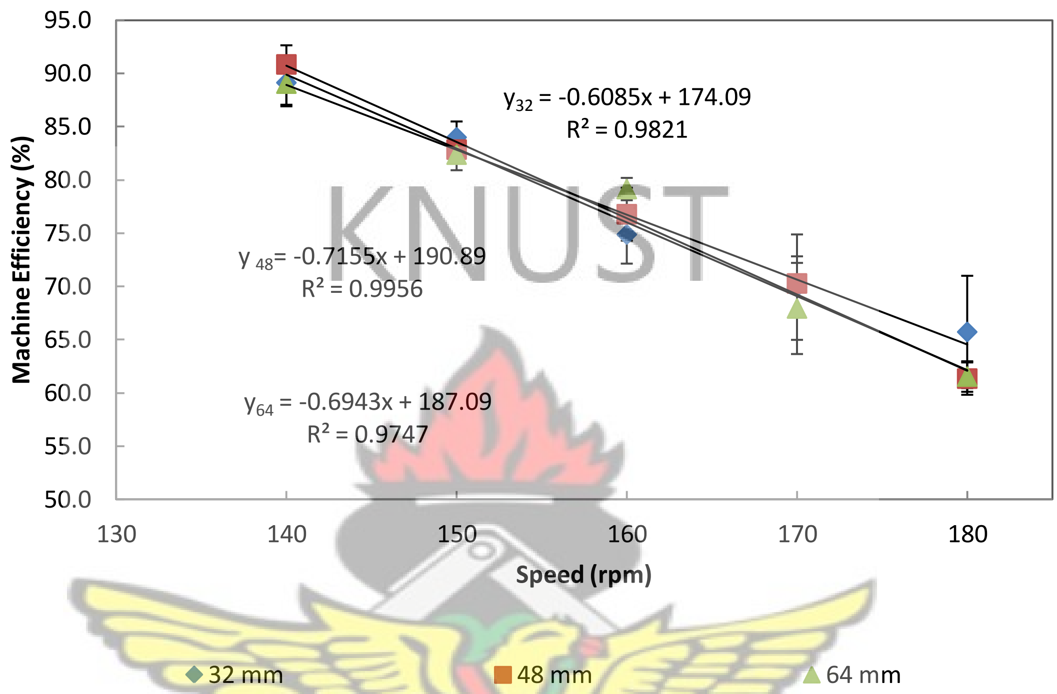

Figure 25: Machine efficiency at different operational speeds and feed gate openings

The feed gate opening had no significant effect on the machine efficiency. At each speed, the machine efficiencies for the 32 mm, 48 mm and 64 mm feed gate openings were very similar. The differences among them ranged from 0.1 % between efficiencies for 32 mm and 64 mm openings at the 140 rpm speed to 7. 2 % between efficiencies for 32 mm and 48 mm at the 180 rpm speed, indicating how close the values were. Table 11 also showed machine efficiency decreasing with increase in feed gate openings. The highest result for the machine efficiency was 90.84 %, produced by 140 rpm speed and 48 mm feed gate opening.

4.3 Results from Oil Extraction

The oil extraction was carried out with samples of *Jatropha curcas* seeds evaluated at different percentage husks (Table 12). The mean values of 58.2 (±1.06) % kernels and 41.8 (±1.06) % husks in *J. curcas* seeds (Appendix 5) were used to compute the weights of husks and kernels required in each sample for the oil extraction (Table 12).

Table 12: Composition of samples for chemical extraction of oil

Sample	Weight of husk (g)	Weight of kernels (g)	Total weight (g)
100 % Husk (uncracked)	41.8	58.2	100
40 % Husk	16.7	58.2	74.9
20 % Husk	8.4	58.2	66.6
0 % Husk (clean kernels)	0	58.2	58.2

The oil obtained from samples with different percentages of *Jatropha curcas* husks through chemical extraction method is shown in Figure 26. Oil yield increased with decrease in husk content from 100 % husk content or uncracked seeds to 0 % husk content or clean kernels. Volume of oil extracted, was maximum for the 0 % husk followed by the 20 % husk, a difference of 16.4 %. For the 40 % husk sample which followed the 20 % husk sample, the difference in yield was 17.4 %. The 100 % husk sample had the least oil yield, with 4.3 % difference from that at 40 % husk content. The difference between the maximum oil yield (0 % husk) and the minimum oil yield (100 % husk) was 40.1 %. This means an increase of 40.1 % in oil yield was achieved as a result of seed cracking. Also, Oil yields for the 20 % and 40 % husk samples were higher than that for the 100 % husk or uncracked seeds sample by 20.4 % and 4.3 %, respectively. This confirms the report of Shukla (2006) and Wim *et al*. (2007) that cracking of *Jatropha curcas* seeds for oil extraction can increase oil recovery and reduced oil retained in the seed cake. Oil yield from 0 % and 100 % husk content samples were significantly different (Appendix 6).

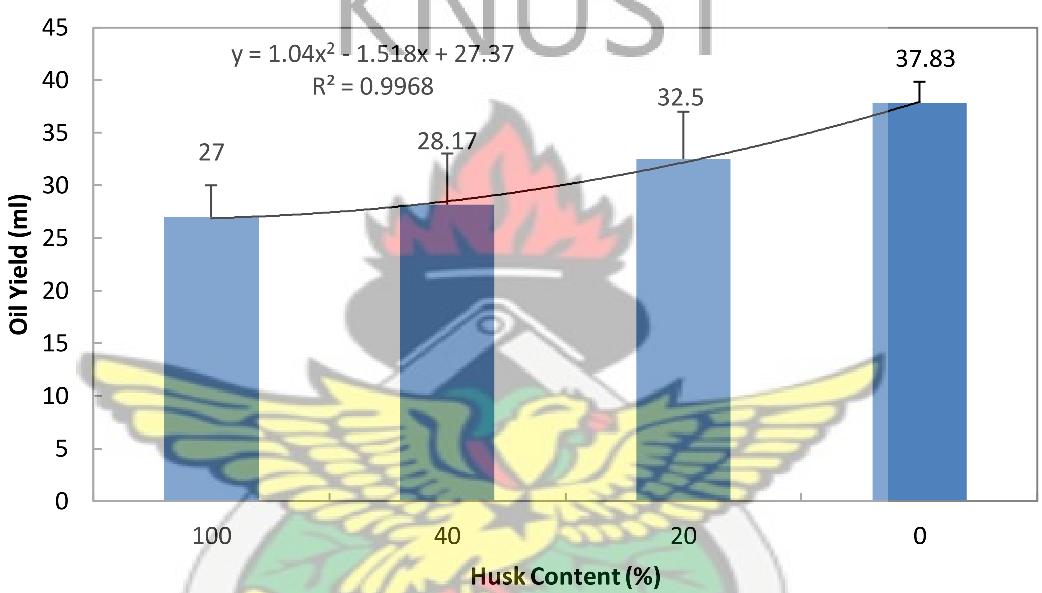

Figure 26: Volume of oil extracted from samples with different percentages of husk

The composition of *Jatropha curcas* oil in the kernel is quoted as 40-60 % (w/w) (Openshaw, 2000; Kumar and Sharma, 2008). Hence, assuming 60 % maximum oil content, the highest amount of oil that could be extracted from the 58.2 g of kernels is 34.92 g. Using the density of *Jatropha curcas* oil at 23°C as 0.863 g/ml (Hossain and Davies, 2010), the volume of maximum expected oil is 40.46 ml. With this value, it can be realised that the percentages of oil extracted from the samples were 66.7 %, 69.6 %, 80.3 % and 93.5 % for the 100 %, 40 %, 20 % and 0 % husk samples, respectively. These percentages were high considering the fact that the maximum percentage of extraction is 99 % using hexane as solvent, which gives slightly better oil yield compared to the petroleum ether used (Shah *et al.*, 2004; Shah *et al.*, 2005; Sayyar *et al.*, 2009).

The results obtained indicate that oil yield increased with decreasing husk content from 100 % husk content to the 0 % husk content. This agrees with the pattern reported by Wim *et al*. (2007) that oil yield decreased with increase in *Jatropha curcas* hull or husk content. That is, samples with 5 % husk gave the highest oil yield whiles that with 100 % husk (uncracked seeds) produced the least *Jatropha curcas* oil yield (Wim *et al*., 2007). This means cracking of *Jatropha curcas* seeds increases oil yield leading to efficient extraction of the oil. In effect, this ensures efficient use of the scarce land put under *J. curcas* cultivation and avoids adoption of cultivated farmlands for its production. Therefore, further experiments are recommended to investigate oil recovery, especially at the 11.35 % husk content, which is the husk composition associated with the recommended 140 rpm speed and 48 mm feed gate opening of the *Jatropha curcas* seed cracker.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The main results obtained after the modification and evaluation of the groundnut cracker for *Jatropha curcas* seeds have been summarised as follows:

1. The physical properties of *Jatropha curcas* seeds and kernels were determined for the design of the sieve and other components of the *Jatropha curcas* cracker.
    a. The *Jatropha curcas* seeds had 18.11 (±0.88) mm length, 11.47 (±0.49) mm equatorial diameter, 8.89 (±0.41) mm breadth, 12.84 (±0.47) mm arithmetic mean diameter, 12.26 (±0.44) mm geometric mean diameter, 0.68 (±0.02) sphericity, 398.46 (±27.84) mm^2 surface area, 0.63 (±0.03) aspect ratio and 541.33 (±0.49) g 1000-unit mass.
    b. *Jatropha curcas* kernels recorded 15.05 (±0.68) mm length, 9.05 (±0.60) mm equatorial diameter, 7.34 (±0.46) mm breadth, 10.44 (±0.46) mm arithmetic mean diameter, 9.99 (±0.46) mm geometric mean diameter, 0.66 (±0.02) sphericity, 264.74 (±24.12) mm^2 surface area, 0.60 (±0.04) aspect ratio and 402.00 (±0.49) g 1000-unit mass.
    c. Coefficient of static friction was highest on mild steel, followed by plywood then galvanised steel for both seeds and kernels. It was also higher for the kernels than the seeds for all surfaces. The seeds recorded 0.48 (±0.04), 0.39 (±0.02) and 0.32 (±0.01) for mild steel, plywood and galvanised steel, respectively while the kernels had 0.53 (±0.01), 0.42

(±0.01) and 0.41 (±0.03) for mild steel, plywood and galvanised steel, respectively.

d. Angle of repose by filling method was higher than emptying method for both seeds and kernels. Also, results for kernels were higher than that for the seeds in both methods. The seeds recorded 38.61 (±2.52) ° and 37.71 (±0.90) ° for the filling and emptying methods, respectively. The kernels also had 42.38 (±1.52) ° and 38.64 (±1.51) ° for the filling and emptying methods, respectively.

2. A sieve with hole size 10 mm in diameter was selected and designed for the *Jatropha curcas* seed cracker.
3. The *Jatropha curcas* seed cracker was evaluated at different operational speeds and feed gate openings with the following results:

   a. The capacity of the cracker increased with increase in feed gate openings 32 mm to 64 mm. Capacity of 1881.40 kg/h was observed to be maximum at 140 rpm speed for 64 mm feed gate opening but 1037.90 kg/h capacity at 140 rpm speed for 48 mm feed gate opening was chosen as best. This was to avoid possible clogging of the machine at the 64 mm feed gate opening.

   b. Blower losses from the cracker increased with increase in speed and feed gate openings. Blower loss of 2.40 % was lowest at 140 rpm speed for 32 mm feed gate opening but 2.76 % blower loss at 140 rpm for 48 mm feed gate opening was chosen as best due to the low capacity (129.05 kg/h) associated with the 140 rpm for 32 mm feed gate opening.

c. Cleanliness of the *Jatropha curcas* kernels increased with increase in speed of operation. Maximum cleanliness of 98.76 % was obtained from 180 rpm speed for 48 mm feed gate opening but cleanliness of 88.65 % (11.35 % husk content) at 140 rpm for 48 mm feed gate opening was selected as best due to the high level of blower loss (17.81 %) that goes with 180 rpm for 48 mm feed gate opening.

d. Percentage of uncracked seeds decreased with increase in speed of operation. The 180 rpm speed for 48 mm feed gate opening had 2.55 % uncracked seeds but 3.32 % uncracked seeds at 140 rpm for 48 mm feed gate opening was selected as best for the equipment. This was because of the high level of blower loss (17.81 %) connected to the 180 rpm for 48 mm feed gate opening.

e. Kernel recovery of the cracker decreased with increase in speed of operation. The 140 rpm speed for 48 mm feed gate opening gave the best results of 48.57 % kernel recovery.

f. Cracking efficiency of the cracker increased with increase in speed of operation. The 180 rpm speed for 48 mm feed gate opening produced the highest result of 97.45 % but 96.68 % cracking efficiency at 140 rpm for 48 mm feed gate opening was chosen as best for the *Jatropha curcas* seed cracker due to the high level of blower loss (17.81 %) associated with the 180 rpm for 48 mm feed gate opening.

g. Machine efficiency of the cracker decreased with increase in speed of operation. The best result of 90.84 % for the machine efficiency was produced by140 rpm speed and 48 mm feed gate opening.

h. Considering the conclusions for all the parameters measured, the 140 rpm speed at 48 mm feed gate opening performed best in the overall evaluation and is recommended for the operation of the *Jatropha curcas* seed cracker.

4. The 0 % husk content sample produced the maximum yield of oil at 93.5 % of oil extracted while the 100 % husk content sample produced the least amount of oil at 66.7 % of oil extracted.

5.2. RECOMMENDATIONS

The following recommendations are made:

a. The *Jatropha curcas* cracker should be evaluated at different seed moisture contents and cracking tyre pressures.

b. More research should be done on the extraction of oil especially at the 11.35 % husk content produced at the recommended 140 rpm speed and 48 mm feed gate opening of the *Jatropha curcas* seed cracker. This can be done by both chemical and mechanical methods of extraction to confirm or refute reports by other researchers.

c. Properties of the *Jatropha curcas* oil and biodiesel with different blends of the husk should be determined and their performances evaluated.

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APPENDICES

Appendix 1: Moisture content of seeds before cracking

Sample	Can (g)	Can + Seeds (g)	Can + Dried seeds (g)	Seeds (g)	Dried seeds (g)	Water (g)	MC, dry basis (%)
1	44	71.4	68.8	27.4	24.8	2.6	10.487
2	42.6	66	63.8	23.4	21.2	2.2	10.38
3	71.9	99.5	96.9	27.6	25	2.6	10.40
Average	**52.83**	**78.97**	**76.50**	**26.13**	**23.67**	**2.47**	**10.42**

Appendix 2

Appendix 2a: Physical properties of Jatropha Seeds

No.	Length (a), mm	Equatorial diameter(b),mm	Breadth(c), mm	Arithmetic mean diameter, mm	Geometric mean diameter, mm	Sphericity	d	Volume, mm^3	Surface area, mm^2	Aspect ratio
1	19.26	11.78	9.32	13.45	12.84	0.67	10.48	760.44	435.45	0.61
2	18.90	11.60	9.34	13.28	12.70	0.67	10.41	739.80	426.45	0.61
3	18.20	11.62	9.56	13.13	12.64	0.69	10.54	745.03	424.12	0.64
4	18.54	11.54	8.70	12.93	12.30	0.66	10.02	667.75	399.85	0.62
5	18.36	11.88	9.20	13.15	12.61	0.69	10.45	734.45	421.51	0.65
6	17.56	11.18	9.00	12.58	12.09	0.69	10.03	647.51	387.31	0.64
7	18.80	11.68	8.74	13.07	12.43	0.66	10.10	687.06	408.01	0.62

8	19.82	12.22	9.28	13.77	13.10	0.66	10.65	804.57	453.32	0.62
9	17.28	11.46	9.12	12.62	12.18	0.70	10.22	671.43	394.06	0.66
10	19.30	12.16	9.20	13.55	12.92	0.67	10.58	778.61	441.68	0.63
11	19.14	11.50	8.88	13.17	12.50	0.65	10.11	695.24	412.79	0.60
12	17.62	12.06	9.06	12.91	12.44	0.71	10.45	716.57	411.31	0.68
13	18.68	11.48	9.28	13.15	12.58	0.67	10.32	719.88	418.47	0.61
14	18.80	12.08	9.30	13.39	12.83	0.68	10.60	770.00	435.88	0.64
15	18.58	11.72	8.27	12.86	12.17	0.65	9.85	641.39	390.89	0.63
16	17.66	11.76	9.10	12.84	12.36	0.70	10.34	699.71	405.83	0.67
17	19.06	11.40	9.36	13.27	12.67	0.66	10.33	730.35	424.22	0.60
18	19.44	10.60	9.92	13.32	12.69	0.65	10.25	726.86	425.30	0.55
19	18.00	11.90	8.90	12.93	12.40	0.69	10.29	698.88	407.46	0.66
20	18.84	12.12	8.76	13.24	12.60	0.67	10.30	720.77	419.70	0.64
21	18.68	11.56	8.80	13.01	12.39	0.66	10.09	681.47	405.39	0.62
22	17.86	12.22	9.18	13.09	12.61	0.71	10.59	745.60	422.38	0.68
23	18.38	12.22	9.00	13.20	12.64	0.69	10.49	740.45	423.63	0.66
24	18.10	11.88	8.96	12.98	12.44	0.69	10.32	705.45	410.26	0.66
25	18.94	11.28	8.40	12.87	12.15	0.64	9.73	632.31	389.75	0.60
26	16.62	11.24	8.50	12.12	11.67	0.70	9.77	588.86	361.47	0.68
27	17.80	11.74	8.88	12.81	12.29	0.69	10.21	681.18	400.29	0.66
28	17.00	10.40	8.66	12.02	11.53	0.68	9.49	556.04	351.55	0.61
29	16.52	11.10	7.86	11.83	11.30	0.68	9.34	526.05	337.91	0.67
30	16.00	11.58	8.44	12.01	11.61	0.73	9.89	592.41	359.54	0.72
31	18.42	11.38	9.00	12.93	12.36	0.67	10.12	680.97	403.73	0.62
32	18.04	12.26	9.00	13.10	12.58	0.70	10.50	735.15	419.92	0.68
33	18.18	11.18	9.40	12.92	12.41	0.68	10.25	696.58	407.70	0.61

