UNIVERSITY FOR DEVELOPMENT STUDIES

PERFORMANCE OF GRAIN GRINDING MACHINES IN TAMALE METROPOLIS

YAKUBU FUSEINI JUUNA

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PERFORMANCE OF GRAIN GRINDING MACHINES IN TAMALE METROPOLIS

BY

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THESIS SUBMITTED TO THE DEPARTMENT OF AGRICULTURE MECHANIZATION AND IRRIGATION TECHNOLOGY, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN POST HARVEST TECHNOLOGY

SEPTEMBER, 2017

DECLARATION

STUDENT

I hereby declare that this thesis is the result of my own original work and that no part of it has been presented for another degree in this University or elsewhere and other materials used are duly cited in the references.

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We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University for Development Studies.

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ABSTRACT

This study was conducted in the Tamale metropolis in the Northern Region of Ghana. The study aimed at evaluating the performance of grain grinding machines in the metropolis. The treatments used were grain condition (moist at a moisture content of 10-18.22 % wb and dry) and burr mills of the same type (A, B, C, D and E). The treatments were replicated three times (5 mills x 2 treatments x 3 replications =30). Fifteen corn samples which were to be ground moist were soaked in water for 48 hours. The other fifteen samples were ground in the dry condition. Five mills were selected from a total population of twenty five mills from the metropolis. In this study, the influence of moisture content and other grinding characteristics on milling performance were studied. The attrition mills were evaluated for their fineness modulus, uniformity index, milling efficiencies, average particle size, milling losses of flour, flour temperature and electrical power requirement during milling. The fineness modulus was high in dry grains milling than moist grains milling. Aggregate of flour fineness was largely associated with moist grains milling than dry grains milling. Average particle size was high among dry grains milling and low in moist grains milling. The milling efficiencies ranged from 54.33 – 63.33 % for dry grains and 63.33 – 75.65 % on moist grains milling. Flour losses were high among moist milling and ranged from 9.04 – 16.20 % and 7.60 – 15.10 % on dry grains milling. Flour temperature increased among dry milling than moist milling ranging from 62.09 - 67.15 ^{o}C and 54.17 – 58.20 ^{o}C respectively. Results of the study have shown that grinding of dry grains to any acceptable fineness as moist grains would requires more energy demand and therefore extra cost of grinding. The study recommends periodic training of grinding mill operators to study performance characteristics of grain grinding.

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DEDICATION

I dedicate this work to my dearly lovely late wife Hamdia Nashiru and child Sa-ad Timtooni Juuna-Yakubu.

ACRONYMS

AACC	American Association for Cereal Chemists
ANOVA	Analysis of variance
ASAE	American Society for Agricultural Engineers
BC	Before Christ
DDGS	Distillers Dried Grains Soluble
F	Multiplication factor
FAO	Food and Agriculture Organizations of the United Nations
FM	Fineness Modulus
GNM	Grit non-soaking method
GSM	Grit soaking method
HR	Hausner ratio
MF	Mass of feed
MoFA	Ministry of Food and Agriculture of Ghana
MP	Mass of product
M.Sc	Master of Science
P	Percentage retained on sieve
PF	Product of F and P
PhD	Doctor of Philosophy
U.S	United States
USDACR	United States Department for Agriculture Commodities Requirement

TABLE OF CONTENTS

Declaration………………………………………………………………………………..ii

Abstract……………………………………………………………………………..….iii

Acknowledgement…………………………………………………………………….iv

Dedication…………………………………………………………………….…….v

Acronyms……………………………………………………………………………vi

Table of contents……………………………………………………………………vii

List of Tables…………………………………………………………………………….xii

List of Figures…………………………………………………………………………...xiv

CHAPTER ONE

1.0 INTRODUCTION……………………………………………………………………….1

1.1 Background of the study…………………………………………………………..1

1.2 Problem Statement…………………………………………………………….…..3

1.3 Justification…………………………………………………………………….……4

1.4 Objectives…………………………………………………………………….……6

CHAPTER TWO

2.0 LITERATURE REVIEW……………………………………………………………7

2.1 Origin of Grinding…………………………………………………………………...7

2.2 Grain Grinding ………………………………………………………………....…7

2.3 Grinding Mills/Machines……………………………………………………………..9

2.3.1 Burr / Plate mills……………………………………………………………………9

2.4 Factors to Consider in Selecting a Grinding Mill…………………………………………11

2.5 Size Reduction……………………………………………………………………………….12

2.6 Factors Affecting Size Reduction……….………………………………………………...14

2.6.1 Moisture Content…………………………………………………………………..….14

2.6.2 Stickiness…………………………………………………………………………………15

2.6.3 Hardness…………………………………………………………………………………15

2.6.4 Toughness……………………………………………………………………………...15

2.7 Mechanism of Size Reduction……………………………………………………………..15

2.8 Factors to Consider in Choosing a Size Reduction System………………………………..17

2.8.1 Feed Control and Moisture………………………………………………………………17

2.8.2 Mill Discharge…………………………………………………………………………....17

2.8.3 Energy Consumption……………………………………………………………………...17

2.9 Criteria for Determining Performance of Grain Grinding Machines………………………18

2.9.1 Fineness Modulus and Uniformity Index………………………………………………...18

2.9.2 Milling Efficiency and Average Particle Size……………………………………………18

2.9.3 Electrical Energy Consumption…………………………………………………………..19

2.10 Size Reduction Forces……………………………………………………………………...19

2.11 Grinding Resistance of Cereal Grains……………………………………………………...20

2.12 Grinding / Milling Properties of Grains……………………………………………………21

2.13 Particle Size…………………………………………………………………………………...22

2.14 Physical Properties……………………………………………………………………….....24

2.14.1 Sphericity…………………………………………………………………………………25

2.14.2 Kernel Volume…………………………………………………………………………....25

2.14.3 Surface Area………………………………………………………………………………25

2.14.4 Bulk Density …………………………………………………………………………..25

2.14.5 Particle Density………………………………………………………………………...27

2.14.6 Porosity……………………………………………………………………….…..28

2.15 Mechanical Properties of Food and Biological Materials……………………………...…..29

2.15.1 Angle of Repose……………………………………………………………………….29

2.15.2 Static Coefficient of Friction…………………………………………………………..30

2.16 Effects of Moisture Content on Physical Properties…………………………………….31

2.17 Concept of Grain Equilibrium Moisture Content on ……………………………………...32

2.18 Factors Affecting Equilibrium Moisture Content………………………………………32

2.18.1 Temperature ……………………………………………………………….……32

2.18.2 Composition of the Product……………………………………………………...…33

2.19 Importance of Grain Soaking ……………………………………………………….33

2.19 Hydration Kinetics of Cereal Grains…………………………………………………...…34

2.21 Effects of Moisture Content on Physical Properties of Cereal Grains …………………...34

2.22 Laws Governing Energy and Power Requirement of Size Reduction Process…………...35

2.23 Grain Hardness……………………………………………………………………...….40

2.24 Cereals……………………………………………………………………………..…41

2.25 Economic Value, Nutritional and Chemical Composition of Cereals and legumes……...44

2.26 Corn...……………………………………………………………………………...……44

2.27 Corn Kernel Composition……….……………………………………………………..45

2.27.1 Pericarp…………………………………………………………………………………46

2.27.2 Germ……………………………………………………………………………...…..46

2.27.3 Endosperm………………………………………………………………………...….47

2.28 Maize Milling Technologies…………………………………………………………...48

2.28.1 Wet Milling……………………………………………………………………..…48

2.28.2 Dry Milling……………………………………………………………………….49

2.28.3 Alkaline Processing……………………………………………………………….50

CHAPTER THREE

3.0 MATERIALS AND METHODS……………………………………………………..…51

3.1 Study Area………………………………………………………………………….51

3.2 Materials………………………………………………………………...….51

3.3 Methodology……………………………………………………………………….53

3.3.1 Sampling of Mills……………………………………………………………...53

3.3.2 Treatments………………………………………………………………………..54

3.3.3 Sample Preparation………………………………………………………..…54

3.3.4 Experimental Design……………………………………………………………..55

3.4 Determination of Parameters………………………………………………………..55

3.4.1 Determination of Moisture Content of Soaked and Unsoaked Grains…………..…55

3.4.2 Determination of Fineness Modulus………………………………………….……..56

3.5.2 Determination of Uniformity Index…………………………………………………56

3.5.3 Determination of Average Particle Size……….…………………………………….57

3.5.4 Determination of Milling Efficiency…………………………….……………..57

3.5.5 Determination of Losses During Milling………..…………………………….….58

3.5.6 Determination of Flour Temperature……………………………..……..……….58

3.5.7 Determination of Electrical Power……………………………………………….….58

3.5 Data Analysis……………………………………………………………….……..…60

CHAPTER FOUR

4.0 RESULTS……………………………………………………………………..61

4.1 Moisture Content…………………………………………………………….61

4.2 Fineness Modulus……………………………………………………..……....62

4.3 Uniformity Index……………………………………………………………63

4.4 Average Particle Size…………………………………………………..……...64

4.5 Milling Efficiency ……………………………………………………….........65

4.6 Losses During Milling ……………………………………………………..…….66

4.7 Flour Temperature………………………………………………………………..67

4.8 Electrical Power Required………………………………..……………..………..68

CHAPTER FIVE

5.0 DISCUSSIONS…………………………………………………………………72

5.1Moisture Content…………………………..……………………………….………..72

5.2 Fineness Modulus………………………………………………………………...73

5.3 Uniformity Index ………………………………………………………………..74

5.4 Average Particle Size ……………………………………………………………74

5.5 Milling Efficiency…………………….……………………………………………75

5.6 Losses During Milling ……………………………..…………………………..76

5.7 Flour temperature…………………………..……………………………………..78

5.8 Electrical Power Required …………………………..……………………………78

5.9 Mill Specific Performance …………………………………………………………80

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS……………………….……….........82

6.1 Conclusions…………………………………………………………………………82

6.2 Recommendations……………………………………………………………..…82

REFERENCES …………………………………………………………………………83

APPENDICES……………………………………………………………..………122

LIST OF TABLES

Table **Page**

Table 4.1: Moisture Content of Soaked and Unsoaked Grains …………………..………….61

Table 4.2: Fineness Modulus ………………………………………………………..…....63

Table 4.3: Uniformity Index……………………………………………………………...64

Table 4.4: Average Particle Size ……………………………………………..……......65

Table 4.5: Milling Efficiency……………………………………………..……………..66

Table 4.6: Losses During Milling ………………………………………..……………...67

Table 4.7: Temperature of Ground Product………………………………………………...68

LIST OF FIGURES

Figure **Page**

Figure 4.1: Relationship between current and time for mill A……………………………..….69

Figure 4.2: Relationship between current and time for mill B……………………………..….69

Figure 4.3: Relationship between current and time for mill C………………………………..70

Figure 4.4: Relationship between current and time for mill D …………………………….....70

Figure 4.5: Relationship between current and time for mill E……………………………..…..71

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the study

Agricultural products are products from the farm which are either for immediate consumption or raw materials for agricultural industries (Sule and Odugbose, 2014). Its processing is a post-harvest operation that adds value to agricultural product (Mijinyawa *et al.*, 2007). In many African countries, post-harvest operations such as threshing, oil extraction and milling are still accomplished manually (Beshada *et al.*, 2006). Most agricultural produce that is sold in markets requires post-harvest processing operations (Omobowale, 2010). Food processing is the technique of changing foods from the original state in which they are harvested to preserve them for future use. Food processing is an integral part of agriculture as most farm produce must undergo one form of conversion or the other either for storage or convenient, workable units for different purposes (Sule and Odugbose, 2014).

Cereal processing is complex and the principal procedure is milling which involves the grinding of the grain so that it can be cooked and rendered into an attractive foodstuff (Nasir, 2005). Grain milling can be done using size reduction machines such as burr mills, hammer mills or roller mills. Particle size reduction is a two-step process involving the disruption of outer seed coat and the exposure of endosperm (Amerah *et al.*, 2007). Every Ghanaian community has at least one grinding mill for daily milling of grains. The grain mill is the machine used to mill cereals, legume, nuts, and spices into flour, paste, puree (Abrefah *et al.*, 2011). Grain milling technologies involve size reduction operation in which grain kernels are broken into pieces of various sizes by machine (Akinoso *et al.*, 2013). One measure of the efficiency of the milling machine is based on energy required to create new surfaces (Akinoso *et al.,* 2013).

Food processing increases shelf life, digestibility, flavour, nutritive value, distribution, increased feed consistency and increase seasonal availability of many foods (Gana *et al*., 2014). The food processing sector is an important component of the food value chain (Miller and Welch, 2013). Grain processing makes the grain products attractive, more satisfying and easier to digest as well as overcoming the deterioration problem (Singh *et al.,* 2015). Processing of grains can reduce food waste, prevent nutritional losses, increase nutrient content through fortification, enhance the acceptability of foods to consumers, reduce risk of foodborne illness, provide jobs and economic development, and reduce the time and energy required for home food preparation (Miller and Welch, 2013). Agricultural products when processed can be an important strategy for improving the nutritional quality of foods available to the poor in developing countries (World Food Programme, 2009). It is believed that decreasing grain particle size improves digestibility of products and improves the solubility of compounds such as B vitamins and ferulic acid for humans (Hemery *et al.,* 2011). Nowadays, food processing is used to preserve foods, enhance food safety, improve flavour, add convenience, enhance nutritional value, and conserve energy (Floros *et al.,* 2010). Continuous reduction of particle size increases both the number and the surface area of particles per unit volume, allowing greater access to digestive enzymes (Goodband *et al.,* 2002). USDACR (2005) stated that flour due for export should have 98 % of particles smaller than 0.300 mm, and 90 % of particles smaller than 0.250 mm in diameter. Grinding at an ambient temperature showed a gradual and continual particle size reduction (Turner, 2012). Particle size analyses of ground grain or complete diet is an important quality control procedure used in determining feed mills' efficiencies (Goodband *et al.,* 2006). The particle size of ground grain performs a critical role in determining feed digestibility, mixing performance, and pelleting (Baker and Herrman, 1995**).** Reducing the particle size of the diet improves feed efficiency (Goodband *et al.,* 2006). Knowledge of the grinding attributes and properties of grain is essential for the correct adjustment of the working parts of grinding and sieving machines for higher and better-quality flour yields (Dziki and Laskowski, 2004).

1.2 Problem Statement

Food processing is the transformation of raw materials into food, or food into their edible forms (Gana *et al.,* 2014). Processing operations are undertaken to add value to agricultural materials after their production of which grain milling is one of the operations (Kudzanai, 2008). Agricultural products are often present in sizes that are too large to be used in the raw state and they must be reduced in size (Ngabea *et al.,* 2015). Milling industries in Ghana are familiar with the design, fabrication and marketing of mills with different techniques of milling. It is frequently necessary to do expression and extraction for solids and liquids regularly to enhance availability and usage of agricultural products (Ngabea *et al.,* 2015). In Ghana, great emphasis has been put in fabrication of mills, speed of mills, heavy metals concentration in milled products, quality of milling plates such as plates' wear. Unfortunately, other parameters which are also very important such as mills' throughput, uniformity of ground flour, losses during milling processes, and power requirements during the milling process have not received attention yet. This will enable existing companies like the Gratis foundation and upcoming companies to favourably compete well with the established foreign companies. In this way, Ghanaian-made mills may be subject to export.

The best way to improve competition with the established companies is through performance evaluation of the milled products (Kudzanai, 2008). Evaluation consists of the engineering parameters established during testing combined with economic and ergonomic parameters, all of which relate to the performance of the equipment, machine and tool (FAO, 1992). Quantifying statistically acceptable results on the performance of parameters such as uniformity of milled particles, energy efficiency, throughput and maintenance requirements gives information for deciding on what milling machine to purchase in relation to intended use (Kudzanai, 2008).

Grain milling takes a lot of time to obtain desirable fine grind and customers do complain of the coarse grind nature of flour particles. The longer the time taken to grind to flour that satisfies consumer requirements, the more the amount of energy consumed leading to high cost of grinding. The milling process takes a considerable amount of time, irrespective of the method of milling (Beshada *et al.,* 2006). To produce flour that satisfies consumer requirements at the lowest cost of production, the flour milling machine consists of sequential and consecutive unit operations of particle size reduction and separation (Loza-Garay and Flores, 2003) should be accomplish by efficient milling machine.

