

**NUMERICAL AND EXPERIMENTAL STUDIES OF THE ENERGY
REQUIREMENTS FOR CUTTING SELECTED TUBER CROP TISSUE AND
VEGETABLES**

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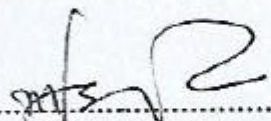
**THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL
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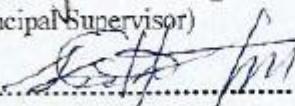
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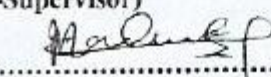
We certify that this research work and write-up on "*Numerical and Experimental Studies of the Energy Requirements for Cutting Selected Tuber Crop Tissue and Vegetables*" was carried out by **ASONYE, GLADYS UCHE (B.ENG, M.ENG)** with registration number, **20114893208** in partial fulfillment for the award of Doctor of Philosophy (Ph.D) in Power and Machinery Engineering in the Department of Agricultural Engineering, Postgraduate School, Federal University of Technology, Owerri, Nigeria.


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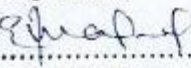
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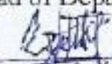
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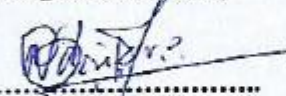
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DEDICATION

To My Hero and lovely angels, Miracle and Unique.

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TABLE OF CONTENTS

Title page	i
Certification	ii
Dedication	iii
Acknowledgments	iv
Table of Contents	v
List of Tables	ix
List of Figures	xi
List of Plates	xiv
Abstract	xv

CHAPTER ONE: INTRODUCTION

1.1 Background Information	1
1.2 Problem Statement	5
1.3 Objectives of the Study	7
1.4 Justification of the Study	7
1.5 Scope of the Study	8
1.6 Expected Contributions to Knowledge	8

CHAPTER TWO: LITERATURE REVIEW

2.1 Nature of Agricultural Products	9
2.2 Agricultural Materials Subjected to Cutting	9
2.3 Indigenous Crops	9
2.3.1 Cocoyam (<i>Colocasia esculenta</i>)	10
2.3.2 Garden egg fruit (<i>Solanum macrocarpon</i>)	11
2.3.3 Okra fruit (Lady Finger) (<i>Abelmoschus esculentus</i> L.)	12
2.3.4 Onion bulb (<i>Allium cepa</i> .)	14
2.4 Physical Properties of Agricultural Materials	16
2.4.1 Physical properties of cocoyam cormels	16
2.4.2 Physical properties of garden egg	17
2.4.3. Physical properties of okra fruit	18
2.4.4. Physical properties of the onion bulb	20
2.5 Cutting Crop Products	21
2.6 Energy for Cutting Agricultural Crops	23

2.7 Development of Cutters for Agricultural Crops	24
2.8 Estimation of Energy for Cutting Agricultural Crops	33
2.9 Modeling the Energy for Cutting Vegetables Using Dimensional Analysis	47
2.10 Optimization of Agricultural Processes using Response Surface Methodology (RSM)	52
2.11 Major Findings from Literature	54

CHAPTER THREE: MATERIALS AND METHODS

3.1 Materials	57
3.1.1 Selected agricultural crops.	57
3.1.2 Materials, instruments and equipment	57
3.1.3 Study area	59
3.2 Methods	
3.2.1 Model development for the cutting energy requirement of the selected crops	59
3.2.1.1 Theoretical development of predictive models for cutting energy of selected crops	60
3.2.1.2 Assumptions made in model development of the selected crops	60
3.2.1.3 Development of the functional energy equation for the selected crops	60
3.2.1.4 Experimental procedure for cutting energy determination for selected crops	69
3.2.1.5 Determination of validation parameters for predictive model of the selected crop samples	70
3.2.1.6 Prediction energy equations for selected crop samples	70
3.2.2 Development of the automated cutter	71
3.2.2.1 Design considerations in cutter development	71
3.2.2.2 Material selection and detailed description	71
3.2.2.3 Basic design calculations	72
3.2.2.3.1 Motor selection	72
3.2.2.3.2 The base plate	73
3.2.2.3.3 U-channel tube	73
3.2.2.3.4 Arduino	74
3.2.2.3.5 Load cell (sensor)	74
3.2.2.3.6 Liquid crystal display (LCD)	75
3.2.3 Detailed drawings of the automated cutter	75
3.2.4 Determination of cutting energy requirement for the selected agricultural crops	81
3.2.4.1 Experimental design	81

3.2.4.2 Fabrication of the cutting edges	83
3.2.4.3 Experimental procedure	83
3.2.5 Optimization of the cutting energy requirement for the selected agricultural crops	85

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 RESULTS	86
4.1.1 Statistical Analysis Obtained for the Model Development of the Cutting Energy Requirement for the studied crops.	86
4.1.1.1 Cocoyam Cormels	86
4.1.1.2 Okra Fruits.	91
4.1.1.3 Onion Bulbs.	97
4.1.1.4 Garden egg fruits	101
4.1.2 Experimental Studies of the Cutting Energy Consumption of the Selected Crops	106
4.1.2.1 Cocoyam Cormels	107
4.1.2.2 Okra Fruits.	108
4.1.2.3 Onion Bulbs.	109
4.1.2.4 Garden egg fruits	110
4.1.3 Development of Predictive Models from Cutting Energy Tests	112
4.1.3.1 Cocoyam Cormels	112
4.1.3.2 Okra Fruits.	113
4.1.3.3 Onion Bulbs.	113
4.1.3.4 Garden egg fruits	113
4.1.4 Optimization of Cutting Energy Consumption and Interactions	114
4.1.4.1 Cocoyam Cormels	114
4.1.4.1.1 Cutting speed and crop size	114
4.1.4.1.2 Knife edge angle and crop size	115
4.1.4.1.3 Knife edge angle and cutting speed	116
4.1.4.2 Okra fruits	117
4.1.4.2.1 Crop size and cutting speed	117
4.1.4.2.2 Knife edge angle and cutting speed	118
4.1.4.2.3 Knife edge angle and crop size	119
4.1.4.3 Onion bulbs	120
4.1.4.3.1 Cutting speed and crop size	120
4.1.4.3.2 Knife edge angle and crop size	121
4.1.4.3.3 Knife edge angle and cutting speed	122
4.1.4.4 Garden egg fruits	123
4.1.4.4.1 Crop size and cutting speed	123
4.1.4.4.2 Knife edge angle and cutting speed	124
4.1.4.4.3 Knife edge angle and crop size	125
4.2 DISCUSSION	126
4.2.1 Discussion on Statistical Analysis Obtained for the Model Development and Validation.	126
4.2.1.1 Cocoyam cormels	126
4.2.1.2 Okra fruits	127
4.2.1.3 Onion bulbs	127

4.2.1.4 Garden egg fruits	128
4.2.2 Discussion on Experimental Studies of Cutting Energy Consumption	129
4.2.2.1 Cocoyam cormels	129
4.2.2.2 Okra fruits	130
4.2.2.3 Onion bulbs	131
4.2.2.4 Garden egg fruits	131
4.2.3 Discussion on Development of Predictive Models for Cutting Energy Tests	132
4.2.3.1 Cocoyam cormels	132
4.2.3.2 Okra fruits	132
4.2.3.3 Onion bulbs	132
4.2.3.4 Garden egg fruits	133
4.2.4 Discussion on Optimization of Cutting Energy Consumption and Interactions	133
4.2.4.1 Cocoyam cormels	133
4.2.4.1.1 Cutting speed and crop size	133
4.2.4.1.2 Knife edge angle and crop size	133
4.2.4.1.3 Knife edge angle and cutting speed	134
4.2.4.2 Okra fruits	134
4.2.4.2.1 Crop size and cutting speed	134
4.2.4.2.2 Knife edge angle and cutting speed	134
4.2.4.2.3 Knife edge angle and crop size	134
4.2.4.3 Onion bulbs	135
4.2.4.3.1 Cutting speed and crop size	135
4.2.4.3.2 Knife edge angle and crop size	135
4.2.4.3.3 Knife edge angle and cutting speed	135
4.2.4.4 Garden egg fruits	135
4.2.4.4.1 Crop size and cutting speed	136
4.2.4.4.2 Knife edge angle and cutting speed	136
4.2.4.4.3 Knife edge angle and crop size	136
4.2.5 Summary of Discussion	136

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion	137
5.2 Recommendations	138
5.3 Contributions to Knowledge	139

REFERENCES	140
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APPENDICES	156
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LIST OF TABLES

TABLE	DESCRIPTION	PAGE
2.1	Central tendencies of some physical properties of cocoyam	17
2.2	Some physical properties of garden egg fruit	18
2.3	Overall average of some physical properties of okra	18
2.4	Some engineering properties of onion bulb	20
2.5	Specifications of the automated lemon cutting machine	27
2.6	Diameter and moisture content values for the different unpeeled vegetables studied	34
2.7	Average specific energy for vegetables using different knife angles and cutting speeds	36
2.8	The relationship between average cutting properties and grape varieties (at moisture content range of 35.2% and 42% wb)	40
2.9	Texture properties of red peppers (cultivar King Arthur) and yellow peppers (Cultivar Bell)	43
2.10	Values registered at the cutting test	46
3.1	List of variables and their dimensions	62
3.2	Dimensional matrix of variables	62
3.3	Values of validation parameters for selected crop samples	70
3.4	Engineering Properties of Stainless steel	72
3.5	Experimental layout of a factorial treatment design	82
4.1	Average values for physical properties of cocoyam cormels at $71.8 \pm 0.16\%$ (w.b)	86
4.2	Average values of hardness and compressive strength results for cocoyam cormels.	87
4.3	Experimental values (E_{measured}) and calculated values of cutting energy for Cocoyam cormels.	87
4.4	Average values for physical properties of okra fruits at $89.41 \pm 0.4\%$ (w.b)	92
4.5	Average values for the hardness and compressive strength test results for okra fruits	92
4.6	Experimental values (E_{measured}) and calculated values of cutting energy for okra fruits	92
4.7	Average values for physical properties of onion bulbs at $86 \pm 0.4\%$ (w.b)	97
4.8	Average values for the hardness and compressive strength test results for onion bulbs	97
4.9	Experimental values (E_{measured}) and calculated values of cutting energy for onion bulbs	98
4.10	Average values for physical properties of garden egg fruits at $88.94 \pm 3.64\%$	

	(w.b)	102
4.11	Average values for hardness and compressive strength test for garden egg fruits.	102
4.12	Experimental values (E_{measured}) and calculated values of cutting energy for garden egg fruits.	103
4.13	Experimental results of the cutting energy requirements for cocoyam cormels	107
4.14	Experimental results of the cutting energy requirements for okra fruits	108
4.15	Experimental results of the cutting energy requirements for onion bulbs	109
4.16	Experimental results of the cutting energy requirements for garden egg fruits	110

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE
2.1	Pictorial view of the pedal operated crop cutter	28
2.2	Isometric view of the multi-crop slicing machine	29
2.3	A perspective view of the Yam Tuber Slicer	30
2.4	Isometric view of the fluted pumpkin leave cutter (with cutting unit open)	31
2.5	Component parts of the potato cutting machine	32
2.6	Isometric view of tomato slicing machine	33
2.7	Whole vegetables and texture of their inner flesh (cross-sectional view)	34
2.8	Knife movement within the Universal Testing Machine (Instron, UK, Model NO 1011, Load cell LVDT, Load Range 500N)	35
2.9a	(Knife angle 15 ⁰ and cutting speed 30mm/min). Force-deformation graph obtained for bitter-gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine.	37
2.9b	Force-deformation graph obtained for pointed gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine (Knife angle 20 ⁰ and cutting speed 30mm/min)	37
2.10	The Lloyd LRX plus materials testing machine	39
2.11a	Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin down	41
2.11b	Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin up	42
2.12	The structure of black radish parenchyma and place of sampling after cutting: a) longitudinally, b) transversely to the fibers	44
2.13	Sample orientation ((longitudinally (sample A) and transversely (sample B) to knife direction	45
2.14	Graph representing relation between cutting energy and diameter in cutting Area	47
2.15	a) The strips with different type of coarseness used for fabrication of the abrasive-cutter brush (from left: very coarse, coarse, mild, fine) b. Different parts of produce's location	51
2.16	Experimental versus predicted values of p. rate (gr/min)	51
3.1	Geographical map of Nigeria showing the study area (Owerri West Local Government Area)	59
3.2	Orthographic views of the cutter	76
3.3	Isometric view of the automated vegetable cutter showing part dimensions	77
3.4	Pictorial view of the cutter	78
3.5	Exploded view of the automated cutter showing parts description	79
3.6	Sectional view of the automated cutter (Vertical section)	80

4.1	Variation of cutting energy against $P = \left(\frac{t_{sw}H_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant	88
4.2	Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{t_{sw}H_d}{A}\right)$ constant	88
4.3	The graph of the relationship between experimental and predicted cutting energy (for subtraction of component energy equations)	90
4.4	The graph of the relationship between experimental and predicted cutting energy. (For summation of component energy equations)	91
4.5	Variation of cutting energy against $P = \left(\frac{t_{sw}H_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant	93
4.6	Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{t_{sw}H_d}{A}\right)$ constant	93
4.7	The graph of the relationship between experimental and predicted cutting energy (for subtraction of component energy equations)	95
4.8	The graph of the relationship between experimental and predicted cutting energy. (for summation of component energy equations)	96
4.9	Variation of cutting energy against $P = \left(\frac{t_{sw}H_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant for onion bulb	97
4.10	Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{t_{sw}H_d}{A}\right)$ constant For onion bulb	98
4.11	The graph of the relationship between experimental and predicted cutting energy (for summation of component energy equations)	101
4.12	Variation of cutting energy against $P = \left(\frac{t_{sw}H_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant	103
4.13	Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{t_{sw}H_d}{A}\right)$ constant	104
4.14	The graph of the relationship between experimental and predicted cutting energy (for summation of component energy equations) for garden egg fruits	106
4.15a	Energy- displacement curve at experimental point (35mm/min, 27 ⁰ , 77.35mm)	111
4.15b	Energy- displacement curve at experimental point (40mm/min, 34 ⁰ , 61.36mm)	111
4.15c	Energy- displacement curve at experimental point (35mm/min, 27 ⁰ , 51.78mm)	112
4.16a	Surface response plot of the interaction effect between speed and size on the peak cutting energy requirement of cocoyam samples	115
4.16b	Response surface plot of the interaction effect between speed and size on the average cutting energy of Cocoyam	115
4.17a	Response surface plot of the interaction effect between angle and size on the peak cutting energy of cocoyam cormels	116
4.17b	Response surface plot of the interaction effect between angle and size on the average cutting energy of cocoyam cormels	116
4.18a	Response surface plot of the interaction effect of angle and speed on the peak cutting energy of Cocoyam	116

4.18b	Response surface plot of the interaction effect of angle and speed on the average cutting energy of cocoyam cormels	117
4.19a	Response surface plot of the interaction effect of speed and size on the peak cutting energy of Onion bulbs	117
4.19b	Response surface plot of the interaction effect of speed and size on the average cutting energy of onion bulbs	118
4.20a	Response surface plot of the effect of angle and size on the peak cutting energy of onion bulbs	118
4.20b	Response surface plot of the effect of angle and size on the average cutting energy of onion bulbs	119
4.21a	3D plot of the effect of knife angle and cutting speed on the peak cutting energy of onion bulbs	119
4.21b	3D plot of the effect of knife edge angle and cutting speed on the average cutting energy of Onion	120
4.22a	Response surface plot of the interaction effect between size and speed on the peak cutting energy for okra fruits	120
4.22b	Response surface plot of the interaction effect between size and speed the average cutting energy for okra fruits	121
4.23a	Response surface plot of the interaction effect between angle and speed on the peak cutting energy for okra fruits	121
4.23b	Response surface plot of the interaction effect between angle and speed on the average cutting energy for okra fruits	122
4.24a	Response surface plot of the interaction between knife angle and crop size on the peak cutting energy of okra fruits	122
4.24b	Response surface plot of the interaction between knife angle and crop size on the average cutting energy of okra fruits	123
4.25a	Response surface plot of the interaction effect between size and speed on Peak cutting energy for garden egg fruits	123
4.25b	Response surface plot of the interaction effect between size and speed on average cutting energy for garden egg fruits	124
4.26a	Response surface plot of the interaction effect between angle and speed on Peak cutting energy for garden egg fruits	124
4.26b	Response surface plot of the interaction effect between angle and speed on average cutting energy for garden egg fruits	125
4.27a	Response surface plot of the interaction effect between size and angle on Peak cutting energy for garden egg fruits	125
4.27b	Response surface plot of the interaction effect between size and angle on average cutting energy for garden egg fruits	126

LIST OF PLATES

PLATE	DESCRIPTION	PAGE
2.1	The cocoyam plant and the corms	10
2.2	The garden egg fruit	12
2.3a	Okra plant with mature and developing fruit	13
2.3b	Raw okra slices	13
2.4a	Roots, leaves and developing bulb of onion	14
2.4b	Onion (unpeeled, peeled and cut forms)	15
2.5	Knives of different shapes and sizes for cutting vegetables	21
2.6	An automated vegetable cutter	25
2.7	Pictorial view of motorized okra slicer	26
2.8	A motorized cutter for tomatoes	26
2.9	An automated lemon cutting machine	27
2.10	An automated banana cutter	31
3.1	Cross-sectional cut views of experimental samples	57
3.2	A bench laboratory oven (Model DHG – 9101) for the moisture content test	58
3.3	Other materials used in the course of the study	58
3.4	Experimental set-up of the cutting mechanism (for cocoyam)	69
3.5	Arduino IDE (Integrated Development Environment)	74
3.6	Load cell	74
3.7	Display screen (LCDs)	75
3.8	Fabricated cutting tools of different edge angles	83
3.9	Samples of cocoyam corms sorted and labeled	84
3.10	Cutting edge just above sample during cutting operation	85