34	17.76	11.00	8.54	12.43	11.86	0.67	9.69	600.69	371.86	0.62
35	19.16	11.72	8.94	13.27	12.61	0.66	10.24	717.13	420.35	0.61
36	17.92	11.88	9.00	12.93	12.42	0.69	10.34	705.01	409.09	0.66
37	17.52	11.14	8.84	12.50	11.99	0.68	9.92	630.15	381.00	0.64
38	18.38	11.50	8.64	12.84	12.22	0.67	9.97	655.99	394.86	0.63
39	18.68	12.50	9.08	13.42	12.85	0.69	10.65	776.49	437.31	0.67
40	18.42	11.78	9.02	13.07	12.51	0.68	10.31	711.48	414.13	0.64
41	16.80	10.72	8.64	12.05	11.59	0.69	9.62	570.88	355.91	0.64
42	18.04	11.90	8.62	12.85	12.28	0.68	10.13	673.53	399.01	0.66
43	17.76	11.28	8.84	12.63	12.10	0.68	9.99	644.95	387.52	0.64
44	17.70	11.56	9.02	12.76	12.27	0.69	10.21	679.05	399.00	0.65
45	17.22	11.12	8.18	12.17	11.61	0.67	9.54	567.12	356.78	0.65
46	17.80	10.80	8.52	12.37	11.79	0.66	9.59	586.95	367.13	0.61
47	17.48	11.44	8.60	12.51	11.98	0.69	9.92	628.57	380.23	0.65
48	16.62	10.48	8.28	11.79	11.30	0.68	9.32	524.57	337.88	0.63
49	16.90	11.72	8.26	12.29	11.78	0.70	9.84	604.19	368.45	0.69
50	16.78	10.66	8.54	11.99	11.52	0.69	9.54	558.79	351.39	0.64
51	19.30	10.94	8.52	12.92	12.16	0.63	9.65	628.04	390.31	0.57
52	18.70	11.14	9.00	12.95	12.33	0.66	10.01	670.29	401.65	0.60
53	18.94	11.48	9.50	13.31	12.74	0.67	10.44	746.60	428.95	0.61
54	17.74	12.28	9.30	13.11	12.65	0.71	10.69	759.02	426.15	0.69
55	19.00	11.36	8.68	13.01	12.33	0.65	9.93	663.99	401.20	0.60
56	16.38	10.18	9.32	11.96	11.58	0.71	9.74	579.02	356.67	0.62
57	18.00	11.72	9.00	12.91	12.38	0.69	10.27	695.47	406.30	0.65
58	18.50	11.34	9.26	13.03	12.48	0.67	10.25	703.40	411.85	0.61
59	18.58	11.44	9.34	13.12	12.57	0.68	10.34	720.03	417.94	0.62

60	19.32	11.40	9.10	13.27	12.61	0.65	10.19	712.53	419.74	0.59
61	17.86	12.48	9.30	13.21	12.75	0.71	10.77	777.04	432.76	0.70
62	18.44	11.60	8.54	12.86	12.22	0.66	9.95	655.01	394.86	0.63
63	19.34	11.72	9.00	13.35	12.68	0.66	10.27	727.14	424.80	0.61
64	17.64	10.96	10.12	12.91	12.51	0.71	10.53	730.20	416.00	0.62
65	18.16	11.88	9.22	13.09	12.58	0.69	10.47	731.56	419.40	0.65
66	18.58	11.48	8.72	12.93	12.30	0.66	10.01	666.35	399.60	0.62
67	17.54	11.16	8.66	12.45	11.92	0.68	9.83	616.59	376.32	0.64
68	19.68	11.60	9.32	13.53	12.86	0.65	10.40	756.99	436.82	0.59
69	19.76	11.78	9.34	13.63	12.95	0.66	10.49	774.83	443.21	0.60
70	19.00	11.62	9.16	13.26	12.65	0.67	10.32	726.76	422.66	0.61
71	17.66	11.74	8.66	12.69	12.15	0.69	10.08	657.85	391.46	0.66
72	17.42	11.48	8.86	12.59	12.10	0.69	10.09	652.85	388.40	0.66
73	17.40	11.34	8.76	12.50	12.00	0.69	9.97	634.14	381.75	0.65
74	18.28	11.00	8.82	12.70	12.10	0.66	9.85	635.53	387.13	0.60
75	18.04	11.48	9.18	12.90	12.39	0.69	10.27	695.66	406.59	0.64
76	19.88	11.92	9.18	13.66	12.96	0.65	10.46	772.85	443.29	0.60
77	18.76	12.42	9.18	13.45	12.88	0.69	10.68	782.73	439.82	0.66
78	18.20	11.42	8.26	12.63	11.97	0.66	9.71	613.02	378.71	0.63
79	18.26	10.42	9.76	12.81	12.29	0.67	10.08	671.63	399.60	0.57
80	17.66	11.42	8.30	12.46	11.87	0.67	9.74	605.00	372.85	0.65
81	18.40	11.32	8.66	12.79	12.17	0.66	9.90	646.05	391.50	0.62
82	17.34	11.24	8.80	12.46	11.97	0.69	9.95	629.57	379.81	0.65
83	18.20	11.54	8.82	12.85	12.28	0.67	10.09	670.93	399.01	0.63
84	17.80	11.80	8.98	12.86	12.36	0.69	10.29	694.66	404.90	0.66
85	16.84	11.28	8.54	12.22	11.75	0.70	9.81	599.36	366.40	0.67
86	19.42	11.60	8.98	13.33	12.65	0.65	10.21	718.38	422.32	0.60

87	17.06	10.90	8.32	12.09	11.57	0.68	9.52	561.86	354.00	0.64
88	17.48	11.72	9.10	12.77	12.31	0.70	10.33	692.69	402.44	0.67
89	18.00	11.98	8.72	12.90	12.34	0.69	10.22	687.46	403.56	0.67
90	18.02	10.90	8.50	12.47	11.86	0.66	9.63	596.36	371.74	0.60
91	18.74	11.50	9.48	13.24	12.69	0.68	10.44	741.41	426.05	0.61
92	15.92	10.50	8.16	11.53	11.09	0.70	9.26	503.47	326.35	0.66
93	18.24	11.14	8.72	12.70	12.10	0.66	9.86	635.59	386.93	0.61
94	19.52	11.34	9.26	13.37	12.70	0.65	10.25	727.61	426.03	0.58
95	17.56	10.86	8.24	12.22	11.63	0.66	9.46	563.05	357.12	0.62
96	16.76	10.90	8.20	11.95	11.44	0.68	9.45	546.24	346.67	0.65
97	18.54	11.46	9.00	13.00	12.41	0.67	10.16	689.45	407.32	0.62
98	16.58	10.42	8.36	11.79	11.30	0.68	9.33	526.23	338.29	0.63
99	17.64	11.38	8.10	12.37	11.76	0.67	9.60	584.85	365.50	0.65
100	17.30	12.10	8.34	12.58	12.04	0.70	10.05	644.04	384.67	0.70
Mean	**18.11 (±0.88)**	**11.47 (±0.49)**	**8.89 (±0.41)**	**12.82 (±0.47)**	**12.26 (±0.44)**	**0.68 (±0.02)**	**10.09 (±0.36)**	**671.76 (±68.80)**	**398.46 (±27.84)**	**0.63 (±0.03)**

Appendix 2b: Physical properties of *Jatropha curcas* kernels

No.	Length (a), mm	Equatorial diameter(b),mm	Breadth(c), mm	Arithmetic mean diameter, mm	Geometric mean diameter, mm	Sphericity	d	Volume, mm^3	Surface area, mm^2	Aspect ratio
1	14.72	8.34	6.90	9.99	9.46	0.64	7.59	298.74	236.29	0.57
2	16.12	8.92	7.58	10.87	10.29	0.64	8.22	383.04	279.49	0.55
3	15.70	9.46	7.76	10.97	10.48	0.67	8.57	414.96	290.59	0.60

4	15.50	9.34	7.26	10.70	10.17	0.66	8.23	374.69	273.01	0.60
5	14.06	9.80	7.20	10.35	9.97	0.71	8.40	370.36	264.54	0.70
6	15.54	9.56	7.56	10.89	10.39	0.67	8.50	404.75	285.66	0.62
7	15.64	9.32	7.62	10.86	10.36	0.66	8.43	398.02	283.38	0.60
8	15.76	9.76	7.42	10.98	10.45	0.66	8.51	409.31	288.58	0.62
9	15.08	9.24	7.56	10.63	10.17	0.67	8.36	381.50	273.87	0.61
10	14.48	9.24	7.58	10.43	10.05	0.69	8.37	373.42	267.72	0.64
11	14.50	8.50	6.58	9.86	9.33	0.64	7.48	286.09	229.53	0.59
12	16.38	9.96	7.74	11.36	10.81	0.66	8.78	451.63	308.62	0.61
13	14.72	8.32	6.18	9.74	9.11	0.62	7.17	261.95	219.19	0.57
14	15.80	9.36	7.10	10.75	10.16	0.64	8.15	370.46	272.66	0.59
15	15.54	9.54	7.24	10.77	10.24	0.66	8.31	383.57	276.92	0.61
16	15.82	9.92	7.52	11.09	10.57	0.67	8.64	424.97	295.22	0.63
17	14.50	8.36	7.46	10.11	9.67	0.67	7.90	325.34	247.18	0.58
18	14.86	9.22	7.84	10.64	10.24	0.69	8.50	393.89	277.98	0.62
19	14.54	9.76	7.88	10.73	10.38	0.71	8.77	419.17	286.78	0.67
20	16.66	9.92	8.10	11.56	11.02	0.66	8.96	479.44	320.92	0.60
21	15.46	9.20	7.70	10.79	10.31	0.67	8.42	393.96	280.84	0.60
22	15.20	9.24	7.16	10.53	10.02	0.66	8.13	359.44	265.14	0.61
23	15.18	9.42	7.52	10.71	10.25	0.67	8.42	389.50	277.67	0.62
24	14.00	8.16	7.46	9.87	9.48	0.68	7.80	309.30	237.86	0.58
25	15.18	8.74	7.98	10.63	10.19	0.67	8.35	382.35	274.70	0.58
26	15.00	8.84	6.80	10.21	9.66	0.64	7.75	318.33	246.35	0.59
27	15.48	9.38	7.46	10.77	10.27	0.66	8.37	388.57	278.71	0.61
28	15.52	9.18	7.52	10.74	10.23	0.66	8.31	383.02	276.59	0.59
29	15.34	9.16	7.66	10.72	10.25	0.67	8.38	387.61	277.64	0.60
30	14.06	8.34	7.08	9.83	9.40	0.67	7.68	299.07	233.52	0.59