1.3 Justification

Food processing contributes to food security through reduced post-harvest food losses and diversified use of the food product in question (Nthoiwa *et al.,* 2013). The palatability of food products among consumers is highly dependent on the appearance, flavour, texture and nutrition of the product (Singh *et al.,* 2015). The Food and Agriculture Organization of the United Nations (FAO, 2011) estimated that world food losses are at 33 % or 1.3 billion tons per year. Food processing absorbs the surplus agricultural products that may otherwise be lost converting them into intermediate or finished consumer products (Nthoiwa *et al.*, 2013). Much work has been done on the design, fabrication and marketing of the grinding mills produced in Ghana but little has been done on the performance evaluation. It is necessary to assess the power requirements of milling machines during milling as a way of determining milling efficiency of grinding mills; thus enabling agricultural engineers to develop energy saving measures where necessary. The ultimate of every miller is to obtain desirably fine flour particle size for a higher flour price (Majzoobi *et al.*, 2012). The grade of grinding (fine, medium and coarse) depends on the fineness of the milled product within each mill (Hanif *et al.*, 2014). The particle size of flour must be in the range of 250 µm to 360 µm to achieve high digestibility from the cooked product (Yawatkar *et al.*, 2010). The evaluation will give the miller an insight into production output from the grinding mills (Kudzanai, 2008).

It is better to reduce the amount of time spent on grinding to obtain fine ground flour in order to meet the expectations of customers in regard to the quality of flour. Also, reducing the time and energy spent on milling could increase the time available for other more productive activities (Beshada *et al.*, 2006). Having efficient milling machines such as the ‘’universal milling machine’’ ensures satisfactory milling quantities at any point in time to meet the expectations of clients (Nasir, 2005). Due to higher levels of competition resulting from flour milling industry, mills must find ways other than the subjective considerations of millers to make these processes more efficient so that they can make profit (Loza-Garay and Flores, 2003). Without the grinding machines, the use of milled cereal in non-food products such as flour for manufacturing sticking paste and industrial alcohol, and wheat gluten for core binder in the casting of metal would be particularly impossible (Nasir, 2005).

1.4 Objectives

The main objective of the study was to evaluate the performance of grain grinding machines in the Tamale Metropolis.

The specific objectives of the study were:

- To determine the uniformity of the flour particles after milling.
- To determine the fineness of milled flour particles.
- To determine the amount of electrical power required to mill a particular quantity of agric feed species.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Origin of Grinding

Grinding has been utilized since the early days of civilization (Demir *et al*., 2010). Flour milling is as old as human history (Williams and Rosentrater, 2007). Ancient farmers used saddle stones or querns to grind their grain into flour (Williams and Rosentrater, 2007). Prior to the invention of the rotary quern, perhaps in north-eastern Spain around the fifth century BC, all grinding were undertaken by rubbing a hand held handstone against a larger base stone (Curtis, 2001). In Italy the millstones were very common as demonstrated by the thousands structures spread all over the country, In the middle ages, gristmills were developed that could grind larger amounts of grain into flour (Williams and Rosentrater, 2007).

2.2 Grain Grinding

The mechanization of cereal processing system came up with the new step 'milling/refining' to make the cereal grain more digestible and appealing through milling which is done in two ways, wet and dry milling (Singh *et al.,* 2015). As a result, the bioactive compounds such as phenolics, vitamins, dietary fiber, protein and minerals of cereals, concentrated in the peripheral layers of the grains are lost (Slavin, 2010). Grain processing is defined as the set of operational activities carried out for grain refining and making it consumable as food and feed (Singh *et al.*, 2015). The grinding of grain is one of the major industries in the world and the one that has had the longest continuous existence of any industrial process (Kent and Evers, 1994). Grinding grains is one of the most labour-intensive tasks performed by women in rural areas of developing countries

(Gbabo and Gana, 2012). Grains are processed to increase the starch availability and digestibility (Gorocica-Buenfil and Loerch, 2005). In Pharaonic Egypt, the cereal grinding quern was a more or less flat or somewhat curved stone, longer than wide, and with a roughened surface, on which a handstone was rubbed back and forth over the long axis to pulverise the grains, and is also known as a saddle quern (Sumner, 1967). Stones were then used to pound grain to release edible seeds from hulls (Muhammad, 2004). The earliest records of food production in Africa show that indigenous crops have long been milled to produce coarse flour for cooking (FAO, 2006). From this primitive beginning about 10000 years ago, milling technology gradually evolved (Muhammad, 2004).

The two predominant techniques for grinding whole grain flours are stone and roller mills (Doblado-Maldonado, 2012). Stone mills are the oldest attrition mills used for making whole grain flours, which simultaneously use compression, shear, and abrasion to grind wheat kernels between two stones and produce a theoretical extraction rate of 100 % (Kihlberg *et al.*, 2004). The history of the flour milling industry started with animal-driven and hand-powered milling (Muhammad, 2004). Modern stone mills are metal plates with composition stones attached (Posner and Hibbs, 2005). The first known mechanically driven mill was introduced by the Greeks in about 450-400 B.C in the form of ungeared water mill (Muhammad, 2004). Stone mills generate considerable heat due to friction (Doblado–Maldonado, 2012). This can result in considerable damage to starch, protein, and unsaturated fatty acids in comparison with other milling techniques (Prabhasankar and Rao, 2001). Furthermore, in large, continuous milling operations, heat generated from stone milling can pose a fire risk (Doblado – Maldonado, 2012). Hundred years later after the Greeks invention of the ungeared water mill, the Romans introduced the geared water mill (Muhammad, 2004). The flour milling process starts with the receiving and storage of whole grain (Williams and Rosentrater, 2007). In about 600 A.D the windmill was invented with arms revolving on a tripod stand (Muhammad, 2004). Years after the invention of the windmill, steam powered units were also introduced. In 1784, the first steam driven mill was erected in London (Muhammad, 2004). Today modern milling equipment and processes have been largely standardized (Muhammad, 2004). From the main floor an elevator would carry grain to the floor above for cleaning before it was transported into the hoppers for grinding (Wood, 1992). Milling procedures for traditional flours have been well established, whole grain flours are produced by a variety of techniques and result in flours with widely different particle sizes and functionalities (Kihlberg *et al.,* 2004). Processing alterations depend on both the physical and chemical composition of the grain and on the objectives of the miller (Pomeranz and Williams, 1990).

2.3 Grinding Mills / Machines

Grinding machines or mills are machines used to reduce the particle size of grain or solid materials to a desirable size. The commonly used grinding machines are roller mills, hammer mills, burr mills, grinding stones and mortar and pistle. Researchers have developed various grinding machine among which the commonly used are: Roller mills, plate mills and hammer mills (Gbabo and Gana, 2012). The burr mill is the only predominant grinding machines used to grind flour in Tamale.

2.3.1 Burr / Plate Mills

Burr / Plate mills also called base mills or disc mills are the commonest mills and the dominant mills used in Ghana. Plate mills are popular in West Africa and the Sudan and operate with a greater component of shear than compression (FAO, 2006). The burr mill can also be referred to as attrition mill and could be powered manually, mechanically or electrically (Sule and Odugbose, 2014). A burr mill or burr grinder is a device to grind hard, small food products between two revolving abrasive surfaces separated by a distance usually set by the user (Fellows, 2003). According to Perry and Green (1997), burr mill (plate mill or disc mill) have two roughened chilled cast iron plates of 4-60 inches (i.e. 102 mm- 1524 mm) in diameter which rub together, one plate is stationary and the other one rotates on a shaft with operation speed usually less than 1200 rpm. According to Feyisetan (2009), locally fabricated burr mill have different constituent parts which when combined forms the machine, these basic features include the hopper, auger and shaft, the grating unit which reduce produce to workable sizes by cutting, grating, or crushing.

Grains fed between the plates are crushed and sheared; the fineness of grinding is controlled by the size and quantity of burrs on the plate and the clearance between the two plates (Kaul and Egbo, 1985). A plate mill consists of a circular chamber made of cast iron or steel within which two plates with a narrow gap between them are mounted face to face (FAO, 2006). The feed comes in near the axis of rotation and is sheared and crushed as it makes its way to the edge of the plate (Earle *et al.*, 1983). The plates are grooved in order to provide a shear mechanism (FAO, 2006). The design of grooves follows a very old style developed for stone mills several thousand years ago (FAO, 2006). Though the power requirement is low, operating empty may cause excessive burr wear and a lot of heat is generated during shearing action (Nwaigwe *et al.*, 2012).

2.4 Factors to Consider in Selecting a Grinding Mill

The selection of a suitable grinding mill for a particular purpose is to achieve the desired size reduction at a minimum cost (Mani *et al.,* 2002). Among the main materials features having significant influence on the course of grinding, hardness, brittleness, toughness, abrasiveness, thermal and chemical stability, structure along with its homogeneity, moisture, shape uniformity are the most essential (Pfost, 1970). Peleg (1992) postulates that particle, mechanical history" and its physical properties like the mechanical ones, i.e., brittleness and strength possess a major influence on the particle fragmentation process.

Mechanical properties of cereal materials change, regarding to type, variety, maturity and many others (Laskowski and Lysiak, 1997). Different parts of cereal kernel, obviously, show dissimilar resistance to mechanical loading (Laskowski *et al.*, 2005).

The kernel endosperm is relatively brittle, whereas the coat is much tougher, and stress values causing it rupture are 10-15 times higher than in the case of the endosperm (Jankowski, 1981). Materials, which are difficult to fragment, are those with relatively high fat and fibre content, like oil seeds, oat, etc (Laskowski *et al.*, 2005). Moisture affects properties of the material's surface, making it less rough (Peleg, 1992). The increase in particle plasticity is often related to the lower rate of grinding with a lower material predisposition to create fines (Brennan *et al.,* 1976). An increase of moisture content stimulates a rise of the cohesion forces within particle body and creation of liquid bridges (Laskowski *et al.,* 2005). This process leads to formation of new agglomerates and need to be again fragmented on one side, and their lower mobility influences processes of segregation and classification on the second (Peleg, 1992). Moisture, as have being discussed, exerts in a great measure material physical properties and consequently the fragmentation process (Laskowski *et al.*, 2005).

The highest changes may be observed in the range from 10 to 17 %, and often the optimum limit for grinding is proposed to 14 % (Jankowski, 1981). From the economical perspective and others resulting from product requirements, i.e., separation of distinct structural components, proportion of bran in flour, grinding at both lower and higher moisture levels is frequently performed (Laskowski *et al.*, 2005). Grinding probability may increase also at low temperatures, especially below zero in the Celsius scale (Heidenreich and Schultz, 1990).

Many of the particles are also stressed to the levels not exceeding material strength and in that case, the energy added is transformed to heat (Laskowski *et al.*, 2005). It is worth a note, that research on physical properties within their variability characteristic for plant materials in terms of variability of objectives, methods, standards, equipment and the like (Szot *et al.*, 1992) give a rise to the most frequent reference of grinding parameters to material moisture (Flizikowski, 1990). In general, behaviour of plant materials exposed to the fragmentation is referred to the moisture in most cases, and this is consistent with industry needs and practical experience (Laskowski *et al.*, 2005).

2.5 Size Reduction

Agricultural materials are lumpy and often irregular in nature and therefore require several breakdowns into workable desirable sizes for future utilization and storage. Grain milling technologies involve size reduction procedures in which grains kernels are broken into pieces of various sizes by machinery (Opa´th, 2014). Milling is defined as an act or process of grinding, especially grinding grain into flour or meal (Bender, 2006). Particle size reduction, milling or communition is a necessity for agro-materials to make them smaller before further processing or utilization (Sule and Odugbose, 2014). Size reduction is one of the least energy-efficient one of all the unit operations and the cost of power is a major expense in crushing and grinding, so the factors that control this cost are important (McCabe *et al.*, 2005). The concentration of essential nutrients decreases with the degree of milling with minor alteration in energy density of pre- and post-meal (Ramberg and McAnalley, 2002). Milling process can be of two kinds, (1) wherein the whole grain is converted into flour without abstracting any parts or, (2) it could undergo differential milling to separate the grain into different parts (Oghbaei and Prakash, 2016). Size reduction is the process of reducing the particle size of a substance to a finer state of subdivision to smaller pieces to coarse particles or to powder (Bhatt and Agrawal, 2007). This improves the eating quality or suitability of foods for further processing and to increase the range of available products (Sule and Odugbose, 2014).

Differential milling or refining results in reduced nutrient content except starch (Slavin *et al.*, 1999). Development of varieties of size reduction machines has resulted in the reduction or total removal of drudgery from processes which hitherto were tedious to accomplish (Sule and Odugbose, 2014). The main methods used in reducing sizes of agricultural materials are crushing, impact, shearing and cutting (Fellows, 2003). According to Earle and Earle (2004) size reduction operation can be divided into two major categories depending on whether the material is a solid or a liquid, they are grinding / cutting (solid materials or emulsification / atomization (liquid materials). Scott *et al.* (2002) highlighted the most common reasons for reducing a material. Energy consumption for grinding depends on biomass initial and final particle size, moisture content, material properties, mass feed rate and machine variables such as screen size and type of grinding equipment (Mani *et al.,* 2004). Specific energies between 46 kJ / kg and 107 kJ / kg were reported for size reduction of corn stover (Dilts, 2007). Mani *et al*. (2004) observed an increase in energy requirement with decreasing final particle size and increased moisture content for corn stover and barley straw.

Omobowale (2010) stated that size reduction can present numerous challenges, some are industry specific while others depend on the material properties and mills designed to overcome these challenges are available using different type of mechanism to achieve reduction in size. Raw materials often occur in sizes that are too large to be used and, therefore, they must be reduced in size (Bhatt and Agrawal, 2007). Particles generated during size reduction are not uniformly sized (Oginni, 2014). Particle size distribution is sometimes used as a measure of efficiency for the size reduction process (Bitra *et al.*, 2009). Application of external high impact forces initiates fractures needed to reduce a material’s particle size, from large particles or lumps into smaller particles (Sule and Odugbose, 2014).

2.6 Factors Affecting Size Reduction

The factors affecting size reduction of agricultural produce include the following: Moisture content of produce, stickiness, hardness and toughness.

2.6.1 Moisture Content

Agricultural materials with high moisture content take a lot of time to grind. The materials tend to cake together which required a need for evaluation of the proper milling moisture content for various grains so as to improve on the milling efficiency (Kudzanai, 2008). Moisture content softens the grains thereby reducing the amount of energy needed in grinding. Very high moisture content can cause grains milled to stick to some parts of the mill. Moisture content of 18-25 % wb of materials if high turn to make the materials too soft for grinding. At a moisture content of 20 % wb and above make particles of flour to become somewhat cooked and consume a lot of milling time and turn to lower the milling rate and brings about loss in flour yield.

2.6.2 Stickiness

Stickiness is a factor which can cause materials to adhere to surfaces of grinding plates and other grinding surfaces. During milling; materials that are sticky become adhere to the milling systems making milling output low and the material may not be ground properly to the desire particle sizes.

2.6.3 Hardness

Agricultural materials that are hard and take a long time to grind require soaking to soften the material. The hard materials may require a lot of energy to grind materials. Hard materials are difficult to be reduced into smaller workable units and can increase power intake leading to high cost of milling.

2.6.4 Toughness

Fibrous materials are difficult to be reduced; they require soaking the materials to lower their toughness before milling.

2.7 Mechanisms of Size Reduction

Flour milling is considered to be an art and the miller has two main aims: first, to supply the customer with the specified product quality and, second, to efficiently separate the endosperm from the bran (Dziki and Laskowski, 2005). Characteristics features of milling processes are operations including the separation of the botanical tissues of the grain (i.e endosperm from pericarp, testa and embryo) and the reduction of the endosperm into flour or grits (Kent and Evers, 1994). The starting material naturally consists of particles which differ significantly in size which makes it necessary to define different size classes (Monov *et al.*, 2012). Kernels with higher bran layer content are more difficult to grind and yield lower flour extraction rates (Gaines *et al.,* 1997). Conventionally, milling of cereal grain is achieved by two popular processes, in the first process the pericarp (bran) and the grain are first removed by degerming or decortication processes, then the endosperm is reduced to grits or flour (Kebakile, 2008). This process is used commercially for maize milling and is describe in detail by Duensing *et al.* *(*2003). The second process involves first breaking open the kernel, then scraping the endosperm from the bran (Kebakile, 2008). The speed of rotation of the mill determines three basic types of operation modes: slow rotation (cascading), fast rotation (cataracting) and very fast rotation (centrifugation) (Monov *et al.*, 2012).

The mechanisms of size reduction are: cutting, compression, impact and attrition. Cutting involves breaking of the materials by means of a sharp blade(s) or plate(s). In compression, pressure is applied to crush materials into small sizes. Impact is a mechanism which involves a stationary or less stationary material(s) being hit up by a high speed moving object/grains or when the moving material(s) strike a stationary surface. This makes the grain materials to shatter into smaller sizes.

