OPTIMIZATION OF THRESHING PERFORMANCE OF A SPIKE TOOTH SORGHUM THRESHING UNIT

SAMUEL OTIENO ABICH

A Thesis Submitted to the Graduate School in Partial Fulfillment for the Requirements of Master of Science Degree in Agricultural Engineering of Egerton University

EGERTON UNIVERSITY

NOVEMBER, 2018

DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been submitted to any other university known to me for the award of any degree.

Signature...Date.......................................

Samuel Otieno Abich

BM11/41502/14

Recommendation

This thesis has been presented with our approval as University supervisors.

Signature... Date …………………………

Prof. G. M. N. Ngunjiri,

Department of Agricultural Engineering,

Egerton University.

Signature... Date …………………………

Dr. M. R. Njue,

Department of Agricultural Engineering,

Egerton University.

DEDICATION

This work is dedicated to my beloved Dorine and children Alspencer, Veronica, Marvin and Leshamta. Thanks for your prayers and patience.

ACKNOWLEDGMENT

I thank God Almighty for enabling me complete my studies. I am grateful to Egerton University and the African Development Bank / Ministry of Education, Science and Technology Scholarship for sponsoring this research. I thank my supervisors Prof. G. M. N. Ngunjiri and Dr M. R. Njue. Their concern and interest made the burden of this work much lighter to bear. My gratitude goes to Eng. Prof. J. Onyando, Prof. D. Nyaanga and Prof. B. M. Mutua, Dr. V. Odongo, Dr. R. Wambua, Dr. R. Okwany and Dr. P. Kundu. May I also appreciate the encouragement received from Dr. Manene, Dr. Owino, Eng. Dr. D. N. Kamau, Eng. Dr. J. Raude, Mr. W. Nasirembe and to all staff members of the Department of Agricultural Engineering.

ABSTRACT

Sorghum threshing in Kenya is characterized by high grain breakages and accounts for grain loss of 4% of total production. Existing threshing methods are time consuming and yield a low throughput. Grain losses mainly occur due to grain damage and incomplete removal of grains from panicles. In order to reduce the losses, optimal levels of machine and operational parameters influencing threshing need to be established. A prototype spike tooth sorghum thresher was therefore developed using engineering principles with the objective of optimizing threshing performance of its threshing unit. The performance tests of sorghum threshing were conducted at three levels for drum diameters (200, 300 and 400 mm), spike spacings (50, 75 and 100 mm) and drum peripheral speeds (8, 10 and 12 m s^{-1}) using a factorial experimental design. The data were subjected to graphical and statistical analysis of variance (ANOVA); and optimization was done using the Taguchi signal/noise ratio method. It was observed that threshing sorghum at spike spacing of 50 mm, drum diameter of 400 mm and drum peripheral speed 12 m s^{-1} produced the highest threshing efficiency of 96%. Minimum mechanical grain damage of 3% was obtained using drum diameter 400 mm, spike spacing 100 mm and drum peripheral speed 8 m s^{-1}. Threshing sorghum at drum diameter of 400 mm, spike spacing 50 mm and drum peripheral speed of 10 m s^{-1} produced maximum throughput per unit energy consumption of 153 kg h^{-1} $(kWh)^{-1}$. Although throughput of the thresher increased as the drum peripheral speed was increased from 8 to 12 m s^{-1}, throughput per unit energy consumption reached a maximum at 10 m s^{-1}. From the study it was concluded that optimal threshing performance could be attained with drum diameter 400 mm, spike spacing 50 mm and peripheral speed 10 m s^{-1}. The study recommends that the performance of sorghum threshers be based on throughput per unit energy consumption rather than throughput as throughput does not take into account the energy consumed during threshing. This recommendation could be extended to other grain threshers since their principles of design and operation are the same. Future studies could be done to determine the influence of drum length, concave clearance, feed rate, sorghum variety and moisture content on the performance of sorghum threshers.

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ABBREVIATIONS AND ACRONYMS

ANN	Artificial Neural Networks
FAO	Food and Agriculture Organization
LSD	Least Significant Difference
RPM	Revolutions Per Minute
RSM	Response Surface Methodology

CHAPTER ONE
INTRODUCTION

1.1 Background to the study

Grain sorghum (*Sorghum bicolor* (L.) *Moench*) is the world's fifth most important cereal crop after maize, rice, wheat and barley. In Africa it is second after maize in terms of importance and is dietary staple food for more than 500 million people in more than 30 countries (Muna *et al.,* 2016). The world annual sorghum production is over 60 million tons, out of which Africa produces about 20 million tons (Sale, 2015). According to Indexmundi (2017), Kenya produced 150,000 tons of sorghum in 2017.

One of the biggest challenges facing the agricultural sector in Kenya is meeting the growing demand for food grains to feed its increasing population. With maize production under threat of armyworm attack, sorghum presents a viable alternative of maintaining the country's grain supply. The crop is becoming a source of livelihood for farmers in arid and semi arid regions as it gives them an opportunity to harvest from low productive land with minimal input (Oyier *et al*., 2016).

Sorghum is important to food security in Kenya because it is drought resistant among cereals and can withstand periods of high temperature and water-logging (Takuji and Baltazar, 2009). It is characterized by an extensive root system, waxy bloom on leaves that reduces water loss and the ability to stop growth in periods of drought and resume it when the stress is relieved (Muui *et al.,* 2013).

Sorghum is used for food, feed and beverage production (Muui *et al.*, 2013). It is used to manufacture wax, starch, syrup, alcohol and edible oils (Agrama and Tuinstra, 2003). As food, the grain is used in making fermented and non fermented porridge and *ugali* (Ministry of Agriculture, 2012). The grain has high levels of iron and zinc used to reduce micronutrient malnutrition (Gerda and Christopher, 2007).

Despite the food and nutritional value of sorghum, its threshing is still a challenge for Kenyan farmers. In Kenya, sorghum grain post-harvest losses amount to 15% of the total production, out of which 24% occur during the threshing and cleaning stages (FAO, 2012).

According to Kamble *et al.* (2003), mechanical sorghum threshing suffers high grain damage and imperfect threshing process. They estimate these losses to amount to four percent of total throughput while Azouma *et al.* (2009) reported manual threshing losses as 8%. These losses are due to incomplete removal of grains from heads and grain damage. Damaged grains are prone to fungal attack, pose less resistance against pests leading and reduce the grade and marketability of the grain (Wang *et al.*, 1994). Further, Spokas *et al*. (2008) reported that when grains are broken their germination rate is reduced by 10%.

The threshing unit plays a key role in determining the performance of a thresher (Sudajan *et al.*, 2005). Its performance is influenced by machine characteristics as well as physical and mechanical properties of sorghum (Osueke, 2013). Important crop factors influencing sorghum threshing and drying are bulk and solid density, moisture content, angle of repose; major, intermediate and minor diameters and coefficient of friction of the grains (Sessiz *et al.*, 2008). Machine parameters include drum speed; concave clearance; type, number and shape of threshing spikes; type of sieve and feed rate (Muna *et al.*, 2016).

Presently, the performance evaluation of sorghum threshers is based on machine throughput, threshing and winnowing efficiencies, grain mechanical damage, cleaning efficiency and throughput capacity (Wangette, 2015). A mechanical thresher should have high threshing efficiency, low mechanical grain damage and a high throughput per unit energy consumption.

1.2 Statement of the problem

Current performance evaluation of sorghum threshers is based on machine throughput, threshing and winnowing efficiencies and grain mechanical damage. However, research data on throughput per energy consumption of a spike tooth sorghum threshers are limited. Different researchers have reported different optimal values of these parameters with inconsistent recommendations. Studies on the influence of drum speed on threshing performance have been on threshing drum angular speed rather than drum peripheral speed. Further, few researchers have given consideration to the influence of other inputs during threshing such as energy on threshing performance.

1.3 Objectives

1.3.1 Broad objective

The broad objective of this study was to optimize the performance of a prototype spike tooth sorghum threshing unit in terms of drum diameter, spike spacing and drum peripheral speed.

1.3.2 Specific objectives

i. To determine the influence of drum diameter, spike spacing and drum peripheral speed on the threshing performance of a spike tooth sorghum threshing unit.
ii. To optimize the threshing performance of the spike tooth sorghum threshing unit.

1.3.3 Research questions

i. How do drum diameter, spike spacing and drum peripheral speed influence the threshing performance of a spike tooth sorghum threshing unit?
ii. What drum diameter, spike tooth spacing and drum peripheral speed of the sorghum thresher results in optimal threshing performance?

1.4 Justification

Optimization of the selected parameters of the threshing unit is a vital step towards reducing threshing losses, improvement of quality of grains and increased sorghum productivity. Lack of standards for the threshing unit has meant artisans use different levels of the design parameters contributing to inefficient threshing. This has hindered the uptake of mechanical threshing by farmers. Results from this study will enable standardization of the threshing unit configuration. This will spur the growth of sorghum mechanical threshing benefitting both artisans and farmers. Energy will be saved when threshers are designed based on the combination of parameters producing optimal throughput per unit energy consumption.

1.5 Scope and limitation

The study covered the development and subsequent performance evaluation of prototype spike tooth sorghum thresher to establish the levels of drum diameter, spike spacing and drum speed that would result in optimal threshing performance. Crop factors (variety and moisture content), machine factors (feeding chute angle, cylinder type, spike shape and size. concave size, shape and clearance) and operational factors (feed rate and machine adjustment) affecting sorghum threshing were not covered.

The performance indicators were limited to grain mechanical damage, threshing efficiency and throughput per unit energy consumption. Cleaning efficiency, germination percentage and grain scatter loss were not studied. The sorghum crop variety used was *andiwo* grown in Migori County.

CHAPTER TWO
LITERATURE REVIEW

2.1 Sorghum production

Sorghum originated in Africa around the Ethiopian Highlands and Southern Sudan and was introduced into eastern Africa in 200 AD. It later spread to America in the middle of the 19th century (Sale, 2015). Sorghum is short-term perennial grass that grows up to 4 m high with a panicle 8 to 40 cm long and spikelet 4 to 6 mm long. The mature spikelets are either red or reddish brown with grain predominantly red or reddish brown (Plate 2.1). The sorghum grain moisture content at the end of the growth period is from 18% to 20%, but is harvested when it is 14% (Saeidirad *et al.*, 2013).

Plate 2. 1: Sorghum head (Source: Saeidirad *et al.*, 2013)

2.2 Sorghum threshing

Threshing is the process of separating the grain from the seed panicles (Buhari, 2016). The process involves loosening the edible part of cereal grain from the scaly chaff that surrounds it through the application of tensile, compressive, bending and torsional forces on the grain heads (Simonyan and Yiljep, 2008).

2.2.1 Manual threshing

Threshing of sorghum by flailing involves beating the crop panicle by sticks on a floor. The threshing floors should be a hard, clean surface in specially flattened outdoor surfaces or inside buildings (El-Behery *et al.*, 2000).

Pounding involves using a wooden mortar and pestle (Plate 2.2). The pounded crop is cleaned by tossing it into a natural breeze and catching the grain on a surface. The crop is then winnowed and wind carries away the chaffs and dust (Buhari, 2016).

Plate 2. 2: Manual threshing using mortar and pestle (Source: Buhari, 2016)

Threshing in racks is accomplished when individuals holds the crop by the sheaves as shown in Plate 2.3 and beats it against a hard object such as a steel oil drum (Buhari, 2016).

Plate 2.3: Threshing using racks (Source: Buhari, 2016)

Ouezou (2009) described trampling as a manual threshing method involving the use of bare feet or animals to thresh crop. The crop, spread over a mat or canvass, is trodden underfoot by humans or animals. After threshing, the straw is separated from the grains and cleaning of the grain is done by winnowing. This method often results in some losses due to the grain being broken or buried in the earth.

2.2.2 Mechanical threshers

The threshing concept entails providing energy for turning materials, drawing in materials to be threshed and creating velocity of different layers to rub grain heads together. The grain separating process directly acts on the linkage of grain and stalk. The threshing chamber is made of drum and concave (Plate 2.4).