31	14.62	9.00	7.66	10.43	10.03	0.69	8.30	368.51	266.30	0.62
32	15.14	9.20	7.48	10.61	10.14	0.67	8.30	375.69	271.73	0.61
33	15.74	8.30	6.54	10.19	9.49	0.60	7.37	292.03	237.82	0.53
34	14.74	9.70	6.92	10.45	9.96	0.68	8.19	358.72	262.70	0.66
35	14.42	8.84	7.74	10.33	9.96	0.69	8.27	362.18	262.71	0.61
36	14.40	8.34	6.56	9.77	9.24	0.64	7.40	277.53	225.13	0.58
37	14.42	9.22	6.76	10.13	9.65	0.67	7.89	323.98	246.23	0.64
38	16.24	10.16	7.68	11.36	10.82	0.67	8.83	455.68	309.51	0.63
39	15.86	9.16	7.40	10.81	10.24	0.65	8.23	380.11	277.01	0.58
40	14.88	9.08	7.38	10.45	9.99	0.67	8.19	360.09	263.93	0.61
41	15.20	9.28	7.44	10.64	10.16	0.67	8.31	378.09	273.02	0.61
42	13.90	8.58	6.78	9.75	9.32	0.67	7.63	291.73	229.49	0.62
43	15.20	8.04	6.52	9.92	9.27	0.61	7.24	273.81	226.91	0.53
44	13.58	9.08	7.12	9.93	9.58	0.71	8.04	326.50	243.64	0.67
45	14.64	9.60	7.72	10.65	10.28	0.70	8.61	402.35	280.42	0.66
46	15.06	9.84	7.48	10.79	10.35	0.69	8.58	405.77	283.78	0.65
47	14.60	10.20	7.66	10.82	10.45	0.72	8.84	428.29	290.72	0.70
48	15.12	8.96	7.88	10.65	10.22	0.68	8.40	387.02	276.36	0.59
49	15.30	9.46	7.72	10.83	10.38	0.68	8.55	405.88	284.97	0.62
50	15.34	7.64	6.16	9.71	8.97	0.58	6.86	243.44	212.91	0.50
51	15.86	8.80	8.14	10.93	10.43	0.66	8.46	405.67	287.59	0.55
52	16.00	9.44	6.86	10.77	10.12	0.63	8.05	362.39	270.20	0.59
53	15.70	9.58	7.04	10.77	10.19	0.65	8.21	375.39	274.26	0.61
54	14.50	8.50	8.08	10.36	9.99	0.69	8.29	365.03	264.28	0.59
55	16.22	9.40	7.70	11.11	10.55	0.65	8.51	416.61	293.82	0.58
56	15.94	9.62	7.72	11.09	10.58	0.66	8.62	424.73	295.71	0.60
57	15.52	9.16	7.68	10.79	10.30	0.66	8.39	391.67	280.18	0.59

58	15.16	9.14	7.50	10.60	10.13	0.67	8.28	374.27	271.23	0.60
59	15.26	9.08	6.66	10.33	9.74	0.64	7.78	324.20	250.14	0.60
60	15.94	9.54	7.90	11.13	10.63	0.67	8.68	432.20	298.71	0.60
61	15.40	9.10	8.00	10.83	10.39	0.67	8.53	405.97	285.48	0.59
62	15.06	8.64	7.42	10.37	9.88	0.66	8.01	344.28	257.99	0.57
63	15.56	9.86	7.52	10.98	10.49	0.67	8.61	417.59	290.98	0.63
64	15.00	9.78	6.96	10.58	10.07	0.67	8.25	368.70	268.14	0.65
65	14.16	8.94	7.46	10.19	9.81	0.69	8.17	347.42	255.25	0.63
66	15.40	9.12	7.88	10.80	10.34	0.67	8.48	399.77	282.95	0.59
67	14.60	8.04	7.14	9.93	9.43	0.65	7.58	296.30	234.64	0.55
68	15.20	9.22	7.86	10.76	10.33	0.68	8.51	400.54	282.31	0.61
69	15.14	7.64	7.10	9.96	9.36	0.62	7.37	284.11	231.45	0.50
70	15.36	10.20	7.46	11.01	10.53	0.69	8.72	427.32	293.93	0.66
71	15.56	8.58	8.18	10.77	10.30	0.66	8.38	391.22	280.19	0.55
72	14.80	9.70	7.88	10.79	10.42	0.70	8.74	420.30	288.45	0.66
73	14.90	8.54	7.36	10.27	9.78	0.66	7.93	334.06	252.82	0.57
74	14.48	9.16	7.36	10.33	9.92	0.69	8.21	356.70	260.66	0.63
75	15.58	8.24	6.68	10.17	9.50	0.61	7.42	294.67	238.31	0.53
76	14.74	9.62	7.64	10.67	10.27	0.70	8.57	399.92	279.89	0.65
77	16.20	9.50	7.50	11.07	10.49	0.65	8.44	408.64	290.47	0.59
78	15.24	9.42	7.46	10.71	10.23	0.67	8.38	386.74	276.81	0.62
79	14.74	8.74	7.32	10.27	9.81	0.67	8.00	338.81	254.15	0.59
80	14.40	8.94	6.44	9.93	9.39	0.65	7.59	294.69	233.02	0.62
81	15.38	9.60	7.36	10.78	10.28	0.67	8.41	391.47	279.43	0.62
82	14.22	8.34	6.48	9.68	9.16	0.64	7.35	271.33	221.45	0.59
83	15.20	9.54	7.36	10.70	10.22	0.67	8.38	385.73	276.20	0.63
84	14.92	8.70	7.46	10.36	9.89	0.66	8.06	347.26	258.63	0.58

85	14.70	9.24	7.50	10.48	10.06	0.68	8.32	372.04	268.15	0.63
86	15.10	9.10	7.22	10.47	9.97	0.66	8.11	355.02	262.79	0.60
87	15.00	8.84	7.52	10.45	9.99	0.67	8.15	358.48	263.80	0.59
88	13.02	7.54	7.36	9.31	8.97	0.69	7.45	264.96	213.40	0.58
89	15.20	9.12	7.42	10.58	10.09	0.66	8.23	369.19	269.28	0.60
90	15.22	9.06	7.12	10.47	9.94	0.65	8.03	349.16	260.84	0.60
91	14.32	7.16	6.14	9.21	8.57	0.60	6.63	214.46	194.07	0.50
92	14.28	8.38	6.98	9.88	9.42	0.66	7.65	298.65	234.29	0.59
93	14.18	8.50	6.68	9.79	9.30	0.66	7.54	287.06	228.57	0.60
94	14.26	9.32	7.00	10.19	9.76	0.68	8.08	339.79	252.41	0.65
95	15.00	9.26	7.08	10.45	9.94	0.66	8.10	352.63	261.31	0.62
96	15.06	8.74	7.16	10.32	9.80	0.65	7.91	334.61	253.79	0.58
97	15.80	9.16	7.88	10.95	10.45	0.66	8.50	408.36	288.39	0.58
98	13.22	8.38	7.40	9.67	9.36	0.71	7.87	305.66	232.89	0.63
99	14.32	8.54	7.46	10.11	9.70	0.68	7.98	331.12	248.91	0.60
100	14.06	8.46	6.76	9.76	9.30	0.66	7.56	287.95	228.46	0.60
Mean	**15.05 (±0.68)**	**9.05 (±0.60)**	**7.34 (±0.46)**	**10.48 (±0.46)**	**9.99 (±0.46)**	**0.66 (±0.02)**	**8.15 (±0.45)**	**361.29 (±51.04)**	**264.74 (±24.12)**	**0.60 (±0.04)**

Appendix 2c: 1000-unit mass for *Jatropha curcas* seeds and kernels

Sample	Seeds	Kernels
1	54.70	39.90
2	53.90	40.30
3	53.80	40.40
Mean	54.13	40.20
100-unit mass	541.33 (±0.49)	402.00 (±0.26)

Appendix 2d: Coefficient of static friction for *Jatropha curcas* seeds on different surfaces

SampleNo.	Plywood		Galvanised steel		Mild steel	
	Angle	Coefficient	Angle	Coefficient	Angle	Coefficient
1	20.50	0.37	17.50	0.32	27.50	0.52
2	21.50	0.39	17.00	0.31	25.50	0.48
3	22.50	0.41	18.00	0.32	24.00	0.45
Mean	**21.50 (±1.00)**	**0.39 (±0.02)**	**17.50 (±0.50)**	**0.32 (±0.01)**	**25.67 (±1.76)**	**0.48 (±0.04)**