2.8 Factors to Consider in Choosing a Size Reduction System

2.8.1 Feed Control and Moisture

Feed control in the mill is vital in obtaining desirable flour particle sizes. The particles in the flour must be of appropriate size, should be of similar size; irregular size feed particles grind with high level of variation in uniformity of product size (Kudzanai, 2008). Feed rate can be milled continuously or discontinuously. Material flow enhances continuous milling of grains. Materials do not flow well if they contain high moisture contents (Coulson *et al.,* 1978). Under this condition the material tends to cake together in the form of balls (Kudzanai, 2008).

2.8.2 Mill Discharge

Ideally, the rate of discharge must be equal to the rate of feed to avoid particles locking during milling. The discharge rate must be such that the working parts of the mill can operate most efficiently in the interval to be reduced (Kudzanai, 2008).

2.8.3 Energy Consumption

Determining the energy requirement for agricultural materials size reduction would help to develop the strategies to reduce the input energy in grinding process (Ghorbani *et al*, 2013). Energy efficiency of the equipment, bulk density and physical properties such as particle size, shape, distribution, density, and particle surface area are major factors in evaluating the efficiency of size reduction (Zhu *et al.,* 2009). A lot of energy is dissipated during size reduction of materials. Among the energy dissipated some are used in overcoming friction, others in the production of heat and noise not necessarily needed for size reduction and others for inertia.

Enormous quantities of energy are consumed during the size reduction operations (Kudzanai, 2008). A large amount of energy goes into the operating of the equipment, producing undesirable heat and noise leaving lesser energy for creating of new surface. Martin and Benke (1984) reported that high energy was consumed for fine grinding of material. Milling process is also affected by types and condition of products to be produced such as grains, size of hammer screens and hence fineness of grind and hammer mill loading conditions (Kudzanai, 2008).

2.9 Criteria for Determining Performance of Grain Grinding Machines

The performance of any grinding process can be enhanced by enhancing both technical and system outputs (Ramesh Babu *et al.,* 2016). The performance of a grinding process is highly influenced by the precision of grinder, the condition of wheel, the wheel and work interaction and process settings including the parameters chosen for dressing and grinding (Pawel *et al.*, 1993). In effect, the performance of grinding process and optimal utilization of grinding machine are mostly dependent on the operator (Ramesh Babu *et al.,* 2016).

2.9.1 Fineness Modulus and Uniformity Index

Fineness modulus indicate how uniformly the flour particles are distributed in a given flour sample. The smaller the fineness modulus value of flour, the finer the size of grind of the material (Hanif *et al.,* 2014). A fineness modulus of 2.10 and below signifies fine flour (Carl and Denny, 1978). Uniformity index shows the proportion of coarse, medium and fine flour particles. The higher the relative proportion of fine flours the better the performance of the grinding machine.

2.9.2 Milling Efficiency and Average Particle Size

Milling efficiency is the ratio between mass of the product and the mass of the feed (Kudzanai, 2008). The efficiency of mills helps in quantifying the amount of flour to produce within certain time ensuring availability and access of flour. Milling efficiencies of mills of 82.30 % and 97.75 % have been reported by Nwaigwe *et al.* (2012) and Kudzanai (2008) respectively.

2.9.3 Electrical Energy Consumption

Electrical energy consumption depends significantly on the degree of comminution of the material (Ahmed *et al.*, 2015). An increase of the degree of comminution causes an increase in the energy requirements of the grinding process (Laskowski *et al.*, 2005). The lesser the amount of electrical energy consumed to obtain desirable size, the better the performance of the grinding machine.

2.10 Size Reduction Forces

Particles in the feed repetitively reduce their size due to the imparting energy of the grinding media which disrupts their binding forces (Monov *et al.*, 2012). Hennart *et al.* *(*2009) proposed that size reduction is as a result of the following three basic fragmentation mechanisms:

-Abrasion occurs when local intensity stresses are applied and the result is fine particles taken from the surface of the mother particle and particles of size close to the size of the mother particle.

-Cleavage of particles occurs when slow and relatively intense stresses are applied (compression) which produce fragments of size 50-80 % of the size of the initial particle.

-Fracture is a result of rapid applications of intense stresses (impact) which produce fragments of relatively small size with a relatively wide particle size distribution. In practice the three different mechanisms never occur alone and the process of particle size reduction involves all of them with possible predominance depending on the type of mill, the operating conditions and the type of the material being ground (Monov *et al.*, 2012). There exist different size reduction forces at work in various size reduction machines (Sule and Odugbose, 2014). Scott *et al*. (2002) highlighted some of the most common reasons for reducing a material. Omobowale (2010) stated that application of high impact forces initiates fractures needed to decrease a feed material's size, from larger particles or into smaller particles. A material's physical and mechanical properties often determine the ease or difficulty in reducing the material to an appropriate particle size, the most common of which can present milling challenges are fibrous, non- friable, heat-sensitive, wet, fatty or Sticky and dense or hard materials (Sule and Odugbose, 2014).

2.11 Grinding Resistance of Cereal Grains

Grinding resistance of solids particles represents their property to resist to mechanical deformations caused by external effort; and crushing forces for compression application are much higher than for the application of shear (Lupu *et al.,* 2014). A generalized characteristic curve for the crushing process of grain is shown in figure 1. The curve is characterized by three zones (Lupu *et al.,* 2014):

• zone I – elastic deformation zone, characterized by proportionality between crushing force F and K grain deformations;

• zone II - plastic deformation zone, characterized by large increases in strain L of grain (Plastic) for small

increases in force;

• zone III - crushing zone, characterized by crushing the grains which takes place after reaching a certain value of the crushing force.

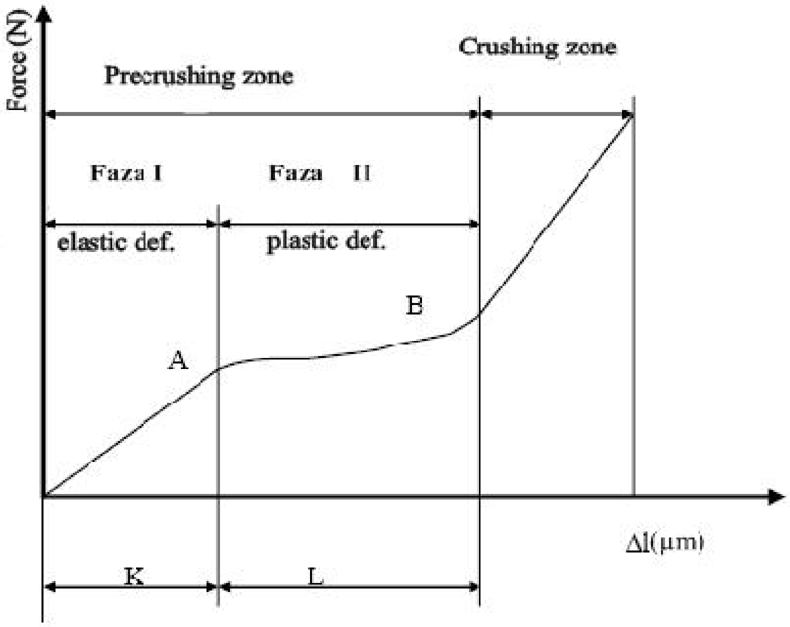

Figure 1: Generalized curve characteristic for crushing process by compression (Naumov, 1962)

2.12 Grinding / Milling Properties of Grains

Milling or grinding is defined as an act or process of grinding, especially grinding grain into flour or meal (Bender, 2006). The basic objective of milling process is to remove the husk and sometimes the bran layers, and produce an edible portion that is free of impurities and in the form of a powder with varying particle size (Oghbaei and Prakash, 2016). The concentration of essential nutrients decrease with the degree of milling with minor alteration in energy density of pre- and post-meal (Ramberg and McAnally, 2002). Grinding or milling is the fundamental operation in the processing of the cereal grain (Dziki, 2008). From the physical properties of grains, the mechanical properties have the greatest influence on grinding energy (Dziki and Laskowski, 2005).

The process of grinding is affected by grain moisture and its mechanical properties that are determined primarily by the cultivar factor (Ahmed *et al.,* 2015). Wetting or drying the grain can also modify them (Dziki and Laskowski, 2005). Lysiak and Laskowski (1999) reported that as the grain moisture content increased, the specific grinding energy increased, too. Romanski and Niemiec (2001) reported that at grain moisture content of 16-17 % the highest specific grinding energy was observed, below and above this level, lowest values of this parameter were obtained. The relation between grinding energy and grain moisture content depend on the used grinding machine (Dziki and Laskowski, 2005). The mechanical properties of an individual grain depend mainly on the endosperm properties and bran layer (fruit and seed coat, nucellus and aleurone) properties (Dziki and Laskowski, 2005). Miling process can be of two kinds, (1) wherein the whole grain is converted into flour without abstraction any parts or, (2) it could undergo differential milling to separate the grain into different parts (Oghbaei and Prakash, 2016). Nutrients and phytonutrients are not evenly distributed throughout the grain; most of nutrients' concentration is higher in outer part of the grain, so differential milling or refining results in reduced nutrient content except starch (Slavin *et al.,* 1999).

2.13 Particle Size

Particle size distribution is a measure of the variation in size of particles after size reduction (Oginni, 2014). Examples of this can be found in studies published on alfalfa forage grinds (Yang *et al.,* 1996), corn stover grind (Mani *et al.,* 2004), barley, canola, oat and wheat straw (Adapa *et al.,* 2009). This skewness is typically obtained for naturally occurring particle population (Rhodes, 1998). An effective way of expressing and comparing particle size distribution of ground material on a statistical basis is the geometric mean diameter and the geometric standard deviation and it is used to describe the particle size and distribution of ground materials (Oginni, 2014). Chou *et al*. (2008) and Wu *et al.* (2009) demonstrated that the micronization of insoluble fibres improved their abilities in lowering the concentration of serum triglycerides, serum cholesterol, and liver lipids, when fed to hamsters. This shows that particle size is an important factor that affects the characteristics and physiological functions of insoluble fibres (Hemery *et al.,* 2011).

Some other studies have investigated the influence of particle size reduction on the properties of wheat and corn bran. Van Craeyveld *et al.* (2009) showed that an extensive (120 h) lab-scale ball-mill treatment increased the level of wheat bran water extractable arabinoxylan from 4 % (untreated bran) to 61 % of the wheat bran arabinoxylan. In particular, mall-particle bran produced greater concentrations of short-chain fatty acids than large-particle bran, this difference being probably due to the increased accessible surface area as particle size is decreased, which enables the bacterial enzymes to have a larger contact area to access fermentable carbohydrates (Jenkins *et al.,* 1999; Stewart and Slavin, 2009).

Studies on corn bran showed that bran of finer particle size was more effective in lowering the plasma cholesterol concentration and was more easily fermented than bran of coarser particle size (Ebihara and Nakamoto, 2001), and that the bioavailability of B vitamins (niacin, pantothenic acid and thiamin) to humans was higher with the finely ground bran than with the coarser corn bran (Yu and Kies, 1993). Thus, decreasing bran particle size is a way to improve the nutritional potential of this product (Hemery *et al.,* 2011). Different processes can be used to decrease the particle size of wheat bran (Hemery *et al.,* 2007). Cryogenic grinding has been reported to increase the production of fine particles from turmeric, cumin seeds and cloves, and to lower the energy consumption needed to grind these materials, by increasing their brittleness, by the use of very low temperatures (Goswami and Singh, 2003). Cryogenic grinding is also said to limit the re-agglomeration of particles and the destruction of thermo-sensitive compounds (Wilczek *et al.,* 2004). Recently, the study of the influence of low temperatures on the mechanical properties of wheat bran and of its constituent layers (outer pericarp, intermediate layers, aleurone layer) showed that negative temperatures (below -46 ^{o}C) decreased the extensibility of bran layers and greatly increased their brittleness (Hemery *et al.,* 2010a). This suggests that cryogenic grinding of wheat bran might allow production of finer particles than grinding at ambient temperature (Hemery *et al.,* 2011).

2.14 Physical Properties

The physical properties of grains and seeds are essential for the design of equipment and the analysis of the behavior of the product during agricultural process operations such as handling, planting, harvesting, threshing, cleaning, sorting and processing (Tavakoli *et al.,* 2009). The knowledge and analysis of physical properties serve as an important factor during grains harvesting, transportation, storage, processing as well as manufacture and operation of various equipments used in processing (Shruti *et al.,* 2015). Knowledge of how the physical properties of grain varies with changes in moisture content is one of the prerequisites for the design and development of efficient processing and handling machines for the grains (Tavakoli *et al.,* 2009). Physical properties are used to design new and retrofit existing bins, hoppers and feeders; determine the basis of flow problems and understand differences between various bulk materials or grades of the same material

(Fitzpatrick *et al.*, 2004). Particle size and moisture content are two intrinsic factors that influence these physical properties (Oginni, 2014).

2.14.1 Sphericity

Agricultural materials are irregular and sphericity of agricultural products decreases with increasing moisture content mainly due to unusual swelling of the products. The sphericity decreased marginally from 64.02 to 63.66 % and 77.90 to 77.68 % at moisture content range of 5.0 % to 9.0 % wb for cashew nut and kernel respectively (Bart-Plange *et al.*, 2012). A similar trend of sphericity has been reported for agricultural products by Özarslan (2002) for cotton and Sacilik *et al.* (2003) for hemp seed.

2.14.2 Kernel Volume

Volume of grains increases as the moisture content increases due to swelling. This resulted in increase in size of the grain. The volume increased linearly with increase in moisture (Bart-Plange *et al.*, 2012). A number of food and agricultural products have recorded similar linear results, some of these products are Popcorn kernel (Karababa, 2006); Millet (Baryeh, 2002).

2.14.3 Surface Area

Addition of water to grains increases the surface area of the grains as a result of expansion of the grains. Similar results for surface area were reported by Sherpherd and Bhardwaj (1986) for pigeon pea; Baryeh (2001) for bambara groundnuts, Baryeh (2002) for millet and Baryeh and Mangope (2002) for pigeon pea.

2.14.4 Bulk Density

Bulk density is the ratio of the mass of a bulk material to its bulk volume (Oginni, 2014). Bulk density significantly impacts supply logistics, engineering design and operation of transportation equipment, material handling systems and processing in the bio-refinery

(Sokhansanj and Fenton, 2006). This is because bulk density is used in estimating storage capacity and the amount of space needed during biomass logistics (Oginni, 2014). Bulk density is the ratio of the mass of a collection of discrete pieces of solid material to the sum of the volumes of: the solids in each piece, the voids within the pieces, and the voids among the pieces of the particular collection (Webb, 2001). Bulk density is a crucial factor in the design and operation of loading vessels, such as bins, tanks, trucks and rail cars (Rosentrater *et al.,* 2006). Bulk density of granular and biological materials, which is affected by particle size and moisture content, is also used in describing the flowability of the materials (Oginni, 2014). The decrease in bulk density with an increase in moisture content is mainly due to the higher increase in volume than the corresponding increase in mass of the material (Bart-Plange *et al.,* 2012). Flow indicators such as compressibility index and Hausner ratio (HR) are calculated from the density values of the material (Probst *et al.,* 2013). Bulk density generally decreases with increase in particle size (Oginni, 2014).

The amount of storage space required for a given material will therefore increase with moisture content increase (Colley *et al.,* 2006). Probst *et al.* (2013) also reported that the bulk density of ground corn was found to decrease from 627.4 to 607.8 kg / m^3 as moisture content increased from 10.4 to 19.6 % (wb). Similar trends were documented for granular biological materials such as rice (Kibar *et al.,* 2010), soybean (Deshpande *et al.,* 1993) and green gram (Nimkar and Chattopadhyay, 2001). This shows that the volume necessary to store or transport biological materials (with identical mass) will increase as moisture content increases (Littlefield *et al.,* 2011).

2.14.5 Particle Density

Partcle density is the ratio of the average mass to average volume of particle that form the bulk solid (Oginni, 2014). Physical properties of biological materials have unique characteristics which set them apart from other engineering materials (Bart-Plange *et al.*, 2012). .Particle density measures the density of the particle matter excluding the air pores, hence it is called true density (Ileleji and Rosentrater, 2008). The study of physical properties helps to detect quality differences during harvesting, handling and storage (Bart-Plange *et al.*, 2012). Various types of cleaning, grading and separation equipment are designed on the basis of their physical properties (Teye and Abano, 2012). Esrif and Halil (2007) stated that knowledge of physical properties constitutes an important and essential engineering data in the design of machines, storage structures, and processing. Particle density is an important parameter that is needed in the design of systems for ventilation and cooling of biomass during storage (Fasina and Sokhansanj, 1995). Particle density is also used as an indicator of the pelletability of a material (Oginni, 2014). Higher values result in good quality pellets and easier pelletability since less energy is needed to achieve densification of the material (Leaver, 1985). Gil *et al.* (2013) reported an increase in particle densities of poplar and corn stover from 1293 to 1457 kg / m^3 and 1450 to 1472 kg / m^3 respectively with a reduction in particle size from 0.70 to 0.26 mm. Mani *et al.* (2004) also reported an increase in the particle density of switch grass from 950 to 1170 kg / m^3 as the particle size decreases from 0.46 to 0.25 mm at a moisture content of 8 % (wb). This phenomenon has been confirmed for DDGS particles (Ileleji *et al.,* 2007). Due to the exclusion of air pores during the measurement of particle density, the values reported for most biological materials are relatively higher than bulk density (Oginni, 2014).