Plate 2.4: Threshing chamber

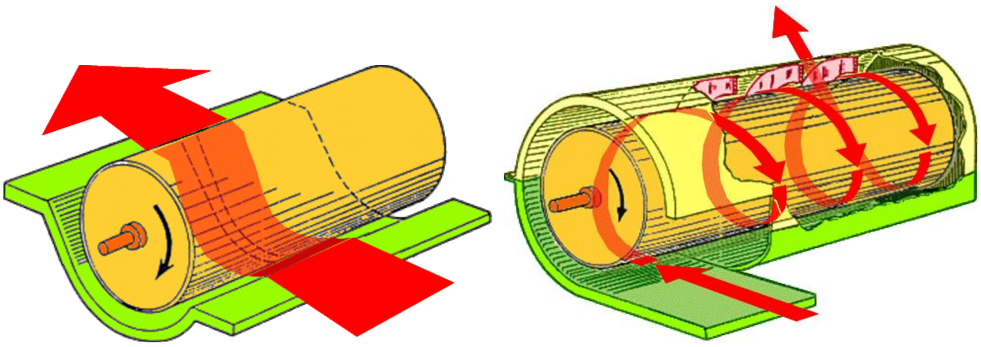
The drum consists of a long cylindrical shape member mounted on bearings to which a series of spikes or rasp bars are attached on the surface. The concave is perforated to enable the threshed product to drop by gravity into a collector (Zhong *et al.,* 2013).

During threshing, crop is fed between the threshing drum and the concave where it is subjected to impact and frictional forces which detach grains from panicles (Amir, 1990). The crop material gets between the circumference of the revolving drum having attached spikes and upper drum casing. The drum beats the panicles of the crop against stationary concave and forces out the grains from the panicle (Muna *et al.,* 2016). Since the speed of the spikes is greater than the crop mass, it strikes the latter resulting in part of the grain being separated from straw. Simultaneously, the drum pulls the mass through the gap between the spikes and the upper casing with varying speed.

There are different types of threshing cylinders. Spike tooth type drum is a drum on whose entire periphery a number of spikes are welded or bolted. These drums thresh based on striking action. Rasp bar type drum has slotted plates which are fitted over to the drum rings in such a way that the direction of slot of one plate is opposite to another plate. Rasp bar cylinders thresh mainly on friction and rubbing. Rasp bar drum types provide more surface area for frictional impact than other types (Addo *et al.,* 2004).

Wire loop type of threshing drum has a hollow drum over which a number of wire loops are fixed for threshing purposes. Threshing is achieved by holding the grain bundle against the loops of revolving drum. The hammer mill type drum uses beaters made of flat iron pieces and fixed radially on the rotor shaft to thresh. The cut crop is fed perpendicular to the direction of motion of rotating beaters (Amir, 1990).

Various types of stationary threshing machines exist. Through-flow threshers consist of a threshing device with spikes, teeth or loops and a cleaning-winnowing mechanism based upon shakers, sieves and centrifugal fan (Ahuja, 2016). In axial flow threshers, the crop moves spirally between the threshing drum and concave for several complete turns (Figure 2.1). This allows for multiple impacts between the drum and concave as the crop is moved along the length of the drum (Ouezou, 2009).



(i) (ii)

Figure 2.1: Movement of crop through (i) through-flow and (ii) axial-flow threshers

(Source Ahuja, 2016)

Hold-on threshers consist of an open rotating drum with teeth which strips the grain from panicles. The head of the cut crops are fed into threshing drum of hold-on threshers with the lower part of the straw being mechanically or manually held (Tamiru and Teka, 2015).

Threshing occurs when the kinetic energy transferred by the beaters to the crop overcomes the gravitational potential energy of the free falling crop fed through the hopper causing the crop to move from bottom to top of the threshing chamber and forward during the threshing process. The thresher stalls when the gravitational potential energy of the crop overcomes the kinetic energy transferred by the beaters (Sessiz and Ulger, 2003). The material layer is struck several times by the spikes against the ribs, causing threshing of grains and breaking stalks into pieces and accelerating them to the outlet.

2.3 Threshing performance indicators

Performance evaluation is a scientific method of ascertaining the working conditions of the main components of a system with a view to establishing how the components contribute to the overall efficiency of the system (Chukwu, 2008). Grain threshing loss and grain damage are the most qualitative indices for evaluating thresher operation performance (Salari *et al.,* 2013).

Shpokas (2007) studied the design characteristics of a thresher apparatus and concluded that the feeding rate of materials into the threshing apparatus and technological parameters such as drum speed and clearance between the drum and concave had significant effect on the threshing performance. Behera *et al.* (1990) noted that the criteria for evaluating performance of threshing mechanisms include threshing efficiency, grain loss, grain damage, output capacity, cleaning efficiency and power requirement. Nalado (2015) added that these criteria are measured against such design variables as drum threshing speed; concave clearance, drum diameter and length.

2.3.1 Mechanical grain damage

Nalado (2015) defined grain damage as the percentage of visually broken, chipped or cracked grain to the total grains threshed per unit time. It is a result of direct impact between the beaters of the threshing drum and the crop fed. A thresher separates grain from pod and stalk by applying pressure and impact force. The movement of the crop between stirring components of the threshing unit and improper clearance between the moving and stationery components causes damage to the grains (Ukatu, 2006).

Grain damage is a qualitative index used to evaluate all the broken grains present within the clean grains collected. It occurs because grains are not sufficiently protected from the impact of the threshing drum and concave (Muna *et al.,* 2016). Spokas *et al.* (1980) noted that grain damage depend on the crop species, characteristics and moisture content and on design and technological parameters of the threshing apparatus. Olaoye (2011) identified other factors affecting crop damage as dwell time and the separating process.

2.3.2 Throughput

Throughput of a thresher is the mass of materials passing through the thresher per unit time. It depends on mean rate of threshing, number of grains passing through the concave openings in one second per impact and dwell time of crop in the thresher (Ndirika *et al.,* 1996). This performance measure, however, does not take into account the energy consumed during the process, maximum throughput should be achieved with minimum energy consumption.

The kernels of the crop are bonded to the crop head by some forces which need to be overcome in order to separate the kernel from the head. This force is dependent upon kind of crop, degree of ripeness of the crop and kernel moisture content and that it varies with size, form and structure of the plant tissue holding the kernels (Salari *et al.*, 2013).

2.3.3 Threshing efficiency

According to Singh *et al.* (2015), threshing efficiency is the ratio of mass of threshed grains received from all the outlets to total grain input per unit time expressed in percentage (%). Threshing efficiency evaluates the percentage of grains detached from the crop per second by the beaters of the threshing mechanism.

2.4 Factors affecting threshing performance

Osueke (2013) classified factors affecting thresher performance as crop factors (variety of crop and moisture content of crop), machine factors (feeding chute angle, cylinder type and diameter, spike shape, size and number. concave size, shape and clearance) and operational factors (cylinder speed, feed rate, method of feeding and machine adjustment). Various researchers have tried to obtain optimal parameter values by varying these parameters at different levels.

2.4.1 Drum diameter

Drum diameter was identified by Huynh *et al.* (1982) as one of the parameters that influence grain separation from the stalks and passage of grains through the concave grate. Using three drum diameters (100, 150 and 280 mm), Osueke (2013) modeled the Influence of drum diameter (λ) and other design parameters of cereal threshers on rate of detachment of grains during threshing as indicated in equation 2.1:

$$\lambda = \frac{1}{Ke}\left(\frac{v\rho c^{2}}{2\left[m-\left(a + b\mu N\right)\frac{\rho c^{2}}{Q\,w}\right]}\right) \tag{2.1}$$

From equation 2.1, the threshing efficiency was worked out as:

$$Efficiency = 1 - e^{-x} \tag{2.2}$$

Where:

$$x = \frac{1}{Ke} \frac{v\rho c^2}{2\left[Qv - \left[(a + b\mu N)\left(\frac{c^2}{Q\ w}\right)\right]\right]} \tag{2.3}$$

Q = mass flow rate (kg/s)

N= normal reaction (N)

μ= coefficient of kinetic friction

v= velocity of the beater (m s^{-1})

w= drum diameter (m)

c= concave clearance (m)

ρ = bulk density of the crop (kg m^{-3})

K_e= kinetic energy of the beater (J)

m = mass of the beater (kg)

a = Coordinate point of impact on the beater resolved along X-axis (m)

b = Coordinate point of impact on the beater resolved along Y-axis (m)

A threshing efficiency of 96.32% and grain damage of 3.67% were obtained in the study.

Ndirika (2006) developed a millet thresher and developed a model to predict mean rate of threshing (λ) as:

$$\lambda = K_T \left(\frac{V_b^2\ \delta_d\ D}{(1-\beta)\ F_r} \right) \tag{2.4}$$

Where:

K_T = threshing constant

V_b = peripheral velocity of beaters (m s^{-1})

δ_d = crop bulk density (dry basis)

D = drum diameter (m)

β = moisture content (wb in decimal)

F_r = feed rate (kg/s)

The grain output obtained varied between 13.31 and 27.19 kg h^{-1} using a 3 kW motor.

2.4.2 Spike spacing

The number of beaters in the drum was identified by Muna *et al.* (2016) among the variables influencing the rate of detachment of grains per second. They modeled this as:

$$E_T = 100\left(1 - e^{-k}\right) \tag{2.5}$$

Where:

$$k = \frac{0.5\ K_T\ N_b\ L_c\ M_b\ V_c^{\ 2}}{M_c\ C_c\ g\ h} \tag{2.6}$$

E_T = threshing efficiency (%)

K_T = threshing constant

N_b = number of beaters

M_b = mass of beater (kg)

L_c = length of threshing cylinder (m)

V_c= velocity of peripheral cylinder (m s^{-1})

g = acceleration due to gravity (9.81N kg^{-1})

h = height of the threshing chamber (m)

M_c = moisture content of the crop (%)

C_c = concave clearance (m)

The threshing efficiency varied between 98.2 and 98.7 %.

Spike tooth threshing system for wheat crop was studied by Banga *et al*, (1984). The studies revealed that increase in cross-sectional area of spikes increased grain damage and power consumption. They further found that longer spikes reduced grain damage and that less number of spikes in rows caused less grain damage. More number of spikes consumed more power due to higher impact forces.

Srison *et al.* (2016) reported that increase in spike tooth clearance resulted in a tendency for power consumption to reduce for a maize sheller. They further reported that increase in spike tooth clearance and concave clearance resulted in an increase of total loss from the shelling unit.

2.4.3 Drum peripheral speed

An optimum speed is desirable for improved performance of a thresher because excessive speed can cause the grain to crack while a low speed can give unthreshed head. Impact force is the primary threshing action for detachment of grain from the ear head. In all types of threshers, this impact force is controlled by the cylinder tip speed (Khazae, 2003). A thresher is operated at the lowest cylinder speed that will shed the most grain with acceptable levels of damage to grain (Osueke, 2013). The speed of the threshing drum influences the capacity and performance of a thresher (Gbabo *et al.*, 2013).

The threshing efficiency of a cowpea thresher was found by Sharma and Devnani (1984) to increase with increase of drum speed. They also noted that energy consumption was directly proportional to drum speed. El-Nono and Mohammed (2000) found that an increase in drum speed decreased the rate of un-threshed grain and increased grain damage and power requirement.

Ajav and Adejumo (2005) evaluated effects of cylinder speed on threshing performance to okra seeds. They reported that the effect of cylinder speed was significant on threshing performance. Similar results were reported by Khazae (2003) who published that cylinder speed had a significant effect on chickpea threshing efficiency and damaged grain percent.

A multi-crop thresher was developed and evaluated by Singh *et al.* (2015) and found that increase in the level of drum speed had significant effect on the threshing efficiency of the thresher. Osueke (2013) carried out a study on the influence of machine and operating parameters on performance of cereal threshers and found out that threshing efficiency increased for all increasing values of cylinder speed.

Saeed *et al.* (1995) fabricated and evaluated a paddy thresher at three threshing drum speeds (15.5, 17.3 and 19.0 m s^{-1}) and three feed rates (44, 720 and 1,163 kg h^{-1}). The results showed that the grain damage was in the range of 0.4% to 1.2%. They concluded that the percentage of grain damaged and threshing efficiency increased with an increase in drum speed for all feed rates.

Desta and Mishra (1990) conducted a research on the performance of a sorghum thresher at three drum speeds (300, 400 and 500 rpm), three feed rates (6, 8 and 10 kg min^{-1}) and two rum concave clearances (7 and 11 mm). Their results showed that threshing efficiency increased with an increase in drum speed for all feed rates and drum concave clearances. The threshing efficiency was found in the range of 98.3 to 99.9%. At a speed of 400 rpm, the power required for operating thresher was 4.95 kW and maximum output of the thresher was 162.7 kg h^{-1} at a feed rate of 10 kg min^{-1} and 11 mm concave clearance.

Addo *et al.* (2004) published that spike tooth threshing drum gave higher throughput values at higher speeds compared to rasp bar threshing drums. They explained that this was due to the impact of the spikes against pods and stalk. Even at lower speeds, the spikes impacted higher velocities to the pods and stalks to exit from the thresher compared to the rasp bar which has a flat threshing surface.