Appendix 2e: Coefficient of static friction for *Jatropha curcas* kernels on different surfaces

SampleNo.	Plywood		Galvanised steel		Mild steel	
	Angle	Coefficient	Angle	Coefficient	Angle	Coefficient
1	22.50	0.41	22.50	0.41	28.00	0.53
2	23.50	0.43	23.50	0.43	28.00	0.53
3	23.00	0.42	21.00	0.38	27.50	0.52
Mean	**23.00 (±0.50)**	**0.42 (±0.01)**	**22.33 (±1.26)**	**0.41 (±0.03)**	**27.83 (±0.29)**	**0.53 (±0.01)**

Appendix 2f: Angle of repose for *Jatropha curcas* seeds by filling and emptying methods (r = 100 mm)

Sample No.	Filling			Emptying		
	height of cone, h (mm)	h/r	Angle	height of cone, h (mm)	h/r	Angle
1	76.00	0.76	37.23	77.00	0.77	37.60
2	88.00	0.88	41.35	75.00	0.75	36.87
3	76.00	0.76	37.23	80.00	0.80	38.66
Mean	**80.00 (±6.93)**	**0.80 (±0.07)**	**38.61 (±2.37)**	**77.33 (±2.52)**	**0.77 (±0.03)**	**37.71 (±0.90)**

Appendix 2g: Angle of repose for *Jatropha curcas* kernels by filling and emptying methods (r = 100 mm)

Sample No.	Filling			Emptying		
	height of cone, h (mm)	h/r	Angle	height of cone, h (mm)	h/r	Angle
1	88.00	0.88	41.35	85.00	0.85	40.36
2	97.00	0.97	44.13	78.00	0.78	37.95
3	89.00	0.89	41.67	77.00	0.77	37.60
Mean	**91.33 (±4.93)**	**0.91 (±0.05)**	**42.38 (±1.52)**	**80.00 (±4.36)**	**0.80 (±0.04)**	**38.64 (±1.51)**

Appendix 3: Clearance between cracking sieve and tyre in cracking unit

Sample No.	Position		
	Blower Pulley side	Middle	Motor Pulley side
1	18	15	21
2	18	15	20
3	19	16	20
4	17	17	17
5	18	15	17
6	17	13	18
7	17	13	18
8	19	12	17

9	17	12	18
10	21	14	19
11	19	13	18
12	19	14	19
Mean	**18.25 (±1.22)**	**14.08 (±1.56)**	**18.5 (±1.31)**

Appendix 4: Minitab Statistical Results of Data from Machine Cracking

Appendix 4a: General Linear Model – Capacity (kg/h) versus Speed (rpm), Opening (mm)

```
Factor         Type   Levels  Values
Speed (rpm)    fixed       5  140, 150, 160, 170, 180
Opening (mm)   fixed       3  32, 48, 64


Analysis of Variance for Capacity (kg/h), using Adjusted SS for Tests

Source         DF   Seq SS   Adj SS   Adj MS        F      P
Speed (rpm)     4    14730    14730     3682     1.28  0.355
Opening (mm)    2  6495245  6495245  3247622  1125.74  0.000
Error           8    23079    23079     2885
Total          14  6533053


S = 53.7110   R-Sq = 99.65%   R-Sq(adj) = 99.38%


Unusual Observations for Capacity (kg/h)

     Capacity
Obs    (kg/h)      Fit  SE Fit  Residual  St Resid
  1    129.05   218.83   36.69    -89.78     -2.29 R

R denotes an observation with a large standardized residual.


Least Squares Means for Capacity (kg/h)

Speed (rpm)      Mean  SE Mean
140            1016.1    31.01
150             971.3    31.01
160             917.7    31.01
170             971.6    31.01
180             976.4    31.01
Opening (mm)
32              173.3    24.02
48              953.6    24.02
64             1784.9    24.02


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Capacity (kg/h)
```

```
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed
(rpm)    Lower  Center   Upper  -------+---------+---------+---------
150     -196.5  -44.83  106.81      (---------*---------)
160     -250.1  -98.46   53.18  (---------*----------)
170     -196.1  -44.48  107.16      (---------*---------)
180     -191.3  -39.68  111.95      (---------*---------)
                                -------+---------+---------+---------
                                    -150         0       150


Speed (rpm) = 150  subtracted from:

Speed
(rpm)    Lower  Center   Upper  -------+---------+---------+---------
160     -205.3  -53.63   98.01     (---------*----------)
170     -151.3    0.34  151.98         (---------*---------)
180     -146.5    5.14  156.78         (---------*---------)
                                -------+---------+---------+---------
                                    -150         0       150


Speed (rpm) = 160  subtracted from:

Speed
(rpm)    Lower  Center  Upper  -------+---------+---------+---------
170     -97.67   53.97  205.6            (----------*---------)
180     -92.87   58.77  210.4             (---------*---------)
                               -------+---------+---------+---------
                                   -150         0       150


Speed (rpm) = 170  subtracted from:

Speed
(rpm)    Lower  Center  Upper  -------+---------+---------+---------
180     -146.8   4.798  156.4         (---------*---------)
                               -------+---------+---------+---------
                                   -150         0       150


Tukey Simultaneous Tests
Response Variable Capacity (kg/h)
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference        SE of             Adjusted
(rpm)    of Means   Difference  T-Value     P-Value
150        -44.83        43.85   -1.022      0.8387
160        -98.46        43.85   -2.245      0.2550
170        -44.48        43.85   -1.014      0.8422
180        -39.68        43.85   -0.905      0.8874


Speed (rpm) = 150  subtracted from:

Speed  Difference        SE of             Adjusted
(rpm)    of Means   Difference  T-Value     P-Value
160        -53.63        43.85   -1.223      0.7401
```

```
170           0.34       43.85    0.008    1.0000
180           5.14       43.85    0.117    0.9999


Speed (rpm) = 160  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
170         53.97       43.85    1.231    0.7359
180         58.77       43.85    1.340    0.6770


Speed (rpm) = 170  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
180         4.798       43.85   0.1094     1.000


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Capacity (kg/h)
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)       Lower  Center   Upper  -------+---------+---------+---------
48         683.2   780.3   877.3  (--*--)
64        1514.6  1611.6  1708.6                              (---*--)
                                  -------+---------+---------+---------
                                       900      1200      1500


Opening (mm) = 48  subtracted from:

Opening
(mm)      Lower  Center  Upper  -------+---------+---------+---------
64        734.3   831.3  928.4   (---*--)
                                -------+---------+---------+---------
                                     900      1200      1500


Tukey Simultaneous Tests
Response Variable Capacity (kg/h)
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
48            780.3       33.97    22.97    0.0000
64           1611.6       33.97    47.44    0.0000


Opening (mm) = 48  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
64            831.3       33.97    24.47    0.0000
```

Appendix 4b: General Linear Model – Blower Losses versus Speed (rpm), Opening (mm)

Factor	Type	Levels	Values
Speed (rpm)	fixed	5	140, 150, 160, 170, 180
Opening (mm)	fixed	3	32, 48, 64

Analysis of Variance for Blower Losses, using Adjusted SS for Tests

Source	DF	Seq SS	AdjSS	Adj MS	F	P
Speed (rpm)	4	347.786	347.786	86.947	136.56	0.000
Opening (mm)	2	14.170	14.170	7.085	11.13	0.005
Error	8	5.094	5.094	0.637		
Total	14	367.050				

S = 0.797939   R-Sq = 98.61%   R-Sq(adj) = 97.57%

Unusual Observations for Blower Losses

Obs	Blower Losses	Fit	SE Fit	Residual	St Resid
13	14.0122	15.4752	0.5451	-1.4630	-2.51 R
14	17.8089	16.5534	0.5451	1.2555	2.15 R

R denotes an observation with a large standardized residual.

Least Squares Means for Blower Losses

Speed (rpm)	Mean	SE Mean
140	3.098	0.4607
150	5.520	0.4607
160	8.514	0.4607
170	12.285	0.4607
180	16.627	0.4607
Opening (mm)		
32	8.057	0.3568
48	9.135	0.3568
64	10.434	0.3568

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Blower Losses
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140 subtracted from:

```
Speed
(rpm)     Lower  Center   Upper    +---------+---------+---------+------
150      0.1691   2.422   4.675    (----*---)
160      3.1639   5.417   7.669          (----*---)
170      6.9343   9.187  11.440                  (---*----)
180     11.2765  13.529  15.782                           (---*----)
                                   +---------+---------+---------+------
                                 0.0       5.0      10.0      15.0
```

Speed (rpm) = 150 subtracted from:

```
Speed
(rpm)    Lower  Center   Upper    +---------+---------+---------+------
160    0.7420   2.995   5.248     (----*---)
170    4.5124   6.765   9.018             (----*---)
180    8.8546  11.107  13.360                      (---*----)
                                  +---------+---------+---------+------
                                0.0       5.0      10.0      15.0


Speed (rpm) = 160  subtracted from:

Speed
(rpm)  Lower  Center   Upper    +---------+---------+---------+------
170    1.518   3.770   6.023       (----*---)
180    5.860   8.113  10.365                (---*----)
                                +---------+---------+---------+------
                              0.0       5.0      10.0      15.0


Speed (rpm) = 170  subtracted from:

Speed
(rpm)  Lower  Center  Upper    +---------+---------+---------+------
180    2.089   4.342  6.595        (----*---)
                               +---------+---------+---------+------
                             0.0       5.0      10.0      15.0
```