ABSTRACT

Numerical and experimental studies of the cutting energy requirements for selected tuber crop tissue and vegetables was undertaken in this research work. Prediction models using dimensional analysis based on Buckingham pi theorem were developed for the cutting energy requirements for four selected crops which are indigenous to the area of study; tuber crop (cocoyam) (*Colocasia esculenta*), fruit vegetable (okra) (*Abelmoschus esculentus*L.), bulb vegetable (onion) (*Allium cepa*.) and fruit vegetable (garden egg) (*Solanium marcrocarpon*). The developed cutting energy prediction models using dimensional analysis based on Buckingham pi theorem for cocoyam (*Colocasia esculenta*), okra (*Abelmoschus esculentus* L.), onion (*Allium cepa*) and garden egg (*Solanium marcrocarpon*) were validated with experimentations. High coefficient of determination (R^2) values of 0.98, 0.99, 0.98 and 0.98 respectively obtained for cutting energy values between the predicted and the measured values with the developed automated cutter showed that the mathematical models are good. The developed arduino-controlled automated cutter consists of two parts; the hardware and software components. The hardware is composed of an electronic windshield motor, four 25mm² stainless steel pipes of 4cm height for supports, a 35cm x 29cm x 8mm stainless steel plate for the base, a 12cm stainless threaded shaft and 4 pieces of 5cm stainless angle irons. The software consists of Arduino microprocessors (Integrated Development Environment, IDE), load cells (sensors) and a Liquid Crystal Display (LCD). The arduino processor automatically and effectively measures, records and stores cutting variables (speed, force, displacement and time) with minimum human supervision. Connecting the cutter to an electrical power source switches on the electronic windshield motor, which causes a rotational motion of the shaft and a subsequent reciprocating motion of the knife holder. The cutting process which is a non-reversible system involves both compressive and shearing deformations. The operational process involves speed selection, movement of knife edge through product, exertion of reactive force on the load cell and computations. The reactive force exerted on the load cell is measured and automatically relayed to a computer via a Universal Serial Bus (USB) port for storage and further processing. Matrix Laboratory (MATLAB) which is a high performance language for technical computing intercepts the stored values and plots the resulting graph of force of cut against displacement which is used in calculating the energy of cut. Variables involved in the model development using dimensional analysis based on Buckingham pi theorem were; tool weight, distance of cut, tool edge thickness, cutting speed, varying crop sizes, crop moisture content, crop contact area and crop density. Lastly, optimization of the cutting process was carried out by studying the interactive effects of three variables on the energy requirement to cut the select crops. It involved experimentations using the Randomized Complete Block Design (RCBD) layout and observing the effect of the different combinations on cutting energy requirements. These variables are cutting speeds and knife edge angles at 5 levels of 20, 25, 30, 35 and 40mm/min and 20⁰, 27⁰, 34⁰, 41⁰ and 48⁰ respectively with equivalent crop sizes of 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 13.28, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus*L.); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa*.) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium marcrocarpon*). The three variables were observed to have significant effects on the cutting energy requirements for the four crops studied. The optimization of the cutting process was observed to occur at equivalent diameter of 33.68mm, cutting speed of 35mm/min and knife edge angle of 20⁰ for cocoyam; 47.61mm, 35mm/min and 20⁰ for onion bulbs; 23.80mm, 50mm/min and 20⁰ for okra and 45.41mm, 35mm/min and 20⁰ for garden egg fruit. All the optimized results were at the lowest knife edge angle of 20⁰ and the 35mm/min cutting speed except okra which occurred at the cutting speed of 50mm/min. The optimization study helped in the determination of the best combination of the chosen factors that would lead to maximizing energy consumption during the cutting process of the understudied agricultural crops. The results of this study find usefulness in designing, analyzing and optimization of the cutting process for these select crops.

Keywords: Cutting process, energy requirement, modeling, Buckingham pi theorem, tuber crop and vegetables, arduino processor, optimization.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Agricultural products often occur in sizes too large to be used, and therefore they need to be reduced and put into different sizes and shapes like cubes, thin slices or rings to facilitate further processing which include drying, packaging, extraction, expression, reduction in heat treatment periods, transportation and storage. The economic importance of agricultural products such as the crops in this study can never be over-emphasized. These include cocoyam starch as a binding agent in tablet manufacture in the pharmaceutical industries and an income earner for farmers; medicinally, garden egg is an antidote for patients with heart diseases and kidney related problems and also contributes to the Gross Domestic Product (GDP) of the country; okra is a multipurpose crop due to the various uses of the fresh leaves, buds, flowers, pods, stems and seeds; industrially, it is raw material for gum, paper glazing and quality soap making and a high income earner for vegetable farmers in producing countries; onion which is described as the queen of vegetables has high medicinal, nutritional and economic benefits which include been an essential ingredient of the cuisine of many regions and a treatment for stomach cancer (Watanabe, 2002; Chinedu *et al.*, 2011; Agarwal *et al.*, 2003; Kartik and Correll, 2015).

Most agricultural products especially fruits and vegetables are characterized with high moisture content of about 70 to 90% (wet basis) at harvest (Nwakuba *et al.*, 2016) and classified as highly perishable commodities that need to be dried to safe moisture level of about 7–15% (wet basis) to obtain long term storage. Their perishability is because of the activities of the micro-organisms, enzymes or ferments in the material which are suppressed at such low levels of moisture content (Arinze *et al.*, 1990).

However, these post-harvest operations on agricultural materials like drying and packaging cannot be successfully carried out with these products in their large sizes except their sizes are reduced. Size reduction has the following benefits among others, in food processing; increase in surface-area to volume ratio of the food thereby increasing the rate of drying, heating, cooling and extraction of liquid components (for example fruit juice or cooking oil extraction); also, when combined with screening, a predetermined range of particle sizes is produced which is important for the correct processing properties of some products (for example icing sugar, spices and cornstarch). However, this size reduction operation is divided into two major categories depending on whether the material is a solid or liquid. If it is solid, the operations are called grinding and cutting; if it is liquid, it is called emulsification or atomization (Hui, 2006).

Cutting, which is a size reduction operation, has been and continues to be a major activity in food processing, involving the breakdown of large pieces of agricultural products into smaller pieces suitable for further processing; it represents the operation of reducing geometrical dimensions of particles following some exterior mechanical actions. According to Fellows (1996) cutting is applied in the fruit and vegetable processing industry to obtain products with desired shape and size and Hui (2006) stated that cut fruits and vegetables are popular due to easy processing. Cutting of agricultural materials is one of the most frequent operations carried out during agricultural technological processes and is always applied during harvesting, separation and subsequent processing of plant components. Also, in the preparation of fodder, cutting, with significant energy consumption is the main operation. Therefore, there is the need to determine quantitatively the energy involvement in the post-harvest operations involving cutting for overall energy optimization.

During cutting, a cutting edge penetrates into a material, overcoming its strength and resistance, thereby separating it. During this process, various deformations occur within the material, depending on the intrinsic properties of the material, the type of cutting edge and the kinematics of the process. Hence, it is not possible to speak generally of the cutting resistance of agricultural materials due to their individual unique characteristics, but in relation to such factors as the physical characteristics of the material, machine parameters, the cutting edge, the kinematics of cutting and the individual cutting energy requirements. In the present study, the degree to which some of these factors affect the energy requirement in the cutting of selected agricultural crops will be determined numerically and experimentally.

Cutting is a highly laborious and tasking operation especially in the food industry, which is required in the processing of meats, tuber crops, fruits, and vegetables; an example is the wing shoulder cutting operation in a typical poultry processing plant (AIS, 2011); This cut is not only difficult for the human operator and very labour intensive, but it is also one that directly affects the yield of the breast meat; the most profitable margin item on a bird. In this operation, cutting line workers are at high risk of developing musculoskeletal disorders (MSDs) which are often attributed to the forces, postures and repetition of the processing tasks (Dempsey and McGorry, 2004). These may also result from high energy put in by the line workers.

Also, cutting is the major operation in the fresh-cut processing industries which produces fresh-cut products i.e. fruits and vegetables that have been trimmed and cut into fully usable products, which is subsequently packaged to offer consumers high nutrition, convenience and flavour while maintaining freshness (IFPA, 2000; Gorny *et al.*, 1998). The drudgery of peeling, trimming and cutting tuber crops like cocoyam and yam, and then combining these ingredients, often discourages the busy housewife from preparing traditional foods. Similarly, the difficulty of cutting vegetables such as okra, cabbage, onion, garden egg, pumpkin, cucumber and watermelon deter consumers from purchasing these

vegetables in their raw form because of the time and energy consumed in the operation. The time and energy consumed need to be estimated with a view of developing equipment or machines to be used in cutting tuber crops and vegetables with minimum energy input i.e. time saving and energy efficient cutters.

Different cutting techniques have been adopted in the cutting of food products which include; An allumette cut, this is a matchstick-sized cut, 6 mm x 6 mm x 5 to 6 mm long, used for potatoes and other firm vegetables (Gisslen, 2012); Brunoise is a culinary knife cut in which food items are cut into cubes of about 3 mm and is adopted for vegetables like carrots, celery and leeks. Chiffonade is a cutting technique in which herbs or leafy green vegetables (such as pumpkin and amaranthus) are cut into long, thin strips. This is accomplished by stacking leaves, rolling them tightly, and then cutting the leaves perpendicular to the roll (Escoffier, 1969). Crinkle-cutting means cutting so that the result is corrugated (forms regular waves). This can be done with specialized knives and is frequently used for potato chips, also referred to as ruffled cuts.

Specialized knives are available in a wide array to suit special functions. This includes; a tourné knife which has a curved blade to make cutting the curved surfaces of root vegetables such as carrots and potatoes easier. it also ensures smooth processing such as even cooking; Paring knives are short knives, having 2- to 4-inch blade used for paring and trimming vegetables and fruits; French knife which is normally 8 to 14 inches long in size is an all-purpose knife used for chopping, slicing, and mincing a variety of long vegetables and Utility knife, generally 5 to 7 inches long is a smaller, lighter chef's knife used for light cutting chores.

Dicing is a knife cut in which the food item is cut into small blocks or dice. This is done to create uniformly sized pieces. Dicing allows for distribution of flavour and texture and a quicker cooking time. Julienne is a culinary knife cut in which the food item is cut into long thin strips, similar to matchsticks, Sometimes called 'shoe string', e.g. shoestring fries; Mincing is a food preparation technique in which food ingredients are finely cut into uniform pieces. Minced food is in smaller pieces than diced or chopped foods, and is often prepared with a chef's knife or food processor (Food Network, 2003). Mincing creates a closely bonded mixture of ingredients and a soft or pasty texture (Michael and Anthony, 2010). Also, firmer foods such as onions and garlic remain in individual chunks when minced (Hertzmann, 2007).

Roll-cutting is a technique used for vegetables like okra and carrots. It exposes more of the surface area of the vegetable. It is carried out by holding the blade perpendicular to the board and cutting straight down on the diagonal; Macedoine is a cutting technique in which a vegetable is cut into cubes of 4 mm (1/6th inch) thick. An important rule when using this cut is to have a steady flat surface to cut on. This will make it easier to maintain control while cutting the fruit or vegetable. However, for the

purpose of this study, roll-cutting will be utilized because the cutting blade will in a perpendicular direction to the platform on which the sample lies in its natural rest position. This will allow a larger surface area of the understudied samples (cocoyam, onion, okra and garden-egg) to be exposed to the cutting operation; hence better statistical inferences will be obtained.

Sharpness is a very important factor as the key to the proper and efficient use of any knife is making sure that it is sharp. A knife with a sharp blade always works better and more safely because it cuts easily, without requiring the exertion of much pressure, which may cause the knife to slip and cause injury (Szabo *et al.*, 2001). All knife blades are given an edge on a sharpening stone and maintained between sharpenings by honing with steel.

Cutting is a compressive and shearing phenomenon and occurs only when the total stress generated by the cutting implement exceeds the ultimate strength of the material being cut. The simplest applicable equation is expressed in Equation 1.1.

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} \quad (\text{Sykut } et al. 2005) \quad 1.1$$

Where;

Stress = Stress measured in Nm⁻² or Pascals(Pa)

F = Force in Newtons (N)

A = Cross-sectional area in m²

The stress applied to a material is the force per unit area applied to the material. The maximum stress a material can stand before it breaks is called the breaking stress or ultimate tensile stress. The stress generated by a cutting implement is directly proportional to the force which is applied to it and inversely proportional to the area of contact with the material. Hence, the smaller the area of contact between the cutting tool and the material, (i.e. the sharper the cutting implement), the more stress is generated by the cutting tool. Two stages are distinguished in the cutting process which involve preliminary compaction (compression) of the material until a pressure is reached at which the material under the cutting-edge yields; while the second concerns motion of the cutting edge in the material (shearing). The working elements that act on the material is the knife, in which flat knives with straight edge have found the most extensive application (Sykut *et al.*, 2005), or cutting blade, whose operating parameters such as the cutting blade orientation and edge thickness affect the efficiency of the cutting operation (Frączek and Mudryk, 2007).

Ciulică and Rus (2011a) describe the dynamics of the cutting process as that of a knife acting with a force P, during the cutting operation, submerging through a material at a constant speed, referred to as the cutting speed. The operating parameters such as the orientation of the cutting edge in relation to

the sample being cut (whether along or across), the mechanics of the cutting (rotational, horizontal) or the speed of cut all affect the degree and type of force(s) involved in the cutting operation (Tim *et al.*, 2005). This value of force P, which is $P = 0$ at the moment the edge comes into contact with the material, increases to a value of P_{max} , which refers to stabilized cutting condition as given in Equation 1.2 by Ciulică and Rus (2011a).

$$P_{max} = P_d + P_e + P_f \quad 1.2$$

Where;

P_e is force expended on elastic and plastic deformation;

P_f is the force, which overcomes friction;

P_d is the disintegration force expended by the cutting edge on the structure of the material.

Mohsenin (1980) stated that the increasing economic importance of food materials together with the complexity of modern technology for their reproduction, handling, storage, processing, preservation, quality evaluation, distribution, marketing and utilization demand a better knowledge of the significant physical properties of these materials so that the machines, processes and handling operations can be designed for maximum efficiency and the highest quality of the end product. Furthermore, the maintenance of quality under adverse conditions of handling, storage and distribution, savings in weight and bulk, reduced cost in handling and processing operations and finding new ways of utilization may result from an understanding of the basic physical properties of economic plant and animal materials. Also important are the conditions of cultivation, the duration and method of storage of the material, degree of ripeness and cultivar-related traits (Nadulski, 2001; Szot *et al.*, 1987).

1.2 Problem Statement

Cutting, which is a size reduction activity, is equally an energy consuming operation (Grzemski, 2013; Yan and Li, 2013 and Leong *et al.*, 2014). As energy continues to be scarce and expensive, there is therefore need for energy saving approaches in the operation of cutting as a size reduction technique. In addition, cutting has been carried out using different methods without considerations to the varying factors both on the part of the cutting tool such as blade sharpness, slicing angle, blade edge geometry, contact length, depth of cut, cutting speed and blade shape; product characteristics which include crop variety, maturity stage, moisture content, average diameter, average length, average width, weight of cop, volume, specific gravity and density of crop and how these variables affect cutting energy consumption; this has led to increased energy usage and high cost of cut products.

Cutting processes in most postharvest operations is a most laborious, time wasting and energy consuming task which deserves research attention. Cutting related studies are necessary in order to discover methods of efficiently improving the cutting process by maximizing the scarce energy, time and resources available and optimally enhancing the post-harvest operations concerned. Hence the

need to undertake the present study which will establish mathematical models using dimensional analysis based on the Buckingham's pi theorem to predict the cutting energy requirements for four selected indigenous crops; cocoyam (*Colocasia esculenta*), okra (*Abelmoschus esculentus*), garden egg fruit (*Solanum macrocarpon*) and onion (*Allium cepa*). The mathematical model will become a design tool for machine designers in the development of energy saving and cost effective cutting systems that will provide good quality cut products.

Although a few research attempts have been made to model cutting processes like mathematical models and laboratory tests of impact cutting behaviour of forage crops, (McRandal and McNulty, 1978); performance modeling of the cutting process in sorghum harvesting, (Mohammed, 2002); mathematical modeling of laser based potato cutting and modeling yield efficiency of peeling, (Ferraz *et al.*, 2007, Somsen *et al.*, 2004); the development of screw-conveyor performance models using dimensional analysis, (Degrimencioglu and Srivastava, 1996); a mathematical model for predicting the cutting energy of cocoyam (*Colocasia esculenta*), (Asonye *et al.*, 2019); a mathematical model for predicting output capacity of selected stationary grain threshers (Ndirika, 2006); a mathematical model for predicting the cracking efficiency of vertical-shaft centrifugal palm nut cracker, (Ndukwu and Asoegwu, 2011); modeling flow rate of egusi-melon (*Colocynthis citrullus*) through circular horizontal hopper orifice, (Asoegwu *et al.*, 2010); numerical and experimental studies on the cutting energy requirements of okra (*Abelmoschus esculentus l.*), (Asonye *et al.*, 2018b); much is left undone on modeling the energy requirement for cutting agricultural crops such as cocoyam, onion, okra and garden egg.

Extensive documentation on the properties of foods and food products exist, however data related to the cutting energy of different vegetables is scarce, even though such data is important in the design of cutters. This observation is affirmed by researchers like Saravacos and Kostaropoulos (2002) in their assessment that less work has been performed on energy involved for cutting of different food materials, and Brown *et al.* (2005) who opined that limited published literatures on specific energy requirement in cutting of fruits and vegetables are available. Also, Mitcham *et al.* (1996) agreed that literature related to cutting of fruits and vegetables are limited. Consequently, there is need to increase research work in the area of energy involvement in the cutting process of agricultural crops.