The best performance of a soybean thresher developed by Baiomy *et al.* (1999) was obtained at a drum speed of 14 m s^{-1} giving machine capacity of 900.11 kg h^{-1}, grain damage of 1.12 % and total grain losses of 1.22 %. An axial flow grain thresher was tested on chickpea by Anwar and Gupta (1990). The thresher worked best with a cylinder speed of 580 rpm at which the thresher capacity was 190 kg h^{-1} with a threshing efficiency of 93% and fuel consumption of 5.7 litres h^{-1}. The total grain damage was 2.2%.

A thresher was designed by Sudajan *et al.* (2005) for analyzing threshing efficiency, grain damage and output capacity. The performance of the machine by a PTO tractor at five levels of drum speeds; 650, 700, 750, 800 and 850 rpm and three feed rates; 2,000, 2,500 and 3,000 kg h^{-1}, were used. The results showed that the no load power requirement of the sunflower thresher at a drum speed of 750 rpm was 1.8 kW. At feed rate of 3,000 kg $h^{-1}$and drum speed of 750 rpm; the thresher capacity was 1,098 kg h^{-1} with a threshing efficiency of 99%, grain damage was less than 1%, cleaning efficiency of 99%, grain loss of 0.82 to 1.07% and specific energy consumption of 3.86 to 4.38 kWh ton^{-1}.

A threshing chamber was developed by Ebaid *et al.* (2004) in a wheat thresher and evaluated it under different operating conditions. The results showed that total grain losses of 0.16 % were achieved at drum speed of 870 rpm. Badway (2002) reported that by increasing drum speed of a thresher from 9.28 to 15.33 m s^{-1} the machine capacity increased from 1800 to 2400 kg h^{-1}. The highest threshing efficiency of this machine was 97.17%.

A threshing drum in a stationary thresher for separation of flax capsules was developed by Zakaria (2006). The machine was tested under four drum speeds (24.25, 25.81, 27.33 and 28.85 m s^{-1}). The results showed that optimum threshing efficiency of 96.92 %.was attained at drum speed of 28.85 m s^{-1}.

The results obtained by Afify *et al.* (2007) for a thresher evaluated at drum speeds, 4.19, 5.23, 6.28 and 7.32 m s^{-1}, indicated that a threshing efficiency of 98.74 % and cleaning efficiency of 95.88 % were obtained at drum speed of 6.28 m s^{-1} and energy consumption of 2.85 kWh ton^{-1}. A millet thresher powered by a 5 hp motor to thresh and clean millet grains was designed by Gbabo *et al.* (2013). The test was done by taking pearl millet at 600, 700 and 800 rpm cylinder speed. They obtained highest threshing efficiency of 63.20 percent 800 rpm cylinder speed.

Saeidirad et *al.* (2013) conducted a study to optimize operational and crop parameters influencing the threshing of sorghum. The effects of four levels of threshing drum speed (13, 17, 21 and 25 m s^{-1}), concave clearance (5, 10 and 15 mm) and feed rate (420, 500 and 590 kg h^{-1}) were investigated on un-separated seed percentage, damaged seed percentage and germination. They reported that the best performance by a sorghum thresher they developed was given at a drum speed of 21 m s^{-1}, 10 mm concave clearance and 590 kg h^{-1} feed rate.

The effect of crop moisture content, drum speed, variety on threshing loss, grain damage and power requirement was studied by Asli-Ardeh *et al.* (2009). They concluded that increasing drum speed reduced threshing loss but increased damaged grain percentage.

The effect of machine parameters on threshing quality for chickpea seed crop was studied by Sinha *et al.* (2009). They concluded that threshing element, cylinder speed and feed rate affected the seed quality and performance of the thresher. They obtained minimum damage to the seeds using Teflon coated iron beater threshing element at 8.94 m s^{-1} cylinder speed.

It is noted from the literature reviewed on influence of speed that most researchers reported their findings based on the drum angular speed rather than peripheral speed on which the kinetic energy of the spikes depend.

2.5 Optimization of threshing parameters

Optimization is the procedure for minimizing (or maximizing) a real function by choosing the values of integer variables from within an allowed set (Nalado, 2015). Various researchers have employed various optimization methods in design of threshers including response surface methodology (RSM), artificial neural networks (ANNs), full factorial experiment and Taguchi technique.

2.5.1 Response Surface Methodology

Response surface methodology is a collection of statistical and mathematical methods for optimizing a response surface influenced by various process parameters. RSM quantifies the relationship between the controllable input parameters and the obtained response surfaces with the aim of optimizing the response variable; it is assumed that the independent variables are continuous and controllable by experiments with negligible errors (Salari *et al.*, 2013).

Singh *et al.* (2008) optimized a pedal-operated paddy thresher using RSM. They obtained optimal performance using wire loop spacing 39.1 mm, wire loop tip height 60.6 mm and threshing drum speed 339.46 m min^{-1}. The corresponding threshing capacity and efficiency were 64.6 kg h^{-1} and 96.4% respectively.

A spike tooth thresher was used for chickpea threshing by Salari *et al.* (2013) at three cylinder speeds (9, 12, 15 m s^{-1}), concave clearance (12, 14, 16 mm), feed rate (80, 160, 240 kg h^{-1}) and seed moisture content (5, 10, 15% wb). The experimental plan for optimization was prepared using RSM technique. With increasing cylinder speed in the range of 9 to 15 m s^{-1}, the grain damage increased from 4.98 to 47.97%, threshing efficiency increased from 96.81 to 99.69%, and seed germination decreased from 85.75 to 55.98%. The optimized point was determined at the cylinder speed of 10.63 m s^{-1}, concave clearance of 13.74 mm, feed rate of 240 kg h^{-1}, and moisture content of 12% with optimum values of grain damage, threshing efficiency, and seed germination being 3, 98.3, and 84.29%, respectively.

2.5.2 Artificial Neural Networks

Artificial neural networks (ANNs) are computer programs which recognize patterns in a given collection of data and produce model for that data. The networks acquire knowledge by through a learning process (trial and error); and interneuron connection strengths (synaptic weights) are used to store the knowledge (Agatonovic-Kustrin and Beresford, 2000). The training algorithm used to determine various parameters of ANN is a key factor influencing the performance of ANNs. However, low convergence speed is experienced when ANN is used (Yu *et al.,* 2015).

Mirzazadeh *et al.* (2012) used ANN to make an intelligent model to forecast grains separation. Results showed that the amount of grain separation had dependent to threshing clearance, speed of threshing cylinder, stem height and feed rate, respectively. The amount of grain separation increased with reduction in stem height, feed rate, threshing clearance ratio and speed up of cylinder

Machine parameters of finger millet thresher were optimized by Mishra and Saha (2016) using ANN. The threshing capacity (32.4 kg h^{-1}) and threshing efficiency (98.41 %) were evaluated at its optimal design parameter settings: number of canvas strips on the drum periphery (8) and peripheral drum speed (7.97 m/s).

2.5.3 Full factorial experiments

Full factorial experiment design consists of two or more factors each with a discrete level and whose experimental units take all possible combinations of those levels across all factors. It allows studying the effect of each factor as well as the effects of interactions between factors on the response variable. Full factorial experiments are preferred where the number of variables is small with strong interactions between them (Thompson, 2009). For f factors each at levels; a full factorial design has L^k runs. This makes factorial experiments labourious and complex if the numbers of factors and levels are many (Rao and Phadmanabhan, 2012).

Several researchers have employed full factorial design to optimize grain threshers. Chandrakanthappa *et al.* (2001) conducted test `using rasp bar type multi-crop thresher to thresh finger millet. A threshing efficiency of 79.61% and mechanical damage of 2.95% were obtained at 4 mm concave clearance, 1000 rpm thresher drum speed and grain moisture content of 10% wet basis.

Shahid *et al.* (2006) conducted a study on wheat thresher at three different threshing drums peripheral speeds (500, 550 and 600 rpm). The thresher performed best at speed of 550 rpm at which threshing capacity was 372 kg h^{-1} with threshing efficiency of 99.6%. They reported total machine loss and seed damage as 0.3% and 0.2% respectively. Joshi (1981) reported that in wheat threshing at a drum speed of 700 rpm and 63.5 mm spike spacing, the threshing efficiency and external damage were 99.63 and 0.47 % respectively.

A motorized stationary sorghum thresher was developed and tested by Simonyan and Imokhene (2008). They investigated threshing efficiency and cleaning efficiency at six threshing speeds (2.64, 3.64, 4.40, 5.03, 5.78 and 6.28 m s^{-1}), six air speeds (3.67, 4.67, 5.17, 5.47, 7.33 and 8.33 m s^{-1}) and five feed rates (492.86, 521.43, 640, 720 and 740 kg h^{-1}). The threshing efficiency ranged between 99.94 % and 99.96 % while cleaning efficiency ranged between 94.35 % and 96.14 %.

El-Desoukey *et al.* (2007) studied the effect of four drum speeds (4.71, 7.85, 10.99 and 14.13 m s^{-1}) and two drum types (spike teeth arrangement at 30° and 90°) on machine productivity energy requirements. They obtained optimum operation conditions at drum speed of 14.13 m s^{-1} which gave a threshing efficiency of 94.4 %, lowest grain damage (1.7 %) and highest productivity (0.628 Mg h^{-1}) with an energy requirement of 2.5 kWh Mg^{-1}.

The threshing efficiency and power consumption for axial flow and tangential flow threshing units were compared at five different drum peripheral speeds (6.44, 8.08, 10.44, 11.93 and 14.36 m s^{-1}) by Sessiz *et al.* (2008). Results obtained from the tests showed that the power consumption increased with increase in drum peripheral speed. The highest power requirement was found at 14.34 m s^{-1} as 1.975 kW. The lowest power consumption was obtained at drum peripheral speed of 6.44 m s^{-1} in both threshing units.

Dhananchezhiyan *et al.* (2013) evaluated a low cost portable paddy thresher at three level of concave clearance (15, 20 and 25 mm), cylinder peripheral speed (11.7, 14.1 and 16.5 m s^{-1}), grain moisture (13.5, 16.5 and 19.5 percent) and feed rate (200, 400 and 600 kg h^{-1}). They got maximum threshing efficiency (99.95 percent), minimum grain damage (2.76 percent) and maximum output capacity (248.27 kg h^{-1}) at the combination of 20 mm concave clearance, 16.5 m s^{-1} cylinder speed, 13.5 percent moisture content and 600 kg h^{-1} feed rate with rasp bar threshing cylinder.

Ukatu (2006) modified the spikes of an existing threshing cylinder of soybean thresher to reduce the impact force acting on the grain and to increase the threshing efficiency and reducing the grain damage. He used rotor speeds of 300 to 500 rpm with the conventional spikes. seed damage ranged between 1.94 and 2.43 percent, threshing efficiency ranged between 99.09 and 99.37 percent, throughput capacity ranged from 1493 to 1658 kg h^{-1} while output capacity ranges from 482.4 to 504.8 kg h^{-1} and with the modified spikes seed damage ranges from 0.83 to 0.98 percent, threshing efficiency ranges from 99.26 to 99.47 percent, throughput capacity ranges from 1525 to 1642 kg h^{-1} and output capacity ranges from 412.5 to 506.1 kg h^{-1}.

Alizadeh and Khodabakshipour (2010) studied the effect of threshing drum speed using five levels of drum speed (450, 550, 650, 750 and 850 rpm) and three levels of moisture content (17.0, 20.0 and 23.0 percent). The result obtained showed that maximum broken grains of 0.677 percent was at 850 rpm and 17 percent moisture content while least value (0.232 percent) was at 450 rpm drum speed and 23 percent moisture content.

Saiedirad and Javedi (2011) studied the effect of thresher variables (cylinder type, cylinder speed, feed rate, concave clearance) and crop variables (moisture content) on shattered seeds, shattered stems and damaged seeds during the threshing of cumin. The result showed that by increasing the cylinder speed from 12.8 to 16.5 m s^{-1} separated seed, shattered stems and damaged seeds percentage increased. The separated seed percentage was highest (96.7 percent) at 5 mm concave clearance and 500 kg h^{-1} feed rate. Rub bar cylinder, 16.5 m s^{-1} cylinder speed and 7 percent grain moisture content were best condition for cumin threshing

An existing soybean thresher was modified by Oforka (2004) and obtained optimal performance at cylinder speed of 850 rpm and feed rate of 30 kg h^{-1} at 10 % moisture content of the grain. They obtained 96 % threshing efficiency, 2.86 % mechanical grain damage, 97 % cleaning efficiency, 2.86 % scatter loss and 33 kg h^{-1} throughput capacity.