Tukey Simultaneous Tests
Response Variable Blower Losses
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140 subtracted from:

Speed (rpm)	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
150	2.422	0.6515	3.717	0.0351
160	5.417	0.6515	8.314	0.0002
170	9.187	0.6515	14.101	0.0000
180	13.529	0.6515	20.766	0.0000

Speed (rpm) = 150 subtracted from:

Speed (rpm)	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
160	2.995	0.6515	4.597	0.0112
170	6.765	0.6515	10.384	0.0001
180	11.107	0.6515	17.049	0.0000

Speed (rpm) = 160 subtracted from:

Speed (rpm)	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
170	3.770	0.6515	5.787	0.0027
180	8.113	0.6515	12.452	0.0000

Speed (rpm) = 170 subtracted from:

Speed Difference   SE of   Adjusted

```
(rpm)     of Means  Difference  T-Value   P-Value
180          4.342      0.6515    6.665    0.0011


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Blower Losses
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)         Lower  Center  Upper  ---+---------+---------+---------+---
48         -0.3634   1.078  2.520  (-----------*-----------)
64          0.9357   2.377  3.819            (-----------*-----------)
                                   ---+---------+---------+---------+---
                                    0.0       1.2       2.4       3.6


Opening (mm) = 48  subtracted from:

Opening
(mm)         Lower  Center  Upper  ---+---------+---------+---------+---
64         -0.1426   1.299  2.741    (-----------*-----------)
                                   ---+---------+---------+---------+---
                                    0.0       1.2       2.4       3.6


Tukey Simultaneous Tests
Response Variable Blower Losses
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of            Adjusted
(mm)       of Means  Difference  T-Value    P-Value
48            1.078      0.5047    2.137     0.1435
64            2.377      0.5047    4.711     0.0038


Opening (mm) = 48  subtracted from:

Opening  Difference       SE of            Adjusted
(mm)       of Means  Difference  T-Value    P-Value
64            1.299      0.5047    2.574     0.0759
```

Appendix 4c: General Linear Model – Cleanliness versus Speed (rpm), Opening (mm)

```
Factor         Type   Levels  Values
Speed (rpm)    fixed       5  140, 150, 160, 170, 180
Opening (mm)   fixed       3  32, 48, 64


Analysis of Variance for Cleanliness, using Adjusted SS for Tests

Source         DF   Seq SS   AdjSS  Adj MS      F      P
Speed (rpm)     4  199.973  199.973  49.993  43.56  0.000
Opening (mm)    2    3.333    3.333   1.667   1.45  0.290
Error           8    9.182    9.182   1.148
Total          14  212.487
```

```
S = 1.07130   R-Sq = 95.68%   R-Sq(adj) = 92.44%


Unusual Observations for Cleanliness

Obs  Cleanliness      Fit  SE Fit  Residual  St Resid
  1      85.9483  87.9102  0.7318   -1.9619     -2.51 R
  3      90.7649  89.0597  0.7318    1.7052      2.18 R

R denotes an observation with a large standardized residual.


Least Squares Means for Cleanliness

Speed (rpm)    Mean  SE Mean
140           88.45   0.6185
150           93.67   0.6185
160           96.56   0.6185
170           97.64   0.6185
180           98.55   0.6185
Opening (mm)
32            94.43   0.4791
48            94.91   0.4791
64            95.58   0.4791


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Cleanliness
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed
(rpm)  Lower  Center   Upper  ----+---------+---------+---------+--
150    2.188   5.212   8.237          (-----*-----)
160    5.085   8.109  11.134                (-----*-----)
170    6.165   9.189  12.214                  (-----*-----)
180    7.071  10.096  13.120                    (-----*-----)
                              ----+---------+---------+---------+--
                                0.0       5.0      10.0      15.0


Speed (rpm) = 150  subtracted from:

Speed
(rpm)    Lower  Center  Upper  ----+---------+---------+---------+--
160    -0.1274   2.897  5.922      (-----*-----)
170     0.9526   3.977  7.002        (-----*-----)
180     1.8589   4.883  7.908          (-----*-----)
                               ----+---------+---------+---------+--
                                 0.0       5.0      10.0      15.0


Speed (rpm) = 160  subtracted from:

Speed
(rpm)   Lower  Center  Upper  ----+---------+---------+---------+--
170    -1.945   1.080  4.105  (-----*-----)
180    -1.038   1.986  5.011    (-----*-----)
                              ----+---------+---------+---------+--
                                0.0       5.0      10.0      15.0
```

```
Speed (rpm) = 170  subtracted from:

Speed
(rpm)    Lower  Center  Upper  ----+---------+---------+---------+--
180     -2.118  0.9063  3.931  (-----*-----)
                               ----+---------+---------+---------+--
                                 0.0       5.0      10.0      15.0


Tukey Simultaneous Tests
Response Variable Cleanliness
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference        SE of            Adjusted
(rpm)    of Means   Difference  T-Value    P-Value
150         5.212       0.8747    5.959     0.0023
160         8.109       0.8747    9.271     0.0001
170         9.189       0.8747   10.506     0.0000
180        10.096       0.8747   11.542     0.0000


Speed (rpm) = 150  subtracted from:

Speed  Difference        SE of            Adjusted
(rpm)    of Means   Difference  T-Value    P-Value
160         2.897       0.8747    3.312     0.0607
170         3.977       0.8747    4.547     0.0119
180         4.883       0.8747    5.583     0.0034


Speed (rpm) = 160  subtracted from:

Speed  Difference        SE of            Adjusted
(rpm)    of Means   Difference  T-Value    P-Value
170         1.080       0.8747    1.235     0.7338
180         1.986       0.8747    2.271     0.2467


Speed (rpm) = 170  subtracted from:

Speed  Difference        SE of            Adjusted
(rpm)    of Means   Difference  T-Value    P-Value
180        0.9063       0.8747    1.036     0.8325


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Cleanliness
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)       Lower  Center  Upper     +---------+---------+---------+------
48        -1.456  0.4799  2.415     (------------*------------)
64        -0.786  1.1495  3.085          (------------*------------)
                                    +---------+---------+---------+------
                                 -1.5       0.0       1.5       3.0
```

```
Opening (mm) = 48  subtracted from:

Opening
(mm)      Lower  Center  Upper     +---------+---------+---------+------
64       -1.266  0.6696  2.605       (-----------*------------)
                                   +---------+---------+---------+------
                                -1.5       0.0       1.5       3.0


Tukey Simultaneous Tests
Response Variable Cleanliness
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
48           0.4799      0.6776   0.7083    0.7656
64           1.1495      0.6776   1.6965    0.2644


Opening (mm) = 48  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
64           0.6696      0.6776   0.9882    0.6041
```

Appendix 4d: General Linear Model – % Uncracked versus Speed (rpm), Opening (mm)

```
Factor        Type   Levels  Values
Speed (rpm)   fixed       5  140, 150, 160, 170, 180
Opening (mm)  fixed       3  32, 48, 64


Analysis of Variance for % Uncracked, using Adjusted SS for Tests

Source        DF   Seq SS   Adj SS   Adj MS      F      P
Speed (rpm)    4  1.08011  1.08011  0.27003  12.72  0.002
Opening (mm)   2  0.07040  0.07040  0.03520   1.66  0.250
Error          8  0.16982  0.16982  0.02123
Total         14  1.32033


S = 0.145699   R-Sq = 87.14%   R-Sq(adj) = 77.49%


Unusual Observations for % Uncracked

Obs  % Uncracked      Fit   SE Fit  Residual  St Resid
  1      3.31889  3.54030  0.09953  -0.22141     -2.08 R
  3      3.72333  3.45385  0.09953   0.26948      2.53 R

R denotes an observation with a large standardized residual.


Least Squares Means for % Uncracked

Speed (rpm)   Mean  SE Mean
140          3.456  0.08412
```

```
150           3.022  0.08412
160           3.084  0.08412
170           2.855  0.08412
180           2.647  0.08412
Opening (mm)
32            3.097  0.06516
48            2.930  0.06516
64            3.011  0.06516


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable % Uncracked
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed
(rpm)    Lower   Center    Upper  ----+---------+---------+---------+--
150    -0.845  -0.4337  -0.0224          (-------*--------)
160    -0.783  -0.3719   0.0395            (--------*-------)
170    -1.012  -0.6004  -0.1890       (-------*-------)
180    -1.220  -0.8089  -0.3975  (-------*-------)
                                 ----+---------+---------+---------+--
                                  -1.00     -0.50      0.00      0.50


Speed (rpm) = 150  subtracted from:

Speed
(rpm)     Lower   Center    Upper  ----+---------+---------+---------+--
160    -0.3495   0.0619  0.47319                    (-------*--------)
170    -0.5780  -0.1667  0.24468              (--------*-------)
180    -0.7865  -0.3752  0.03616         (-------*--------)
                                  ----+---------+---------+---------+--
                                   -1.00     -0.50      0.00      0.50


Speed (rpm) = 160  subtracted from:

Speed
(rpm)     Lower   Center     Upper  ----+---------+---------+---------+--
170    -0.6399  -0.2285   0.18282             (-------*--------)
180    -0.8484  -0.4370  -0.02569        (-------*--------)
                                   ----+---------+---------+---------+--
                                    -1.00     -0.50      0.00      0.50


Speed (rpm) = 170  subtracted from:

Speed
(rpm)     Lower   Center   Upper  ----+---------+---------+---------+--
180    -0.6199  -0.2085  0.2028             (-------*-------)
                                 ----+---------+---------+---------+--
                                  -1.00     -0.50      0.00      0.50


Tukey Simultaneous Tests
Response Variable % Uncracked
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference       SE of           Adjusted
```

```
(rpm)     of Means  Difference  T-Value   P-Value
150        -0.4337      0.1190   -3.646    0.0386
160        -0.3719      0.1190   -3.126    0.0784
170        -0.6004      0.1190   -5.047    0.0064
180        -0.8089      0.1190   -6.800    0.0009


Speed (rpm) = 150  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)     of Means  Difference  T-Value   P-Value
160         0.0619      0.1190    0.520    0.9828
170        -0.1667      0.1190   -1.401    0.6437
180        -0.3752      0.1190   -3.154    0.0754


Speed (rpm) = 160  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)     of Means  Difference  T-Value   P-Value
170        -0.2285      0.1190   -1.921    0.3786
180        -0.4370      0.1190   -3.674    0.0372


Speed (rpm) = 170  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)     of Means  Difference  T-Value   P-Value
180        -0.2085      0.1190   -1.753    0.4571


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable % Uncracked
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)        Lower   Center    Upper  -------+---------+---------+---------
48        -0.4310  -0.1678  0.09546  (---------*----------)
64        -0.3497  -0.0864  0.17680     (----------*---------)
                                     -------+---------+---------+---------
                                         -0.25      0.00      0.25


Opening (mm) = 48  subtracted from:

Opening
(mm)        Lower   Center   Upper  -------+---------+---------+---------
64        -0.1819  0.08133  0.3446            (---------*----------)
                                    -------+---------+---------+---------
                                        -0.25      0.00      0.25


Tukey Simultaneous Tests
Response Variable % Uncracked
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
48          -0.1678     0.09215   -1.821    0.2236
```