Particle density of biological material has been reported to generally decrease linearly with increase in moisture content (Oginni, 2014). A geometric mean diameter of 0.68 mm, corn stover was reported to decrease in particle density from 1120 to 1112 kg / m^3 with an increase in moisture content from 7 to 15 % (wb) (Mani *et al.,* 2004). Bahram *et al.* (2013) reported a particle density reduction from 1652 to 1443 kg / m^3 of wormy compost with an increase in moisture content from 25 to 35 % (wb). This implies that the volume of biological materials increases at a higher rate than the increase in mass as moisture content increases (McMullen *et al.,* 2005).

2.14.6 Porosity

Porosity is a measure of the void spaces in a material, and is a fraction of the volume of voids over the total volume with values that range between 0 and 100 % (Oginni, 2014). Food powders have bulk densities in the range of 300 to 800 kg / m^3 while the particle density of most food powders is about 1,400 kg / m^3 , so these values are an indication that food powders have high porosity, which can be internal, external or both (Ortega-Rivas, 2009). Porosity can be a good prediction of the sphericity or irregularity of the particles in a bulk solid (Oginni, 2014). An average porosity calculation of 0.4 is normal for spheroid particles, whereas irregular shaped or very small particulates have higher porosity values (Woodcock and Mason, 1987).

Particle size and moisture content have a significant effect on porosity of biological materials. (Oginni, 2014). Lam *et al.,* (2008) reported an increase in porosity of ground corn stover from 0.91 to 0.94 with an increase in particle size from 0.25 to 0.71 mm. Littlefield (2010) also found the porosity of pecan shell to significantly increased ($p < 0.05$) from 0.67 to 0.71 as particle size increased from the 0.21 to 2.19 mm. However, Lam *et al.* (2008) reported that the porosity of switch grass decreased from 0.87 to 0.82

with increase in particle size from 0.25 to 0.71 mm. Increase in moisture content of biological material causes volumetric expansion which is faster than increase in the mass of the material, therefore this results to less air space among particles thereby leading to reduction in porosity (Oginni, 2014).

2.15 Mechanical Properties of Food and Biological Materials

Mechanical properties are properties concerning the behaviour of agricultural materials under applied forces (Bart-Plange, 2014). Knowledge of mechanical properties of agricultural materials is essential for texture analysis and better mechanical properties of food and biological materials include structural, geometrical and strength of the materials. Damages done to agricultural materials during harvesting, handling and transportation can reduce their structural integrity (Mohsenin, 1986). Those damages that are often recorded include bruising and splitting (vegetables and fruits), cracking and chipping (grains, seed sand eggs), and cuts (fruits and seeds) (Geankpolis, 1983). The amount of force required to produce a given amount of deformation depends on many factors including the rate at which the force is applied, the previous history of loading, moisture content and the composition of the product (Bahnasawy, 2007). Many researchers have studied the mechanical properties of various food and biological materials (Khan *et al*., 2010) for industrial hemp stalks; (Corrêa *et al*., 2007) for rough rice (Kalkan and Kara, 2011) for wheat grains.

2.15.1 Angle of Repose

The angle of repose is the angle compared to the horizontal at which material will stand when piled (Tarighi *et al.*, 2011). It is affected by the surface characteristics, shape and the moisture content of the grains (Bart-Plange, 2014). The angle of repose is also important in designing the equipment for mass flow and structures for storage (Stroshine and Hamann, 1995). Tavakoli *et al*. (2009) found the values for the filling angle of repose to increase from 31.16° to 36.90° with an increasing moisture range of 7.34 %–21.58 % (d.b.) for barley grains. A linear increase in angle of repose as the seed moisture content increases has also been reported by Baryeh and Mangope (2002) for pigeon pea, Bart-Plange and Baryeh (2003) for cocoa beans. Angle of repose increase with moisture content because the surface layer of moisture surrounding the particle holds the aggregate of the grain together by the surface tension (Pradhan *et al.,* 2008). The angle of repose determines the maximum angle of a pile of grain in the horizontal plane, and is important in the filling of a flat storage facility when grain is not piled at a uniform bed depth but rather in a conical heap (Varnamkhasti *et al.*, 2007).

2.15.2 Static Coefficient of Friction

Coefficient of static friction is known as the $\tan^{-1}$of the angle which the tilting table makes with the horizontal when grains just start moving along the table (Bart-Plange, 2014). Static coefficient of friction of biological materials can be determined using three surfaces (compressed plastic, plywood and galvanized iron/steel). Static coefficient of friction increased linearly with increase in moisture content for all surfaces (Tarighi *et al.,* 2011).

The knowledge of friction coefficients of grain is needed for designing conveying equipment conveyors because friction is necessary to hold cocoa beans to the conveying surface without slipping or sliding backward (Bart-Plange, 2014). For instance friction between an un-consolidated material and a conveyor belt affects the maximum angle with the horizontal, which the conveyor can assume when transporting the solid. Husking characteristics of paddy are also dependent upon its shape and size (Shitanda *et al.*, 2001;

Varnamkhasti *et al*., 2007). An increase in the coefficient of static friction with moisture content has been observed by Tavakoli *et al*. (2009) for barley grains using glass, galvanized iron sheet and plywood; Singh and Goswami (1996) for cumin seeds using plywood, galvanised steel and aluminium; Kabas *et al*. (2007) for cowpeas using rubber, plywood and galvanized shee and Aviara *et al.* (2005) for sheanut using metal sheet, formica and plywood.

2.16 Effects of Moisture Content on Physical Properties.

The relative percentage of moisture in food materials is dynamic and it influences the physical properties and product quality of nearly all food materials at all stages of processing and final product existence as well (Werolowski, 2003). The optimum performance of processing equipment may be attained within a certain moisture range and therefore knowledge about these physical properties of the cereals and legumes and their variation with moisture is very important in the construction of storage, handling and processing equipment (Baryeh, 2001). Bulk density decreased with increase in moisture content of the grain (Lazaro, *et al.,* 2005). Tavakoli *et al.* (2009) carried out a study to evaluate the effect of moisture content on some physical properties of barley grains.

2.17 Concept of Grain Equilibrium Moisture Content

The moisture content of the product when it is in equilibrium with the surrounding atmosphere is called the equilibrium moisture content (EMC) or hygroscopic equilibrium (Hall, 1980). EMC is directly related to drying and storage (Chakraverty, 1994). Different materials have different equilibrium moisture contents and it is dependent upon the temperature and relative humidity (RH) of the environment and on the variety and maturity of the grain (Dokurugu, 2009). Brooker *et al.* (1992) have grouped EMC determination methods into two; the techniques are either static or dynamic. In the static method, a grain sample is allowed to come to equilibrium in still, moist air whereas in the dynamic method, the air is mechanically moved (Dokurugu, 2009). At high humidity and temperature, the grain may mould before equilibrium is attained. The dynamic method is quicker and thus, preferred (Brooker *et al.*, 1992). Equilibrium relative humidity (ERH) is defined as the ratio of the vapour pressure of water in the product to the pressure of saturated water vapour at specified temperature (Hall, 1980). Hunt and Pixton (1947) stated that, ERH can be expressed mathematically as follows:

$$Water\ activity = \frac{P}{P_O} = \frac{\%\,relative\ humidity}{100}$$

2.18 Factors Affecting Equilibrium Moisture Content

Equilibrium moisture content is mainly affected by the physical, structural, and chemical composition of grain. Hall (1957) and Brooker *et al*. (1974) indicated that EMC is dependent upon the humidity and temperature conditions of the grain.

2.18.1 Temperature

Pixton (1982) reported that, for grains which moisture content remained constant in the range of 10 % – 20 %, the ERH increases or decreases approximately 3 % for every 10 ^{o}C rise or fall in temperature respectively. The moisture content of product and the ERH is different at different temperatures (Alla, 1998). Beriscain *et al*. (1996) reported that, at 23 ^{o}C – 45 ^{o}C temperature range, the rate of water absorption by Gum Arabic increases as the temperature increases. Pixton and Warbuton (1971) indicated that, for different cereal grains and tick beans, a linear relationship between percent relative humidity and temperature exist over a range of temperature above 40 °C .

2.18.2 Composition of the Product

Hall (1980) showed that, at 63 % relative humidity the water adsorption varies directly with the carbohydrate content and inversely with the protein content. Mackay (1967) indicated that, foods with high oil content have low moisture content than foods with low oil content at the same relative humidity.

2.19 Importance of Soaking of Grains or Legumes

Many grains and legumes are pretreated by soaking them in water before milling to make the milling easy and faster. The hydration of cereals and legumes is an important step in the production of traditional food especially soybean derivatives, such as soy sauce (Nelson *et al.,* 1976). The saturation process modifies the textural characteristics of legumes and makes protein extraction easier (Antwi, 2011). The textural changes are known to result from the absorption of water during hydration which also affects softening the hard pit to facilitate grinding (Liu, 1995). Also, grain or legume hydration reduces: the cooking time, the bean processing mass losses, and improves the product quality (Wang *et al.,* 1979). Soaking enhances better quality protein retention and it is therefore necessary to reduce the cooking time, which can be achieved by soaking before cooking as reported by other researchers (Molina *et al.,* 1975). Legumes require hydration to thoroughly eliminate anti-nutritional factors, to improve protein digestibility, and to reduce cooking time (Ellenrieder *et al.,* 1981).

2.20 Hydration Kinetics of Cereal Grains

Cereal processing of cereals often requires that the seeds be hydrated first to facilitate the consecutive extraction or cooking (Antwi, 2011). To control and predict the process, optimizing the hydration condition is vital since hydration governs the subsequent operations and the quality of the final product (Kashaninejadl *et al.,* 2007). During soaking of grains, water diffuses into the grain and some components leach out (Antwi, 2011). Both phenomena are functions of time and temperature (Chiang and Yeh, 2002). Thus soaking at room temperature may provoke microbial contamination, which affects quality attributes (such as colour, taste and flavour) of the product (Bello *et al.,* 2004). Soaking grains in warm water shorten the soaking time, because higher temperature increases hydration rate (Antwi, 2011).

2.21 Effects of Moisture Content on Physical Properties of Cereal Grains.

Knowledge of how the physical properties of grain vary with changes in moisture content is one of the prerequisites for the design and development of efficient processing and handling machines for the grains (Tavakoli *et al.,* 2009). Among the engineering properties, the physical properties of materials are more important in the agricultural process engineering for the post harvest operations (Vaishnava *et al.,* 2000). The relative percentage of moisture in food materials is dynamic and it influences the physical properties and product quality of nearly all food materials at all stages of processing and final product existence as well (Werolowski, 2003). The optimum performance of processing equipment may be attained within a certain moisture range and therefore knowledge about these physical properties of the cereals and legumes and their variation with moisture is very important in the construction of storage, handling and processing equipment (Baryeh, 2001). Bulk density decreased with increase in moisture content of the grain (Lazaro *et al.*, 2005).

2.22 Laws Governing Energy and Power Requirement of Size Reduction Process

Grinding is a very inefficient process and it is important to use energy as efficiently as possible (Bhatt and Agrawal, 2007). Over decades there have been several pseudoscientific attempts to develop fundamental laws governing grinding, in the interest of understanding and improving grinding efficiency (Lameck, 2005). The laws of size reduction in general use today include those of Rittinger (1867), Kick (1885), and Bond (1952). These first attempts related the degree of grinding to the specific energy used in creating new surfaces areas of particles with a mean size of 80 % passing screen size (Lameck, 2005). The amount of energy needed to fracture food is determined by its tendency to crack (its friability), which in turn depends on the structure of the food (Dziki *et al.*, 2012). Harder foods absorb higher energy and consequently require a greater energy input to create fractures (Dziki and Laskowski, 2006). Several models such as Kick, Rittinger (Henderson and Perry, 1970) explained that energy consumption in size reduction process depended on initial and new surface area. The laws of size reduction in general use today include those of Rittinger (1867), Kick (1885), and Bond (1952). They expressed that the required energy to reduce a specific mass of particles from one size to another (Ghorbani *et al.*, 2013) follows as:

$$E = \int_1^2 \frac{dL}{L^n} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..1$$

Where, E is the energy consumption (Kj / kg), dL is the differential size (dimension less), L is size (mm) and n is constants. The amount of energy required for size reduction of solid foods can be theoretically calculated based on the following equation: $dE = -K\frac{dx}{x^n}$ ……………………….2

where: dE is the energy required in breaking a unit mass of diameter x about size dx,

K and n are constants depending on the ground material and grinding methods.

The Rittinger and Kick Laws are said by Heywood (1957) to be compatible because the former relates the energy required for the reduction to the new surface produced, whereas the latter relates it to the volume or weight of the particles. Rittinger assumed that the energy required for size reduction is directly proportional, not to the change in length dimensions, but to the change in surface area (Bhatt and Agrawal, 2007). For fine grinding of solid materials, Rittinger's law is used. Rittinger's law, who postulated that the energy expenditure during the fragmentation process is proportional to the new surface formed (Laskowski *et al.*, 2005). Rittinger's energy, W, required for grinding may be determined by $W = K_R\ fc(R-1)\ L2/L1$ ………………..3

Where W is total energy required for size reduction; K_R is Rittinger's constant, fc is crushing strength; L1, L2 are initial and final dimensions of the particles; and R, size reduction ratio.

The Kick's law states that the energy required to reduce the size of particles is proportional to the ratio of the initial size of a typical dimension (for example the diameter of the particles) to the final size of that dimension (Dziki *et al.*, 2012). This relation is derived directly from the elasticity theory of ideal brittle solids. In practice it has been found that Kick's law gives reasonably good results for coarse grinding in which there is a relatively small increase in surface area per unit mass (Gorlov *et al.*, 2009). In the Kick model (Henderson and Perry, 1970), it is assumed that the energy requirement is a function of a common dimension of the material and further assumed that size reduction is essentially a shearing procedure. Consequently, the energy required is proportional to the new surface created, which, in turn, is proportional to the square of a common linear dimension, so "n" in equation. 1 is equal to -2 (Ghorbani *et al.*, 2013).

For coarse crushing Kick assumed that the energy required to reduce a material in size was directly proportional to the size reduction ratio $\frac{dL}{L}$ (Bhatt and Agrawal, 2007). Kick stated that for any unit mass of material the energy required to produce a reduction ratio is constant, and independent on particle size (Laskowski *et al.*, 2005). Kick's law has been favored: $W = K_k fc \, 1n \, R$ ……………….4

Where K_k is Kicks constant. It implies that the specific energy required to crush a material, for example from 10 cm down to 5 cm, is the same as the energy required to crush the same material from 5 mm to 2.5 mm (Bhatt and Agrawal, 2007).

The bond law of grinding has been widely used for mill sizing and design (Lameck, 2005). In Bond model (Bond, 1952), n = 3/2. The model is an empirical equation based on analysis of data from laboratory and industrial mills (Lameck, 2005). Based on the present considerations, no such effort has been made to predict specific energy consumption, using physical and mechanical properties of materials (Ghorbani *et al.*, 2013). It is based upon the two-power calculation approaches used in majority of ball and rod mill design processes (Smit, 2000). Bond's law, who concluded that the work input to break a particle of dimension x_1 lies between $x_1{}^3$ and $x_1{}^2$, a compromise between Rittinger and Kick (Laskowski *et al.*, 2005). Bond has compromised to some extent to make his law applicable to both coarse and fine grinding (Bickle, 1960).

$$E = 2K\left(\frac{1}{\sqrt{X_2}} - \frac{1}{\sqrt{X_1}}\right) \qquad \text{………………………………..5}$$

Where

Where E - Grinding energy

2K = 10Wi (Bond work index)

X_1 - Feed size

X_2 - Product size

Charles (1957) extended existing theories of comminution and proposed the equation to calculate the comminution energy (*E*) necessary to obtain the particle size *y* from the material with the initial size x_{max}:

$$E = \int_0^y \int_{x_{max}}^x (-Kx^{-n}\, dx)\mathrm{d}M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

where: d*M* represents the mass of particles in the range of sizes from *x* to *x*+d*x*. According to Stambolidis (2002) the mass of particles with sizes lower then *x* can be expressed as:

$$M_x = W_o \left(\frac{x}{y}\right)^{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

where: *Wo* is the mass of particles taken for comminution and is the coeffi cient of particle size distribution. The derivative of equation of Sokolowski (1995) is as follows:

$$dM = \alpha W_o \frac{x^{\alpha-1}}{y^{\alpha}} dx \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

The solution of equation (8), after dividing at both sides of equation by *Wo* can be expressed as:

$$E_{Ch} = \frac{K_{Ch}}{(n-1)(\alpha-n+1)} y^{1-n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

where: K_{Ch} is a constant dependent on the properties of ground material.