A sunflower threshing unit was designed and fabricated by Salokhe *et al.* (2005) to study the effect of machine and crop variables and to accumulate enough information for the best possible design of the thresher. Three concave holes size, four concave clearances and four drum speeds were studied. The threshing efficiency varied from 99.94 to 100%. The grain damage and grain loss figures were less than 1.5 and 1.0% respectively at drum speeds of 675 to 875 rpm and 29 to 35mm concave clearance. The lowest specific energy consumption was obtained with a 35 mm concave clearances at all drum speeds. The best combination of drum speed, and concave clearance to obtain high output capacity, high threshing efficiency, low grain damage, low grain losses and low specific energy consumption was a combination of 750 to 850 rpm drum speed (10.9 to 12.4 m s^{-1}) and 35 mm concave clearance.

2.5.4 The Taguchi Method

The Taguchi method was developed by Dr. Genichi Taguchi for improving the quality of goods manufactured (Park and Ha, 2005). According to Mostafa *et al.* (2013), Taguchi technique is an engineering methodology for obtaining product and process conditions which produce high-quality products with less development and cost of manufacturing. Two tools used in Taguchi method are the orthogonal array and the signal to noise (S/N) ratio. An orthogonal array is a matrix of numbers arranged in rows and columns and each column indicates a value of a factor. Every row represents a set of parameters for one run of the experiment. The experimental results are then transformed in to a signal to noise (S/N) ratio.

The signal-to-noise ratio is an average performance characteristic value for each experiment. Depending on objectives, the Taguchi method defines three different forms of mean square deviations: the *nominal-the-better*, the *larger-the-better* and the *smaller-the-better*. The *higher-the-better* is used if the system is optimized when the response is as large as possible and *smaller-the-better* in case the system is optimized when the response is as small as possible. The *nominal-the-better* arises when neither a smaller nor a larger value is desired. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics (Mezarcioz and Ogulata, 2011).

The Taguchi technique has the advantantage over the other optimization methods including arriving at the best parameters for optimal conditions with the least number of analytical investigations and at a lower cost than the corresponding full factorial experiment (Ballal *et al.,* 2012). It also provides for a significant reduction in the size of experiments thereby speeding up the experimental process (Mezarcioz and Ogulata, 2011).

Youssef *et al.* (1994) compared full factorial design, fractional factorial design and Taguchi design. They found that Taguchi design was sufficient for screening process parameters and was able to reduce experiments from 288 trials of full factorial design to only 16 trials. The data analyzed by Taguchi method was reliable and more economical than full factorial design.

Said *et al.* (2013) made a comparison between Taguchi method and response surface methodology (RSM) to optimize machining condition for aluminum silicon alloy and found that Taguchi method required less number of experiments than RSM and accurately optimized machining condition. Wangete *et al.* (2015) developed a groundnut sheller and reported an optimal throughput per unit energy consumption of 921.03 kg $h^{-1}(kWh)^{-1}$ at shelling speed of 12.2 m s^{-1}, 1200 kg h^{-1} feed rate and 10 mm concave clearance using Taguchi Technique.

2.6 Summary of knowledge gaps in the literature reviewed

From the literature review, it is evident that limited studies have been carried out on the influence of drum diameter and spike spacing on sorghum threshing performance. The influence of speed on threshing performance has been in terms of angular rather than drum peripheral speed. Threshing performance indices used in these studies did not take into consideration the influence of other inputs in the threshing process such as energy consumed. This study therefore hopes to fill in these knowledge gaps.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Design considerations

The following factors were considered in the development of the threshing unit of the sorghum thresher:

i. The peripheral speed rather than angular speed was used as a parameter due to the fact that the impact-force required to thresh the kernels of the sorghum from the panicles depends on the peripheral speed.
ii. The size and total weight of the machine were considered for easy transportation.
iii. As evidenced in the literature reviewed, running the thresher at speeds below 5.5 m s^{-1} would not achieve effective threshing of the crop, while speeds above 12.0 m s^{-1} may cause wastage of energy without corresponding increase in threshing efficiency and accelerate depreciation of the thresher.
iv. The drum length was chosen based on ergonomic considerations for convenient manual feeding during threshing.

3.2 Components of the thresher

The threshing unit consisted of a spike tooth drum and perforated concave. The threshing drum was made of galvanized cylindrical metal pipe of 150 mm diameter, 645 mm long through which a 25.4 mm shaft passed and supported on bearings at both ends. Spikes were welded in a staggered helical manner on the drum as shown in Plate 3.1. At the end of the drum shaft a double groove V belt pulley made of cast iron was mounted on the shaft driven by a three phase 2.20 kW electric motor.

Plate 3.1: Threshing drum and concave

The concave was 250 mm wide and 640 mm long. A concave clearance of 18 mm (Sale, 2015) was used in the design of the thresher and the same cylinder-concave clearance was maintained throughout the performance evaluation of the thresher. The support frame (Plate 3.2) was fabricated from iron hollow section 39 mm by 25 mm. The overall frame dimensions were 740 mm long, 250 mm wide and 450 mm high. A throw-in type trapezoidal feeding hopper was made from mild steel sheet gauge 18 and tilted at an angle of 30^0 to the horizontal to feed the sorghum heads by gravity flow. The height of hopper from the ground level was 1400 mm.

Plate 3. 2: The developed sorghum thresher

3.3 Sizing the components

The design analysis was carried out to evaluate the necessary design parameters, strength and size of materials for consideration in the selection of various machine parts. This was done to avoid failure by yielding and fatigue during the operation of the machine.

3.3.1 Power transmission system

i. Drum pulley diameter

The maximum drum angular speed was determined according to Sale (2015):

$$N = \frac{60\,V}{3.14\,D_P} \tag{3.1}$$

Where:

V=drum peripheral speed (m s^{-1})

D_p= drum diameter (m)

A threshing drum of diameter 400 mm was designed to thresh at a speed of 12.0 m s^{-1} (572.96 rpm). The drum shaft pulley diameter was calculated according to Derese (2014):

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \tag{3.2}$$

Where:

N_1 = Speed of prime mover pulley (rpm)

N_2 = Speed in rpm of driver pulley (rpm)

d_1 = Diameter of prime mover pulley (mm)

d_2 = Diameter of driven pulley (mm)

For motor speed 1430 rpm, drum peripheral speed, 572.96 rpm and motor pulley size of 101.60 mm, the diameter of the pulley was determined as 253.57 mm from equation 3.2. A pulley of 254 mm diameter was therefore selected for the drum shaft.

ii. Power required to turn unloaded drum

The power required to drive the threshing drum shaft was obtained from Olaoye (2011):

$$P_d = \frac{2\pi\ N\ M_d}{60\ x\ 75}\left(g + \frac{V^2}{r}\right) \tag{3.3}$$

Where:

M_d = total mass of drum (kg);

R = radius of the driven pulley (m);

r = effective radius of the drum (m);

V = maximum peripheral velocity of the drum (m s^{-1});

g = acceleration due to gravity (9.81 m s^{-2})

The mass of the threshing drum (M_d) was 3.75 kg with radius 20 mm. The shaft was designed for threshing drum speed 12.00 m s^{-1}. The power required to drive the shaft was therefore determined as 2189.44 W.

Power needed to detach grain was calculated according to Olaoye (2011):

$$P_g = \frac{3}{2}\ k_e \left(\frac{v_g^{\frac{3}{2}}\ f_r^{\frac{3}{2}}}{\rho_w\ L_c^{2}}\right) \tag{3.4}$$

Where:

K_e = A constant (grain size characteristics)

L_c = concave length (mm)

v_s = Speed of grain crop which is equal to peripheral drum velocity (m s^{-1})

f_r = feed rate (kg h^{-1})

ρ_w = Bulk density (kg m^{-3})

For sorghum at 12% moisture content (wb), Ndirika *et al.* (2006) determined Ke as 0.29 and ρ_w as 7839 kg m^{-3}. Using a feed rate of 240 kg h^{-1} and peripheral drum speed of 12 m s^{-1}, the power needed to detach grain was 23.82 W. The total power required was 2213.26 W

3.3.2 Selection of belt

V-Belts are wedge shaped with trapezoidal cross-section. They have nylon chords for load carrying and are covered with cotton fabric and molded in rubber for good friction co-efficient (Kazi *et al*., 2016).

i. Length of belt between prime mover and drum pulleys

According to Gupta and Khurmi (2005), the nominal pitch length (L) is given as:

$$L = \frac{\pi}{2}(D + d) + 2C + \frac{(D - d)^2}{C} \quad (3.5)$$

Where:

L = Length of belt connecting the pulleys (mm)

d = diameter of prime mover pulley (mm)

D = diameter of drum shaft pulley (mm)

C= distance between the centres of prime mover and driven pulley (mm)

The center distance was determined according to Maciejczyk and Zdziennicki (2000):

$$\frac{(D + d)}{2} + d \le C \le 2(D + d) \quad (3.6)$$

Taking D = 254 mm and d = 101.6 mm, C was calculated as 460 mm. The length of belt connecting the pulleys was then calculated from equation 3.5 as 1529.0 mm. Based on minimum pulley diameter (101.6 mm) and the available standard V-belts in the local market, B 60 with a length 1050 mm was selected for power transmission.

ii. Angle of lap of belts on pulley

The equation below, according to Khurmi and Gupta (2009), was used to determine the angle of lap (θ) of belt on pulleys:

$$\theta = 180 - 2\ Sin^{-1}\left(\frac{D - d}{C}\right) \qquad (3.7)$$

Where:

θ = angle of contact (^{0})

D = diameter of driven pulley (mm)

d = diameter of drive pulley (mm)

C= the distance between the centre of the two pulleys (mm).

The angle of contact for the drive pulley was determined from equation 3.7 as 160.93^0 (2.81 rads) and 199.07^0 (3.47 rads) for the driven pulley

iii. Power transmitted by the belt

The density, cross sectional area and allowable tensile stress (σ) of a V-belt of B cross section were taken as 1000 kg m^{-3}, 148.5 mm^2 and 2.5 M Pa respectively (Khurmi and Gupta, 2009). The mass of the belt per unit length was calculated as 0.2272 kg m^{-1} using equation 3.8 (Derese, 2014):

$$= \text{Cross sectional area } (m^2) \text{ x Length } (m) \text{ x Density } (kg\,m^{-3}) \qquad (3.8)$$

The centrifugal tension of the belt (T_c) was calculated as 350.65 N according to Derese (2014):

$$T_C = m\ x\ v^2 \qquad (3.9)$$

Where, m = weight of the belt per meter length, N

v = velocity of the belt, m s^{-1}

The tension in the slack side of the belt was calculated according to Khurmi and Gupta (2009):

$$\frac{T_t}{T_S} = e^{\mu\ \theta\ \text{cosec}\,\beta} \qquad (3.10)$$

where:

T_t = tension in the tight side (N)

T_s = tension in the slack side (N)

θ = angle of lap (radian)

μ= coefficient of friction between belt and pulley

β = half angle of V-groove of the pulley (^{0})

Taking μ= 0.42 and β = 20 ° (Khurmi and Gupta, 2009), maximum tension was determined as 445.50 N, tension in tight side of the belt as 94.54 N and tension in the slack side as 1.34 N.

The power transmitted per belt was obtained as 118.3 W from:

$$P = (T_t - T_s)\, v \tag{3.11}$$

where:

P = power transmitted by the belt to cylinder during threshing (W)

T_t = tension in the tight side (N)

T_s = tension in the slack side (N)

v = velocity of the belt (m s^{-1})

This power was required to thresh the grains and drive the drum and needed two belts as determined from equation 3.12:

$$\text{Number of belts} = \frac{\text{Total power transmitted}}{\text{Power transmitted per belt}} \tag{3.12}$$

Two belts were therefore selected with a double grooved pulley. Figure 3.1 shows the belt details.