Cutting processes can be found in almost every aspect of the Agricultural industry. An understanding of the process of cutting is necessary for the optimal design and performance of mechanical cutters, hence, development of an energy model as one type of mathematical models for a cutter will not only enable Agricultural engineers to identify appropriate design parameters for cutting equipment, but also the optimization of these parameters to ensure energy saving. The mathematical model will introduce effective operational parameters related to the cutting tool and product characteristics which are

industrially applicable and influential on energy requirement. Also, the model can be developed and applied in a wide range of mechanical cutters of fruits and vegetables as the models formed will help designers to avoid the trial and errors involved in the development of agricultural products handling machines with efficient use of time and energy resources.

Results from this study which considers the cutting energy requirements of selected agricultural crops with different physical characteristics such as size and moisture content could be utilized for the design of cutting systems or devices, with optimum energy requirements. Furthermore, varying knife edge angles, cutting speed and crop size within this study of cutting energy requirements for selected agricultural crops with distinct characteristics will facilitate the selection of appropriate existing cutting devices and will equally serve as a guide in the development of energy saving cutters.

1.3 Objectives of the Study

The main objective of this study is to carry out numerical and experimental studies of the energy requirements for cutting selected tuber crop and vegetables; tuber crop tissue (cocoyam), fruit vegetables (okra and garden egg fruit) and bulb vegetable (onion).

The specific objectives are to:

- i. Determine the machine parameters and crop characteristics that interplay during the cutting of the selected crops: tuber crop (cocoyam), fruit vegetables (okra and garden egg fruit) and bulb vegetable (onion).
- ii. Develop mathematical models predicting the energy requirement for cutting each of the selected crops using dimensional analysis based on the Buckingham pi theorem.
- iii. Develop an automated cutter for the experimental studies.
- iv. Generate experimental data on the cutting energy consumption of the selected crops.
- v. Validate the mathematical models developed with experimental data.
- vi. Optimize the cutting process for the selected crops using Response Surface Methodology (RSM).

1.4 Justification of the Study

The study makes available relevant technical information on characteristics of the chosen crops such as crop variety, moisture content, density, weight, crop size etc. and knife parameters such as cutting speed, knife edge angle and distance of cut which are necessary for optimal design and operation of cutters for these Nigerian crops (thereby reducing the unnecessary waste of scarce resources such as time and energy expended in the development of agricultural machinery). Furthermore, the ability to use the data generated from the electronically controlled cutter to model the cutting process and predict

optimal conditions for an energy maximizing cutting operation for each of the selected crop samples also justify the study.

1.5 Scope of the Study

This study focuses on the effect of engineering characteristics of selected indigenous crops: such as moisture content (on wet basis) of $71.8 \pm 0.16\%$ for cocoyam, $89.41 \pm 0.4\%$ for okra, $86.0 \pm 0.4\%$ for onion, $88.94 \pm 3.64\%$ for garden egg; crop size (equivalent diameters of 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 13.28, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus* L.); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa.*) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium marcrocarpon*) and the cutting tool parameters such as cutting speed,(20, 25, 30, 35 and 40mm/min) and knife edge angle (20^0 , 27^0 , 34^0 , 41^0 and 48^0) on the cutting operation of these crops in terms of energy consumption. Selected crop characteristics and tool parameters will be used to develop the mathematical models using Dimensional analysis based on the Buckingham pie theorem, and experimental results from a developed cutter equipped with Arduino – controlled microprocessor will be used to validate the developed model. Finally, Response Surface Method (RSM) will be used to optimize the cutting energy requirements for the selected tuber crop and vegetables by studying the interaction effects among three independent variables (cutting speed, knife edge angle and crop size).

1.6 Expected Contributions to Knowledge

This research work aims at filling up research gap by contributing the following to knowledge.

- Development of prediction models for the cutting energy requirement for selected tuber and vegetable crops
- Design and construction of an automated cutter which measures and records cutting parameters such as cutting speed, distance of cut, force and energy of cut with minimum human supervision through the use of Integrated Development Environment (IDE) and micro-processor known as Arduino.
- Optimization of the cutting process of the studied tuber and vegetable crops.

CHAPTER TWO

LITERATURE REVIEW

2.1 Nature of Agricultural Products

Every existing object has certain qualities or characters that make it different from others. Similarly, each product has peculiar behavioural pattern when subjected to a particular condition. These qualities, attributes, characters and patterns of behavior single these products out from others. Crops, like other agricultural products are biological materials with distinct characteristics that distinguish them from non-biological materials. They are most often described as irregular in shape and variable in size as in seeds, fruits and vegetables. According to Wilhelm *et al.* (2004), seeds, fruits and vegetables are characterized by non-normal frequency distribution, heterogeneous composition, diverse varieties, constant bio-chemical change, moisture variation, respiration and enzymatic activities; neglecting these levels of variability in the design of crop handling and processing equipment results in serious frustration (Mohsenin, 1980). Their engineering properties (physical characteristics, mechanical, thermal, optical, sonic, magnetic and electrical properties) describe the unique and characteristic way food and agricultural products respond to various kinds of treatments such as in cutting.

2.2 Agricultural Materials Subjected to Cutting

Agricultural materials commonly subjected to cutting could be classified as:

- (i) Non-fibrous, liquid cell materials having uniform properties in all direction at the time of cutting, e.g. cucumber, garden egg, okra and carrot.
- (ii) Fibrous materials with high tensile strength fibers oriented in a common direction with comparatively low strength of materials holding the fibers together, e.g. oranges, onions, cocoyam and sweet potatoes (Sitkei, 1986).

2.3 Indigenous Crops

Indigenous crops can be seen as crops from the natural environment which became included into the cultural food use patterns of a group of people. Indigenous foods can be categorized as plant foods, animal foods or earth elements such as salts. In the context of this study, the term 'indigenous crops' are crops that are native to the West African nation of Nigeria. Some of the indigenous crops include cassava, cocoyam, sweet potatoes, garden egg fruit, African yam bean, amaranthus leaves, fluted pumpkin, baobab, oil palm, onion and okra (Anyanwu *et al.*, 1986).

However, for the purpose of this study, four of these indigenous crops will be considered; cocoyam (*Colocasia esculenta*), okra (*Abelmoschus esculentus*), garden egg fruit (*Solanium macrocarpon*) and onion (*Allium cepa*). These crops were selected because they are indigenous to the country Nigeria,

especially the southeastern part of the country where the study is been undertaken. In addition, the selected crops fall among those that has received least research attention and is yet well utilized. However, they suffer a lot of post-harvest losses due to inadequate technology in their handling and processing operations (Nguyen and Nguyen, 1987; Goenaga and Heperly, 1990).

2.3.1 Cocoyam (*Colocasia esculenta*)

Local Names: Ede (Igbo); Coco (Yoruba); Gwaza (Hausa)

Cocoyam (*Colocasia esculenta*) is the tuber crop of interest in this study shown in Plate 2.1.

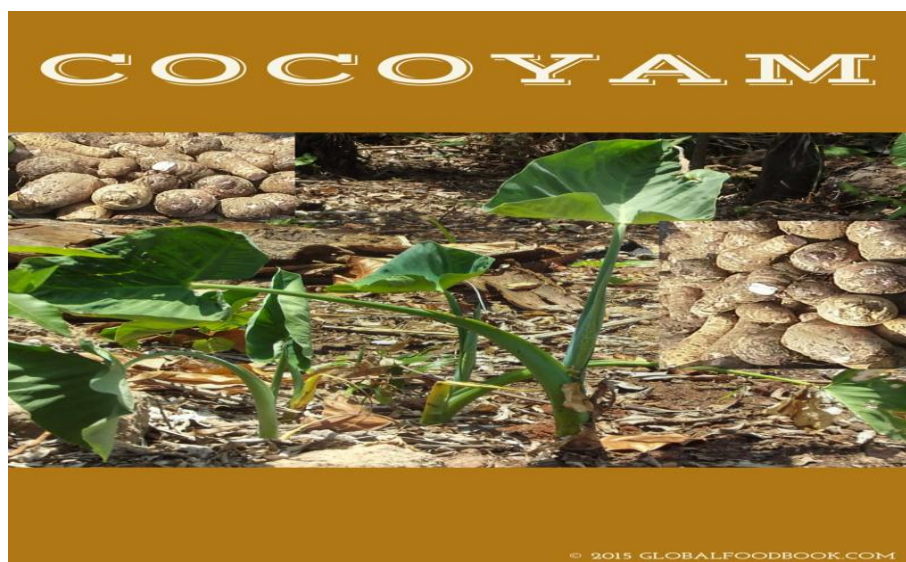


Plate 2.1: The cocoyam plant and the corms.

Source: Balami *et al.* (2014)

Cocoyam is a member of *Araceae* family and in the group of monocotyledons, constituting one of the six most important root and tuber crops worldwide (Edet and Nsukka, 2000). Cocoyam is an aroid because it is grown mainly for its edible cormels and some of the varieties include; tannia (*Xanthosoma sagittifolium*), taro (*Colocasia esculenta*) eddo (*Colocasia antiquorum*), tarul, arum, *Alocasia macrorrhizos* and *alocasia odora* (Ekanem and Osuji, 2006). Although, many consider them as less important than other tropical root crops such as yam, cassava and sweet potato, they are still a major staple in some parts of the tropics and sub-tropics (Opara, 2002). The highest proportion of cocoyam production is recorded in Africa with the minority from Asia and the least proportion from the Caribbean.

Nigeria been the world's largest producer of cocoyam, accounts for about 37% of total world output (FAO, 2006) with the annual production of cocoyam in Nigeria estimated at 26.587 million Mg. Cocoyam has been found to have nutritional, medicinal and industrial benefits. It is rich in digestive starch, good quality protein, vitamin C, thiamine, riboflavin, niacin and high scores of protein and essential amino acids (Onayemi and Nwigwe, 1987; Lewu *et al.*, 2009). Iwuoha and Kalu (2000) stated

that cocoyam can be processed into cocoyam flour, chips and poi, a processed form of cocoyam which is popular in Hawaiian. Also because of the highly digestible nature of the flour, it is suitable for making confectionaries and baby food. Subhadhirasakul *et al.*, (2001) reported that cocoyam starch can effectively replace maize as a binding agent in tablet manufacture while Lawal (2004) has confirmed that cocoyam starches could be modified to substitute other industrial starches.

Ekwe *et al.* (2009) reported that cocoyam has minimal starch grains that are easily digestible and as such makes it an ideal source of carbohydrate for diabetic patients which is affirmed by Eleazu *et al.*, (2013) in their work on the ameliorative potentials of cocoyam (*Colocasia esculenta L.*) and unripe plantain (*Musa paradisiacal L.*) on diabetic patients. Emmanuel-Ikpeme *et al.* (2007) also reports that the starch grains of cocoyam are quite small, which suggests why they aid easy food digestion. The easy digestibility factors of the crop make it suitable for patients recovering from sicknesses, for those suffering from pancreatic disease, peptic ulcer, gallbladder disease, chronic liver problems and those suffering from inflammatory bowel disease.

In Nigeria, cocoyam is consumed in different ways through roasting, cooking, frying, baking, pounding and milling while in the Eastern part of Nigeria. It serves as staple food and is used as a thickener in soup preparations especially the varieties *Colocasia esculenta* and *Xanthosoma cultivar*. However, in spite of its many industrial, medicinal and nutritional benefits, studies reveal that it is an under-exploited and insufficiently studied crop which portends a danger of gradual disappearance from our meal time table and eventual extinction unless urgent attention is given to it. Also, it suffers a lot of postharvest losses due to inadequate post-harvest handling technologies which makes the crop scarce and expensive when it is not in season. (Nguyen and Nguyen, 1987; Goenaga and Heperly, 1990; Giacometti and León, 1994 and Watanabe, 2002). Hence, in postharvest processes such as drying, frying, grinding, pelleting, packaging, transportation and storage of cocoyam cormels, size reduction by cutting is a necessary operation that increases the surface area of the processed cormel for the processing operations envisaged.

2.3.2 Garden egg fruit (*Solanium macrocarpon*)

Garden egg (*Solanium macrocarpon*), a fruit vegetable shown in Plate 2.2, is the second crop of interest in this study.

Local Names: Aghara (Igbo); Igba (Yoruba); Ganyen gauta (Hausa)



Plate 2.2: The garden egg fruit.

Source: Anosike *et al.* (2012)

The garden egg (*Solanum macrocarpon*) is a popular traditional vegetable originating from tropical Africa (Norman, 1992). It is grown for its leaves and fruits (Anosike *et al.*, 2012), which can be consumed fresh. Garden egg (*Solanum spp*) is a vegetable that is beginning to gain increasing interest in the world (Pessarakli and Dris, 2003). It is an economic flowering plant belonging to the family *Solanaceae*, whose members are mostly herbaceous plants. Eggplants vary from purple, yellow, green, red, to milky white in color. In shape, they come as oval, round or elongated like banana, or as small as an egg. Despite all these variations in shape and color, they still possess a common characteristic, that is, the milky whitish color of their flesh and seeds. Its benefits include nutritional benefits; high in potassium, a necessary salt that helps in maintaining the function of the heart and regulate blood pressure (Chinedu *et al.*, 2011).

Medicinally, a meal of garden egg is proven to be of benefits to patients suffering from heart diseases and *arteriosclerosis* (Chiamaka, 2018; The Nigerian Guardian, 2009); The juice obtained by the maceration of the leaves is applied in the treatment of uterine complaints in various parts of Africa and the leaf extracts serves as a sedative and is applied in the treatment of tetanus associated with miscarriages; Also, cutting garden egg into pieces and boiling the cut pieces to extract the chlorophyll content helps in the prevention of kidney related problems Ikrang and Okoko (2014). Economically, the crop represents the main source of income for producing households in the forest zones of West Africa (Danquah-Jones, 2000). The cut pieces of the garden egg fruit are used in the preparation of the popular African salad and other savoury dishes common to the southeastern part of Nigeria. Cutting the fruit of garden egg also help in reducing the bulk weight and enhances further processing like drying, packaging, transportation and storage.

2.3.3 Okra (Lady Finger) (*Abelmoschus esculentus* L.)

Local Names: ‘ókùrù’ (Igbo); Ila (Yoruba); Bubewa (Hausa)

The third crop of interest in this study is okra (*Abelmoschus esculentus* L.), a fruit vegetable. Plate 2.3a shows the okra plant with mature and developing fruit and Plate 2.3b shows cut pieces of the okra fruit.



Plate 2.3a: Okra plant with mature and developing fruit

Source: National Research Council (2006).



Plate 2.3b: Raw okra slices

Source: National Research Council (2006).

Okra or lady's finger, deriving its name from the 'Igbo' word 'ókùrù' (McWhorter, 2000) is a widely cultivated vegetable crop in most parts of the world and one of the most popular vegetables in many West African markets and some other regions of the world (Oyelade *et al.*, 2003; Andras *et al.*, 2005; Saifullah and Rabbani, 2009). About 10% of the world's annual okra production comes from West Africa with Nigeria as the leading producer (Burkil, 1997). In South-Western Nigeria, the three known cultivars of okra are *yaaya* or *kògbóyè*, which has long slender pods; *kúdìkán* or *ilá-òjò*, which has short, sturdy pods and *ilá-ìròkò* which has long sturdy pods (Farinde *et al.*, 2007).

Okra is a multipurpose crop due to the various uses of the fresh leaves, buds, flowers, pods, stems and seeds. The benefits derivable from the okra fruit include nutritional benefits; a good source of minerals, vitamins, carbohydrate, protein and essential amino acids; (Adeboye and Oputa, 1996; Adom *et al.*, 1996; Okra Food, 2003; Sobukola, 2009), medicinal benefits; detoxifies and aids digestion in human nutrition (Makose and Peter, 1990; Owolarafe and Shotonde, 2004) industrial benefits; valuable material for gum, paper glazing and quality soap making, contains glycans used in aqueous suspensions, an excellent source of iodine and raw material for flocculant used for removal of solid wastes from tannery effluent (Owoeye *et al.*, 1990; Agarwal *et al.*, 2003; Falade and Omojola, 2010) and economically it is a high income earner for vegetable farmers in producing countries (Schippers, 2000).

Okra, like many other vegetables is highly perishable due to its relatively high moisture content, soft texture and high respiration rate (Atanda *et al.*, 2011) and the traditional method of preserving fresh okra pods which involves spreading it in the air for few hours during cold weather only makes it preserve for just 3-4 days (Schippers, 2000 and Sobukola, 2009) after which, it becomes tough and unsuitable for use as a fresh vegetable. The unsold lots are processed by manually cutting into slices and sun-drying to preserve it, thereby extending its availability from one season to the other, improving the shelf life and also forestalling seasonal wastage. This manual cutting operation is a most laborious, time consuming one with the challenges of contaminations of the product and injury to the hand. There have been efforts made by some researchers at developing equipment for handling the cutting operation (Owolarafe *et al.*, 2007, Ogbobe *et al.*, 2007).

However, in spite of its many industrial, medicinal, economic and nutritional benefits, studies reveal that it is among the least studied vegetables (Giacometti and León, 1994; Watanabe, 2002), which portends a danger of gradual disappearance from our meal menu and eventual extinction unless urgent attention is given to it. Also, it suffers a lot of postharvest losses due to inadequate post-harvest handling technologies which makes the crop scarce and expensive when it is not in season. Hence cutting of okra as a postharvest handling operation will enhance further processing such as drying, packaging and preparation into several food forms.

2.3.4 Onion bulb (*Allium cepa.*)

Local Names: Ayabasi (Igbo); Alubosa (Yoruba); Albasa (Hausa)

The fourth crop of interest in this study is the onion bulb (*Allium cepa.*), a bulb vegetable shown in Plate 2.4a and Plate 2.4b.



Plate 2.4a: Roots, leaves and developing bulb of onion

Source: FAOSTAT (2006).



Plate 2.4b: Onion (unpeeled, peeled and cut forms)

Source: FAOSTAT (2006).