The detailed way of determining the above equation and coeffi cients α i n was described by Stambolidis (2002). He found out that for most materials the expression ($\alpha - n + 1$) is equal to zero, thus the equation of Velu *et al.* (2006) cannot be used to determine the energy of comminution and he proposed the formula:

$$E_s = \frac{c}{(n-1)} \frac{\ln y^{\alpha}}{y^{\alpha}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

Hukki (1962) assumed that in the equation of Velu *et al.* (2006) exponent (1-n) is not constant, but depends on the size of comminuted material and degree of fineness. For large particles (order of magnitude 0,01 m) and when the degree of fineness is low, the grinding energy is mainly derived from the volume of material and Kick's theory of grinding is adequate.

The grinding energy is proportional to the area of comminuted particles and thus the Rittinger's grinding theory can be used (Dziki *et al.*, 2012). Morrell (2004) observed that grinding energy increased is caused by the fact that the small particles need much more stresses to comminution and modified the Bond's theory and proposed the following equation:

$$E_r = M_i \,.K(d_{80}^{f(d)} \text{-} D_{80}^{f(D)}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

where: *Mi* represents the index depending on the method of grinding, *K* is the grinding constant, and d_{80} and D_{80} have the same meaning as in the equation of Gorlov *et al.* (2009). For particles with size *x*, the function describing the changing of exponent can be calculated as follows by Morrell (2004):

$$f(x) = -(a + b^{x}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 12$$

where: *a* and *b* are constants, and *x* is such a size of the screen diameter for which 80 % of particles are sieved.

2.23 Grain Hardness

The basic process in grain processing is milling, whose aim is first the separation of the endosperm, the pericarp and germs and the reduction of the endosperm particles to a fraction, which passes through a sieve with an aperture of not larger than 200 μm (Posner, 2003). The result of the milling process is affected by both the milling scheme used and the grain properties and the design and settings of the equipment (Warechowska *et al.*, 2013). Cereal grain property depends on genetic factors and environmental conditions and on agrotechnical practices-especially nitrogen fertilization (Pomeranz *et al.*, 1985). Grain characteristics play a role in determining the particle size distribution of the milled product in both pulses and cereals (Indira and Bhattacharya, 2006).

Within cereal varieties, the surface protein (e.g. friabilin in wheat) can affect the endosperm hardness which alters the milling characteristics (Baldwin, 2001). Svihus *et al*. (2005) reported that friabilin reduces bonding properties between starch granules and matrix protein, and this can give rise to softer endosperm that fractures more easily during milling, and results in a finer textured product. The most important physical properties of grain affecting milling include grain hardness and vitreousness (Greffeuille *et al.*, 2007a). One of the most important factors influencing cereal grinding is the hardness of the grain (Campbell *et al.*, 2007). Grain hardness significantly affects the energy consumption of grinding (Warechowska *et al.*, 2013). Hard kernels require more energy during milling into flour than soft kernels (Kilborn *et al.*, 1982). Hardness is a genetic characteristic, and little affected by local growing conditions (Pomeranz and Williams, 1990).

In the food industry, hardness is a single most important characteristic in determining the milling quality (Van Berneveld and Hewitt, 2003). Grain vitreousness is often interrelated with grain hardness (Warechowska *et al.,* 2013). Kernels with more vitreous endosperm are most often harder (Glenn and Johnston, 1994) and increased endosperm vitreousness for hard wheat is associated with higher flour yields (Haddad *et al.*, 1999). According to Marshall *et al. (*1986), the geometric properties of grains such as length, width, thickness, sphericity and endosperm size also affect milling directly. Grain length, width and area have been associated with a 40 % variation in the milling quality of winter wheat cultivars (Berman *et al.*, 1996).

2.24 Cereals

Cereal crops are grasses belonging to monocot family of *Poaceae* or *Gramineae* (Singh *et al.*, 2015). Cereals have a long history of use by humans as staple foods and important sources of nutrients in both developed and developing countries (Nthoiwa *et al.*, 2013). Cereals and cereal products are an important source of energy, carbohydrates, protein, and fibre, as well as containing a range of micronutrients such as vitamin E, some of the B vitamins, magnesium and Zinc (Mckevith, 2004). It has been reported that the whole cereal grain consisting of phytochemicals work synergistically to protect body against cardiovascular diseases (Katcher *et al.,* 2008), cancer (Flight and Clifton, 2006) and diabetes (Venn and Mann, 2004). The heterogeneity and complex chemical structure of cereal cell walls, polysaccharides such as arabinoxylan (Zheng *et al.,* 2011), β-glucan, and cellulose along with associated phenolics act as barriers for digestive enzymes (Cui and Wang, 2009).

The major compositional difference between whole grains and their milled form is reduction of all nutrients that are stored in external layer, dietary fiber, and the components associated with fibers including phytic acid, tannin, polyphenol, and some enzyme inhibitors like trypsin inhibitor, as well as minerals and some vitamins (García-Estepa *et al.*, 1999). Many different processing activities are utilized to turn coarse cereal grains into products ready for human consumption (Nthoiwa *et al.*, 2013). Starch in cereal is the most abundant energy source for most domestic production animals (Svihus *et al.*, 2005) though the availability of energy from starches is not complete. Studies report that methanolic extracts from red sorghum showed higher antioxidant activity and contain higher polyphenolic levels compared to rice, foxtail millet, proso millet and barley (Choi *et al.*, 2007).

Bran, a byproduct of milling has antioxidant potential due to phenolic acids such as *p*-coumaric acid and vanillic acids that are concentrated in the bran portion of cereal kernels (Pushparaj and Urooj, 2014). Bran makes up 5 % of total kernel and composed of valuable components like dietary fiber, vitamins, phytochemicals etc., (Izydorczyk and Biliaderis, 1995). Millet is considered as a highly palatable and good source of energy, protein and minerals (Devi and Sangeetha, 2013). Millet is the fifth most important cereals in the world ranging from wheat, maize, rice and barley (Shayo *et al.*, 2001). The value addition of food has assumed significant importance in the last decade due to some socio-economic and industrial factors (Devi and Sangeetha, 2013).

The use of whole meal flour is one strategy for development of healthy products as the consumption of whole grain has been shown to reduce the risk of colorectal cancer, cardiovascular diseases, diabetes and obesity (Slavin, 2004). Consumption of whole grain cereals can protect against diabetes, obesity, constipation, cardiovascular disease, and other lifestyle disorders (Anderson, 2003). Using whole grain or milled flour without sieving and separating different portion can be beneficial for health (Schatzkin *et al.*, 2007). Milling of grains results in major losses (in descending order) of thiamine, biotin, vitamin B6, folic acid, riboflavin, niacin, and pantothenic acid; there are also substantial losses of calcium, iron, and magnesium (Fardet, 2010). The process of dehulling and milling improves the starch content of grain and its digestibility (Kerr *et al.*, 2000). In fact, it is shown that various characteristics of wholegrain products are responsible for the potential health benefits, including a reduced energy density, increased volume and particle size, and a high content of dietary fibre and bioactive micro- and non-nutrients such as betain, magnesium (Mg), calcium (Ca), and B vitamins (Slavin, 2003). Maize, sorghum and millet are important agricultural crops that play significant role in the diet of the people all over the world particularly in the developing nations (Akinoso *et al.*, 2013). FAO (2012) respectively ranked maize, sorghum and millet as third, fifth and sixth important cereals in the world. Products from these cereals include grit, meal, flour, flakes, starch and paste of different forms (Akinoso *et al.*, 2013). Normally, cereal grains contain 10-15 % water, 8-14 % protein, 70-75 % carbohydrates and 2-7 % fat as well as variety of minerals and vitamins (Polumahanthi and Nallamilli, 2014).

2.25 Economic Value, Nutritional and Chemical Composition of Cereals and Legumes

A number of cereals and legumes that are readily available in West Africa have been found to have nutrient potentials that could complement one another if properly processed and blended (Fernandez *et al.*, 2002). A study conducted by Solomon (2005) revealed that ready-to-eat complementary food products formulated from locally available food commodities, can meet the macro nutritional needs of infants and children. These assertions led to efforts to formulate composite blends and scientific studies carried out to ascertain the nutritive adequacy of these locally available blends (cereal and legumes) for possible use as complementary foods, especially by the rural and poor urban mothers during weaning period (Antwi, 2011).

2.26 Corn

Corn (*Zea mays* L.) is an important cereal grain in the world as it ranks third after wheat and rice in importance (Sandhu *et al.*, 2007). Corn ranks first among all other annual crops in terms of worldwide production, and has a great variety of end uses (Egesel and Kahriman, 2012). It has a diverse form of utilisation including human food uses, animal feed formulation and as a basic raw material for industrial purposes (Mejia, 2005). Corn is a relevant food and animal feed worldwide and occupies a dominant place in the world economy and trade as an industrial grain crop (White and Johnson, 2003). The grain is fermented to give corn dough in Ghana, in Nigeria and other countries in Africa and is decorticated, degermed and precooked (Hesseltine *et al.*, 1979). Corn tuwo (a maize-based non fermented food gel) is one of the numerous African food products that can be obtained from maize (Okoruwa, 1997). The food product is particularly popular across West Africa sub-region and is normally prepared from non fermented corn flour to form a gel-like product (Bolade *et al.,* 2009).

Corn is a popular and major staple food in African countries which provides energy and nutrients for every household. In Ghana, corn is the most popular of all grain crops and it is grown all over the country (Abrefah *et al.,* 2011). Corn is processed into corn flour which is used in the preparation of many local foods such as 'kenkey', 'banku,' 'tuo zaafi', 'akple', 'porridge', 'abolo' (Lokko *et al.,* 2004). Corn is an important staple food grown in many parts of the tropics which serves as food for many people and animals (Abrefah *et al.,* 2011). However, there has been a tremendous increase in corn grain utilization for animal feed formulations in the developing countries in recent times due to a rapid increase in poultry consumption (Okoruwa, 1997). Corn milling is a major activity in Africa, especially in Ghana since over 95 % of all Ghanaians enjoy delicacies prepared from milled corn (MoFA, 2001). Delicacies prepared from milled corn include '*banku*', '*kenkey*', '*akple*','*aprenprensa*' and corn porridge (*Kwofie et al.*, 2011). Corn gruel is the most popular form of cereal consumption in West Africa (Simolowo, 2011).

2.27 Corn Grain Kernel Composition

The corn kernel is classified as a caryopsis; it is a single-seeded fruit, in which the fruit coat (pericarp) does not separate naturally from the seed (Watson, 1987b). Due to its unique structure and composition, corn is broadly useful as animal feed and food grain and has specific industrial value (Watson, 1988). A precise knowledge of the structure and composition of the mature corn grain is necessary for understanding how it can be processed and efficiently utilized (Watson, 1987b). Mature corn grains are composed of four major parts: pericarp (hull or bran), germ (embryo), endosperm, and tip cap (Eckhoff, 1992a). For corn industrial processes, maize grain is separated into the three main parts of the grain: pericarp, endosperm and germ (Eckhoff and Paulsen, 1996). A grain consists of three main parts including the endosperm, embryo, and bran (Evers and Millar, 2002).

2.27.1 Pericarp

The pericarp or hull, the true fruit coat of the maize grain (Watson, 1987b), is the outer protective covering composed of dead cells that are primarily cellulose and hemicellulose (Wolf *et al.,* 1952b). The term ‘’bran’’ is sometimes used to describe the pericarp-containing product of dry-milling or wet milling that includes the tip cap, aleurone layer, and adhering pieces of starchy endosperm (Watson, 1987b). The pericarp protects the grain from deterioration by resisting penetration of water, and from microbial infection and infestation (Eckhoff, 1992a). The pericarp makes up 5-6 % of the grain dry weight (Watson, 1987b).

2.27.2 Germ

The germ is composed of the embryo and the scutellum and it contains genetic information, enzymes, vitamins, and minerals for germination (Watson, 1987b). The germ comprises about 10 to 14 % of the weight of the grain in different varieties of maize (Wolf *et al.,* 1952a). From the perspective of processing of maize, the germ is important for two reasons (Eckhoff and Paulsen, 1996): 1) the germ is a concentrated source of oil and 2) the germ has a higher rate of moisture absorption than the other parts of grain components and acts as a pathway into the endosperm during water absorption (Ruan *et al.,* 1992). Embryo or germ is diploid formed by the fertilization of male and female gametes, which is rich source of unsaturated fat, vitamins (E and B), protein and minerals

(Singh *et al.,* 2015). Most vitamins and minerals (44.45 %) are found in the germ and bran portion of grains (Oghbaei and Prakash, 2016).

2.27.3 Endosperm

The endosperm comprises about 80 to 84 % of the grain dry weight (Wolf *et al.,* 1952a) and is the source of energy and protein for germinating seed (Eckhoff, 1992a). Structurally, all grains are composed of endosperm, germ, and bran (Oghbaei and Prakash, 2016). The structure of corn endosperm is very important for maize processing industries (e.g. dry milling and wet milling) because it must be broken into particles of the desired size during the milling process (Wolf *et al.,* 1952a) for the production of various food and industrial products. Corn endosperm consists of an aleurone layer which is a thin outer layer containing pigments, oil and protein matrix (Wolf *et al.,* 1952c). The protein matrix is composed of an amorphous protein material known as ''glutelin'' (Eckhoff and Paulsen, 1996), where distinct protein bodies are embedded (Watson, 1987b). ''Zein'' an alcohol soluble protein, which is extremely low in lysine, is a major composition of the protein bodies (Kim, 2000). Corn endosperm is composed of two types, hard (also called horny, corneous, vitreous, or translucent) and soft (also called floury or opaque) (Eckhoff and Paulsen, 1996). Milling of corn may be done either 'wet' or 'dry' (level of moisture content of maize before milling) depending on the intended use (*Kwofie et al.*, 2011). Primary processing methods of these foods require size reduction in either wet or dry form (Akinoso *et al.,* 2013).

2.28 Corn Milling Technologies

One of the most important characteristics of grain processing is kernel hardness, especially in milling (Bettge and Morris, 2000). Approximately 25% of ethanol is produced by wet mills and the remainder of ethanol produced is through dry-mill ethanol plants (Rendleman *et al.*, 2007). Corn fractionation is traditionally accomplished by using dry- or wet-milling procedures (Moeller *et al.*, 2009). Pre-milling treatment reduces milling time and increases the milling efficiency compared to all traditional methods (Dronachari and Yadav, 2015).

2.28.1 Wet Milling

Corn wet-milling is a stepwise process by which corn is separated into various components. Wet mill plants utilize corn or better due to the fact that products for human consumption are produced along with ethanol (Stock *et al.*, 2000). Wet milling and wet sieving are unit operations in processing grains to drinks (Gana *et al.*, 2014). The wet milling separates the seeds into its various components: germ, protein, fiber, and starch (Jasper, 2005), while the wet sieving separates the filtrate (milk) which is use for various industrial products including drinks from the residue which is useful as animal feed and can be used for other applications (Gana *et al.*, 2013). Corn processed by wet milling is typically separated into 5 basic components: starch, germ, gluten, fiber and steep liquor (Blanchard, 1992). Wet milling is capable of producing high fructose corn sweetener, corn syrups used as a sugar substitute (Stock *et al.*, 2000). The wet milling process involves a series of steps which produce the various fractions described below (Corn Refiners Association, 2000).