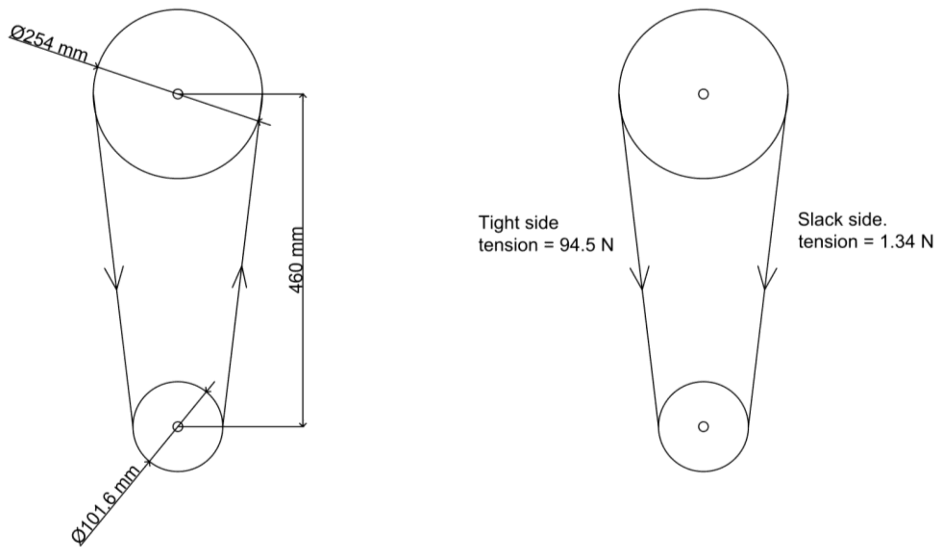


Figure 3. 1: Belt and pulley showing design dimensions

3.3.3 Design of shaft

A shaft is usually subjected to torsion, bending and axial loads. Bending and twisting moments occur on shaft as a result of applied loads and belt tensions

i. **Design of shaft based on shear strength**

Torsional strength is the torque per unit maximum shear stress. The maximum shear stress induced on the outer surface should not exceed the allowable value (Kazi *et al.*, 2016). The drum, including the beaters, was physically weighed and found as 98.10 N. Since the weight of sorghum inside threshing chamber was 19.62 N, the total force or weight on the shaft in the threshing unit, F_s was 117.72 N

Total vertical force on cylinder pulley was determined as:

W_D = weight of pulley and belt + vertical tensions in belt (3.13)

$= T_t + T_s + W_p$

Where,

T_t = Tension at tight side (N)

T_s = Tension at slack side (N)

W_p =Weight of the pulley (N)

The pulley and belt were physically weighed and their total mass found as 2.50 kg. The force applied at the point of pulley attachment on the shaft was calculated as 216.29 N. R_A and R_B were calculated as 44.34 N and 289.67 N respectively. The shear force values on the shaft at different points on the shaft were found as F_D = -216.29 N, F_B = 73.38 N and F_A = 44.34 N. The resultant bending moments on the shaft were determined as: ΣM_A= 2.90 N mm, ΣM_B = -10814.50 N mm, ΣM_C = 16519.55 N mm and ΣM_D = 0 N mm.

Torsional moment (M_t) on the shaft was calculated as 37280.00 N mm using (Khurmi and Gupta, 2009):

$$M_t = 2(T_t - T_s)\ x\ \frac{D_2}{2} \qquad (3.14)$$

Figure 3.2 shows free body force diagram of the shaft.

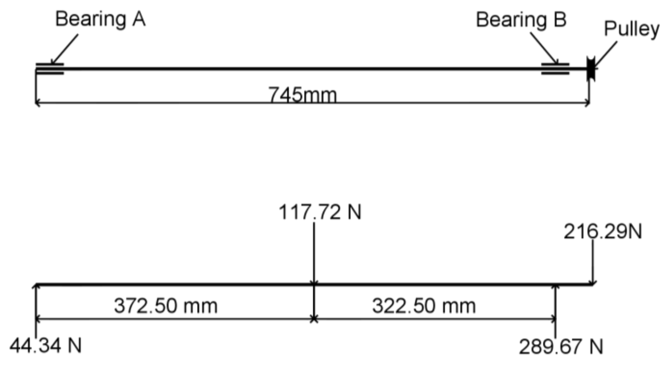


Figure 3.2: Free body force diagram of the shaft

The shear force and bending moment diagrams are shown in Figures 3.3 and 3.4 respectively,

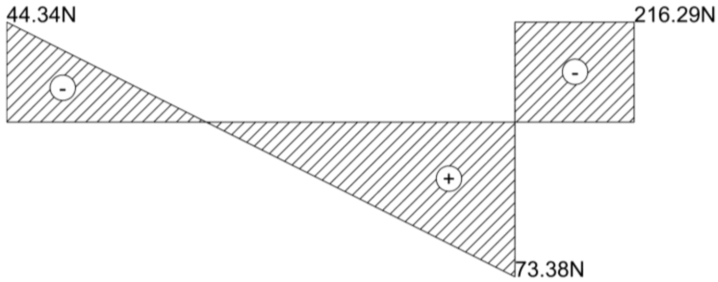


Figure 3.3: Shear force diagram of the shaft

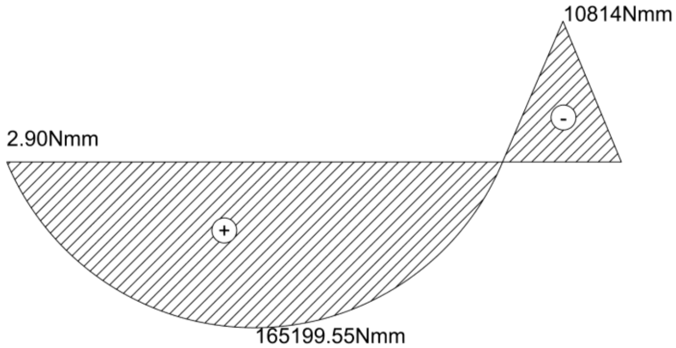


Figure 3.4: Shaft bending moment diagram

The shaft diameter was obtained according to Khurmi and Gupta (2009):

$$D^3 = \frac{16}{\pi\tau_a}\sqrt{(K_b\ M_b)^2 + (K_t\ M_t)^2} \tag{3.15}$$

where:

D = diameter of shaft to be determined (m)

K_b = the combined shock and fatigue factors for bending moment

K_t = the combined shock and fatigue factors for torsional moments

M_b = maximum bending moments in Newton metre (Nm)

M_t = the maximum torsional moments in Newton metre (Nm)

τ_a = the allowable stress in the shaft material (Pa)

From Figures 3.4 and 3.5, maximum torsional and bending moments were determined as 37280 and 16520 Nmm respectively. Taking K_b = 1.50 and K_c = 1.00 (Khurmi and Gupta, 2009) and substituting in equation 3.18, D was found as 16.10 mm

ii. Design of shaft based on rigidity

Rigidity is the torque required to produce a unit angle of twist in a specified length of the shaft. The diameter of the shaft is determined based on the prescribed value of the limiting angle of twist, θ (Kazi *et al.*, 2016). According to Hall *et al.* (1980), the amount of permissible twist depends on the type of load applied and varies between 0.3 degree per metre (^{0} m^{-1}) for a machine tool shaft to about 3 ^{0} m^{-1} for line shafting.

The permissible angle of twist, θ, caused by torque on the shaft for the sold shaft was given by:

$$\theta = \frac{584\ M_t\ L}{G\ d^4} \tag{3.16}$$

where: θ = Angle of twist (^{0})

M_t = torsional moment (Nm)

L = length of the shaft (m)

G = modulus of rigidity (Pa)

d = diameter of shaft (m)

The length of the shaft used was 795 mm. Taking modulus of rigidity of the steel as 84×10^9 Pa and assuming maximum permissible angle of twist of 1^0 (Khurmi and Gupta, 2009), from equation 3.19, d was calculated as 24.20 mm. Based on the two criteria above, a shaft of diameter **25.4 mm** was selected.

3.3.4 Concave radius

The radius of curvature of the concave grate, r_c, was determined according to Nalado (2015):

$$r_c = r_d + h_p + C_c \tag{3.17}$$

Where:

r_c = radius of concave (mm)

r_d = radius of cylinder drum (mm)

h_p = spike height above the drum (mm)

C_c = concave clearance (mm)

Since a concave clearance of 18 mm was maintained, concave radius was determined as 293 mm,

3.4 Experiment design

Completely randomized design (CRD) in a 3^3 factorial experiment with three replications in each treatment was used to determine the influence of drum diameter, spike spacing and drum peripheral speed on threshing performance. The Taguchi Method was used to optimize the threshing performance.

3.5 Influence of selected parameters on threshing performance

The performance tests of the thresher were carried out in selected sorghum farms in Migori County. Indigenous variety of sorghum (*andiwo*) was used as test material. Digital tachometer (*DT* 6236B) was used to determine the speed of the drum. The time taken for the threshing process was determined by a stop clock. The weights of threshed, unthreshed and damaged grains were measured using weighing balance. Electric energy consumed by the motor was determined by a digital watt-meter connected to its cable.

3.5.1 Drum diameter

The threshing drum consisted of a cylindrical metal pipe to which spikes were welded. The diameter was taken as the length between the tips of spikes at the opposite ends of circumference of the cylinder. The diameter of a drum was therefore varied by changing the length of the spikes.

A known weight of sorghum at 13% moisture content was threshed using a 200 mm diameter threshing drum at pre-set levels of spike spacing and threshing drum. The procedure was repeated for drum diameters 300 and 400 mm.

3.5.2 Spike spacing

Three levels of spike spacings (50, 75 and 100 mm) were used. Sorghum of known weight was threshed at pre-set levels of drum diameter and drum peripheral speed with spikes spaced at 50 mm. The experiments were repeated with spike spacings 75 and 100 mm. Each experiment was replicated three times.

3.5.3 Drum peripheral speed

Based on literature review, three speed levels of 8, 10 and 12 m s^{-1} were chosen. Speeds were measured using a tachometer and were electronically adjusted. A specified weight of sorghum was threshed at a drum peripheral speed of 8 m s^{-1} at selected levels of drum diameter and spike spacings. This was repeated for drum peripheral speeds 10 and 12 m s^{-1}. Each experiment was replicated three times.

3.6 Determination of threshing performance

3.6.1 Threshing efficiency

Three samples each 500 g of threshed material were collected and then cleaned. The clean grain was weighed using an electronic balance. The unthreshed grains were manually plucked by hand, cleaned and weighed. The threshing efficiency was then calculated according to Ndirika *et al.* (2006):

$$\eta_{th} = \left(1.00 - \frac{M_u}{M_t + M_u}\right) x \ \ 100 \tag{3.18}$$

Where:

M_t = Mass of threshed grain (kg)

M_u = Mass of unthreshed grains (kg)

3.6.2 Mechanical grain damage

Three samples weighing approximately 300 g each were taken at random from the clean grain. Damaged grain was sorted out manually from each of these samples and weighed. Percentage of damaged grain (G_d) was then calculated according to Tesfaye and Dibaba (2015):

$$G_d = \frac{M_d}{M_t} \ x \ 100 \tag{3.19}$$

Where:

M_d =Mass of damaged grains (kg)

M_t = Mass of threshed grain (kg)

3.6.3 Throughput per unit energy consumption

The throughput was determined by weighing the total grain (whole and damaged) received per given time at main grain output of the thresher. The throughput per unit energy consumed was then calculated according to Wangete *et al.* (2015):

$$f = \frac{M_t}{pt} \tag{3.20}$$

Where:

M_t = Mass of threshed grain (kg)

p = Electric power consumed (kW)

t = time of test run (h)

3.7 Optimization of threshing parameters

The parameters investigated in this study together with their selected levels are shown in Table 3.1.

Table 3.1: Selected parameters used in the study

Parameter	Level 1	Level 2	Level 3
Drum diameter (mm)	200	300	400
Spike spacing (mm)	50	75	100
Drum peripheral speed ($m\ s^{-1}$)	8	10	12

Optimization of the performance of the thresher was done using the Taguchi method. The selection of the orthogonal array was done according to Athreya and Venkatesh (2012) who noted that for L levels and P parameters:

$$\text{Minimum number of experiments} = P\ (L - 1) + 1 \qquad (3.21)$$

Since the minimum number of experiments for optimization was determined as 7 an L^9 orthogonal array (Table 3.2) was chosen.

Table 3.2: The Taguchi L_9 orthogonal array for optimization experiments
(Source: Taguchi *et al.*, 2005)

Exp. No	Control parameters		
	Drum diameter	**Spike spacing**	**Drum peripheral speed**
1	1	1	3
2	1	2	2
3	1	3	1
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	2
8	3	2	3
9	3	3	1

Experiments were conducted using L_9 orthogonal array with 9 rows corresponding to the number of experiments as shown in Table 3.3.