The onion (*Allium cepa* L.) also known as the bulb onion or common onion, is a vegetable that is the most widely cultivated species of the genus *Allium*. Its close relatives include the garlic, shallot, leek and chive (Block, 2010). It typically grows to a height of 15 to 45 cm (6 to 18 in). The leaves are yellowish- to bluish green and grow alternately in a flattened, fan-shaped swathe. They are fleshy, hollow, and cylindrical, with one flattened side. They are at their broadest about a quarter of the way up, beyond which they taper towards a blunt tip. The base of each leaf is a flattened, usually white sheath that grows out of a basal disc. From the underside of the disc, a bundle of fibrous roots extends for a short way into the soil. As the onion matures, food reserves begin to accumulate in the leaf bases and the bulb of the onion swells. It is called the ‘queen of vegetables’ according to some persons because of the strong taste, pungent flavor and is an essential ingredient of the cuisine of many regions (Anonymous, 1993; Brickell, 1992).

World production of onion is estimated at over 61.6 million metric tons of bulb, and yield per hectare averaged 18.45 tons with Nigeria’s average yield put at 14.8 tons (FAOSTAT, 2006). Based on the level of consumption and popularity as a spice in diets, onion ranks 5th most important vegetable in Nigeria (Denton and Ejeifo, 1990). Onion is a highly perishable vegetable with its post-harvest losses estimated to be up to 40%, of which storage losses account for up to 18-25% (Gherghi, 1989). It is of high nutritional composition (Narasinga *et al.*, 1993). Also, it has potentials for the treatment of cardiovascular disease, hyperglycemia, and stomach cancer (Kartik and Correll, 2015).

However, cutting of onion is a nuisance to many consumers due to the lachrymatory properties of the volatiles generated that bring tears to eyes and leave a distinct odor on hands. As a result, there is now an increasing demand for fresh-cut, value-added, and ready-to-eat onion in households, large scale retail shops and various food industries (Lokke *et al.*, 2012; Siddiq *et al.*, 2013; Berno *et al.*, 2014). Also cutting onion bulbs will enhance its further processing as it will aid such operations as drying (increased surface area), packaging, transportation and storage.

2.4 Physical Properties of Agricultural Materials

A study of the physical properties of agricultural materials is essential for the design of processing machines, storage structures, and environmental parameter controls; Such data are useful in the analysis and determination of the efficiency of a machine or an operation; development of new products and new equipment and final quality of new products (Mohsenin, 1986). The size of agricultural materials such as grains, pulses and oil seeds have been described by measuring their principal axial dimensions (Kukello *et al.*, 1987; Oje *et al.*, 2001; Koya and Adekoya, 1994). Geometrical mean of the axial dimensions have also been shown to be adequate for calculating Reynold's number, projected areas and drag coefficient of food grain (Perez – Alegria *et al.*, 2001). Density and specific gravity of agricultural materials also play important roles in many applications such as drying and storage of hay products, design of silos and storage bins (Mohsenin, 1970; Bern and Charity, 1975). The following sections take a brief look at some of the physical characteristics of the understudied crops relevant to the cutting process and the cutting energy requirements.

2.4.1 Physical properties of cocoyam

Cocoyams (*Colocasia esculenta*) are brown in colour when they are not peeled (pericarp is present) and white in colour when they are peeled i.e., when the pericarp is removed (Balami *et al.*, 2014). Furthermore, some species of cocoyam can be classified in terms of shape as conical using the charted standards, since they are tapered towards the apex end, while some species are spherical in shape (Balami *et al.*, 2014). Central tendencies of some physical properties of cocoyam are given in Table 2.1.

Table 2.1: Central tendencies of some physical properties of cocoyam

S/N	Calculated Parameters	Unit	Maximum Value	Minimum Value	Mean	Standard Deviation	Coefficient of Variation (%)
1	Arithmetic Mean Diameter	mm	68.83	37.00	51.38	8.73	16.4
2	Geometric Mean Diameter	mm	62.91	34.82	49.09	8.01	16.13
3	Square Mean Diameter	mm	65.30	35.86	50.07	8.30	16.4
4	Equivalent Diameter	mm	65.48	35.75	50.18	8.34	16.4
5	Sphericity		0.56	0.62	0.66	0.57	0.86
6	Aspect Ratio		0.41	0.46	0.55	0.43	0.77
7	Particle Density	g/cm^3	1.08	1.05	1.35	1.06	1.02
8	Weight	N	1.03	0.26	0.69	0.24	0.34
9	Surface Area	mm^2	12433.38	3808.96	7570.70	201.56	834.69

Source: Balami *et al.* (2014)

Asonye *et al.* (2019) in the study titled a mathematical model for predicting the cutting energy of cocoyam (*Colocasia esculenta*) determined the effect of some physical properties such as mass, equivalent diameter, circumference and area on the cutting energy requirement of cocoyam cormels. Results obtained showed significant effect of these properties on the energy requirements to cut cocoyam cormels. The highest cutting energy of 192.21J was observed for the largest range of crop sizes tested and the lowest cutting energy of 75.22J was reported for the least range of crop sizes tested (over 60% reduction in the cutting energy values from highest size range to lowest size range). Furthermore, while C₁ (largest size range) is 63.4% bigger in size than C₄ (least size range), the cutting energy components measured for C₁ were found to be 60.9%, 63.3% and 86.6% higher than for C₄ which goes to authenticate the significant effect of crop size on the cutting energy requirement of cocoyam cormels.

2.4.2 Physical properties of garden egg

Ikrang and Okoko (2014) studied some engineering properties of the garden egg fruit (*Solanum aethiopicum*) necessary for post-harvest handling operations such as cutting. Experiments were carried out to determine shape, volume, and surface area. The results of the experiments revealed that average value of volume and surface area of the studied garden egg fruits were 17.97cm³ and 26.58cm²

respectively. The observed and the predicted values of volume for garden egg fruit were significant at both 95 and 99% confidence interval. Table 2.2 gives the dimensions of some of the physical properties of the garden egg fruit needed for postharvest handling operations such as cutting. The shape was also determined to be prolate spheroid for garden egg.

Table 2.2: Some physical properties of garden egg fruit.

Physical properties of garden egg	Dimensions
Shape	Prolate spheroid
Colour	Purple, yellow, green, red, white.
Varieties	<i>Solanum melongena</i> , Indian eggplant, white garden egg.
Volume	7.97cm ³
Surface area	26.58cm ²
Geometric mean diameter	Ranged between 1.50 and 2.80cm.
Mass (g)	8.77g
Density(g/cm ³)	1.11g/cm ³
Roundness	0.18
Sphericity	0.76

Ikrang and Okoko (2014)

2.4.3. Physical Properties of Okra Fruit

The average values of some physical properties of the okra fruit are given in Table 2.3

Table 2.3: Overall average of some physical properties of okra

S/N	Physical properties	Mean	Std. dev.	Minimum	Maximum
1	Length (mm)	107.97	17.65	78	136
2	Diameter (mm)	35.17	7.97	24.5	54
3	Mass (g)	13.27	4.07	3.13	25.43
4	True density (g/cm ³)	0.26	0.12	0.08	0.27
5	Bulk density (g/cm ³)	0.14	0.02	0.10	0.19
6	Porosity (%)	58.06	27.66	17.16	91.97

Source: Sahoo and Srivastava (2002)

Sahoo and Srivastava (2002) studied the physical properties of okra seed as a function of moisture content. The average length, breadth and thickness of the seed varied from 5.92 to 7.30, 4.71 to 5.40 and 4.59 to 5.36 mm respectively, as the moisture content increased from 8.16 to 87.57% d.b. The

roundness and sphericity increased from 77.76 to 79.35% and 74.48 to 76.52%, respectively, with increase in moisture content from 8.16 to 19.56% d.b. In the moisture range of 8.16–87.57%, the seed volume increased from 0.067 to 0.124 cm³, 1000 seed weight, W₁₀₀₀ from 65.78 to 129.75 g and the angle of repose from 27.60 to 39.47°. The bulk density, true density and porosity decreased from 0.592 to 0.558 g cm⁻³, 1.107 to 0.986 g cm⁻³ and 46.34 to 43.20%, respectively, in the moisture range from 8.16 to 87.57% d.b. The static coefficient of friction increased on four structural surfaces namely, aluminium (0.390–0.484), bakelite (0.345–0.480), galvanised iron (0.368–0.493) and mild steel (0.389–0.480) as the moisture content increased from 8.16 to 87.57% d.b. The properties studied were significantly affected by moisture content, and by implication will also affect cutting processes of okra fruits and other agricultural crops with their cutting energy requirements (Onwulata *et al.*, 2013; Correa *et al.*, 2010; Gamble and Rice, 1988).

Ikrang and Okoko (2014) studied some physical properties of the okra fruit that are relevant to post harvest processing such as cutting. Factors studied include; major, intermediate and minor diameters; mass, surface area, volume and density. Results obtained from their study showed that okra fruit had a geometric mean diameter ranging from 1.66cm to 2.80cm with a mean value of 2.15cm. The mass, surface area and volume had mean values of 13.93g, 52.69 cm² and 13.28cm³ respectively. The average values for density, roundness and sphericity were 1.04g/cm³, 0.3 and 0.31 respectively. They further concluded that knowledge of these properties will enhance the appropriate handling and further processing of the okra fruit.

Asonye *et al.* (2018b) in their work on the numerical and experimental studies of the cutting energy requirements of okra (*Abelmoschus esculentus l.*) reported the effect of crop size on the cutting energy requirement for the okra fruit. Results of the study showed significant effect of changes in crop size on the energy requirements to cut okra fruits. The highest cutting energy of 23.63J was observed for the largest range of crop sizes tested and the lowest cutting energy of 3.45J was reported for the least range of crop sizes tested (over 85% reduction in the cutting energy values from highest size range to lowest size range). Furthermore, while C₁ (largest size range) is 50.04% bigger in size than C₄ (least size range), the cutting energy components measured for C₁ were found to be 83.17%, 50.02% and 75.04% higher than for C₄ which goes to authenticate the significant effect of crop size on the cutting energy requirement of okra fruits.

2.4.4. Physical properties of the onion bulb

The ranges of values for some engineering properties of onion bulb are presented in Table 2.4

Table 2.4: Some engineering properties of onion bulb

Engineering properties of onion bulb	Range of values
Varieties	Red, yellow, white onion; Ramp, Shallot.
Colour	Red, Yellow, White, Green.
Shape	Spherical
Unit mass (g)	10.28 ± 2.74 to 66.16 ± 18.33
Bulb polar diameter(mm)	29.07 ± 3.31 to 47.23 ± 5.34
Equatorial diameter(mm)	28.88 ± 3.15 to 54.54 ± 5.30
Geometric mean diameter(mm)	28.38 ± 2.62 to 51.18 ± 4.22
Transverse diameter(mm)	27.43 to 52.35
Shape index	1.03 to 1.10
True density	906.2 to 1014.8kg/m ³
Bulk density	589.63 to 621.30 kg/m ³
Co-efficient of static friction	
Plywood	0.27 to 0.31
Galvanized iron sheet	0.31 to 0.32
Mild steel sheet	0.30 to 0.33
Plastic surface	0.20 to 0.24
Compressive strength (gram-force)	2702.81 to 4262.75

Karthik and Correll (2015)

From careful observation of the range of values obtained for the studied physical properties as given in Table 2.4, such as the compressive strength value which ranged from 2702.81 to 4262.75 gram-force, this variation will significantly affect the cutting energy requirement as onion bulbs with larger compressive strength will demand higher energy for their cutting and vice-versa.

2.5 Cutting Crop Products

The art of cutting crop products, for example vegetables' cutting is known to be as old as man in its development. In the primitive ages, cutting of vegetables have been carried out with stones or any sufficiently sharp object as long as it has the hardness sufficiently higher than the object being cut and applied with sufficient force. In modern times, cutting is been done using tools such as knives as shown in Plate 2.5 which however, has its associated difficulties like time constraints, injuries to the hand and contaminations. The 20th century saw a tremendous revolution in the development of many different models of vegetable cutters ranging from the simplest types which consist of a metal screen with blades and two handles that can be operated manually to the commercial vegetable cutters which are automatically operated and designed for a productivity of 200 to 3,500 kg per hr. The principal parts of a vegetable cutter are the loading hopper (feeder), the shaft with attached blades, and the drive (Tony *et al.*, 2014).



Plate 2.5: Knives of different shapes and sizes for cutting vegetables

Source: Allen and Smith (2013)

The life of a cutting tool is affected by factors like cutting speed, feed, depth of cut, heat treatment of the tool, work material, tool material, tool extension length and nature of cutting. The tool material which can withstand maximum cutting temperature without losing its principal mechanical properties

especially hot hardness and geometry will ensure maximum tool life. Hence, it should give the most efficient cutting both in terms of quality of cut products and energy expended in the cutting process. Therefore, when choosing the working method, the fact that cutting operation must lead to a superior quality product with low energy consumption must be taken into account (Panainte *et al.*, 2007).

In order to produce cut vegetables with desired quality, cutting parameters like blade sharpness should be selected properly. Blade sharpness affect the required cutting forces, contact between the cutting object and the blade is an area (Zhou and McMurray, 2011). Blade sharpness also directly influences the cutting moments and the grip forces applied by an operator such as the research performed by McGorry *et al.* (2003). They studied the magnitude of the grip force and moment using three kinds of blades with different sharpness; namely polished, smooth and coarse knife. They found that a finely polished knife significantly reduced mean grip force and cutting moment during the cutting operation This is important because studies by Barry-Ryan and O' Beirne (2000) have shown that if you are using a knife to cut your fresh vegetables, a dull knife can cause unnecessary and unwanted damage i.e. an increase in the amount of electrolyte leakage from vegetables (including leakage of potassium and calcium) the amount of off-odors, increase in the risk of bacterial growth and excessive softening that can be avoided with the use of a sharp knife.

Even the sharpest of knives cause a small amount of cell rupture in the product, but dull knives cause greater amount of cell rupture, resulting in reduced yield and quality (Szabo *et al.*, 2001). Processors cutting foods for dehydration and drying purposes must pay particular attention to knife sharpness as it is extremely important that nutritional value of the food product is not compromised until the product is dried. A sharp edge is most useful in its ability to penetrate the product cleanly to start the cut, beyond this point, most materials tend to split or separate some distance ahead of the edge. Thick knives or blunt edges increase cause loss of cutting control while thin knives with sharp edges allow the knife to enter the product gently, guiding the path of the split more accurately (Atkins *et al.*, 2004). Hence there is no economy in operating any cutting machine with dull or unserviceable knives because the cost of lost time and product waste far exceeds the cost of knife maintenance and replacement.

Cantwell (1998) studied the impact of blade sharpness on the quality of fresh-cut melons stored at 5°C. The results indicated that melon chunks cut with a dull blade were susceptible to a translucence disorder, increased leakage and high ethanol concentrations in the package (Portela and Cantwell, 2001). Pear slices cut with a freshly sharpened knife retained their visual quality longer than pears cut with a dull hand slicer (Gorny and Kader, 1996). O'Beirne (2007) showed that cutting with a blunt blade enhanced the penetration of fresh-cut carrots by *E. coli* and impaired on its subsequent survival during storage. Frequent sharpening of cutters and hand knives, proper cleaning and sanitizing of

cutting equipment and surfaces that come in contact with fresh-cuts is clearly a key control point in fresh-cut vegetable processing (Ansah *et al.*, 2018).

In developing the cutter used for the present studies, considerations were given to factors such as the knife edge angle, depth of cut and cutting speed and the sizes of the crops studied as this should affect the energy consumed for the cutting operation. Also, automation with arduino-controlled processors was incorporated to reduce the level of human involvement in the operation of the cutter. These features are believed to be improvement of significant magnitude that would make an impact in the lives of users, thereby distinguishing the cutter from the numerous commercial cutters available.

2.6 Energy for Cutting Agricultural Crops

Energy, generally has been defined as the capability of an object or system to do work on another object or system. The crop cutting process is a size reduction operation as well as an energy consumption activity. Grzemeski (2013), Yan and Li (2013) and Leong *et al.* (2014) stated that cutting is an energy intensive process, and there is the need to conduct research on the impact of various factors such as blade sharpness, slicing angle, contact area, depth of cut, cutting speed, and the engineering properties of crops such as crop variety, maturity stage, moisture content, average diameter, average length, average width, and fibre orientation on energy consumption during the cutting of crop products. Energy requirement for cutting crops is however important for the following reasons; i) to aid in the engineering design of appropriate cost effective cutting systems which will consume minimum amount of energy to cut given crops with known physical characteristics. ii) to estimate the optimum amount of energy, cutting speed and cutting time most suitable for a particular variety of crop. iii) to simulate and mathematically model cutting processes, aimed at improving the overall process and reducing the energy demand, while still providing high quality cut products.

Since energy is an important but scarce commodity in developing countries like Nigeria, the agricultural industry will continue to seek ways to maximize the available energy at its disposal and equally harness energy from alternative sources. For the post-harvest operation of cutting, the known sources of energy for its operation in Nigeria have been manual and use of cutters powered electrically. The source of power is either from the public power supply or alternatively with the use of generating sets which is cost intensive. There is the need to study parameters involved in the cutting of agricultural crops in order to maximize energy use and obtain optimum cutting efficiency.

Frigg (1976) reported that the amount of energy needed to fracture food is determined by its tendency to crack, which in turn depends on the structure of the food. To him, harder foods absorb higher energy and consequently require greater energy input to create cuts. Molendowski (2005) and Kowalski (1993) reveal that studies concerned with the process of cutting and fragmentation of agricultural materials, comprise in most cases the determination of relations between the level of fragmentation of

the material, its operating parameters and the energy expenditure. Sharpness, rigidity of cutting tools and knife speeds are effective parameters in cutting operations and strongly influence the energy required, production rate and final surface finish of the cut vegetables (McGorry *et al.*, 2003; Blahovec, 2007; McCarthy *et al.*, 2007; Atkins, 2009).

Dowgiaaao (2005) observed that the cutting force for different materials like beets, carrots and potatoes were decreased as cutting speed reduces while cutting resistance during knife movement is related to the sharpness of the cutting edge. This is in line with the study on the determination of the optimum cutting angle using single edge knife by Ciulica and Rus (2012). According to Dowgiaaao (2006) the possibility of calculating the cutting energy is a prerequisite for the design of properly operating and energy saving machines in which the cutting process is realized. Researchers like Yee *et al.* (2012), Saravacos and Maroulis (2011) and Singh *et al.* (2016) observed that cutting energy depends upon the intrinsic texture of the material and that the cutting rate for vegetables were decreased with increasing hardness.