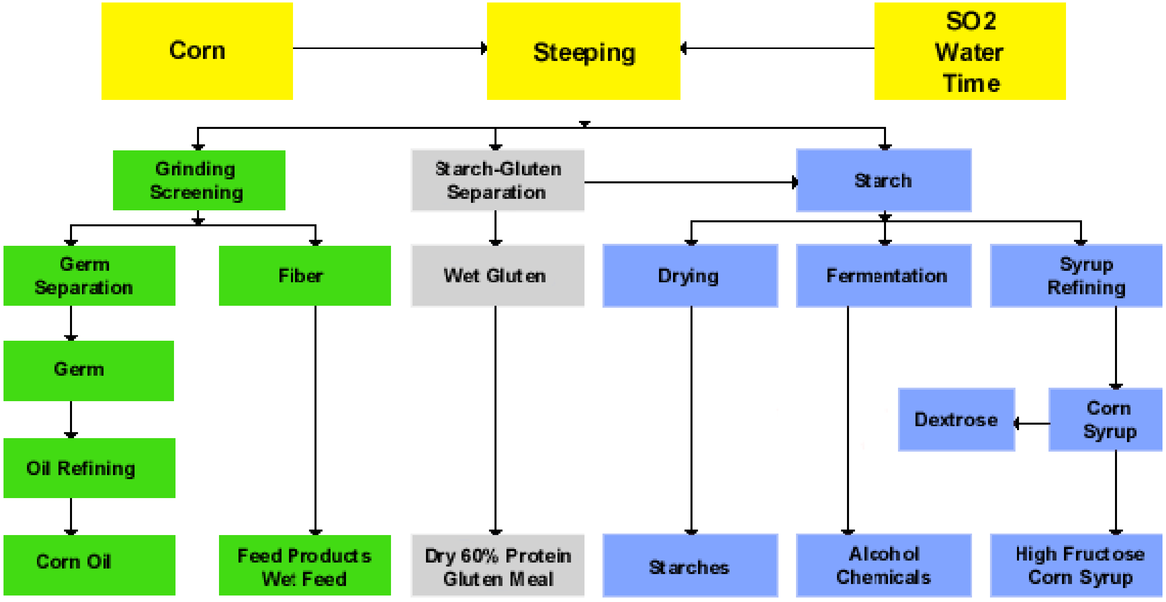

Fig.2.1: Wet milling processes

Source: Minnesota Corn Processors, LLC: http://www.mcp.net/info/wetmill.html

2.28.2 Dry Milling

The objective of the dry milling process is to separate maize grain into three parts using mechanical force: endosperm, germ and bran or hull fractions (Brekke, 1970). The endosperm is processed into grits, meal, and flour, and the germ is processed into oil while the mainly bran, is used for animal feed (Kim, 2000). These dry-milled products are used to make cornflakes for breakfast cereals (Fast, 1990), extruded corn snacks, brewed alcoholic beverages, corn meal for snack foods, corn flour for food mixes, bread making and for nonfood products such as gypsum board or plastics (Eckhoff, 1992a). Effective dry milling processing depends on certain physical properties of maize such as; 1) grain hardness 2) primary products uses are in foods where purity is highly important, and, 3) the dry milling process has less ability to purify products than does the wet milling process (Watson, 1988). Dry milling is used mostly in milling of flour for household used in Ghana. In the U. S., the primary cereal grains utilized during dry milling are corn and sorghum, however wheat, barley, beets, sugar cane or a combination of grains may be used (Stock *et al.,* 2000).

2.28.3 Alkaline Processing (Nixtamalization)

Corn alkaline produces ‘masa’, which is fried or baked into, corn chips, or other various snacks and foods (Eckhoff and Paulsen, 1996). The processing method was developed by native Latin Americans and such products are still the major source of energy and nutrition in many Central American Countries (Eckhoff, 1992a). For alkaline processing, the grain is cooked at near boiling temperature (85-100 ^{o}C) in lime solution (about 1 % CaO in water) for a relatively short time (5-50 minutes), steeped overnight (for up to 15 hours), and then washed to produce nixtamal (i.e, the cooked and steeped corn containing about 50 % moisture on a wet weight basis), which is ground into a soft moist dough called ‘masa’ (Eckhoff and Paulsen, 1996).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Area

The study was conducted in the Tamale Metropolis. Grains milling into flour were carried out at selected mills in the Tamale Metropolis whiles the particle size analyses were determined using an automatic sieve shaker D411 at the Spanish laboratory of the Nyankpala campus of the University for Development Studies.

3.2 Materials

1. Raw Materials

The corn which is the main raw material for the study was obtained from Tamale Aboabo market stored in bags. Three hundred and fifty kilograms of the corn was procured for this purpose. The corn was cleaned through winnowing and stored in polypropylene sacks in a room.

2. Equipment

1. **Automatic Sieve Shaker Machine**

   Automatic Shaker D411 of seven sieves and a pan with each having a capacity to hold 2 kg ground material. The sieves sizes range from 63, 90, 125, 180, 250, 500 and 700 µm.

2. **Weighing Machine**

   a. Model: Titarius.

   Capacity: 1000 g x 0.01 g.

b. Top pan balance

Model: Camry

Capacity: 15 kg x 0.05 kg.

3. Oven

Model: SPH-102

Temperature range: 0-200 ^{o}C

Power: 220-240V

4. Plastic Basins

Thirty plastic basins each of volume 20 litres were used for the soaking and dry grains as well as for the containment of the ground product.

5. Ammeter

Model: Analog Ammeter

Measuring range: 0-50 A

Digit colour: Black

6. Voltmeter

Model: Digital Panel Voltmeter

Measuring range: AC 0-500 V

Power supply: AC 80-500 V

Digit colour: Black

7. **Stopwatch**

   Product type: Digital Timer

   Timing capacity: 100 hr

8. **Simple Thermometer**

   Model: Taylor

   Measuring range: 0-100 ˚C

3.3 Methodology

3.3.1 Sampling of Mills.

Mills used were sampled from a total population (N) of 25 using systematic sampling method. The mills were labeled in order starting from one up to the twenty fifth mill. A sampling frame (n) of five (5) mills located at Channi, Gumbihini, Sakasaka, Warizhehi, Mossi Zongo, Tamale Aboabo, Tishigu, Saabonjida, Zogbeli, Lamakara, Dagbandabba Fong, Lamashegu, Kalanda SDA, Anbariya, Nyanshegu and Dohinnaayili were used. The sampling interval (K) was calculated using the relation of Barreiro and Albandoz (2001) below:

$$K = \frac{N}{n}$$

Where K = Sampling interval

N = Total population

n = sampling frame

$$K = \frac{25}{5}$$

K=5

Mills selection for the purpose of this experiment were sampled using the sampling interval of five, after selecting the first mill as mill A, The next mill was the tenth mill as mill B, The next was the fifteenth mill as mill C, The next mill was the twentieth mill as mill D and finally, the 25th mill was the mill E based on the above sampling interval.

3.3.2 Treatments

The two treatments were about the grain condition (Soaked and Unsoaked) and mills (A, B, C, D and E). The treatments were replicated three times. The total treatments used were thirty (5 mills x 2 treatments x 3 replications= 30 treatments).

3.3.3 Sample Preparation

Each of the thirty plastic basins was given 8 kg of dry Obatanpa corn variety. The thirty basins of corn were randomly assigned for 5 grinding mills, that is each mill was assigned 6 basins. These 6 basins were further divided into the 2 treatments including the three replications. Fifteen corn samples which were to be ground moist were soaked in water for 48 hours. Before the samples were sent to the grinding mills; the water was drained from the corn. The other fifteen corn samples were ground in the dry condition. Milling in mill A was done on day one, milling in mill B took place on the fourth day, milling took place in mill C on the seventh day, milling on mill D was on the tenth day and milling in milling on mill E was done on the thirteenth day.

3. 3. 4 Experimental Design

The experiment was a factorial experiment laid in randomized complete block design in three replications. The factors were grain condition (moist grinding and dry grinding) and mills (A, B, C, D and E).

3.4 Determination of Parameters

3.4.1 Determination of Moisture Content of Soaked and Unsoaked Grains

Moisture content was determined by drying the samples using the standard oven method. The weight of sample before oven drying was recorded and the sample was placed in the oven at 105 ^{o}C for 24 hours. The samples were taken out and then weigh again. Moisture content was calculated as follows:

$$MCwb = \frac{Ww - Wd}{Ww} \times 100\ \%$$

Where MCwb- moisture content expressed on wet basis

Ww-Wet weight

Wd-Dry weight

A sample of the dry grain measured for the study was later taken from the total dry grain quantity to determine its moisture content. All the moist grains samples were milled before the dry grains samples. A sample was also taken from the moist grain total quantity on the day of milling for the determination of the moisture content

3.4.2 Determination of Fineness Modulus

Fineness modulus is an empirical figure and represents the sum of the weight fractions retained on each of a specified sieve divided by 100. Fineness modulus indicates the uniformity of the grind in the resultant product. The sieves used were designated 1-7 starting from the smallest to the biggest and the pan was designated as zero (0). Samples of milled flour (250 g) each were put on the topmost sieve, and the sieves were shaken for 5 minutes. The mass of the sample left on each sieve was measured. Sieves were clean after each experiment. The percentage of material retained on each screen was calculated and multiply by a designated factor according to the sieve. The sum of the product obtained from each sieve was divided by 100 to determine the fineness modulus. Fineness modulus is thus:

$$FM = \sum \frac{PF}{100}$$

Where P - Percentage retained on each sieve

F -Multiplication factor

PF - Product of F and P.

3.4.3 Determination of Uniformity Index

Uniformity index indicates the relative proportions of coarse, medium and fine materials which are in the sample. The uniformity index was determined from a table ; the proportion of coarse particles was determined by adding the percentages of weight retained on the first, second and third sieves and dividing by10; the proportion of medium particles was determined by the addition of the percentages retained on the fourth and fifth sieves and dividing by 10; the proportion of fine materials in the mix was obtained by the addition of the percentages of particles retained on the sixth and seventh sieves and in the pan, and dividing by 10. Uniformity Index (UI) was calculated as:

$$UI = \frac{Coarse}{10} : \frac{Medium}{10} : \frac{Fine}{10}$$

3.4.4 Determination of Average Particle Size

The average particle size of the flour was determined by using automatic D411 sieve shaker machine which carries a set of 63, 90, 125, 180, 250, 500, 700 µm and a pan with cover. A sample of 250 g flour was placed in the topmost sieve and the set of sieves were placed on a sieve shaker machine and was shaken for 5 minutes. The material on each sieve was collected after shaking and weighed. Average particle size was determined by using the following relation:

$$D = 0.0041 \times 2^{FM} \times 25.4\ mm$$

Where

D- Average particle size

FM- Fineness modulus.

3.4.5 Determination of Milling Efficiency

The grinding efficiency was determined for each treatment by taken the mass of the feed material (mf) and mass of the product material (mp). Each treatment was replicated three times and the product weights taken and their averages represented the product mass. The milling efficiency was determined using the formula proposed by Kudzanai (2008) below.

$$Milling\ efficiency = \frac{Mp}{Mf} \times 100\ \%$$

Where Mp - Mass of product

Mf-Mass of feed material.

3.4.6 Determination of Flour Losses

Masses of feed material before milling (mb) and mass of product after milling (ma) were measured using mass balance. The losses were determined using Adekomaya and Samuel (2014) formula below:

$$L = \frac{(mb - ma)}{mb}$$

Where L is loss of flour during milling processes

ma is the mass of the product material after milling

mb is the mass of the feed material before milling.

3.4.7 Determination of Flour Temperature

The temperature of the ground produce was determined by dipping the bulb of a thermometer into the flour immediately after grinding. Some time was given for the rise in mercury column of the thermometer to stabilize and the reading taken as the ground produce temperature.

3.4.8 Determination of Electrical Power

An ammeter was connected between the electric motor of the grinding mill and the electrical supplies. The feed was then poured into the grinding machine and ammeter readings were taken every 5 seconds intervals to a point where all the grains emptied was ground. This was noticed by the meter reading going back to idle electrical current value in Amperes (A). Their averages represented the current and time taken to milled the feed materials. The electrical current (I) consumed was calculated using

I= Maximum current – Idle current

A voltmeter was also connected alongside to read the potential difference or voltages across the milling process. The power requirement during milling of each of the treatments during the milling process was determined following the procedure of El Shal *et al.* (2010) as follows:

$$P = \frac{\sqrt{3} \times I \times V \times \eta \times Cos\theta}{1000}$$

Where P is the power (kW) required during milling.

I is the current delivered

V is the potential difference

Ƞ is the mechanical efficiency assumed (95%)

cosϴ is the power factor (being equal to 0.84).

3.5 Data Analysis.

Quantitative data collated were subjected to statistical Analysis of Variance (ANOVA) using Genstat (Genstat Discovery Edition 3) (Genstat Discovery, 2007). Probability level $P \leq 0.05$ was considered significant for all analyses. Results of the analyses were presented in tables and graphs.

CHAPTER FOUR

4.0 RESULTS

The results of this chapter are put into four folds: data gathered on moisture content, data collected on flour particle sizes, data on electrical power consumption during milling, and flour losses during milling and flour temperature. Graphs and tables are used to explain the results of this chapter.

4.1 Moisture Content

Table 4.1 shows the average moisture content for both dry and moist corn before grinding at the various mills.

Table 4. 1: Moisture Content

Mills	Grain Condition	Moisture Content (% wb)
A	Dry	11.20^{bd}
	Moist	17.51^{am}
B	Dry	11.30^{bd}
	Moist	17.32^{am}
C	Dry	11.53^{ad}
	Moist	17.21^{am}
D	Dry	11.07^{bd}
	Moist	18.22^{am}
E	Dry	10.81^{bd}
	Moist	16.01^{bm}
S.E.D		**0.72**
CV (%)		**6.20**

Values expressed are means of three replications on moisture content. S.E.D-Sum of error of the difference. CV-Coefficient of variation.

For moist grains, the highest average moisture content recorded was 18.22 % (wb) from mill D, whilst the least average moisture content was 16.01 % (wb) from mill E as shown in Table 4.1. For dry grains, the highest average moisture content recorded was 11.53 % (wb) from mill C, whilst the least average moisture content was 10.81 % (wb) from mill E as shown in Table 4.1. Moisture content for moist grains was not significantly different among mills A, B, C and D. Mill E was significantly different from the other mills for moist grains moisture content. Dry grains moisture content was not significant among mills A, B, D and E whiles mill C was significantly different from the rest of the mills.

4.2 Fineness Modulus

Table 4.2 shows the average fineness modulus for both dry and moist corn after grinding at the various mills. For moist grains, the highest average fineness modulus recorded was 5.42 from mill B, whilst least average fineness modulus was 2.96 from mill E as shown in Table 4.2. For dry grains, the highest average fineness modulus recorded was 5.62 from mill B, whilst the least average fineness modulus was 3.21 from mill E as shown in Table 4.2.

Moist grains flour average fineness modulus was not statistically different among mill A and mill D; no significant difference was observed for mill C and mill E whilst mill B was significantly different from the rest of the mills. Fineness modulus value for dry grains flour was not significant different form mill A and mil C, mills B, D and E were all significantly different from each other.

Table 4. 2: Fineness modulus

Mill	Grain Condition	Fineness Modulus
A	Dry	4.54^{cd}
	Moist	4.37^{bm}
B	Dry	5.62^{ad}
	Moist	5.42^{am}
C	Dry	4.02^{cd}
	Moist	3.56^{cm}
D	Dry	5.26^{bd}
	Moist	4.39^{bm}
E	Dry	3.21^{dd}
	Moist	2.96^{cm}
S.E.D		**0.65**
CV (%)		**16.50**

Values expressed are means of three replications on fineness modulus. S.E.D-Sum of error of the difference. CV-Coefficient of variation, m-moist grains, d-dry grains.

4.3 Uniformity Index

Table 4.3 show the uniformity index for both dry and moist corn after grinding at the various mills. For moist grains, mill C grinds with the highest fine flour particles of 50 %, 30 % medium particles and 20 % coarse particles; whilst the highest coarse particles of 50 %, 30 % medium and 20 % fine particles were obtained from mill D as shown in Table 4.3.

Table 4. 3: Uniformity Index

Mills	Grain Condition	Uniformity Index
A	Dry	3:3:4
	Moist	3:2:5
B	Dry	4:2:4
	Moist	4:2:4
C	Dry	1:4:5
	Moist	2:3:5
D	Dry	4:2:4
	Moist	5:3:2
E	Dry	5:2:3
	Moist	3:3:4

Values expressed are means of three replications on uniformity index.

For dry grains, mill C grinds with 50 % fine particles, 40 % medium particles and 10 % fine particles were obtained from mill E as shown in Table 4.3.

4.4 Average Particle Size

Table 4.4 shows the average particle size of the ground product samples. For moist grains, the largest average particle size of flour recorded was 4.46 mm from mill B, whilst the least average particle size of flour was 0.81 mm from mill E as shown in Table 4.4. For dry grains, largest average particle size of flour was 5.12 mm from mill B, whilst the least average particle size of flour was 0.96 mm from mill E as shown in Table 4.4.

Average particle size for moist grains flour from mill A and mill B was not significant, no significant difference was observed for mill C and mill E whilst mill A was statistically different from the other mills. The average particle size of dry grains flour was not significant different among mill A and mill D, mill C and mill E had no significant difference whiles mill B was statistically different from the rest of the mills.