Table 3.3: The optimization experimental setup

Exp. No,	Drum diameter (mm)	Spike spacing (mm)	Drum peripheral speed (m/s)
1	200	50	**12**
2	200	75	10
3	200	100	8
4	300	50	10
5	300	75	12
6	300	100	8
7	400	50	10
8	400	75	12
9	400	100	8

The experimental observations were then transformed into signal to noise ratio. Since it was desired to maximize the threshing efficiency and throughput per unit energy consumption, the *higher-the-better* quality characteristic was employed (Wysk *et al.*, 2000):

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right] \tag{3.22}$$

Where:

S = Signal (dB)

N = Noise (dB)

n = number of experiment replications in a trial and

y_i= ith measured output value for the trial

The *smaller-the-better* quality characteristic was used to obtain minimum mechanical grain damage according to Mezarcioz and Ogulata (2011):

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \tag{3.23}$$

Where:

S = Signal (dB)

N = Noise (dB)

n = number of experiment replications in a trial and

y_i= ith measured output value for the trial

3.8 Data analysis

The data obtained from the experiment were subjected to graphical and statistical analysis of variance (ANOVA) where degrees of freedom, sums of squares and mean sums of squares were calculated. The levels of significance between the factors were determined using the F-test. The treatment means that were different at 5% levels of significance were separated using least significance difference (LSD) according to Gomez and Gomez (1984).

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Influence of selected parameters on threshing performance

The results and discussion presented in this chapter are based on experiments carried out to determine the effect of three drum diameters (200, 300 and 400 mm), three spike spacings (50, 75 and 100 mm) and three drum peripheral speeds (8, 10 and 12 m s^{-1}) on the performance of a prototype sorghum thresher.

The performance indices studied were threshing efficiency, mechanical grain damage and throughput per unit energy consumption. Threshing efficiency evaluated the percentage of grains detached from the sorghum heads. Mechanical grain damage estimated the percentage of broken grains present within the grains collected at the outlets. Throughput per unit of energy consumption was a measure of the quantity of threshed grain per hour per unit of energy consumed. The results of the study are summarized in Tables A1.1, A1.2 and A1.3.

4.1.1 Threshing Efficiency

The results of threshing efficiency are summarized in Table 4.1 and Figure 4.1.

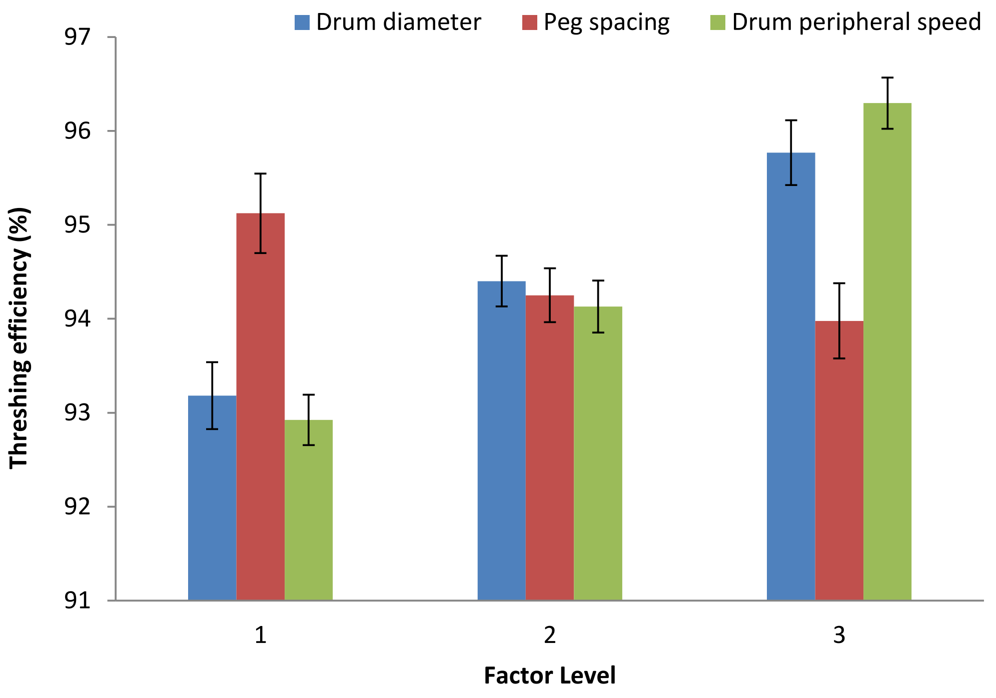
Table 4.1: Percentage threshing efficiency at three drum diameters spike spacing and drum peripheral speed

	Factor Level		
	1	**2**	**3**
Drum diameter	93.2 ± 0.4	94.4 ± 0.3	95.8 ± 0.3
Spike spacing	95.1 ± 0.4	94.3 ± 0.3	94.0 ± 0.4
Drum peripheral speed	92.9 ± 0.3	94.1 ± 0.3	96.3 ± 0.3

Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

i. Influence of drum diameter on threshing efficiency

The mean threshing efficiency rose from about 93 to 96% when drum diameter was increased from 200 to 400 mm (Table 4.1 and Figure 4.1). From Table A2.1, it was observed that the threshing efficiency for the 400 mm drum diameter of 96% was significantly ($p<0.05$) higher than those for the 200 and 300 mm drum diameters of 93% and 94% respectively.



Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

Figure 4.1: Threshing efficiency as influenced by selected parameters

The increase in threshing efficiency with drum diameter could be attributed to the increased threshing surface area between threshing drum and concave as drum diameter was increased resulting in more abrasion between sorghum heads and concave and a longer dwell time of crop in threshing chamber.

The observed trend between drum diameter and threshing efficiency is consistent with the findings of Osueke (2013) that threshing efficiency increased with increase in drum diameter. However, the researcher obtained a maximum threshing efficiency of 92% compared to 96% obtained in this study.

ii. Threshing efficiency as influenced by spike spacing

Table 4.1 and Figure 4.1 show that mean threshing efficiency decreased by 1% from 95 to 94% when spike spacing was widened from 50 to 100 mm. Although this change appears insignificant in practice, statistical analysis at the 0.05 level of significance showed that the threshing efficiency of 95% obtained with 50 mm spike spacing was higher than 94% obtained with 75 and 100 mm spike spacings. This decrease in threshing efficiency could be attributed to the fewer spikes on the drum as spike spacing was increased thereby reducing the number of spike collisions with the grain heads.

This finding was in agreement with the results for a wire loop thresher reported by Singh *et al.* (2006) that threshing efficiency decreased with spacing of the wire loops in a wire loop thresher. Their threshing efficiency of 96.4% was higher than the value obtained in this study of 94% due to the difference in type of spikes used.

iii. Influence of drum peripheral speed on threshing efficiency

The results indicated that threshing efficiency increased from 93 to 96% when drum peripheral speed was increased from 8 to 12 m s^{-1} (Table 4.1 and Figure 4.1). Table A2.1 showed that drum peripheral speed significantly affected threshing efficiency at the 5% level of confidence. Comparison of treatment means of the different drum speeds revealed that the threshing efficiency of drum speed 12 m s^{-1} of 96% was higher than those for 8 and 10 m s^{-1} drum speeds of 93 and 94% respectively.

The increase in threshing efficiency with drum speed could be attributed to high frequency of collisions and impacts between spikes and grain heads and also due to increased abrasion between the concave and grain heads.

The finding that threshing efficiency increased with drum speed was also observed by Simonyan and Yiljep (2008) who obtained a mean threshing efficiency of 99.5% and Desta and Mishra (1990) who obtained a mean of 99%. The reason for lower mean threshing efficiency of 95% observed in this study may have been due to the difference in crop variety used in the two studies.

iv. Effect of factor interactions on threshing efficiency

All interactions between drum diameter, spike spacing and drum peripheral speed were significant ($p<0.05$) on threshing efficiency (Table A2.1) meaning that variations in the treatment means could not be solely attributed to the three factors. The interaction between drum diameter and spike spacing was the most significant while the interaction between drum diameter and peripheral speed was the least significant.

Threshing sorghum at spike spacing 50 mm, drum diameter 400 mm and drum peripheral speed 12 m s^{-1} produced the highest threshing efficiency of 99% while threshing using spike spacing 100 mm, drum diameter 200 mm and drum peripheral speed 8 m s^{-1} produced the lowest threshing efficiency of 91%.

4.1.2 Mechanical grain damage

Table 4.2 and Figure 4.2 present the results of determination of mechanical grain damage for the sorghum thresher.

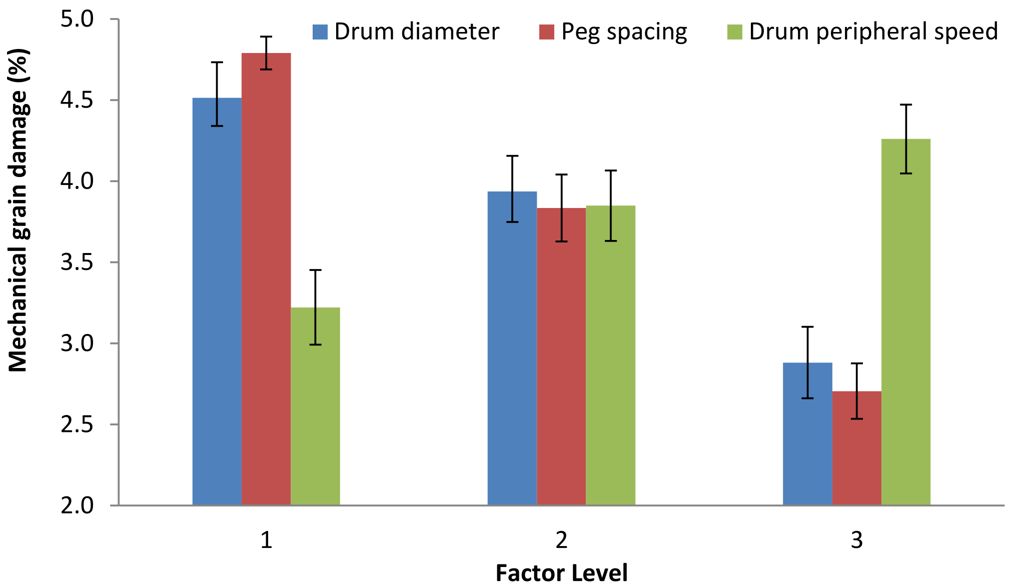
Table 4.2: Percentage grain damage at three factor levels

	Factor Level		
	1	**2**	**3**
Drum diameter	4.5 ± 0.2	3.9 ± 0.2	2.9 ± 0.2
Spike spacing	4.8 ± 0.1	3.8 ± 0.2	2.7 ± 0.2
Drum peripheral speed	3.2 ± 0.2	3.8 ± 0.2	4.1 ± 0.2

Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

i. Grain damage as influenced by drum diameter

The grain damage decreased from 5% to 3% as the drum diameter was increased from 200 to 400 mm (Table 4.2 and Figure 4.2). Although practically this change appears not to be significant, statistical analysis at the 5% level of confidence showed that mechanical grain damage at 200 and 300 mm drum diameter were higher than 400 mm diameter.



Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

Figure 4.2: Mechanical grain damage at three factor levels

The decrease in mechanical grain damage could be attributed to the fact that for any given feed rate, the sorghum heads became loosely packed in the threshing chamber as drum diameter was increased and this might have reduced abrasion among grain heads.

The finding that mechanical grain damage decreased with increase in drum diameter agrees with the observation made by Banga *et al.* (1984) that longer spikes in a spike tooth thresher reduced mechanical grain damage. They obtained a mean grain damage of 3.5% which compares well with that obtained in this study of 3.7%.

ii. Influence of spike spacing on grain damage

It was observed that mechanical grain damage decreased with increased spike spacing, reducing from 5% at 50 mm spike spacing to 3% at 100 mm spike spacing (Table 4.2 and Figure 4.2). Although this change appears insignificant practically, statistical analysis at the 0.05 level of significance showed that the mechanical grain damage of 5% obtained with 50 mm spike spacing was higher than 3% and 4% obtained with 75 and 100 mm spike spacings respectively.

The decrease in mechanical grain damage could be due to the reduced number of spikes per row as spike spacing was increased. This might have resulted in fewer collisions between spikes and grain heads at wider spacings.

This result was in agreement with the conclusion by Banga *et al.* (1984) that less number of spikes in rows caused less grain damage in axial flow threshers. However, Srison *et al.* (2016) found no relationship between spike spacing and mechanical grain damage and reported lower mechanical grain damage of 0.4%.

iii. Grain damage as affected by of drum peripheral speed

As can be seen from Table 4.2 and Figure 4.2, increasing the drum peripheral speed led to increased grain mechanical damage for the three drum diameters and spike spacings. ANOVA (Table A2.2) at the 5% level of confidence showed that mechanical gain damage of 4% for both drum peripheral speeds 10 and 12 m s^{-1}, was higher than 3% observed for drum peripheral speed of 8 m s^{-1}.