64	-0.0864	0.09215	-0.938	0.6331

Opening (mm) = 48 subtracted from:

Opening (mm)	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
64	0.08133	0.09215	0.8826	0.6655

Appendix 4e: General Linear Model – Kernel Recovery versus Speed (rpm), Opening (mm)

Factor	Type	Levels	Values
Speed (rpm)	fixed	5	140, 150, 160, 170, 180
Opening (mm)	fixed	3	32, 48, 64

Analysis of Variance for Kernel Recovery, using Adjusted SS for Tests

Source	DF	Seq SS	AdjSS	Adj MS	F	P
Speed (rpm)	4	388.536	388.536	97.134	101.73	0.000
Opening (mm)	2	0.380	0.380	0.190	0.20	0.824
Error	8	7.638	7.638	0.955		
Total	14	396.554				

S = 0.977139   R-Sq = 98.07%   R-Sq(adj) = 96.63%

Least Squares Means for Kernel Recovery

Speed (rpm)	Mean	SE Mean
140	47.94	0.5642
150	44.42	0.5642
160	41.13	0.5642
170	37.10	0.5642
180	33.62	0.5642
Opening (mm)		
32	41.03	0.4370
48	40.86	0.4370
64	40.64	0.4370

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Kernel Recovery
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140 subtracted from:

```
Speed
(rpm)    Lower  Center   Upper  ----+---------+---------+---------+--
150      -6.28   -3.53   -0.77                     (-----*----)
160      -9.57   -6.81   -4.05               (----*-----)
170     -13.60  -10.85   -8.09       (----*-----)
180     -17.08  -14.33  -11.57  (----*-----)
                                ----+---------+---------+---------+--
                                -15.0     -10.0      -5.0       0.0
```

```
Speed (rpm) = 150  subtracted from:

Speed
(rpm)    Lower  Center   Upper  ----+---------+---------+---------+--
160      -6.04   -3.28  -0.524                          (----*-----)
170     -10.08   -7.32  -4.561                  (----*-----)
180     -13.56  -10.80  -8.041          (----*-----)
                                ----+---------+---------+---------+--
                                -15.0     -10.0      -5.0       0.0


Speed (rpm) = 160  subtracted from:

Speed
(rpm)    Lower  Center   Upper  ----+---------+---------+---------+--
170      -6.80  -4.037  -1.278                        (-----*----)
180     -10.28  -7.517  -4.758               (-----*----)
                                ----+---------+---------+---------+--
                                -15.0     -10.0      -5.0       0.0


Speed (rpm) = 170  subtracted from:

Speed
(rpm)    Lower  Center    Upper  ----+---------+---------+---------+--
180     -6.239  -3.480  -0.7213                        (----*-----)
                                 ----+---------+---------+---------+--
                                 -15.0     -10.0      -5.0       0.0


Tukey Simultaneous Tests
Response Variable Kernel Recovery
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
150         -3.53      0.7978    -4.42    0.0140
160         -6.81      0.7978    -8.53    0.0002
170        -10.85      0.7978   -13.59    0.0000
180        -14.33      0.7978   -17.96    0.0000


Speed (rpm) = 150  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
160         -3.28      0.7978    -4.11    0.0207
170         -7.32      0.7978    -9.17    0.0001
180        -10.80      0.7978   -13.54    0.0000


Speed (rpm) = 160  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
170        -4.037      0.7978   -5.060    0.0063
180        -7.517      0.7978   -9.422    0.0001


Speed (rpm) = 170  subtracted from:
```

```
Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
180        -3.480      0.7978   -4.362    0.0150


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Kernel Recovery
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)       Lower   Center  Upper  --------+---------+---------+--------
48        -1.933  -0.1671  1.598    (---------------*-------------)
64        -2.154  -0.3884  1.377  (--------------*-------------)
                                  --------+---------+---------+--------
                                       -1.2       0.0       1.2


Opening (mm) = 48  subtracted from:

Opening
(mm)       Lower   Center  Upper  --------+---------+---------+--------
64        -1.987  -0.2213  1.544   (--------------*--------------)
                                  --------+---------+---------+--------
                                       -1.2       0.0       1.2


Tukey Simultaneous Tests
Response Variable Kernel Recovery
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
48          -0.1671      0.6180  -0.2704    0.9607
64          -0.3884      0.6180  -0.6286    0.8091


Opening (mm) = 48  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
64          -0.2213      0.6180  -0.3581    0.9323
```

Appendix 4f: General Linear Model – Cracking Efficiency versus Speed (rpm), Opening (mm)

```
Factor        Type   Levels  Values
Speed (rpm)   fixed       5  140, 150, 160, 170, 180
Opening (mm)  fixed       3  32, 48, 64


Analysis of Variance for Cracking Efficiency, using Adjusted SS for Tests

Source        DF   Seq SS   Adj SS   Adj MS      F      P
Speed (rpm)    4  1.08011  1.08011  0.27003  12.72  0.002
Opening (mm)   2  0.07040  0.07040  0.03520   1.66  0.250
```

```
Error          8  0.16982  0.16982  0.02123
Total         14  1.32033


S = 0.145699   R-Sq = 87.14%   R-Sq(adj) = 77.49%


Unusual Observations for Cracking Efficiency

       Cracking
Obs  Efficiency      Fit  SE Fit  Residual  St Resid
  1     96.6811  96.4597  0.0995    0.2214      2.08 R
  3     96.2767  96.5461  0.0995   -0.2695     -2.53 R

R denotes an observation with a large standardized residual.


Least Squares Means for Cracking Efficiency

Speed (rpm)    Mean  SE Mean
140           96.54  0.08412
150           96.98  0.08412
160           96.92  0.08412
170           97.14  0.08412
180           97.35  0.08412
Opening (mm)
32            96.90  0.06516
48            97.07  0.06516
64            96.99  0.06516


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Cracking Efficiency
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed
(rpm)      Lower  Center   Upper  ---------+---------+---------+-------
150      0.02236  0.4337  0.8450           (--------*-------)
160     -0.03949  0.3719  0.7832          (-------*--------)
170      0.18903  0.6004  1.0117               (-------*-------)
180      0.39755  0.8089  1.2202                   (--------*-------)
                                  ---------+---------+---------+-------
                                        0.00      0.50      1.00


Speed (rpm) = 150  subtracted from:

Speed
(rpm)     Lower    Center   Upper  ---------+---------+---------+-------
160     -0.4732  -0.06185  0.3495  (--------*--------)
170     -0.2447   0.16667  0.5780      (--------*--------)
180     -0.0362   0.37519  0.7865          (---------*-------)
                                   ---------+---------+---------+-------
                                         0.00      0.50      1.00


Speed (rpm) = 160  subtracted from:

Speed
(rpm)     Lower  Center   Upper  ---------+---------+---------+-------
```

```
170    -0.1828  0.2285  0.6399       (--------*-------)
180     0.0257  0.4370  0.8484            (-------*-------)
                                 ---------+---------+---------+-------
                                        0.00      0.50      1.00


Speed (rpm) = 170  subtracted from:

Speed
(rpm)    Lower  Center   Upper   ---------+---------+---------+-------
180    -0.2028  0.2085  0.6199       (-------*-------)
                                 ---------+---------+---------+-------
                                        0.00      0.50      1.00


Tukey Simultaneous Tests
Response Variable Cracking Efficiency
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
150        0.4337      0.1190    3.646    0.0386
160        0.3719      0.1190    3.126    0.0784
170        0.6004      0.1190    5.047    0.0064
180        0.8089      0.1190    6.800    0.0009


Speed (rpm) = 150  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
160      -0.06185      0.1190  -0.5199    0.9828
170       0.16667      0.1190   1.4010    0.6437
180       0.37519      0.1190   3.1538    0.0754


Speed (rpm) = 160  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
170        0.2285      0.1190    1.921    0.3786
180        0.4370      0.1190    3.674    0.0372


Speed (rpm) = 170  subtracted from:

Speed  Difference       SE of           Adjusted
(rpm)    of Means  Difference  T-Value   P-Value
180        0.2085      0.1190    1.753    0.4571


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Cracking Efficiency
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)       Lower   Center   Upper   ----+---------+---------+---------+--
48       -0.0955  0.16778  0.4310            (----------*---------)
64       -0.1768  0.08644  0.3497         (---------*----------)
```

```
                                       ----+---------+---------+---------+--
                                        -0.25      0.00      0.25      0.50


Opening (mm) = 48  subtracted from:

Opening
(mm)       Lower    Center   Upper  ----+---------+---------+---------+--
64       -0.3446  -0.08133  0.1819  (----------*---------)
                                    ----+---------+---------+---------+--
                                     -0.25      0.00      0.25      0.50


Tukey Simultaneous Tests
Response Variable Cracking Efficiency
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
48          0.16778     0.09215   1.8207    0.2236
64          0.08644     0.09215   0.9381    0.6331


Opening (mm) = 48  subtracted from:

Opening  Difference       SE of           Adjusted
(mm)       of Means  Difference  T-Value   P-Value
64         -0.08133     0.09215  -0.8826    0.6655
```