Table 4. 4: Average Particle Size

Mills	Grain condition	Average particle size (mm)
A	Dry	2.42^{bd}
	Moist	2.15^{am}
B	Dry	5.15^{ad}
	Moist	4.46^{am}
C	Dry	1.69^{cd}
	Moist	1.23^{cm}
D	Dry	3.99^{bd}
	Moist	2.18^{bm}
E	Dry	0.96^{cd}
	Moist	0.81^{cm}
S.E.D		**1.19**
CV (%)		**44.90**

Values expressed are means of three replications on average particle size. S.E.D-Sum of error of the difference. CV- Coefficient of variation.

4.5 Milling Efficiency

Table 4.5 shows milling efficiency for both dry and moist grains during milling. For moist grains, the highest milling efficiency recorded was 75.67 % from mill C, whilst least milling efficiency of 64.33 % was recorded for both mills D and E as shown in Table 4.5. For dry grains, the highest milling efficiency recorded was 63.33 % from mill C, whilst the least milling efficiency of 54.33 % was from mill D as shown in Table 4.5. Milling efficiency for moist milling was not significant among mills A, B, D and E whilst the milling efficiency for mill C was significantly different from all the mills. Dry grains milling efficiency was not significantly different from mills A, B, D and E whilst mill C was statistically different from the other mills.

Table 4.5: Milling Efficiency

Mills	Grain Condition	Milling Efficiency (%)
A	Dry	58.72^{bd}
	Moist	67.72^{bm}
B	Dry	58.04^{bd}
	Moist	63.73^{bm}
C	Dry	63.33^{ad}
	Moist	75.67^{am}
D	Dry	54.33^{bd}
	Moist	64.33^{bm}
E	Dry	57.00^{bd}
	Moist	64.33^{bm}
S.E.D		**3.90**
CV (%)		**7.60**

Values expressed are means of three replications on milling efficiency. S.E.D-Sum of error of the difference. CV-Coefficient of variation.

4.6 Losses During Grinding

Table 4.6 shows flour losses during milling for both dry and moist grains. For moist grains, the highest flour losses during milling recorded was 16.20 % from mill A followed by that for mill D which recorded 14.20 % flour losses, whilst the least flour losses during milling of 9.04 % was obtained from mill C as shown in Table 4.6. For dry grains, the highest flour losses during milling recorded was 15.10 % from mill A, whilst the least flour losses during milling of 7.60 % was obtained from mill C as shown in Table 4.6. All the mills were significantly different from each other and mill A recorded statistically higher flour losses during milling for both dry milling and moist milling.

Table 4. 6: Losses During Milling

Mills	Grain Condition	Flour Losses (%)
A	Dry	15.10^{ad}
	Moist	16.20^{am}
B	Dry	10.90^{dd}
	Moist	12.40^{dm}
C	Dry	7.60^{ed}
	Moist	9.04^{em}
D	Dry	12.20^{cd}
	Moist	14.20^{bm}
E	Dry	12.70^{bd}
	Moist	13.04^{cm}
S.E.D		**0.06**
CV (%)		**14.40**

Values expressed are means of three replications on losses. S.E.D-Sum of error of the difference. CV-Coefficient of variation.

4.7 Flour Temperature

Table 4.7 shows flour temperature immediately after milling for both dry and moist grains. For moist grains, the highest flour temperature recorded was 58.20 ^{o}C from mill E, whilst the least flour temperatures of 54.24 ^{o}C and 54.17 ^{o}C were obtained from both mills B and C respectively as shown in Table 4.7. For dry grains, the highest flour temperature recorded was 67.15 ^{o}C from mill E, whilst the least flour temperature of

62.09 °C was obtained from mill C as shown in Table 4.7. Ground flour temperature for moist milling was not significant among mills A, B, C and D whilst mill E was statistically different from the rest of the mills. Flour temperature for dry milling was not significantly different among mills B, C and D whilst mills A and E had no significant difference.

Table 4.7: Temperature of Ground Product

Mills	Grain Condition	Temperature (°C)
A	Dry	65.06^{ad}
	Moist	55.10^{bm}
B	Dry	65.04^{bd}
	Moist	54.24^{bm}
C	Dry	62.09^{bd}
	Moist	54.17^{bm}
D	Dry	63.03^{bd}
	Moist	56.01^{bm}
E	Dry	67.15^{ad}
	Moist	58.20^{am}
S.E.D		**3.80**
CV (%)		**7.90**

Values expressed are means of three replications on flour temperature. S.E.D-Sum of error of the difference. CV-Coefficient of variation.

4.8 Electrical Power Required

Figure 4.1 shows the relationship between current and time for both dry and moist grains milling at mill A. For moist grains, the electrical power consumed was 4.20 kW, whilst that for dry grains was 11.58 kW.

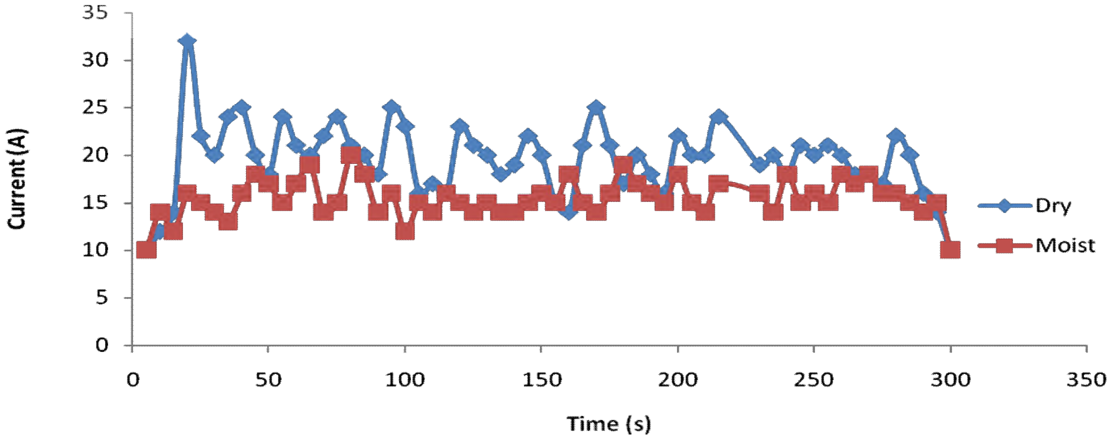

Figure 4.1 : Trend Graph Between Current and Time for Mill A.

Figure 4.2 shows the relations hip between current and time for both dry and moist grains at mill B. For moist grains, the electrical power consumed was 5.61 kW, whilst that for dry grains was 7.14 kW.

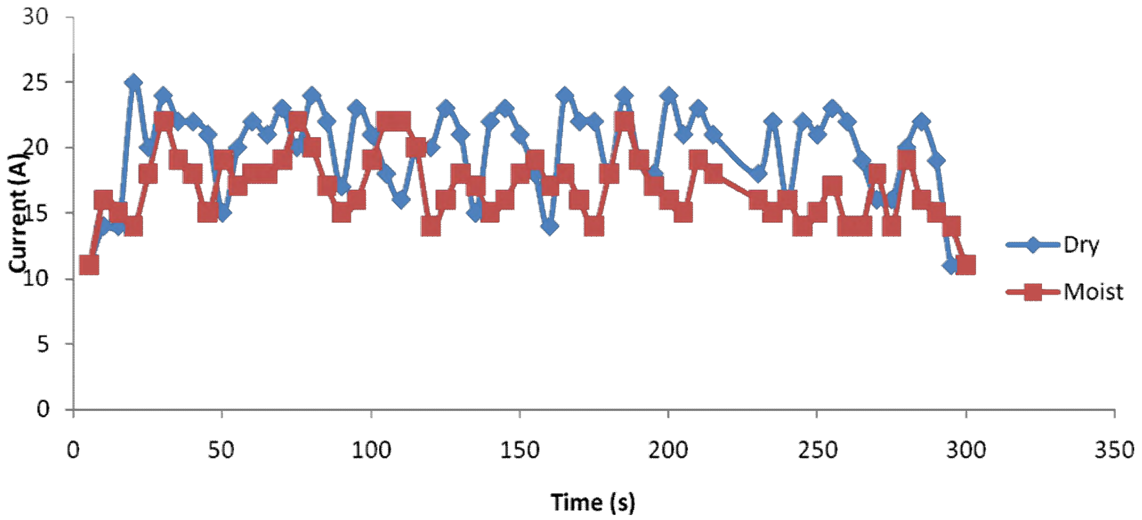

Figure 4.2: Trend Graph Between Current and Time for Mill B.

Figure 4.3 shows the relationship between current and time for both dry and moist grains at mill C. For moist grains, the electrical power consumed was 4.34 kW, whilst that for dry grains was 6.52 kW.

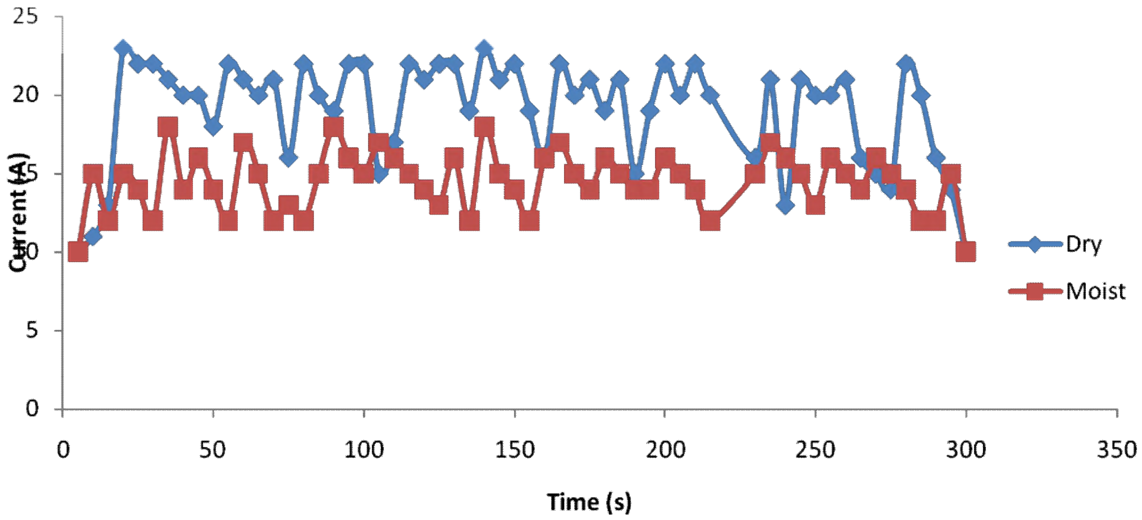

Figure 4.3: Trend Graph Between Current and Time for Mill C.

Figure 4.4 shows the relationship between current and time for both dry and moist grains at mill D. For moist grains of mill D, the electrical power consumed was 10.37 kW and that for dry grains was 13.82 kW.

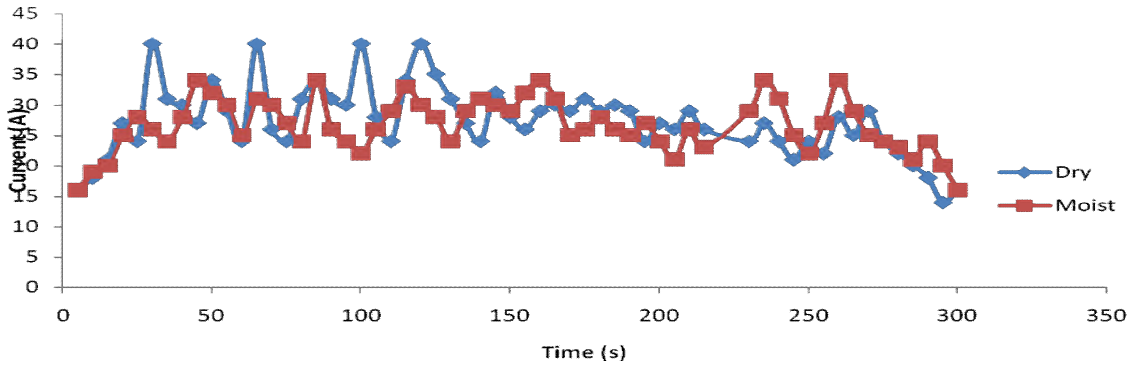

Figure 4.4: Trend Graph Between Current and Time for Mill D

Figure 4.5 shows the relationship between current and time for both dry and moist grains during milling at mill E. For moist grains at mill E, the electrical power consumed was 4.48 kW whilst that for dry grains was 7.83 kW.

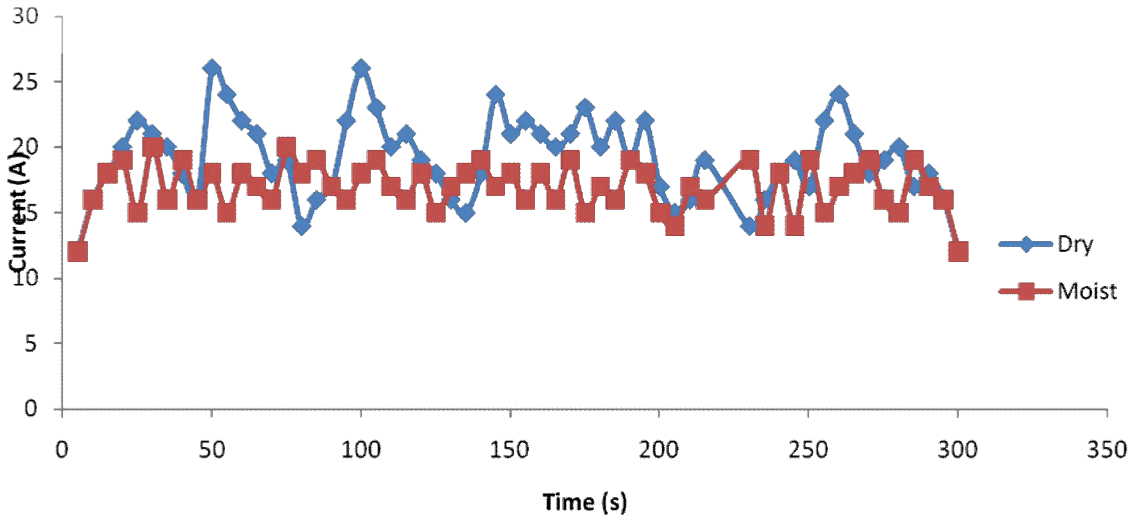

Figure 4.5: Trend Graph Between Current and Time for Mill E

An overall assessment showed that the highest electrical power of 10.37 kW was recorded from mill D in the milling of moist grains, whilst the least electrical power of 4.20 kW was obtained for mill A. For dry grains, the highest electrical power of 13.82 kW was recorded from mill D, whilst the least electrical power consumption of 6.52 kW was obtained from mill C.

CHAPTER FIVE

5.0 DISCUSSIONS

This chapter discusses the results of the investigation conducted.

5.1 Moisture Content

The results of the study in Table 4.1 revealed that moisture content (wb) of dry grains during the milling period ranged between 10.81 % and 11.53 % whilst that of moist grains varied between 16.01 % and 18.22 %. These differences in moisture content of corn could be attributed to changes in relative humidity of the air as a result of fluctuations in weather conditions. The moisture contents of the grains were measured at different times and days. Corn kernels are hygroscopic and will either absorb or loose moisture (Chukwu and Ajisegiri, 2005). This confirmed the findings of Iqbal *et al.* (2012) which indicated that as relative humidity changes, object's water content adjust to the new relative level, creating new equilibrium. This agreed with the findings of Mbofung *et al.* (2013) which purported that relative humidity fluctuations resulted in changes in moisture content of seeds.

This also agreed with Fuzek (1985) who stated that at higher relative humidity there is more water in biological materials. This again confirmed the assertion of Chen *et al.* (2005) which stated that as the relative humidity of the surrounding increases, the moisture absorption also increases and as the relative humidity decreases desorption take place. This also corroborated the findings of Saville (1999) who indicated that differences in moisture content of dry grains and among the moist grains could be due to hysteresis between moisture uptake and moisture loss. Also, Ashour *et al.* (2010) reported that the effect of relative humidity on equilibrium moisture content is very high.

5.2 Fineness Modulus

From Table 4.2, the results showed that fineness modulus of dry grains flour varied between 3.21 and 5.62 whilst that of moist grains ranged between 2.96 and 5.42. Mill E performed best than the rest of the mills for dry grains milling. Mill E performed best in terms of moist grains milling than all the mills. Under the same milling conditions, moist grains achieved a lower fineness modulus than dry grains. As the general rule, the lower the fineness modulus the better the flour obtained from the grinding. These variations in fineness modulus among mills could be due to variations in plate clearance as well as differences in moisture content of grains. This interpretation corroborated the assertion of Ramappa *et al. (*2011) which indicated that fineness modulus of flour increased with the increase in plate clearance. These ranges of fineness modulus values gave an indication of low performance compared to that of Yawatkar *et al.* (2010) using pin mill which gave a highest fineness modulus value of 3.92.