The increase in grain damage was probably due to the increase in frequency of the abrasion between grains and the drum walls as well as among grain heads as speed increased. The collisions of spikes and grain heads were also frequent and impacts were harder at higher speeds, leading to increased grain damage.

This observation that increase in drum speed increased mechanical grain damage is consistent with those of Alizadeh and Khodabakshipour (2010) who noted a similar trend between drum speed and grain damage. The mechanical grain damage they obtained of 0.68% is lower than the mean value of 4% obtained in this study. This may be due to the fact that they used lower cylinder threshing speeds (400 to 450 rpm) than those used in this study (478 to 573 rpm).

iv. Effect of factor interactions on mechanical grain damage

The effect of first and second interactions of drum diameter, spike spacing and drum peripheral speed were highly significant ($p<0.05$) on mechanical grain damage (Table A2.3). This implied that the influence of one factor on grain damage was dependent on the levels of the other factors. The interaction between drum diameter and spike spacing had the most effect on mechanical grain damage while the interaction between all the three factors had the least effect.

The maximum mechanical grain damage of 6 % occurred with drum diameter 200 mm, spike spacing 50 mm and drum peripheral speed 12 m s^{-1}. Minimum mechanical grain damage of 1% was obtained using drum diameter 400 mm, spike spacing 100 mm and drum peripheral speed 8 m s^{-1}.

4.1.3 Throughput per unit energy consumption

The results of determination of throughput per unit energy consumption are summarized in Table 4.3 and Figure 4.3.

i. Influence of drum diameter on throughput per unit energy consumption

From Table A2.3, drum diameter was found to significantly ($p<0.05$) affect throughput per unit energy consumption. Throughput per unit energy consumption increased from 92 to 118 kg h^{-1} $(kWh)^{-1}$ when the drum diameter was increased from 200 to 400 mm (Table 4.3 and Figure 4.3).

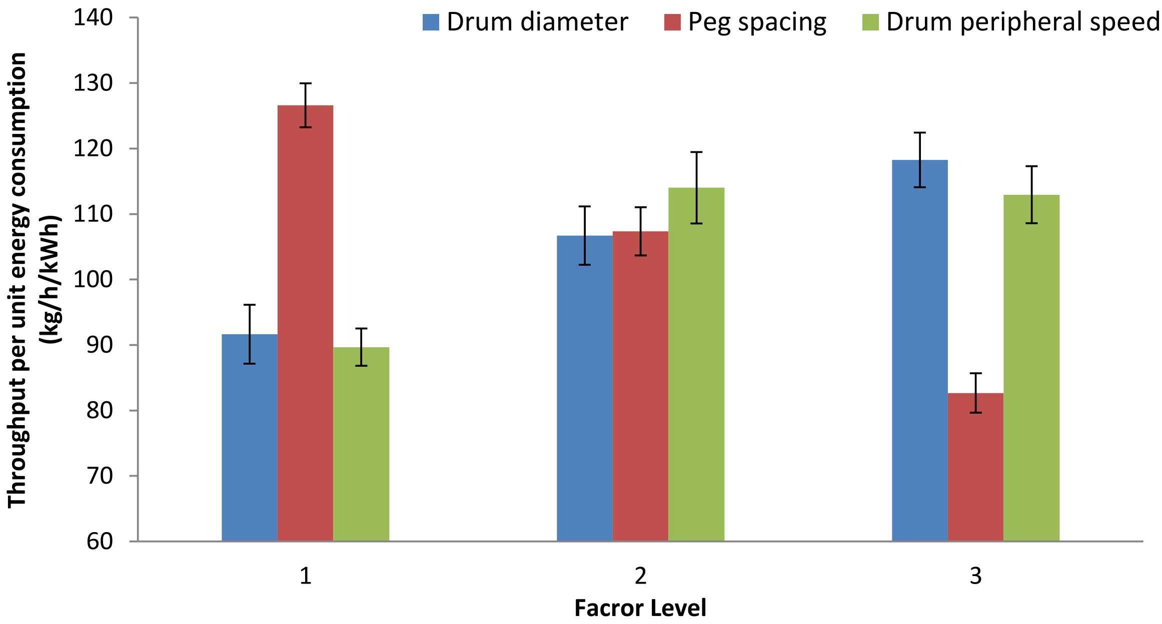
The throughput per unit energy consumption of 118 kg h^{-1} $(kWh)^{-1}$ for drum diameter 400 mm was found at the 0.05 level of confidence to be higher than the 92 and 107 kg h^{-1} $(kWh)^{-1}$ obtained for diameters 200 and 300 mm respectively.

Table 4.3: Throughput per unit energy consumption at three factor levels

	Factor Level		
	1	**2**	**3**
Drum diameter	91.7 ± 4.5	106.7 ± 4.5	118.3 ± 4.2
Spike spacing	126.6 ± 3.4	107.4 ± 3.7	82.7 ± 3.0
Drum peripheral speed	89.7 ± 2.9	114.0 ± 5.4	112.9 ± 4.3

Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

The increase in throughput per unit energy consumption could be attributed to the fact that larger diameter drums had bigger threshing chambers and therefore threshed more sorghum heads per unit time than smaller drum diameters.



Key: 1: Drum diameter =200 mm, Spike spacing = 50 mm and Drum speed = 8 ms^{-1}
2: Drum diameter =300 mm, Spike spacing = 75 mm and drum speed = 10 ms^{-1}
3: Drum diameter =400 mm, Spike spacing = 100 mm and drum speed = 12 ms^{-1}

Figure 4.3: throughput per unit energy consumed at various factor levels

This finding is in agreement with the observation by Desta and Mishra (1990) that throughput per unit energy consumption of an axial flow sorghum thresher increased with increase in drum diameter. Their mean value of 32.9 kg h^{-1} $(kWh)^{-1}$ is however lower than 106 kg h^{-1} $(kWh)^{-1}$ obtained in this study.

ii. Influence of spike spacing on throughput per unit energy consumption

As given in Table 4.3 and Figure 4.3, the mean throughput per unit energy consumption decreased from 127 to 83 kg h^{-1} $(kWh)^{-1}$ when the spike spacing was widened from 50 to 100 mm. The throughput per unit energy consumption of 127 kg h^{-1} $(kWh)^{-1}$ at 50 mm spike spacing was found to be higher than 107 and 83 kg h^{-1} $(kWh)^{-1}$ for the 75 mm and 100 mm spike spacing respectively at the 5% level of significance (Table A2.3).

The decrease in throughput per unit energy consumption could be attributed to the number of spikes in each row being less at wider spike spacing. This led to fewer collisions between spikes and the sorghum heads.

The decrease in throughput per unit energy consumption with increase in spike spacing was also observed by Sudajan *et al.* (2005). However, their mean throughput per unit energy consumption of 610 kg h^{-1} $(kWh)^{-1}$ was higher than 106 kg h^{-1} $(kWh)^{-1}$ obtained in this study. This could be because they used a wider threshing unit than the one used in this study.

iii. Throughput per unit energy consumption as influenced by drum peripheral speed

Throughput per unit energy consumption was significantly affected by drum peripheral speed at the 5% level of confidence (Table A3.3). As indicated by Table 4.3 and Figure 4.3, increasing drum peripheral speed from 8 to 10 m s^{-1} led to rise in throughput per unit energy consumption from 90 to 114 kg h^{-1} $(kWh)^{-1}$ which dropped to 113 kg h^{-1} $(kWh)^{-1}$ when speed was increased to 12 m s^{-1}.

Statistical analysis (Table A3.3) at the 0.05 level of confidence showed that throughput per unit energy consumption of 114 kg h^{-1} $(kWh)^{-1}$ for drum peripheral speeds 10 m s^{-1} was not different from the 112 kg h^{-1} $(kWh)^{-1}$ obtained for speed 12 m s^{-1} but was significantly higher than 90 kg h^{-1} $(kWh)^{-1}$ observed for drum peripheral speed of 8 m s^{-1}.

Figure 4.4 compares the throughput and throughput per unit energy consumption of the thresher at three drum peripheral speeds used in the study. Although the throughput of the thresher increased with speed, throughput per unit energy consumption was noted to rise to a maximum at 10 m s^{-1} then decrlined marginally with further increase in speed. Operating the thresher at drum peripheral speed 12 m s^{-1} produced the highest throughput but more energy was consumed in the process. Supplying this extra energy to the thresher at 10 m s^{-1} would make throughput at this speed higher than at 12 m s^{-1}, suggesting that selection of a thresher should consider other inputs involved in threshing, such as energy.

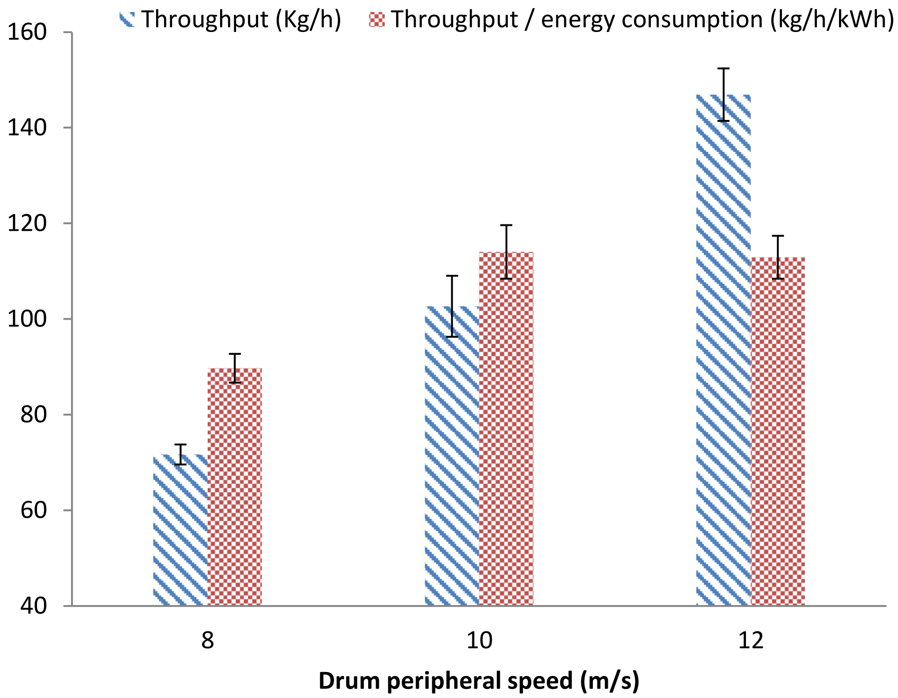


Figure 4.4: Comparison of throughput and throughput per unit energy consumption

The increase in throughput with speed could have been due to the spikes making harder and frequent impacts on sorghum heads and the increased abrasion between grain heads. Additionally, the fast rotation of drum could have caused the grain mass in the threshing unit to thin out therefore allowing more grains to pass through the straw. The decline in throughput per unit energy consumption after 10 m s^{-1} could be attributed to a latge increase in energy cnsumption of 0.4 kWh when drum speed was increased from 10 to 12 m s^{-1} compared to the corresponding increase in energy cnsumption of 0.1 kWh when speed was increased from 8 to 10 m s^{-1}.

Wangete *et al.* (2015) found that throughput per unit energy consumption increased with drum peripheral speed contrary to the finding in this study of a decline in throughput per unit energy consumption at higher speeds. They obtained a mean value of 95 kg h^{-1} $(kWh)^{-1}$ which was lower than the 106 kg h^{-1} $(kWh)^{-1}$ obtained in this study.

iv. Effect of factor interactions on throughput per unit energy consumption

Table A2.3 indicate that all interactions between drum diameter, spike spacing and drum peripheral speed were significant ($p<0.05$) on throughput per unit energy consumption implying the effect of one factor on throughput per unit energy consumption was dependant on the levels of the other factors. The interaction between spike spacing and drum peripheral speed had the most effect on throughput per unit energy consumption while that between all the three factors had the least effect.

Threshing sorghum with a drum diameter of 400 mm, spike spacing 50 mm and drum peripheral speed of 10 m s^{-1} produced maximum throughput per unit energy consumption of 153 kg h^{-1} $(kWh)^{-1}$ while a minimum value of 62 kg h^{-1} $(kWh)^{-1}$ was obtained using drum diameter 200 mm, spike spacing 100 mm and drum peripheral speed of 10 m s^{-1}.

4.2 Optimization of threshing performance

The results of optimization experiments using the Taguchi method are presented in Table A3.1.