Cutting energy, also depends upon the homogenous or heterogeneous texture of the material (Singh *et al.*, 2016). Yee *et al.* (2012) reported that the cutting rate of vegetables decreases with increasing hardness and increasing moisture content respectively while Onwulata *et al.* (2013) demonstrated that change in moisture content affects the internal structures of fruits and vegetables stating that high moisture content results in a softer texture of vegetable and significantly affects both the degree and the mechanism of breakdown in foods. Researchers like Correa *et al.* (2010) categorized vegetables which have a moisture content less than 10% as brittle and as such frequently cause a cracked texture during cutting while Gamble and Rice (1988) postulated that vegetables of high moisture content facilitate precise cutting i.e. cutting with uniform shape and size without any texture deformation because the moisture behaves like a lubricant during the cutting operation and reduces the friction.

2.7 Development of Cutters for Agricultural Crops

Several researchers (Tony *et al.*, 2014; Ogbobe, *et al.*, 2007; Shittu *et al.*, 2017; etc.) have worked at either developing new cutters for different crops or improving on existing ones all in a bid to enhance the overall cutting process in terms of efficiency, power consumption, eliminating associated problems with manual cutting or to obtain high quality cut products. Tony *et al.* (2014) developed an automated cutter for vegetables in order to eliminate the drawbacks such as the contamination, additional manpower and time consumption associated with manual processing. The setup involved a hopper arrangement, a pressure block actuated by a pneumatic cylinder which undergoes reciprocatory motion and cutting grids which can be interchanged to give variety of cuts. The air supply to the cylinder is controlled by a solenoid actuated directional control valve (DCV), which in turn is controlled by a microcontroller which varies the pressure needed for cutting the vegetables. A tray is placed at the bottom of the apparatus to collect the vegetable pieces after processing. The researchers suggested that

the automatic vegetable cutter shown in Plate 2.6 is efficient in terms of automating the vegetable entry into the cutting apparatus, eliminating power fluctuation, less time consumption and lesser initial investment.



Plate 2.6: An automated vegetable cutter.

Source: Tony *et al.* (2014)

Raji and Igbeka (1994) designed, fabricated and tested a pedal-operated chipping and slicing machine for tubers and it was reported that the machine performed satisfactorily with production of slices of uniform thickness ranging from 1 mm to 13 mm thickness and a throughput of about 376 kg/h at an efficiency of about 83%.

Ukatu and Aboaba (1996) designed, constructed and evaluated a machine for slicing yam and it was reported that the machine's thickness of cut can be varied from 2 mm to 20 mm and the slicing efficiency ranged from 82 to 93% and the rate of work is 45 cuts per minute.

Ogboke *et al.* (2007) developed a motorized cutter for okra and evaluated it by comparing its performance with a manual cutter and the conventional method of cutting with knives. This was done to solve the problem of knife cut injuries, low output due to drudgery and fatigue, poor quality okra slices and waste of time. The motorized okra cutter shown in Plate 2.7 was found to have a capacity of 42.8 kg/hr and efficiency of 95% when compared with the manually operated machine and hand slicing methods. Also, the cutter produced okra slices of uniform thickness with standard deviation and variance of 0.13 and 0.14, respectively. The variation in thickness of the slices was highest for hand compared to manual cutter and the developed motorized cutter. The time required to produce a given quantity of okra slices using hands was considerably reduced from 57.75 minutes to 10.14 minutes for manual cutter and 5.5 minutes for the developed motorized cutter.

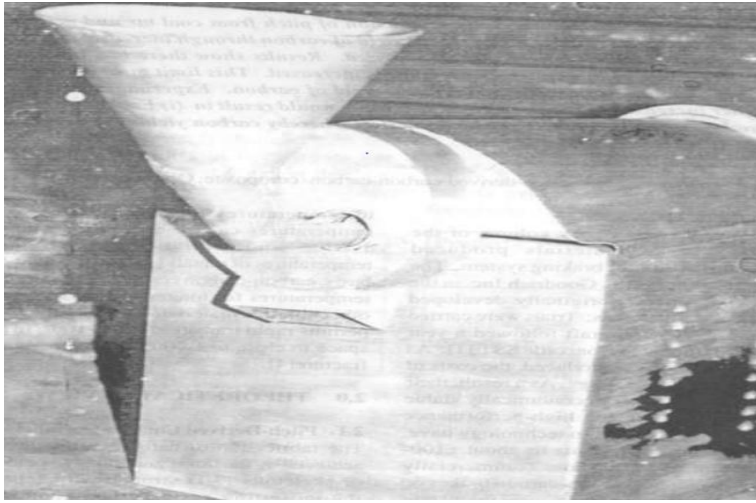


Plate 2.7: Pictorial view of motorized okra slicer. Ogbobe *et al.* (2007)

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Shittu *et al.* (2017) developed a motorized cutter for tomato (*Solanum copersicum L.*). The cutter consists mainly of a feeding unit, cutting compartment, collection unit, power section, and tool frame. Tomato fruits fed through the feeding unit go down to the cutting compartment by gravitational force and the reciprocating motion of knives cut the fruits by shearing action. In the development of the tomato cutter, locally available materials were used for the fabrication which includes power screw, metal sheet, stainless blades, ball bearings and an electric motor. The machine shown in Plate 2.8 was designed to produce tomatoes slices of 20mm thick for quick drying and the results of performance evaluation showed that the machine has an output capacity of 468kg/h and percentage efficiency of 60.34%.



Plate 2.8: A motorized cutter for tomatoes

Source: Shittu *et al.* (2017)

Hrishikesh *et al.* (2013) developed an automated lemon cutting machine in order to replace the conventional method of using sharp knives to manually cut lemons which is labour intensive and unhygienic. The machine shown in Plate 2.9 cuts lemon hygienically into four pieces of similar shape based on stationery cutters and rotating centralizing plate concept with a unique knife assembly consisting of two bird wing shaped knives, joined by welding perpendicularly to a vertical knife, so that the lemon can be cut into four pieces in a single sweep. Six numbers of rotating centralizing slit plates of 90° are welded on to the side plates and the plates carry a groove on its inner face, to enable the wing shaped knife complete the horizontal cut. The machine is powered by an electric geared motor and has a capacity of over 5,000 lemons/h with a power consumption of 0.11 kW. The machine specifications are given in Table 2.5.



Plate 2.9: An automated lemon cutting machine.

Source: Hrishikesh *et al.* (2013)

Table 2.5: Specifications of the automated lemon cutting machine

Description	Value
Throughput	3600 – 5400 Nos/h
Speed of centralizing disc	10 – 14 RPM
Diameter of side plates	0.25m
Diameter of groove	0.2m
Overall size of the machine	0.40m x 0.44m x 0.80m (Length x Width x Height)
Power required	0.11KW
Weight of machine	≈50 Kg
Attendants required to operate	1No.

Source: Hrishikesh *et al.* (2013)

Manjunath and Kalyaniradha (2017) in a bid to improve on the design of the manually operated crop cutter by Awili *et al.* (2009) in order to minimize the time spent, and stress involved in the manual cutting of crops developed a pedal operated crop cutter. This design of the crop cutting machine is operated using the treadle from a sewing machine. The operator pedals the treadle with his legs; the oscillatory motion from the pedaling of the treadle is converted into the rotary motion of the crankshaft by using pitman rod and flywheel. The rotary motion is then translated into a reciprocating motion through a lever; one end of the lever is connected to the pressing tool and the slicing tool holder is connected to the other end, and thus is controlled by the pedaling operation. The result gotten from the evaluation of this machine is that for every one rotation of the flywheel, one cutting stroke accrues at the pressing tool and one stroke at the slicing tool. According to the pedaling speed, the operator can get a minimum of 45 rpm, but the operator has to take some time for the feeding of the crops (Manjunath and Kalyaniradha, 2017). This design is suitable for small and medium quantities of crops because the treadle is manually operated using the legs and thus may result to fatigue when used in cutting large quantity of crops. Figure 2.1 shows a well labeled pictorial view of the pedal operated crop cutting machine.

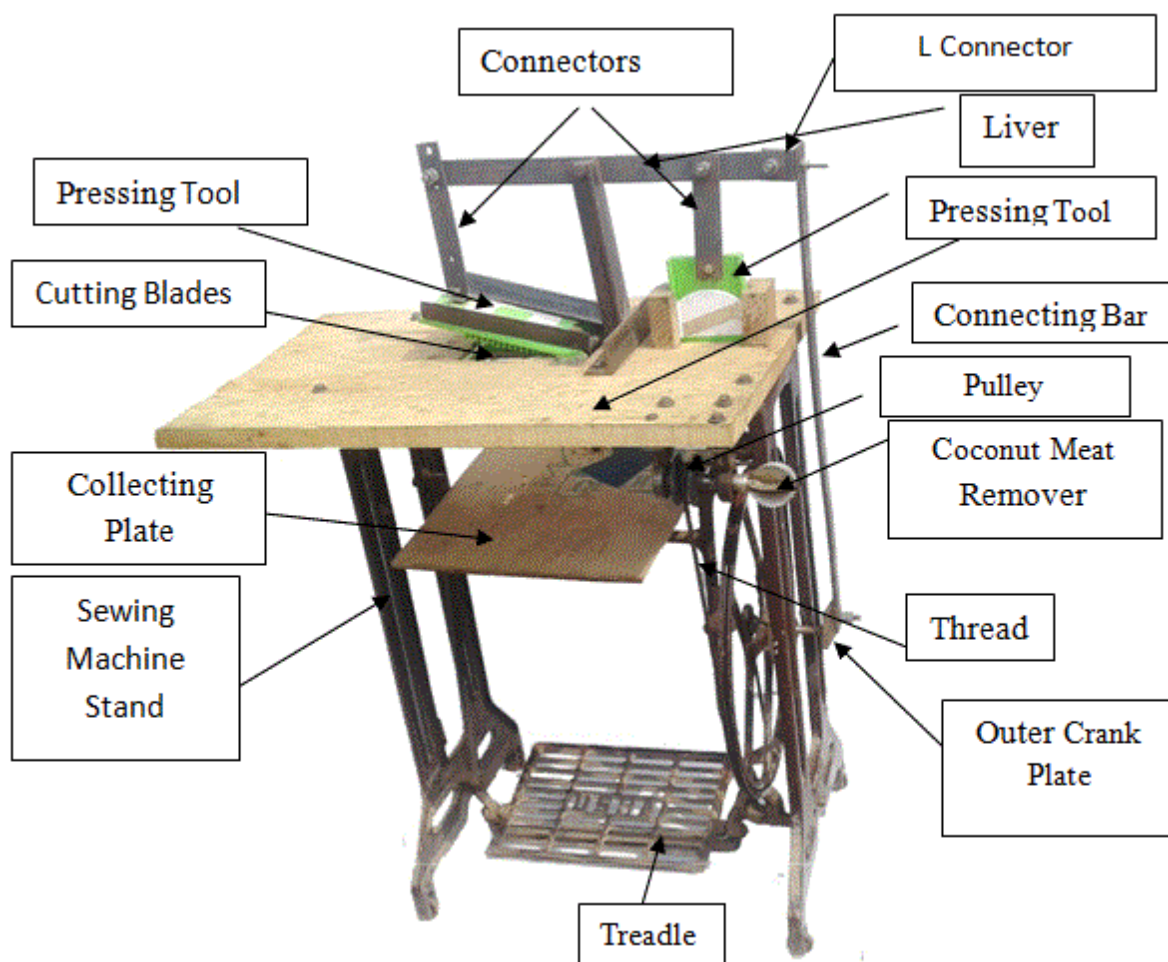


Figure 2.1: Pictorial view of the pedal operated crop cutter

Source: Manjunath and Kalyaniradha (2017)

A multi-crop cutting machine was designed, fabricated and evaluated for performance by Agbetoye and Balogun (2009). The major components of the machine include the hopper, mainframe, conveying disc, slicing unit, slicing shaft, idler shaft, pulley, bearing, electric motobase and outlet. The machine is powered by a three-phase, 1400 rpm, and 2kW electric motor. The performance of the machine was evaluated in slicing four selected crops (carrot, potato, onion and yam) grouped into three sizes (small, medium and large) at five machine speeds of 39 rpm, 41 rpm, 43rpm, 46 rpm and 48 rpm respectively. The parameters that were investigated were slicing efficiency and throughput capacity. A speed of 46 rpm was found to favour the slicing of large size crops only, while a throughput capacity of 48.9 kg/h and efficiency of 95.4% were obtained for carrot. Medium and large size samples gave good result for potato at a speed of 41 rpm with capacities and efficiencies of 72.8 kg/h, 88.9 kg/h, 97.9% and 94.8% respectively. Best result for small and medium size grade of onion was achieved at speed of 41rpm with capacities and efficiencies of 44.6 kg/h, 71.6 kg/h, 91.7% and 96.4% respectively. A throughput capacity of 135.7 kg/h at a speed of 41 rpm and efficiency of 96% was obtained for yam. The machine shown in Figure 2.2 is observed to perform best at the optimum operating speed of 41 rpm for all the crops selected except carrot. The results of the study showed that the machine can slice root and tuber crops satisfactorily and efficiently.

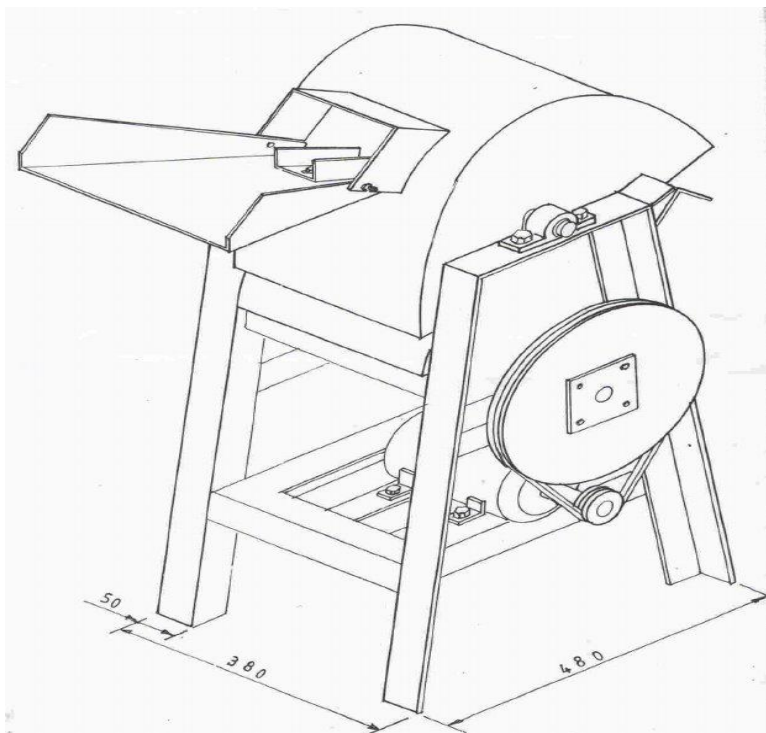


Figure 2.2: Isometric view of the multi-crop slicing machine.

Source: Agbetoye and Balogun (2009).

Ehiem and Obetta (2011) designed and developed a motorized yam-slicing device shown in Figure 2.3 to improve drying by increasing the surfaces area of yam tubers. It consists of rotary blades, feeding chutes and electric motor. The operating power was obtained from 1.5 hp electric motor (1,400 rpm) and, using pulley and belt with complete drive. The device is manually fed with one tuber at a time.

Performance of the device was evaluated using the following parameters: slicing efficiency, throughput and percentage of non-uniform slices. The slicing efficiency, throughput and non-uniform slices obtained were 52.3%, 315 kg/h and 47.65% respectively. According to the researchers, making the chute adjustable to different tuber thickness would eliminate wobbling and further reduce the percentage of non-uniform slices.

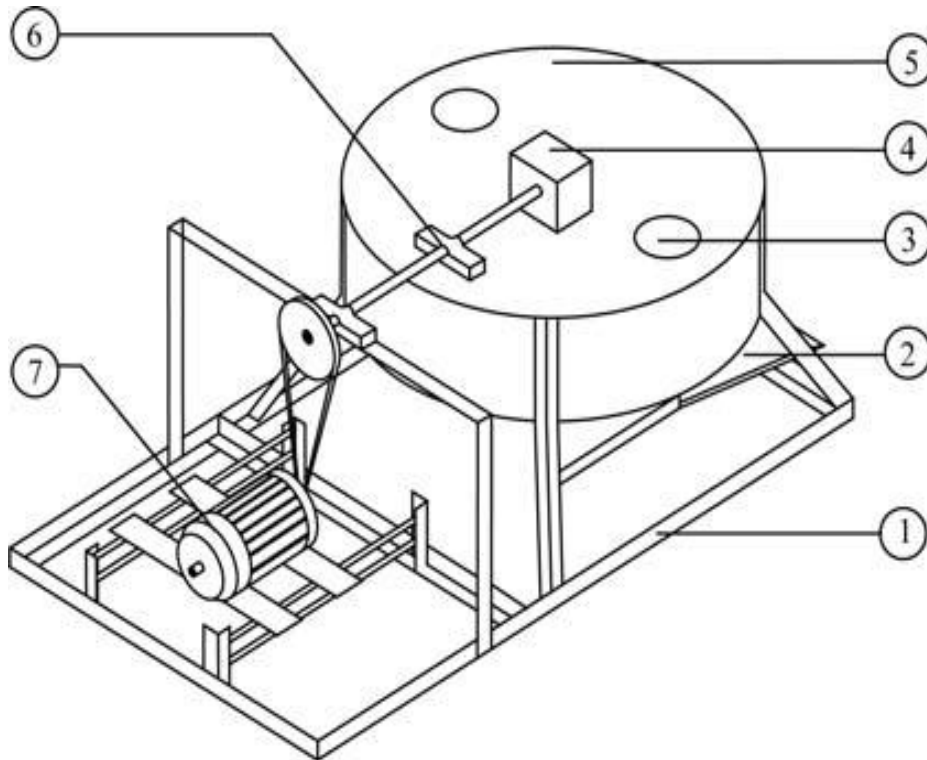


Figure 2.3: A perspective view of the Yam Tuber Slicer. Source: Ehiem and Obetta (2011)

1. Device Frame
2. Collector
3. Feeding Chute
4. Gear Box
5. Blade Housing
6. Bearing
7. Electric Motor

Sonawane *et al.* (2011) developed a motorized cutter for banana to be used by small scale food processing industries. The cutter displayed in Plate 2.10 mainly consists of feeders for producing round slices, power transmission mechanism, base support and frame. The power operated rotary cutter consists of three blades operating at 360rpm speed. The cutter was developed to overcome drawbacks of existing hand or power operated rotary cutters which include drudgery and poor quality cut products and also to meet the demands of small scale processing industries. With the cutter, an efficiency of about 93–94% with effective capacity of about 100kg/h for both varieties of banana was obtained. The mean thickness of cut for both varieties was about 2.00 ± 0.194 mm, whereas mean roundness was of 0.84 and 0.70 for Nendran and Dwarf Cavendish varieties respectively.