Appendix 4g: General Linear Model – Machine Efficiency versus Speed (rpm), Opening (mm)

```
Factor         Type   Levels  Values
Speed (rpm)    fixed       5  140, 150, 160, 170, 180
Opening (mm)   fixed       3  32, 48, 64


Analysis of Variance for Machine Eff. %, using Adjusted SS for Tests

Source         DF   Seq SS   AdjSS  Adj MS       F      P
Speed (rpm)     4  1358.97  1358.97  339.74  101.73  0.000
Opening (mm)    2     1.33     1.33    0.66    0.20  0.824
Error           8    26.72    26.72    3.34
Total          14  1387.02


S = 1.82745   R-Sq = 98.07%   R-Sq(adj) = 96.63%


Least Squares Means for Machine Eff. %

Speed (rpm)    Mean  SE Mean
140           89.66   1.0551
150           83.07   1.0551
160           76.93   1.0551
170           69.38   1.0551
180           62.87   1.0551
```

```
Opening (mm)
32            76.73   0.8173
48            76.42   0.8173
64            76.00   0.8173


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Machine Eff. %
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed
(rpm)    Lower  Center   Upper  --+---------+---------+---------+----
150     -11.75   -6.59   -1.44                      (----*-----)
160     -17.89  -12.73   -7.57                (----*----)
170     -25.44  -20.28  -15.12         (----*----)
180     -31.95  -26.79  -21.63  (----*----)
                                --+---------+---------+---------+----
                                -30       -20       -10         0


Speed (rpm) = 150  subtracted from:

Speed
(rpm)    Lower  Center   Upper  --+---------+---------+---------+----
160     -11.30   -6.14   -0.98                       (----*----)
170     -18.85  -13.69   -8.53               (----*----)
180     -25.36  -20.20  -15.04         (----*----)
                                --+---------+---------+---------+----
                                -30       -20       -10         0


Speed (rpm) = 160  subtracted from:

Speed
(rpm)    Lower  Center   Upper  --+---------+---------+---------+----
170     -12.71   -7.55  -2.391                    (----*-----)
180     -19.22  -14.06  -8.899               (----*----)
                                --+---------+---------+---------+----
                                -30       -20       -10         0


Speed (rpm) = 170  subtracted from:

Speed
(rpm)    Lower  Center   Upper  --+---------+---------+---------+----
180     -11.67  -6.508  -1.349                      (----*-----)
                                --+---------+---------+---------+----
                                -30       -20       -10         0


Tukey Simultaneous Tests
Response Variable Machine Eff. %
All Pairwise Comparisons among Levels of Speed (rpm)
Speed (rpm) = 140  subtracted from:

Speed  Difference       SE of            Adjusted
(rpm)    of Means  Difference  T-Value    P-Value
150         -6.59       1.492    -4.42     0.0140
160        -12.73       1.492    -8.53     0.0002
170        -20.28       1.492   -13.59     0.0000
```

```
180        -26.79       1.492   -17.96    0.0000


Speed (rpm) = 150  subtracted from:

Speed  Difference       SE of            Adjusted
(rpm)    of Means  Difference  T-Value    P-Value
160         -6.14       1.492    -4.11     0.0207
170        -13.69       1.492    -9.17     0.0001
180        -20.20       1.492   -13.54     0.0000


Speed (rpm) = 160  subtracted from:

Speed  Difference       SE of            Adjusted
(rpm)    of Means  Difference  T-Value    P-Value
170         -7.55       1.492   -5.060     0.0063
180        -14.06       1.492   -9.422     0.0001


Speed (rpm) = 170  subtracted from:

Speed  Difference       SE of            Adjusted
(rpm)    of Means  Difference  T-Value    P-Value
180        -6.508       1.492   -4.362     0.0150


Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Machine Eff. %
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening
(mm)       Lower   Center  Upper      +---------+---------+---------+------
48        -3.614  -0.3125  2.989        (---------------*----------------)
64        -4.028  -0.7265  2.575      (---------------*----------------)
                                      +---------+---------+---------+------
                                   -4.0      -2.0       0.0       2.0


Opening (mm) = 48  subtracted from:

Opening
(mm)       Lower   Center  Upper      +---------+---------+---------+------
64        -3.716  -0.4139  2.888       (---------------*----------------)
                                      +---------+---------+---------+------
                                   -4.0      -2.0       0.0       2.0


Tukey Simultaneous Tests
Response Variable Machine Eff. %
All Pairwise Comparisons among Levels of Opening (mm)
Opening (mm) = 32  subtracted from:

Opening  Difference       SE of            Adjusted
(mm)       of Means  Difference  T-Value    P-Value
48          -0.3125       1.156  -0.2704     0.9607
64          -0.7265       1.156  -0.6286     0.8091


Opening (mm) = 48  subtracted from:
```

```
Opening  Difference       SE of            Adjusted
(mm)       of Means  Difference  T-Value    P-Value
64          -0.4139       1.156  -0.3581     0.9323
```

Appendix 5: Weights of the compositions of three (3) samples of 100g seed for oil extraction

Sample	Mass of kernels (g)	Mass of husks (g)	Total Mass (g)
1	58.6	41.4	100
2	59.0	41.0	100
3	57.0	43.0	100
Average	**58.2 (±1.06)**	**41.8 (±1.06)**	**100**

Appendix 6: Minitab statistical results for oil yield for different husk contents

One-way ANOVA: Oil Yield (ml) versus Husk Content (%)

```
Source             DF     SS    MS     F      P
Husk Content (%)    3  217.2  72.4  5.09  0.029
Error               8  113.8  14.2
Total              11  331.1

S = 3.772   R-Sq = 65.62%   R-Sq(adj) = 52.72%


                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level  N    Mean  StDev  ---+---------+---------+---------+------
  0    3  37.833  2.021                      (--------*-------)
 20    3  32.500  4.500             (--------*---------)
 40    3  28.167  4.856     (--------*-------)
100    3  27.000  3.000   (-------*-------)
                            ---+---------+---------+---------+------
                            24.0      30.0      36.0      42.0

Pooled StDev = 3.772


Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Husk Content (%)

Individual confidence level = 98.74%
```

```
Husk Content (%) =   0 subtracted from:

Husk
Content
(%)        Lower   Center   Upper   -+---------+---------+---------+--------
 20      -15.199   -5.333   4.532         (---------*---------)
 40      -19.532   -9.667   0.199    (---------*---------)
100      -20.699  -10.833  -0.968   (---------*---------)
                                    -+---------+---------+---------+--------
                                   -20       -10         0        10
```

```
Husk Content (%) =  20 subtracted from:

Husk
Content
(%)        Lower  Center  Upper   -+---------+---------+---------+--------
 40      -14.199  -4.333  5.532          (---------*---------)
100      -15.366  -5.500  4.366         (---------*--------)
                                  -+---------+---------+---------+--------
                                 -20       -10         0        10
```



```
Husk Content (%) =  40 subtracted from:

Husk
Content
(%)        Lower  Center  Upper   -+---------+---------+---------+--------
100      -11.032  -1.167  8.699            (---------*---------)
                                  -+---------+---------+---------+--------
                                 -20       -10         0        10
```

Appendix 7: Weights of the compositions of three (3) samples of 100g seed for cracker evaluation

Sample	Mass of kernels (g)	Mass of husk (g)	Total Mass (g)
1	52.6	47.4	100
2	53.1	46.9	100
3	54.7	45.3	100
Average	**53.47 (±1.10)**	**46.53 (±1.10)**	**100**

Appendix 8: Orthographic views of *Jatropha curcas* cracker sieve