4.2.1 Threshing efficiency

Maximum threshing efficiency was achieved at 400 mm drum diameter, 50 mm spike spacing and 12 m s^{-1} drum peripheral speed (Table 4.4). The greatest influence on threshing efficiency was found to be drum peripheral speed while drum diameter had the least influence (Table A3.1).

Table 4.4: Mean threshing efficiency for three levels of the selected factors

	Level 1	**Level 2**	**Level 3**
Drum diameter	93	95	96*
Spike spacing	96*	95	93
Drum speed	92	95	96*

* Maximum threshing efficiency.

4.2.2 Mechanical grain damage

Minimum mechanical grain damage was achieved with 400 mm drum diameter, 100 mm spike spacing and 8 m s^{-1} drum peripheral speed (Table 4.5). The mean S/N ratios for mechanical grain damage indicated that the greatest influence on mechanical grain damage was spike spacing while drum diameter had the least Influence (Table A3.3).

Table 4.5: Mean percentage grain damage three levels of the selected factors

	Level 1	Level 2	Level 3
Drum diameter	5.3	4.0	2.8*
Spike spacing	5.0	4.2	2.1*
Drum speed	2.1*	4.6	(4.6)

* Minimum grain damage

4.2.3 Throughput per unit energy consumption

Table A3.4 give mean S/N ratio for throughput per unit energy consumption with the mean throughput per unit power consumption are presented in Table 4.6. Maximum throughput per unit energy consumption was achieved with 400 mm drum diameter, 50 mm spike spacing and 10 m s^{-1} drum peripheral speed. Spike spacing was found to have the greatest Influence on throughput per unit energy consumption while drum peripheral speed had the least Influence.

Table 4.6: Mean throughput per unit energy consumption at three levels of selected factors

	Level 1	Level 2	Level 3
Drum diameter	96	113	123*
Spike spacing	139*	118	76
Drum speed	75	131*	126

* Maximum throughput per unit energy consumption

4.3 Threshing performance at optimal factor levels

Table 4.7 summarizes the threshing performance at the various optimal factor combinations from the performance evaluation of the thresher. Based on the need for higher throughput per unit energy consumption and low mechanical grain damage, 400 mm drum diameter, 50 mm spike spacing and drum peripheral speed 10 m s^{-1} was selected as the optimal factor levels.

The results of confirmation experiments carried out at the selected optimal setting were 98%, 5% and 158 kg h^{-1} $(kWh)^{-1}$ for threshing efficiency, mechanical grain damage and throughput per unit power consumption respectively. These results were in close agreement with the output at the optimal factor levels in Table 4.7.

Table 4.7: Factor combinations for optimal threshing performance

	Drum diameter (mm)	Spike spacing (mm)	Drum speed (m/s)	Threshing Efficiency (%)	Mechanical grain damage (%)	Throughput per unit energy consumption (kg h^{-1}) $(kWh)^{-1}$
1	400	50	12	99	5	140
2	400	100	8	93	1	84
3	400	50	10	97	4	153

The use of Taguchi method in optimizing drum diameter, spike spacing and drum peripheral speed involved 27 runs compared to the factorial method which involved 81 runs in obtaining similar results. This supported the conclusions of Youssef *et al.* (1994) and Ballal *et al.* (2012) that optimization using Taguchi method involved less number of analytical investigations than factorial method.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Performance evaluation was carried out to quantify the Influences of drum diameter, spike spacing and drum peripheral speed on threshing efficiency, mechanical grain damage and throughput per unit energy consumption. Three diameters, three spike spacing and three drum peripheral speeds were investigated to identify the combination of the factors yielding optimal threshing performance. Based on the results obtained, the following conclusions can be drawn:

Threshing efficiency and throughput per unit energy consumption increased while mechanical grain damage decreased with increase in drum diameter. Optimal threshing performance was obtained with the 400 mm drum diameter;

Wider spike spacing reduced threshing efficiency, mechanical grain damage and throughput per unit energy consumption. Spike spacing of 50 mm yielding optical threshing performance;

Increasing drum peripheral speed led to rise in threshing efficiency and mechanical grain damage while throughput per unit energy consumption increased to a maximum value at 10 m s^{-1};

Optimal threshing performance was achieved using drum diameter 400 mm, spike spacing 50 mm and drum peripheral speed 10 m s^{-1} for the drum length and sorghum variety used in the study.

5.2 Recommendations

Based on the findings obtained, the following recommendations are made:

i. Since the feeding of sorghum was done manually in this study, future studies could incorporate an automatic feeding mechanism which would enhance experimental efficiency;
ii. Throughput per unit energy consumption should be used as a threshing performance indicator rather than throughput. This recommendation could be extended to other grain threshers since the principles of design and operation are the same However, more investigations are needed to show that throughput per unit energy consumption t actually declined with speed;

iii. Future studies could optimize the threshing performance using other optimization methods such as response surface methodology (RSM) and artificial neural networks (ANN) to confirm or otherwise the optimal settings;

iv. The influence of sorghum variety and moisture content on the performance of the spike tooth sorghum threshing unit could be investigated in future studies.

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APPENDICES

Appendix 1: Performance evaluation results

Table A1.1 Mean percentage threshing efficiency at three levels of selected parameters

Drum speed (m/s)	Spike spacing 50 mm			Spike spacing 75 mm			Spike spacing 100 mm				
	Drum diameter (mm)										
	200	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**	**Mean**	**SD**
8	91.1	94.6	95.1	92.2	92.9	94.0	91.0	92.3	93.1	92.9	0.3
10	93.1	95.1	97.0	93.0	94.1	94.5	92.2	93.0	95.2	94.1	0.3
12	94.5	96.6	99.0	94.5	96.0	97.0	97.0	95.0	97.0	96.3	0.3
Mean	92.9	95.4	97.0	93.2	94.3	95.2	92.0	93.4	95.1	**94.5**	
SD	0.3	0.2	0.4	0.2	0.3	0.3	0.6	0.3	0.4		

Table A1.2: Mean percentage grain damage at three levels of selected parameters

Drum speed (m/s)	Spike spacing 50 mm			Spike spacing 75 mm			Spike spacing 100 mm				
	Drum diameter (mm)										
	200	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**	**Mean**	**SD**
8	4.9	4.5	4.0	2.5	3.2	2.0	3.0	2.2	1.2	3.1	0.2
10	5.3	4.8	4.3	4.8	3.6	3.8	3.5	2.9	1.7	3.9	0.2
12	5.8	5.0	4.5	5.3	4.9	3.0	4.0	3.5	2.3	4.3	0.2
Mean	4.5	3.9	2.9	4.8	3.8	2.7	3.2	3.8	4.3	**3.8**	
SD	0.1	0.0	0.0	0.3	0.2	0.2	0.1	0.1	0.1		

Table A1.3: Mean throughput per unit energy consumption (kg h^{-1} $(kWh)^{-1}$) at three levels of selected parameters

Drum speed (m/s)	Spike spacing 50 mm			Spike spacing 75 mm			Spike spacing 100 mm				
	Drum diameter (mm)										
	200	**300**	**400**	**200**	**300**	**400**	**200**	**300**	**400**	**Mean**	**SD**
8	97.5	107.8	112.3	75.2	90.1	97.5	67.9	75.2	83.5	89.7	3.0
10	128.9	141.9	153.3	97.9	116.5	132.7	62.2	81.6	111.1	114.0	5.6
12	123.7	134.6	139.6	100.8	123.9	131.5	70.8	88.7	102.9	112.9	4.5
Mean	116.7	128.1	135.0	91.3	110.2	120.6	67.0	81.9	99.1	**105.5**	
SD	3.2	3.4	4.0	2.7	3.4	3.8	0.8	1.3	2.7		

Appendix 2: ANOVA of performance indicators

Table A2.1: ANOVA for threshing efficiency

Source of variation	DoF	SS	MSS	$F_{cal.}$	$F_{crit.}$ (5%)
Total	80	314.59	======	======	=====
Drum diameter (D)	2	90.44	45.22	2747.01*	3.17
Axial spike spacing (P)	2	19.31	9.66	586.62*	3.17
Drum peripheral speed (S)	2	157.64	78.82	4788.45*	3.17
Drum diameter x spike spacing	4	21.44	5.36	325.55*	2.54
Drum diameter x peripheral speed	4	4.59	1.15	69.68*	2.54
Spike spacing x peripheral speed	4	6.30	1.57	95.62*	2.54
D x P x S	8	12.35	1.54	93.79*	2.12
Error	54	0.89	0.02	======	======

* Significant

DoF = Degrees of freedom SS = Sums of squares MSS = Mean sums of squares

Table A2.2: ANOVA for mechanical grain damage

Source of variation	DoF	SS	MSS	$F_{cal.}$	$F_{crit.}$ (5%)
Total	80	116.49	======	======	======
Drum diameter (D)	2	36.96	18.48	1784.85*	3.168
Axial spike spacing (P)	2	58.79	29.39	2838.93*	3.168
Drum peripheral speed (S)	2	14.75	7.37	712.06*	3.168
Drum diameter x spike spacing	4	3.22	0.80	77.73*	2.543
Drum diameter x peripheral speed	4	0.24	0.06	5.87*	2.543
Spike spacing x peripheral speed	4	1.55	0.39	37.39*	2.543
D x P x S	8	0.42	0.05	5.11*	2.115
Error	54	0.56	0.01	======	======

* Significant

DoF = Degrees of freedom SS = Sums of squares MSS = Mean sums of squares

Table A2.3: ANOVA for throughput per unit energy consumption

Source of variation	**DoF**	**SS**	**MSS**	**$F_{cal.}$**	**$F_{crit.}$ (5%)**
Total	80	49929.93	======	======	====
Drum diameter (D)	2	9578.49	4789.25	852.04*	3.17
Axial spike spacing (P)	2	26190.21	13095.11	2329.70*	3.17
Drum peripheral speed (S)	2	10210.32	5105.16	908.24*	3.17
Drum diameter x spike spacing	4	571.83	142.96	25.43*	2.54
Drum diameter x peripheral speed	4	838.37	209.59	37.29*	2.54
Spike spacing x peripheral speed	4	1948.35	487.09	86.66*	2.54
D x P x S	8	288.83	36.10	6.42*	2.12
Error	54	303.53	5.62	======	===

* Significant

DoF = Degrees of freedom SS = Sums of squares MSS = Mean sums of squares

Appendix 3: Optimization experimental results

Table A3.1: Results of optimization experiments

Expt. No.	Drum diameter (mm)	Spike spacing (mm)	Drum peripheral speed (m s^{-1})	Threshing efficiency	Mechanical grain damage	Throughput /energy consumption
				Mean (%)	Mean (%)	Mean (kg h^{-1} $(kWh)^{-1}$)
1	200	50	12	94.5	5.8	123.7
2	200	75	10	93.0	4.8	97.9
3	200	100	8	91.0	3.0	67.9
4	300	50	10	95.1	4.8	141.9
5	300	75	12	96.0	4.9	123.9
6	300	100	8	92.3	2.2	75.2
7	400	50	10	97.0	4.3	153.3
8	400	75	12	97.0	3.0	131.5
9	400	100	8	93.1	1.2	83.5

Table A3.2: Mean S/N values for threshing efficiency

Factors	Mean S/N ratios (dB)				
	Level 1	Level 2	Level 3	Range	Rank
Drum diameter	52.1	57.5	57.6*	5.50	3
Spike spacing	59.6*	54.3	53.3	6.34	2
Drum speed	53.3	54.3	59.6*	6.36	1

* S/N values for optimum output.

Table A3.3: Mean S/N values for mechanical grain damage

Factors	Mean S/N ratio (dB)				
	Level 1	Level 2	Level 3	Range	Rank
Drum diameter	-12.7	-11.2	-7.5*	5.1	3
Spike spacing	-13.7	-12.2	-2.8*	10.9	1
Drum speed	-5.5*	-6.6	-12.7	7.2	2

* S/N values for optimum output

Table A3.4: Mean S/N for throughput per unit energy consumption

Factors	Mean S/N Ratio (dB)				
	Level 1	**Level 2**	**Level 3**	**Range**	**Rank**
Drum diameter	32.6	32.20	34.07*	1.98	2
Spike spacing	34.43*	32.20	33.98	2.23	1
Drum speed	33.06	34.07*	33.56	1.01	3

* S/N values for optimum output

Appendix 4: Plates

Plate A4.1: Sorghum samples for threshing

Plate A4.2: Threshing drums

Plate A4.3: Sorghum threshing process

Plate A4.4: Bags of threshed sorghum

Appendix 5 NACOSTI Authorization

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