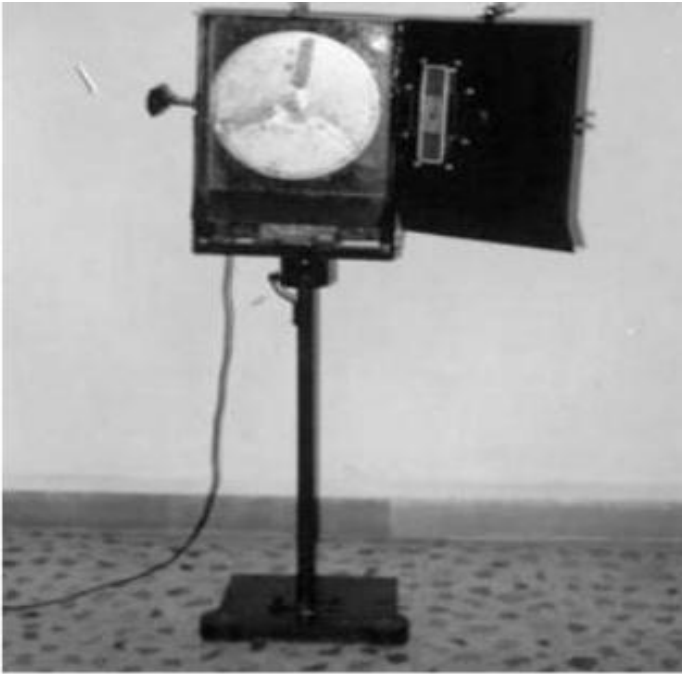


Plate 2.10: An automated banana cutter

Source: Sonawane *et al.* (2011)

Anyanwu *et al.* (2018) developed and evaluated the performance of a motorized fluted pumpkin leaves cutter (Figure 2.4). The machine comprises a conveyor system made from a rubber belt, two pairs of bearings and two hollow metal rods and a frame made from metal sheets for support. The slicing unit comprises the cutting blades and a drive (transmission) shaft, and finally a 746 W (1 hp) power drive mechanism (electric motor). Tests carried out on the machine involved placing 1 kg of fluted pumpkin leaves on the conveyor belt, which was then conveyed to the slicing unit, where it was chopped to desired size. It took an average of 9 minutes to process 1kg of the fluted pumpkin leaves during the test. Series of tests were carried out on the machine, which showed that it had an efficiency of 73.2% and is much faster than hand/manual slicing method.

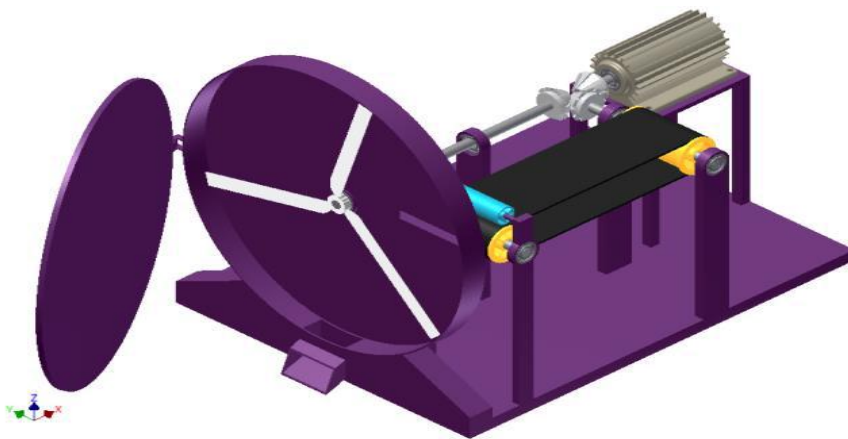


Figure 2.4: Isometric view of the fluted pumpkin leave cutter (with cutting unit open)

Source: Anyanwu *et al.* (2018)

Aremu *et al.* (2017) developed and evaluated the performance of a potato cutting machine (Figure 2.5). Materials used for the construction of the slicing machine were sourced locally and the selection of materials was based on cost adaptation, portability, durability and ergonomics adequacy. Essential features of the slicing machine include: frame, slicing disc, hopper, table, Outlet, Electric Motor Seat. The performance of the machine was evaluated five times; parameters determined include machine capacity and functional efficiency and slicing efficiency. The machine capacity ranged from 35.5 – 47 kg/hr with an average value of 41.2 + 1.2 while the functional efficiency ranged from 39.9 – 83.5% with an average value of 63.8% + 14.7. The cost of maintenance of the machine is low and it is simple to operate. The capacity of the machine will help to conserve timeliness of operation, improve productivity and reduce drudgery which is very significant in the manual production of potato chips.

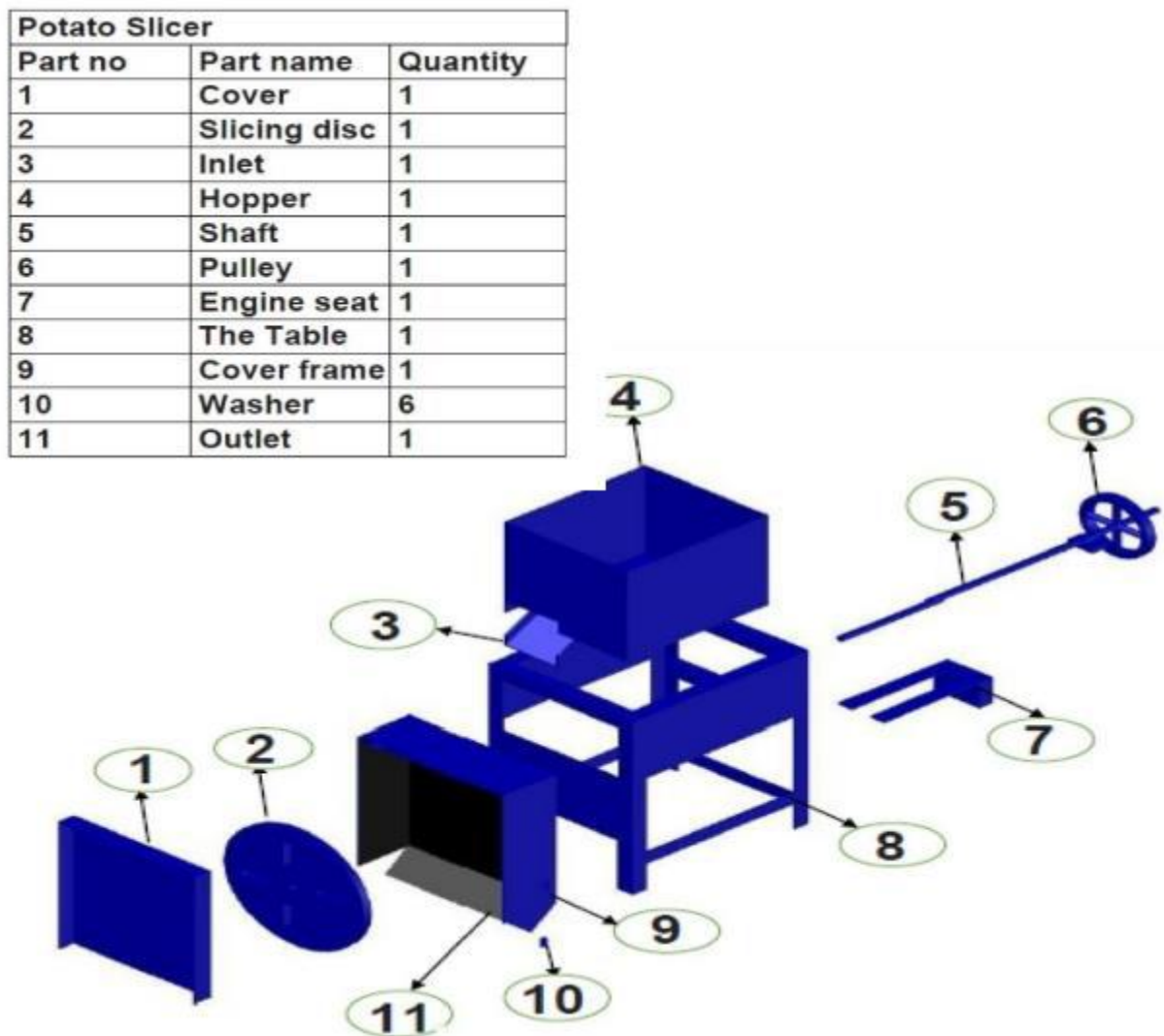
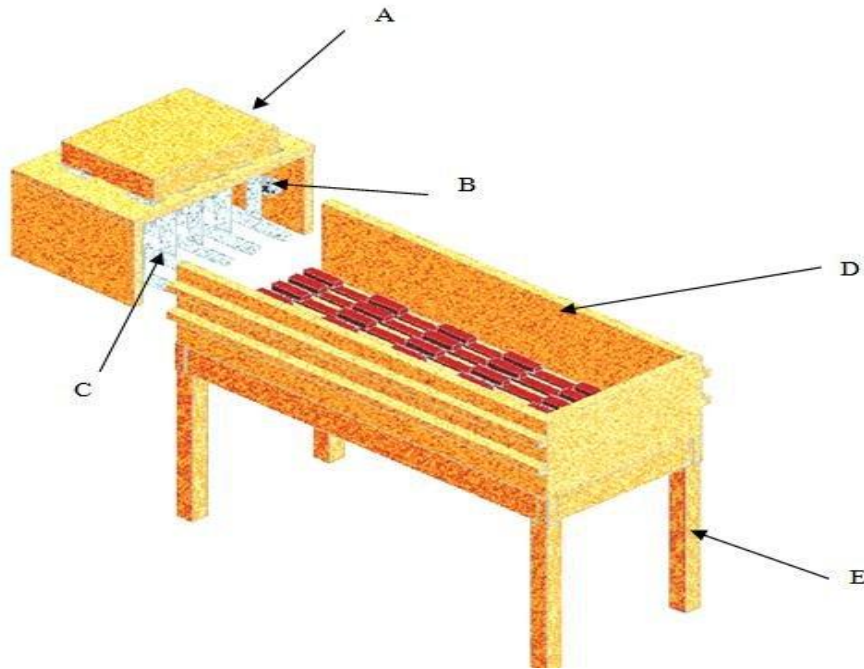


Figure 2.5: Component parts of the potato cutting machine. Source: Aremu *et al.* (2017)

Kamaldeen and Awagu (2013) reviewed cutting principles and developed a tomato slicing machine shown in Figure 2.6 based on appropriate technology. Locally available materials like wood, stainless steel and mild steel were used in the fabrication. The machine which was made to cut tomatoes into 2cm thickness had a capacity of 540.09g per minute and its performance efficiency was 70%.



[A] = Knife compartment [B] = Ball bearing [C] = Stainless knife [D] = Slicing compartment
[E] = Slicer stands

Figure 2.6: Isometric view of tomato slicer machine. Source: Kamaldeen and Awagu (2013)

2.8 Estimation of energy for cutting agricultural crops

Singh *et al.* (2016) carried out a study on the effect of knife edge angle and speed on the specific energy requirement when cutting vegetables varying in their textural characteristics of rind and flesh. Nine vegetables were chosen for the study categorized as, homogenous texture (potato, raddish and carrot), single layer texture (bell pepper), multilayer texture (onion), heterogeneous texture with flesh and seeds (pointed gourd and bitter gourd), heterogeneous texture with soft seeds (cucumber) and soft and spongy texture (aubergine) as shown in Figure 2.7.

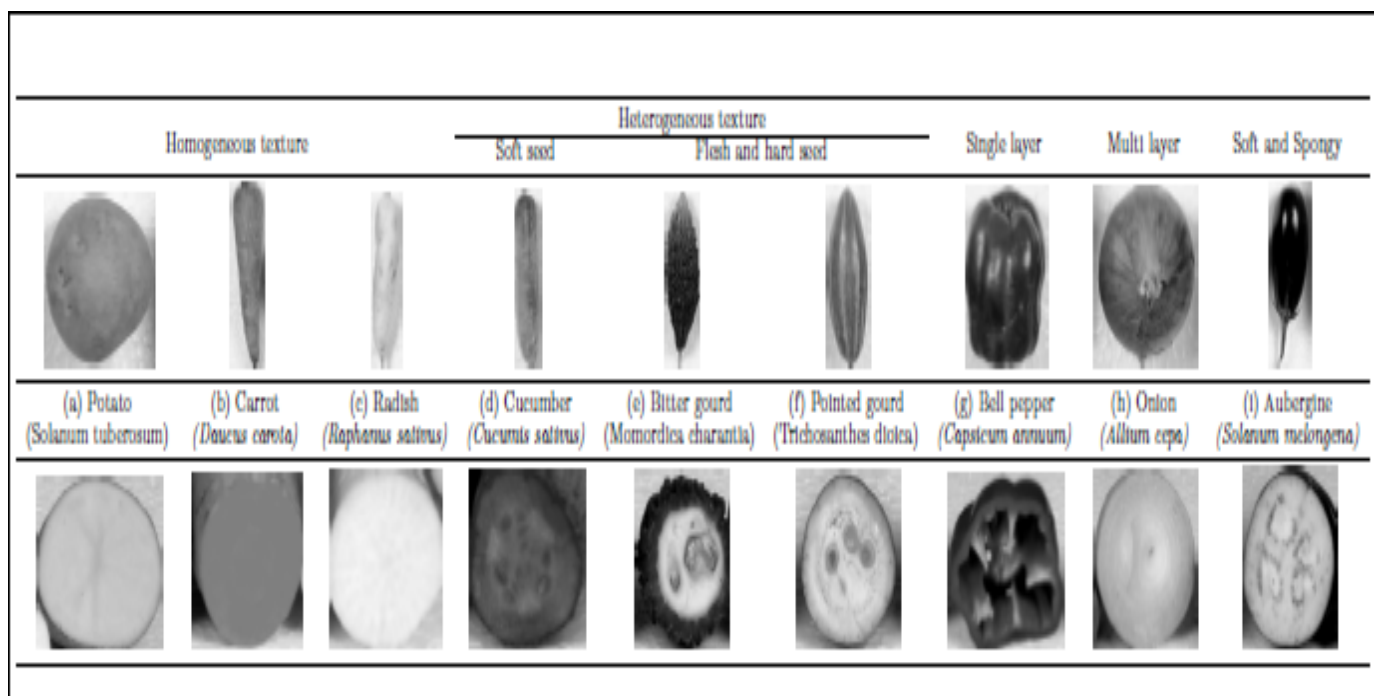


Figure 2.7: Whole vegetables and texture of their inner flesh (cross-sectional view).

Singh et al. (2016)

Diameter values (major, intermediate and minor) of the vegetables and moisture content of the respective vegetables were measured by oven drying method (AOAC, 1999) and varied between 78.52 to 93.59%wb and presented in Table 2.6.

Table 2.6: Diameter and moisture content values for the different unpeeled vegetables studied

Unpeeled Vegetable	Diameter (mm) [#]						Moisture content [#]		
	Major S.D.	± C.V	Intermediate S.D.	± C.V.	Minor S.D	± C.V	(%) wb ± S.D	C.V.	
Potato	54 ±1.9	0.035	47 ±4.6	0.097	40 ±3.9	0.097	78.52±2.12	0.027	
Carrot	95 ±3.1	0.032	31 ±9.8	0.316	29 ±3.5	0.120	89.14±1.89	0.021	
Radish	33.5 ±5.2	0.155	32 ±6.7	0.209	30 ±5.9	0.196	93.02±0.31	0.003	
Cucumber	102.3±4.4	0.043	33.2 ±9.1	0.274	27 ±4.6	0.170	93.01±1.64	0.017	
Bitter gourd	88.5 ±3.7	0.041	32 ±8.5	0.265	26 ±3.7	0.142	90.55±1.34	0.014	
Pointed gourd	52 ±5.5	0.105	36 ±4.4	0.122	29±2.6	0.089	78.92±1.80	0.022	
Bell pepper	57 ±8.8	0.154	51 ±5.4	0.105	42±4.3	0.102	93.59±1.54	0.016	
Onion	51 ±5.5	0.107	42 ±3.1	0.073	40±5.2	0.130	86.05±2.19	0.025	
Aubergine	97 ±4.7	0.048	54.3 ±13.5	0.248	41±6.2	0.151	92.16±1.35	0.014	

Note: [#]Values based on five replicates, β = average value of five replicates with standard deviation (for example, 54±1.9 means the average major diameter is 54mm and the S.D = 1.9mm). S.D = Standard Deviation, C.V= Coefficient of Variation (standard deviation / average value of replicates)

Source: Singh et al. (2016).