The differences in performance between this study and those reported by Yawatkar *et al.* (2010) could be attributed to the differences in milling machines used. Again, the results for moist grains milling performed better than those obtained by that of Young (1970) who reported that fineness modulus for high moisture rolled corn was 5.81 and that for low moisture corn was 3.37. The differences in fineness modulus could be due to different milling operators experience as well as differences in mills used. The higher the fineness modulus value the coarser the flour particles. A fineness modulus of 2.10 and below signifies fine flour (Carl and Denny, 1978). This is supported by the findings of Abdel–Wahab *et al*. (2007) which indicated that performance of milling process depends on different factors including physical properties of grains and operational factors.

5.3 Uniformity Index

The results from Table 4.3 showed that mill C performed best whilst mill E performed worst in terms of dry grains milling. Mill C performed best, followed by mill A whilst mill D performed worst in terms of moist grains milling. In terms of distribution of the grain flour by aggregates, moist grains were associated with greater percentage of fineness in grinding than the case of dry grinding. These differences in performance of the mills could be attributed to variation in plates clearance and grains moisture content. The uniformity index of flour from dry milling ranged from 1:4:5 to 5:2:3 and that for moist milling ranged from 2:3:5 to 4:2:4. These results showed that there was low percentage of fineness associated with the ground flour from the mills when compared to that of 0:1:9 as reported by Yawatkar *et al. (*2010). This difference in percentage of fineness of flour particles could be due to differences in hardness of grains. The results however disagreed with that of Young (1970) who indicated that high moisture rolled corn had a greater proportion of coarse particles than fine.

5.4 Average Particle Size

The results from Table 4.4 indicated that average particle size of dry grains flour ranged between 0.96 mm and 5.15 mm whilst that of moist grains varied between 0.81 mm and 4.46 mm. For dry grains milling, mill E performed best, followed by mill C, whilst the worst performed one was mill B. Moist milling produced flour with smaller particle sizes than dry milling. The smaller the particle size the better the performance. These differences in particles sizes of dry and moist millings could be due to reduction in friction needed to rub the grains against the milling plates. This contradict the assertion of Bolade (2009) which observed that mean particle size ranged between 0.2033 mm and

0.2205 mm with Soaking Method and Non-Soaking Method giving the lowest and highest values respectively. This could be attributed to the moisture content, higher friction produced among the feed particles and fillings of the grinding plate, equipment and corn characteristics as well as weak endosperm cohesive forces. This was in compliance with Balasubramanian *et al.* (2011) which stated that higher friction produced among the feed particles due to sufficient filling of the grinding cavity with the feed during grinding process with the increased in feed rate.

The results confirmed the assertion of Rausch *et al.* (2005) which stated that particle size distribution is affected by both equipment and corn characteristics. Bolade (2009) further indicated that the lowest mean particle size of grain soaking method may be attributed to the weakened associative forces binding the endosperm together thereby giving rise to smaller-size particle during milling. The grinding conditions, type of grinding equipment, velocity of working parts can affect size distribution (Henderson, 1976). The differences in average particle sizes among dry and moist grains could be due to differences in the moisture content of the grains. This observation agreed with that reported by Chiang and Yeh (2002) which indicated that soaking affects the particle size distribution of flour. Moisture made the maize kernels softer creating more chances for further disintegration into smaller pieces. This claim is in accordance with Asmeda *et al.* (2015) which reported that as more water diffused, grains kernels become softer and make it easily broken resulting in small particle granules during grinding process. The results of average particle size distribution were not in tune with that of Hanif *et al.* (2014).

5.5 Milling Efficiency

From Table 4.5, the results revealed that milling efficiency of dry grains milling ranged between 54.33 % and 63.33 % whilst that of moist grains varied between 64.33 % and

75.67 %. Mill A performed best and D performed worst in terms of dry milling. For moist grains milling, mill C performed best whilst mill B performed worst. Moist grains milling performed better than dry grains milling. Mill C performed best than the rest of the mills in terms of milling efficiency for both dry grains milling and moist grains milling. The milling efficiencies were however higher for moist grains milling than dry grains milling. The results was in accordance with those reported by Akinoso *et al.* (2013) and Dincer *et al.* (2005) which reported higher milling efficiencies for wet milling than dry milling. The results of the study gave a smaller milling efficiencies as compared to the highest value of machine efficiency of 92.9 % and 85 % as reported by El Shal *et al.* (2010) and Ramappa *et al.* (2011) respectively.

These agreed with Olajide *et al.* (2016) and Feyisetan (2009) which reported that efficiency of a fabricated burr mill depended on the moisture content of the grains. These mills used for the study were found to have smaller milling efficiencies as compared to 96 % and 94 % for dry cassava and dry maize respectively (Nasir, 2005). The mills performed comparatively low as compared to Ogedengbe and Abadariki (2014) which also reported a milling efficiency of 81.14 % for bone milling cum pulverizing machine. These mills efficiencies also performed lower when compared with that of Mohamed *et al.* (2015) which observed a milling efficiency of 92.50, 93.60 and 93.71 % at a respective feed rate of 1.92, 2.03 and 2.09 kg/min at a moisture content of 13 % for broad beans. This variation in milling efficiencies could be attributed to the differences in mills, grains type, and mechanical properties of grains, feed rate and plate clearance. Mohamed *et al.* (2015) reported that differences in milling efficiencies were due to mechanical properties of grains. Differences in milling efficiencies could be due to variations in plate clearance. This observation was in tune with that of Shankar *et al.*

(2013) which reported a milling efficiency of 85 % at a plate clearance of 0.3 mm and reduced to 61.70 % at a plate clearance of 0.7 mm. Lower milling efficiency of mills could be due to delay in feeding the hopper by the operator (Adetola and Oyejide, 2015).

5.6 Losses During Milling

The results of the investigation from Table 4.6 showed that mill C performed best and mill A was the worst performed mill for dry grains milling. For moist grains milling, mill C performed best whilst mill A performed worst. Dry grains milling performed better than moist grains milling. With respect to losses, mill C performed best than the rest of the mills. These differences in milling losses could be due to moisture content of grains.

These mills were found to perform lesser as compared to 0.04 % flour losses reported by Nasir (2005) and losses of 7.25, 6.40 and 6.29 % at different feed rate of 1.92, 2.03 and 2.09 kg/min have been reported by Mohammed *et al.* (2015).

These mills performance partly agreed with that of a quantitative loss of 10 % as reported by Kudzanai (2008). This variation in losses could be attributed to the moisture content of the grains which reduces the shearing ability of the plates and some flour remaining stuck to parts of the milling processes. This confirmed the findings of Raji and Famurewa (2008) which stated that when moisture is high, shearing effect of the plates is reduced resulting in the reduction in yield. Shankar *et al.* (2013) observed that milling losses increased from 15-38.30 % with increased in feed rate and plate speed. These results however disagreed with that of Balasubramanian *et al. (*2011) which reported that milling loss was found to be higher at lower moisture level and decreased with increase of moisture content as well as feed rate.

5.7 Flour Temperature

From Table 4.7, the results showed that mill C performed best and mill E was the worst performed mill in terms of dry grains milling. For moist grains milling, mill C performed best whilst mill E performed worst. For both dry grains milling and moist grains milling, it was observed that moist grains milling performed better than dry grains milling. Mill C performed best than all the mills. This could be due to kernel hardness and high friction between the grains and the milling plate as well as the energy associated with the prime mover.

The rise in flour temperature among mills could be as a result of gelatinization of starch. This observation was supported by Caprita *et al.* (2011) which reported a significant increase in temperature at 60 ^{o}C caused gelatinization of starch and indicated that the optimum temperature is 40 ^{o}C. Flour is a very hygroscopic material and its moisture changes with the changes in temperature and humidity of the store environments (Hruskova and Machova, 2002). Milled flour must have a low temperature for better performance of the machines. These mills used for the experiment were found to have a very high temperature as compared to that of Jeffers and Rubenthaler (1977) which reported a flour temperature of 36 ^{o}C. This trend of results agreed with that of Raji and Famurewa (2008) which reported that, during milling, the part of the kinetic energy from the prime mover for disintegration of the seeds is converted into heat and the heat is more in dry milling than wet milling.

5.8 Electrical Power Requirement

The results of the study from Figures 4.1, 4.2, 4.3, 4.4, and 4.5 revealed that dry milling of grains to fineness consumed higher amount of electrical energy than moist grains milling. The lower the electrical energy consumed by a mill to produce fine flour particles sizes, the better the performance of the mill. As such, moist grains milling performed better than dry grains milling. Mill C which recorded lower electrical energies for both grains condition performed better than the rest of the mills. These mills performance was in tune with the electrical power consumption of 4.95-7.26 kW as reported by Kudzanai (2008). This increase in electrical power consumption could be due to increase in cohesion between particles. This interpretation was in tune with that of Ghorbani *et al.* (2011) which stated that an increase in cohesion and contact area between particles caused increase in specific energy consumption. Soaking of grains increased the moisture content of grains and subsequently reduced the rupture forces in the milling process. This interpretation was in tune with that of Gana *et al.* (2014) which reported that soaking of grains resulted in an increase in moisture levels of grains, the rupture force required by the grains was observed to be low and the deformation at that point was high. This increase in moisture content could be due to weaknesses of internal texture (Akinoso *et al.,* 2013).

These results disagreed with those obtained by Dziki and Laskowski (2005), Hassan (1994), Ohunakin *et al.* (2013) and Dabbour *et al.* (2015) which purported that an increased in moisture content causes increase in kernel plasticity therefore increases the shear strength of the corn grains which leads to higher energy consumption. The results similarly disagreed with that reported by Glenn and Johnston (1992), Mabille *et al.* (2001) and Annoussamy *et al.*(2000) which stated that an increase in moisture content causes increase in kernel plasticity therefore increases the shear strength of the corn grain, which leads to higher energy consumption for grinding. The results further disagreed with Ohunakin *et al.* (2013) which reported high average total energy intensities for wet milling than dry milling. These results trend however disagreed with that of Akinoso *et al.* (2013), Altuntas and Yildiz (2007) and Fathollahzadeh and Rajabipour (2008) which reported that forces required to initiate rupture decreased with increase in moisture content on faba bean and barbery fruits respectively. The results of the study also corroborated with that of Wang (2009) which reported a higher energy expanded for dry soybean milling.

5.9 Mill Specific Performance

The best performed mill is expected to have low values of fineness modulus, average particle sizes, losses during milling, flour temperature, and electrical power required during milling and high proportion of fineness of flour particles and milling efficiency. For dry grains milling, mill C and mill E performed creditably, however, mill C ground with more fine flour particles than mill E, as such mill C was the best performed mill for dry grains milling. For moist grains milling, mill C performed best than the rest of the mills because more fine flour particles were obtained from mill C than all the mills. Mill C ground with more uniformity of flour particles than the rest of the mills for both dry grains milling and moist grains milling.

In general, moist grains showed better characteristics in grinding for fineness modulus, uniformity index, average particle sizes, milling efficiency and flour temperature. Dry grains on the other hand showed better results in terms of lower milling losses and electrical power requirement during milling. Mill C performed best in terms of uniformity of ground product, fineness of the ground product and minimum electrical power required during milling hence mill C was the best performed mill among the mills selected for this investigation. The overall performance of the mills showed that moist grains milling performed better than dry grains milling.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

Introduction

This chapter presents the conclusions arrived at, and the recommendations derived from the conclusions made.

6. 1 Conclusions

The results showed that the performance of mills with regards to the uniformity of the milled products was influenced by moisture. Higher moisture content led to more uniformity of the milled products. The study revealed that fineness of flour particles were affected by moisture content. High moisture content led to high proportions of fine flour particle sizes. Generally it was evident that given the same milling conditions, moist grains produced comparatively lower average particle size of flour than dry grains. Therefore the grinding of dry grains to an acceptable fineness as moist grains flour would require extra energy with subsequent increase in cost. The mill which exhibited the best performance amongst the five mills had the highest milling efficiency and the least temperature of the ground product, which are some of the positive characteristics of a grinding mill. However, the performance of any mill could also be attributed to the skills and expertise of the mill operator.

6.2 Recommendations

From the results, findings and conclusions made, it is recommended that milling operators would have to undergo periodic orientation training to study the rudiments of grain grinding for optimum performance of the mills.

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APPENDICES

Trends between current and time for the various mills.

MILL A

t/s	Dry	Moist
5	10	10
10	12	14
15	14	12
20	32	16
25	22	15
30	20	14
35	24	13
40	25	16
45	20	18
50	18	17
55	24	15
60	21	17
65	20	19
70	22	14
75	24	15
80	21	20
85	20	18
90	18	14
95	25	16
100	23	12
105	16	15

MILL B

t/s	Dry	Moist
5	11	11
10	14	16
15	14	15
20	25	14
25	20	18
30	24	22
35	22	19
40	22	18
45	21	15
50	15	19
55	20	17
60	22	18
65	21	18
70	23	19
75	20	22
80	24	20
85	22	17
90	17	15
95	23	16
100	21	19
105	18	22

MILL C

t/s	Dry	Moist
5	10	10
10	11	15
15	13	12
20	23	15
25	22	14
30	22	12
35	21	18
40	20	14
45	20	16
50	18	14
55	22	12
60	21	17
65	20	15
70	21	12
75	16	13
80	22	12
85	20	15
90	19	18
95	22	16
100	22	15
105	15	17

110	17	14
115	16	16
120	23	15
125	21	14
130	20	15
135	18	14
140	19	14
145	22	15
150	20	16
155	15	15
160	14	18
165	21	15
170	25	14
175	21	16
180	17	19
185	20	17
190	18	16
195	16	15
200	22	18
205	20	15
210	20	14
215	24	17
230	19	16
235	20	14
240	18	18
245	21	15

110	16	22
115	20	20
120	20	14
125	23	16
130	21	18
135	15	17
140	22	15
145	23	16
150	21	18
155	18	19
160	14	17
165	24	18
170	22	16
175	22	14
180	18	18
185	24	22
190	19	19
195	18	17
200	24	16
205	21	15
210	23	19
215	21	18
230	18	16
235	22	15
240	16	16
245	22	14

110	17	16
115	22	15
120	21	14
125	22	13
130	22	16
135	19	12
140	23	18
145	21	15
150	22	14
155	19	12
160	16	16
165	22	17
170	20	15
175	21	14
180	19	16
185	21	15
190	15	14
195	19	14
200	22	16
205	20	15
210	22	14
215	20	12
230	16	15
235	21	17
240	13	16
245	21	15

250	20	16
255	21	15
260	20	18
265	18	17
270	18	18
275	17	16
280	22	16
285	20	15
290	16	14
295	14	15
300	10	10

250	21	15
255	23	17
260	22	14
265	19	14
270	16	18
275	16	14
280	20	19
285	22	16
290	19	15
295	11	14
300	11	11

250	20	13
255	20	16
260	21	15
265	16	14
270	15	16
275	14	15
280	22	14
285	20	12
290	16	12
295	14	15
300	10	10

MILL D

T/S	Dry	Moist
5	16	16
10	18	19
15	21	20
20	27	25
25	24	28
30	40	26
35	31	24
40	30	28
45	27	34
50	34	32

MILL E

T/S	Dry	Moist
5	12	12
10	16	16
15	18	18
20	20	19
25	22	15
30	21	20
35	20	16
40	18	19
45	16	16
50	26	18

55	29	30
60	24	25
65	40	31
70	26	30
75	24	27
80	31	24
85	34	34
90	31	26
95	30	24
100	40	22
105	28	26
110	24	29
115	34	33
120	40	30
125	35	28
130	31	24
135	27	29
140	24	31
145	32	30
150	28	29
155	26	32
160	29	34
165	30	31
170	29	25
175	31	26
180	29	28

55	24	15
60	22	18
65	21	17
70	18	16
75	19	20
80	14	18
85	16	19
90	17	17
95	22	16
100	26	18
105	23	19
110	20	17
115	21	16
120	19	18
125	18	15
130	16	17
135	15	18
140	18	19
145	24	17
150	21	18
155	22	16
160	21	18
165	20	16
170	21	19
175	23	15
180	20	17

185	30	26
190	29	25
195	24	27
200	27	24
205	26	21
210	29	26
215	26	23
230	24	29
235	27	34
240	24	31
245	21	25
250	24	22
255	22	27
260	28	34
265	25	29
270	29	25
275	24	24
280	22	23
285	20	21
290	18	24
295	14	20
300	16	16

185	22	16
190	19	19
195	22	18
200	17	15
205	15	14
210	16	17
215	19	16
230	14	19
235	16	14
240	18	18
245	19	14
250	17	19
255	22	15
260	24	17
265	21	18
270	18	19
275	19	16
280	20	15
285	17	19
290	18	17
295	16	16
300	12	12