The cutting which was carried out under compression mode was actualized using the Universal Testing Machine (UTM) consisting of a special fixture for movement of the knife as shown in Figure 2.8. Three cutting edge angles, 15, 20 and 25⁰ were used in the study and three cross-head speeds, 20, 30 and 40 mm/min were set for each of the vegetables. Force and depth of cut (travel of knife) profiles were recorded using an x-y chart recorder coupled with two independent variables i.e. knife-edge angle and cutting speed taken on the UTM (the coupled x-y chart with UTM automatically generate the graphs for variation of cutting force with increasing depth of cut), for the nine vegetables, with five replications of each.

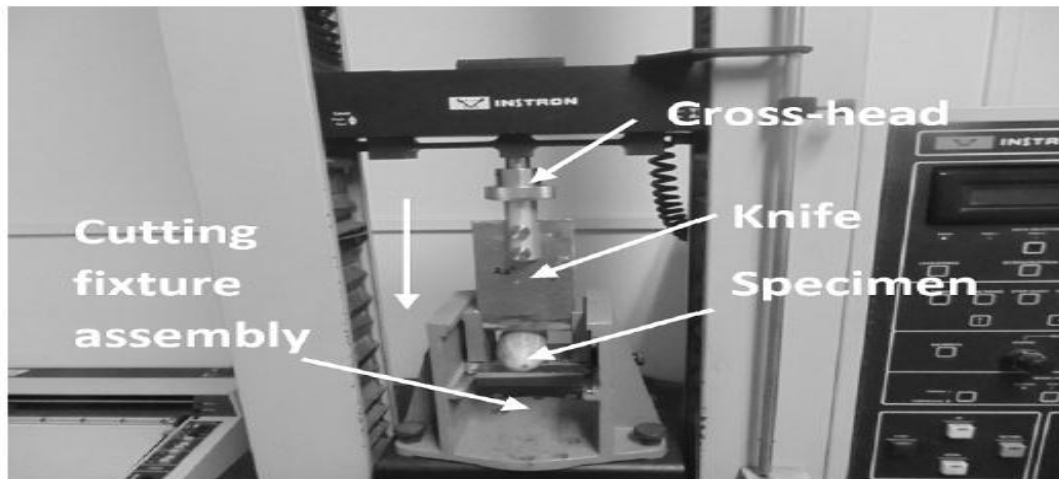


Figure 2.8: Knife movement within the Universal Testing Machine (Instron, UK, Model NO 1011, Load cell LVDT, Load Range 500N). Source: (Singh *et al.*, 2016).

The total energy requirement for cutting (area under force-depth of cut curve) was read from the digital display on the machine, and with a dial mounted slide caliper, the cross-wise diameters of each specimen were measured and the area of cut (transverse section) was then calculated. The specific energy requirement of cutting for each specimen was calculated from the expression in Equation 2.1.

$$\text{Specific energy for cutting} = \frac{\text{total energy required for cutting}}{\text{area of cut}} \quad (\text{in J/m}^2 \text{ equivalent to N/m}) \quad 2.1$$

(Singh *et al.*, 2016).

The average specific energy values of all vegetables at different cutting speeds and knife-edge angles are reported in Table 2.7. Vegetables, like potato, carrot and radish, showed a steady increase in specific energy that attained peak values of 525J/m², 722J/m² and 350J/m² respectively (for knife angle 15⁰ and knife speed 20mm/min) followed by its steady decrease as the depth of cut was increased. This type of increase up to a peak value around the mid-point and decrease thereafter could be attributed to increase and decrease in shearing area (for cylindrical shape body) during blade penetration. However, there were least fluctuations in the energy values for potato, carrot and radish all through the cutting process showing homogeneity in texture. The little increase in magnitude for the specific energies for

cutting cucumber (238J/m² to 373J/m²) and bell pepper (232J/m² to 346J/m²) all through the process of cutting is indicative of the soft core texture with soft seeds of cucumber and the single layer, inside hollow texture of bell pepper. In the case of aubergine, this change in specific energy was consistent with an increase in knife angle, and the range was highest (450J/m² to 1340 J/m²). This highest energy value recorded for aubergine shows the tough nature of the skin of aubergine. Onion with a multiple layer texture showed a slow increase in specific energy (526J/m² to 744J/m²) with increasing depth all through the cutting process indicating progressive cutting of layers.

Table 2.7: Average specific energy for vegetables using different knife angles and cutting speeds.

Knife speed (mm/min)	Specific energy±S.D., (Nm ⁻¹) [§]			Specific energy±S.D., (Nm ⁻¹) [§]				
	Vegetable	Knife angles			Vegetable	Knife angles		
		15°	20°	25°		15°	20°	25°
20		525±48.96Y	578±58.46	545±27.03		430.27.03	597±59.56	471±59.58
30	Potato	558±38.56	629±39.1	602±62.90	Pointed gourd	492±51.77	659±47.83	523±26.18
40		578±29.85	670±44.03	639±48.09		522±72.71	699±41.42	544±78.22
20		722±22.67	921±81.33	976±79.62		232±33.49	314±39.15	305±40.51
30	Carrot	906±112.23	1140±166.75	1150±154.68	Bell pepper	249±46.26	316±12.83	329±53.82
40		958±116.43	1220±158.55	1250±132.57		279±14.71	322±36.52	346±43.71
20		350±39.23	573±69.02	501±45.09		526±59.46	628±8.34	682±8.18
30	Radish	454±50.48	553±11.61	584±58.42	Onion	671±11.17	716±16.79	707±8.90
40		605±40.42	625±54.62	643±81.77		718±64.21	741±13.83	744±77.71
20		238±22.31	292±49.09	301±24.87		450±75.63	590±77.08	858±98.56
30	Cucumber	257±23.28	308±24.81	318±31.12	Aubergine	541±68.05	766±77.08	1080±172.77
40		282±22.33	372±42.21	373±30.46		622±65.87	1100±102.83	1340±111.67
20		620±64.35	935±122.63	963±107.89				
30	Bitter gourd	719±73.28	980±141.13	1020±91.02				
40		781±102.42	1000±129.06	1100±154.70				

Average of five replicates, ¥=Average specific energy with standard deviation (for example, 525±3.84 means 525N/m is the average specific energy and 3.84N/m is the standard deviation).

Source: Singh *et al.* (2016).

Vegetables with multiple seeds, such as bitter gourd and pointed gourd, showed typical force depth of cut characteristics having peaks and ripples as shown in Figures 2.9a and 2.9b. Bitter gourd has a tough and thick rind attributing for its large variation in specific energy (620J/m^2 to 1100J/m^2).

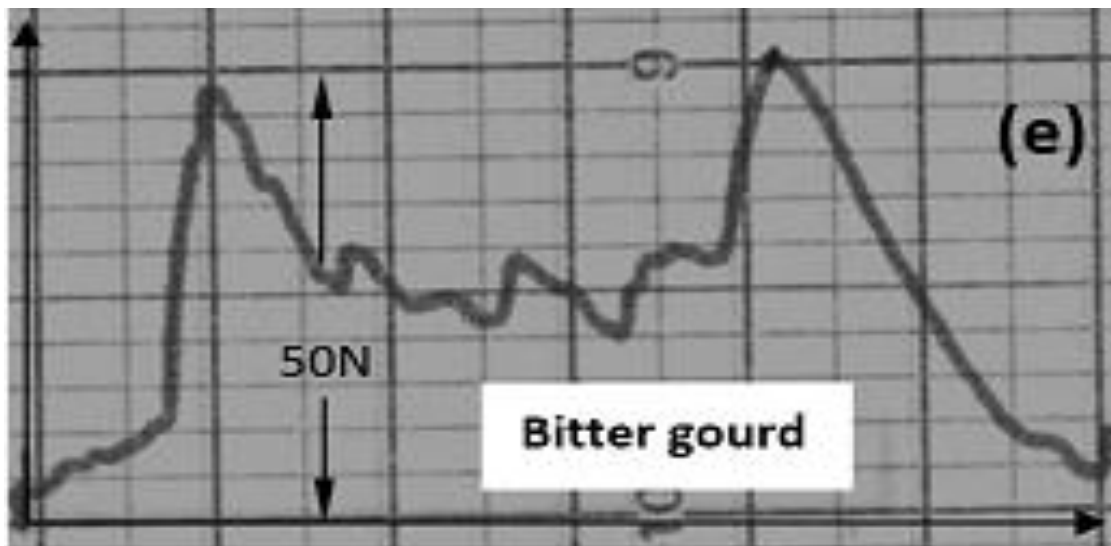


Figure 2.9a: (Knife angle 15° and cutting speed 30mm/min). Force-deformation graph obtained for bitter-gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine. Source: Singh *et al.* (2016).

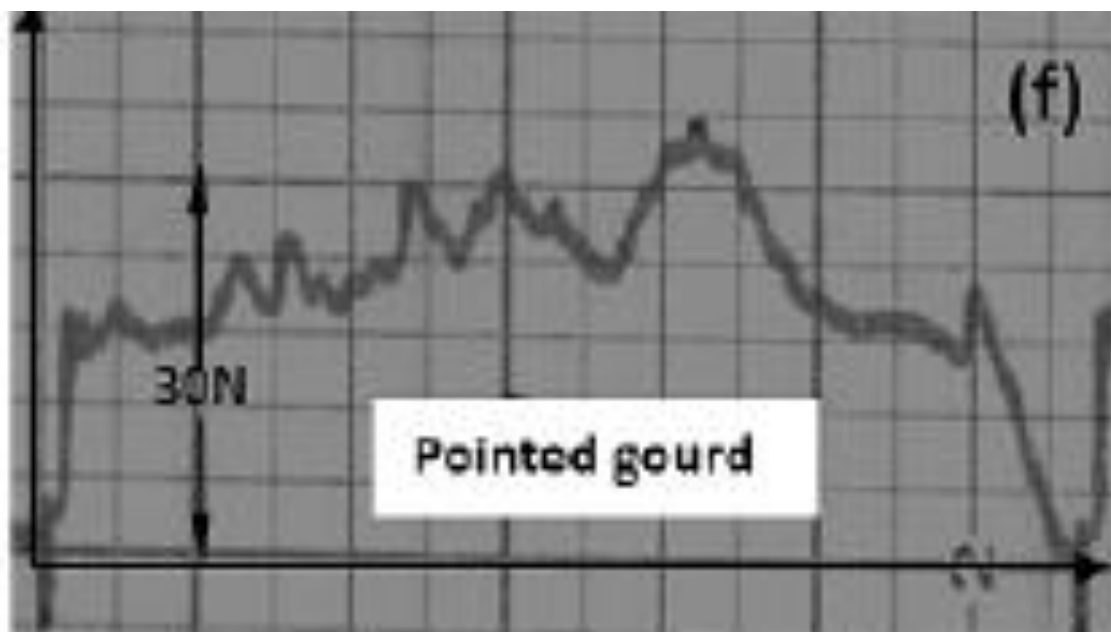


Figure 2.9b: Force-deformation graph obtained for pointed gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine. (Knife angle 20° and cutting speed 30mm/min). Source: Singh *et al.* (2016).

However, for all the vegetables studied, the specific energy of cutting increased with increased value of cutting knife speed and knife edge angle, showing that cutting speed and knife-edge angle significantly influence the specific energy of cutting for these vegetables. Also, the peak specific energy required to cut these vegetables depends upon the texture of the rind and flesh, and their homogeneity as observed from the study. Furthermore, the study showed that high speed (40mm/min) and large knife edge angle (25⁰) required highest specific energy to cut the vegetables, this can be attributed to the larger area of the material covered by the large wedge angle, hence more energy will be needed to cut through this area. Conclusively, their study showed that a combination of low speed cutting (20mm/min) with a sharp angle cutter (15⁰) is favoured for low peak specific energy (least cutting energy)

In the study conducted by Abdullah *et al.* (2015) on cutting properties of different grape varieties, the cutting properties such as cutting force, cutting strength, cutting energy of different wine grape branches as a function of moisture content, diameter and variety were investigated. The cutting properties were measured at three moisture content levels (35.2, 42.4, and 46%), four cross-sectional areas (12.56, 28.27, 50.26 and 78.54mm²) and eight wine grapes varieties (Tannat, Merlot, Cot, Chardonnay, Viognier, Cabernet Sauvignon, Shiraz, Cabernet Franc). In carrying out the cutting test, samples of grape branches were obtained from a commercial farm in Mezopotamia Province in Turkey during the grape pruning season in 2012. Specimens were kept in the refrigerator at 4°C and the initial moisture content was determined by using Equation 2.2 (ASAE, 2006; Alizadeh *et al.*, 2011). Samples were weighed and dried in an oven of 105°C for 24 h and then reweighed.

$$MC = \frac{SB-SA}{SB} \times 100 \quad 2.2$$

(ASAE, 2006; Alizadeh *et al.*, 2011)

Where: MC = Moisture content (%)

SB = Sample mass before drying, (g)

SA = Sample mass after drying, (g)

The experimental results were evaluated according to the moisture content values of 35.2, 42.4, and 46% respectively. The Lloyd LRX plus materials testing machine displayed in Figure 2.10 was used to measure the cutting force and cutting energy. A cutting speed of 100mm/min was used for all tests. The cutting strength was measured using a shear apparatus.



Figure 2.10: The Lloyd LRX plus materials testing machine

Source: Abdullah *et al.* (2015)

The maximum shearing strength of the grape branches were determined by dividing the shearing force by two sectional areas of the branches as given in Equation 2.3 (Mohsenin, 1980; Beyhan, 1996; Sessiz, 2003; Amer Eissa *et al.*, 2008; Zareiforoush *et al.*, 2010).

$$\delta_S = \frac{F_{max}}{2A} \quad 2.3$$

(Mohsenin, 1980)

Where:

δ_S = maximum cutting strength in (MPa),

F_{max} = maximum cutting force in (N) and

A = cross-sectional area of cane in (mm²)

Cutting energy was calculated by measuring the surface area under the cutting force-deformation curve (Heidari and Chegini, 2011; Nazari *et al.*, 2008 and Zareiforoush *et al.*, 2010) with the help of the force and displacement data got from the NEXYGEN computer program. From the cutting energy data, specific cutting energy was determined by using Equation 2.4 (Heidari and Chegini, 2011).

$$E_{sc} = \frac{E_c}{A} \quad 2.4$$

(Heidari and Chegini, 2011).

Where;

E_{sc} = Specific cutting energy, J/mm²

E_c = Cutting energy, J

A = Cross-sectional area in mm²

The experimental results were tested using standard variance analysis (ANOVA) for the randomized complete block design. Cutting properties were determined with 3 replications in each treatment and the means were compared at the 1% and 5% levels of significance using the multiple range tests in JAMP software. The effect of grape varieties on cutting force, cutting strength and cutting energy are presented in Table 2.8.

Table 2.8: The relationship between average cutting properties and grape varieties (at moisture content range of 35.2% and 42%wb).

Grape varieties	Cutting Force (N)	Cutting Strength (MPa)	Cutting Energy (J)
Tannat	981.65	13.94	2.39
Merlot	1011.97	13.98	2.64
Cot	1049.65	14.29	2.90
Chardonnay`	1145.06	15.83	3.05
Viognier	1158.07	16.13	3.334
Cabernet Sauvignon	1166.68	16.47	3.386
Shiraz	1214.42	16.55	3.481
Cabernet Franc	1394.6	21.68	3.686
Mean	1140.25	16.11	3.11
LSD	97.88	1.744	0.472

Source: Abdullahi *et al.* (2015)

Variance analysis and result of tukey test show that the difference between varieties were found significant ($p < 0.05$). The results indicated that cutting force, cutting strength and cutting energy requirement varied from variety to variety. The maximum cutting force, cutting strength and cutting energy were obtained at Cabernet Franc grape variety as 1397.60N, 21.68MPa and 3.68J, respectively, followed by varieties Shiraz, Cabernet, Viognier, Chardonnay, Cot, Merlot and Tannat respectively. The minimum cutting force, cutting strength and cutting energy were obtained at Tannat grape variety as 981.65N, 13.94MPa, and 2.39J, respectively.

The average cutting strength of Cabernet Franc was about 1.5 times greater than Tannat variety. This effect could be related to higher stem wall thickness and cross-sectional area of Cabernet Franc compared to the other examined varieties which confirms that differences exist in the physical, mechanical and physiological properties of stem varieties (Eseghbeygi *et al.*, 2009; Hoseinzadeh and Shirneshan, 2012). In conclusion, the study revealed big differences among the different grape varieties in terms of cutting force, cutting strength and cutting energy which suggest that these

information are very valuable for development and selection of suitable cutting apparatus and equipment and will also play an important role in maximizing cutting energy requirements.

Effect of knife wedge angle on the energy of cutting the fruits of two peppers cultivars – red pepper (King Arthur) and yellow pepper (Bell) was investigated by Elżbieta and Agnieszka (2012). The variable parameters were the peppers cultivars (fresh, healthy, and free of mechanical damage) and the orientation of the material being cut. The cutting process was conducted on the texture analyser, type TA.XT plus, maintaining constant orientation of the cutting knife. The knives used in the tests were of various wedge angles: 2.5°, 5°, 7.5°, 10°, 12.5°, 15°, 17.5° and 20° while samples of peppers were placed parallel to the base of the analyzer, skin down or skin up, and loaded in the perpendicular direction with the cutting element at a constant velocity of 50 mm/min. Results of the measurements were in the form of graphs representing the relation between the cutting force and knife displacement from which the values of the cutting energy were determined; also textural analyses of the samples were carried out. The relations presented in Figure 2.11a are described by the regression Equations 2.5 and 2.6 and that of Figure 2.11b are described by regression Equations 2.7 and 2.8, respectively, which showed that increasing the knife wedge angle causes an increase in the values of peppers' cutting energy. The high R^2 value shows that a significant relationship exists between values of the knife wedge angles and the cutting energy values.

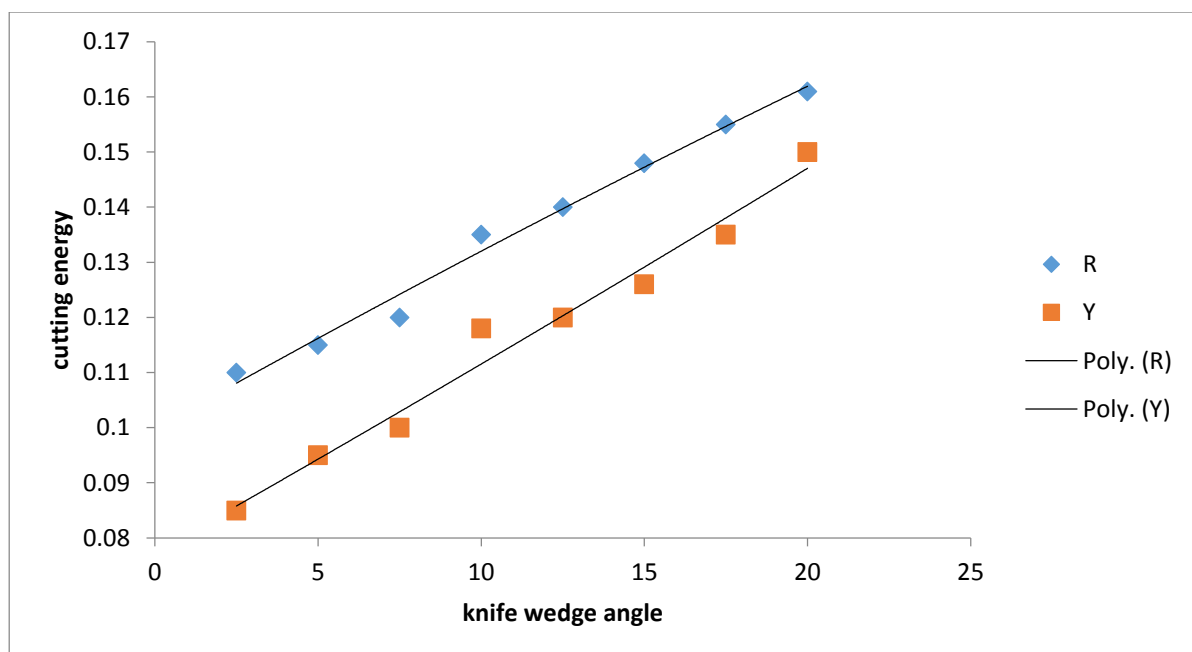


Figure 2.11a: Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin down.

Source: Elżbieta and Agnieszka (2012).

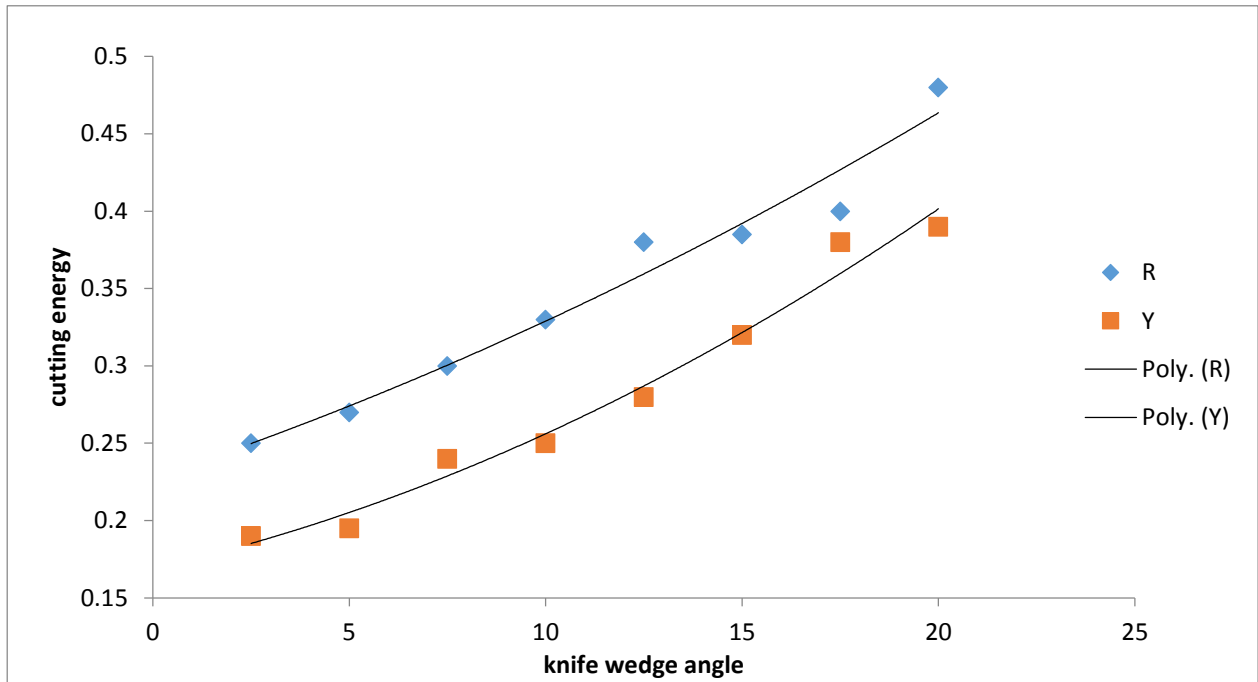


Figure 2.11b: Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin up. Source: Elżbieta and Agnieszka (2012).

$$yR = -1E - 5x^2 + 0.003x + 0.099; \quad R^2 = 0.99 \quad 2.5$$

$$yY = 7E - 6x^2 + 0.003x + 0.077; \quad R^2 = 0.98 \quad 2.6$$

$$yR = 0.000x^2 + 0.008X + 0.227; \quad R^2 = 0.96 \quad 2.7$$

$$yY = 0.000x^2 + 0.005X + 0.168; \quad R^2 = 0.98 \quad 2.8$$

Source: Elżbieta and Agnieszka (2012).

Where; yR = cutting energy of red pepper; yY = cutting energy of yellow pepper; x = wedge angle with material positioned skin down; X = wedge angle with material positioned skin up.

Results from the study showed that the cutting energy values for both pepper cultivars were higher when the cutting is done with the material positioned skin up than values obtained when material is positioned skin down, it can therefore be deduced that the material has a tougher outer structure resulting in higher values when positioned skin up and a softer inner structure resulting in lower values when positioned skin down. The highest energy value of 0.471J was obtained when cutting with a knife with wedge angle of 20° (red peppers cultivar King Arthur, cut with the skin up), this can be attributed to the large area covered by the large wedge angle, hence more work need to be done to penetrate through this large area in addition to the tougher outer structure when material is positioned skin up while the lowest energy value of 0.085J obtained when cutting with wedge angle of $\alpha=2.5^\circ$ (yellow peppers cultivar Bell, cut with the skin down) is indicative of the little work done while penetrating the smaller area covered by a thinner wedge angle and the softer inner texture of the material when positioned skin down.

These results are supported by Bolin and Huxsoll (1991) in their statement that cutting resistance is related to blade angle and sharpness of the knife blade and Ciulica and Rus (2012) who opined that cutting resistance during knife movement is related to the sharpness of the cutting edge. Furthermore, the result of their study showed that irrespective of the positioning of the specimens, higher values of the cutting work were obtained in the case of cutting fruits of red peppers, compared to fruits of yellow peppers in which cutting work values were the highest for red peppers cv. King Arthur, (0.246J – 0.471J), compared to yellow pepper cv. Bell (0.188J – 0.392J) which could be traced to the higher values of textural properties (hardness, brittleness and chewability) of the red peppers compared to the yellow peppers as shown in Table 2.9.

Table 2.9. Texture properties of red peppers (cultivar King Arthur) and yellow peppers (Cultivar Bell)

Variety	Hardness [N]	Brittleness [N]	Elasticity [-]	Cohesiveness [-]	Chewability [N]
Red peppers	81.909	41.824	0.497	0.326	13.271
Yellow peppers	62.096	39.274	0.536	0.326	10.85

Source: Elżbieta and Agnieszka (2012).

In their study on the effect of varying knife speed and contact area on peak cutting force during cutting of peeled potato (*Solanum tuberosum*), Singh *et al.* (2016) observed the relation of different knife speeds (20, 30, 40 mm/min) and contact area of 200, 300, 400 and 500 mm² on peak cutting force for a constant knife cutting edge of 15° fixed in universal testing machine. Length and thickness of the vegetables were measured with the help of dial mounted slide calliper and the moisture content of test sample (potato cuboids) (78.5 ± 3.67% on wet basis) was determined with the oven drying method (AOAC, 2003).

Contact area indicates surface area of potato in the contact of knife during vertical movement of knife in the cutting operation (i.e. for a sample of length and thickness 20 and 10 mm respectively, resistance force occurred on 20mm length up to knife travel of 10mm resulting into a contact area of 200mm² (20mm×10mm)). From their work, it was observed that knife cutting speed and contact surface area of sample significantly influences magnitude of force required to cut as the minimum cutting energy of 0.175J was observed for least contact surface area (200mm²) and minimum knife speed (20mm/min), and the highest cutting energy of 1.296J was observed for highest contact

surface area (500mm^2) at maximum knife speed (40 mm/min) respectively. Low speed (20mm/min) of cutting and less contact surface area (200 mm^2) were therefore suggested for lower value of cutting energy. Furthermore, the study also showed least fluctuations in the values of peak cutting energies (e.g. 0.175J , 0.1978J , and 0.208J) for contact area of 200mm^2 at 20 , 30 and 40mm/min respectively, indicating the homogeneous texture of potato.

Agnieszka and Elzbieta (2016) in their study on the impact of the wedge angle on the specific cutting energy of black radish (variety *Murzynka*), considered the structure of the black radish which is heterogeneous and, therefore, in order to study the specific cutting energy, its parenchyma was taken from a few specific places. The samples were cut with a longitudinal and transverse orientation of the fibers relative to movement of the working tool displayed in Figure 2.12 at the knife wedge angles: 2.5° ; 5° ; 7.5° ; 10° ; 12.5° ; 15° , moving at the speed of 0.83mm/s (about 50mm/min).

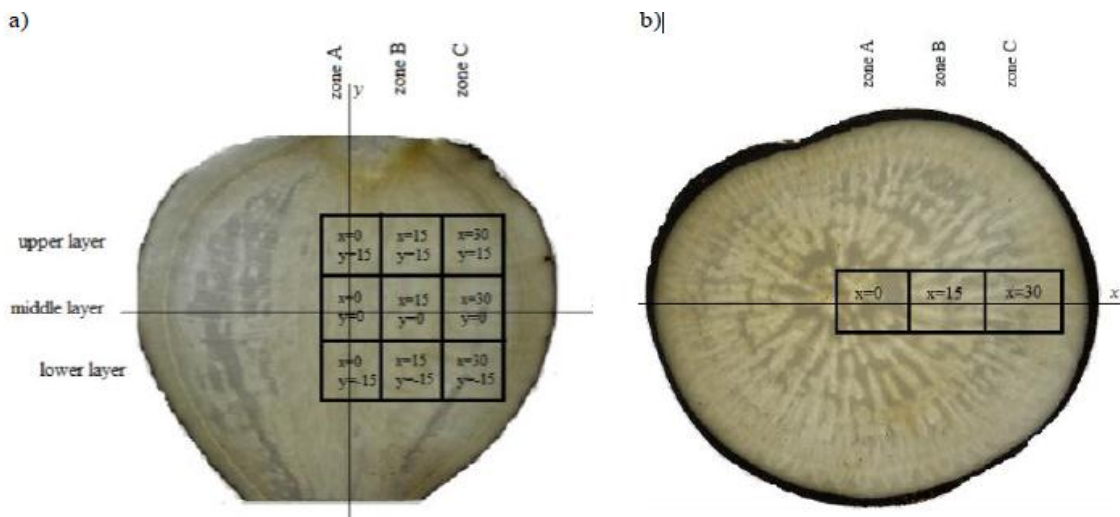


Figure 2.12: The structure of black radish parenchyma and place of sampling after cutting: a) longitudinally, b) transversely to the fibers. Source: Agnieszka and Elzbieta (2016).

The process of cutting the black radish was conducted on the Texture Analyzer TA.XT plus Stable Micro Systems cooperating with the computer having software Texture Exponent 32. The cutting samples were laid longitudinally to the fibers (sample A) and transversely to the fibre (sample B) (Figure 2.13).

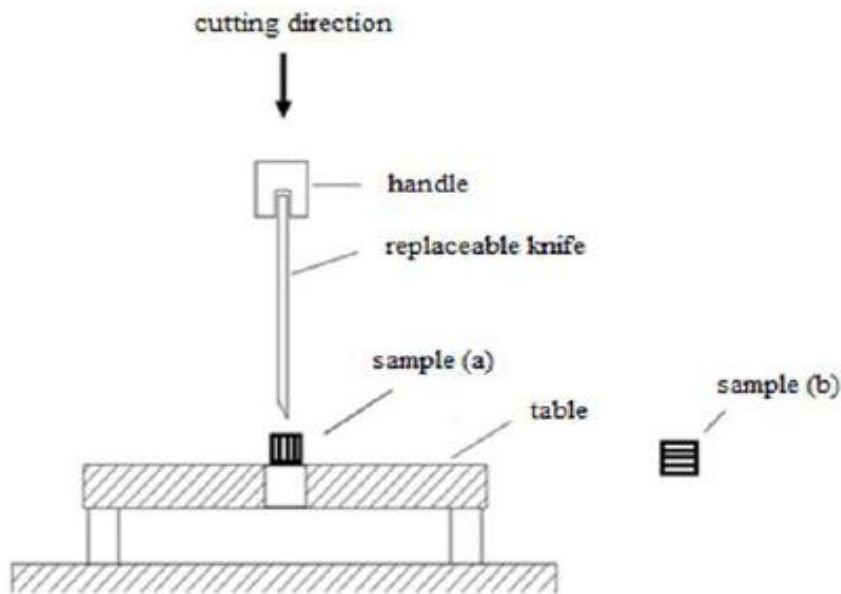


Figure 2.13: Sample orientation ((longitudinally (sample A) and transversely (sample B) to knife direction. Source: Agnieszka and Elżbieta (2016).

Measurement graphs were obtained showing the relationship between the force and displacement of the cutting knife, and using Equation 2.9, the specific cutting energy, was calculated, defined as the labor required to cut the specific area of the material:

$$Ej = \frac{L}{A} \quad 2.9$$

Where:

Ej – Specific cutting energy [J/m²]

L – Work of cutting [J],

A – Surface area of the sample [m²]

(Agnieszka and Elżbieta, 2016).

Results of their experiment showed that the knife wedge angle significantly affects the specific cutting energy of black radish confirming the findings made by Bolin and Huxsoll (1991) in their statement that cutting resistance is related to blade angle and sharpness of the knife blade and (Ciulica and Rus, 2011; Ciulica and Rus, 2012) in their opinion that cutting resistance during knife movement is related to the sharpness of the cutting edge. Increasing the knife angle from 2.5⁰ to 15° caused a corresponding increase of the specific cutting energy of black radish from 347 to 851 J/m² (at the longitudinal orientation of fibers), and from 388 to 1033J/m² (at the transverse orientation of fibers). These higher values of the specific cutting energy obtained at the transverse direction of the black radish parenchyma fiber than at the longitudinal direction is indicative that structural features such as fibre orientation significantly affects the cutting process of vegetables.

On the influence of maturity degree of vegetables on their cutting resistance force, Ciulică and Rus (2011a) experimented with carrots, by subjecting each one of the vegetables to the determination

of cutting resistance in three different areas on the vegetable length, thereby varying the cutting diameter. A maturity meter which is an electronic device which measures firmness of vegetables and fruits and indicates their optimal maturity was used to obtain the maturity of the vegetables in grams. The cutting process was done with a special stand created by Zwick /Roell composed of a drive mechanism for the knife holder, a control panel and a device for vegetables application. The equipment works with software called Test Expert, which stores data in its Windows operating system for acquisition, visualization and data analysis. The values registered during the cutting test experiments are presented in Table 2.10.

Table 2.10. Values registered at the cutting test.

Probe number	1			2			3			4		
Material	Carrot			Carrot			Carrot			Carrot		
Diameter in cutting area, (mm)	25	20	21	30.4	26.28	22.6	45	40	32.16	49.02	41	28.4
Maximum cutting strain [N]	84.62	90.89	53.80	130.28	137.55	94.31	210.4	240.3	128.2	206.62	193.7	156.9

Source: Ciulică and Rus (2011a).

For each of the four samples that were subjected to cutting operations in three different areas, largest diameter corresponds to the upper area of the carrot, middle diameter corresponds to the middle area, and the minimum corresponds to lower part of the carrot. Following the experimental measurements, it can be seen that to an optimum degree of maturity for consumption, carrots cutting operation is influenced by cutting their sectional area, so that with increasing cutting section, there is an increase in the cutting force as shown in Table 2.10. However, results equally showed that the highest cutting forces of 90.89N, 137.55N and 240.3N were recorded in the middle area of carrots (Samples 1, 2 and 3 of diameters 20mm, 26.28mm and 40mm respectively), subjected to cutting operations indicating a stronger internal structure in this area for these vegetable samples, while the top area of the carrots, which, although carrying a larger diameter of 25mm, 30.4mm and 45mm respectively has lower values of cutting forces (84.62N, 130.28N and 210.4N respectively).

Their results support the findings by Lurie and Crisosto (2005) while working on carrot vegetables, that the maximum cutting force is higher for the inner part (such as xylem and phloem) than for the upper layers and Mc Carthy *et al.* (2007) in their opinion that the force required to penetrate carrot

increases with increasing elastic behavior. Cutting force is however, lowest at the bottom of carrots, where the section cutting area is smallest (53.80N, 94.31N and 128.2N respectively). A slightly different position was observed with sample 4 (probe number 4) which shows a normal characteristic pattern of decreasing cutting forces of 206.62N, 197.3N and 156.8N with decreasing cutting diameters of 49.02mm, 41mm and 28.4mm respectively. The relation presented in Figure 2.14 is described by Equation 2.10 showing a high R^2 value which is indicative of a significant relationship between the diameter in cutting area and the cutting energy.

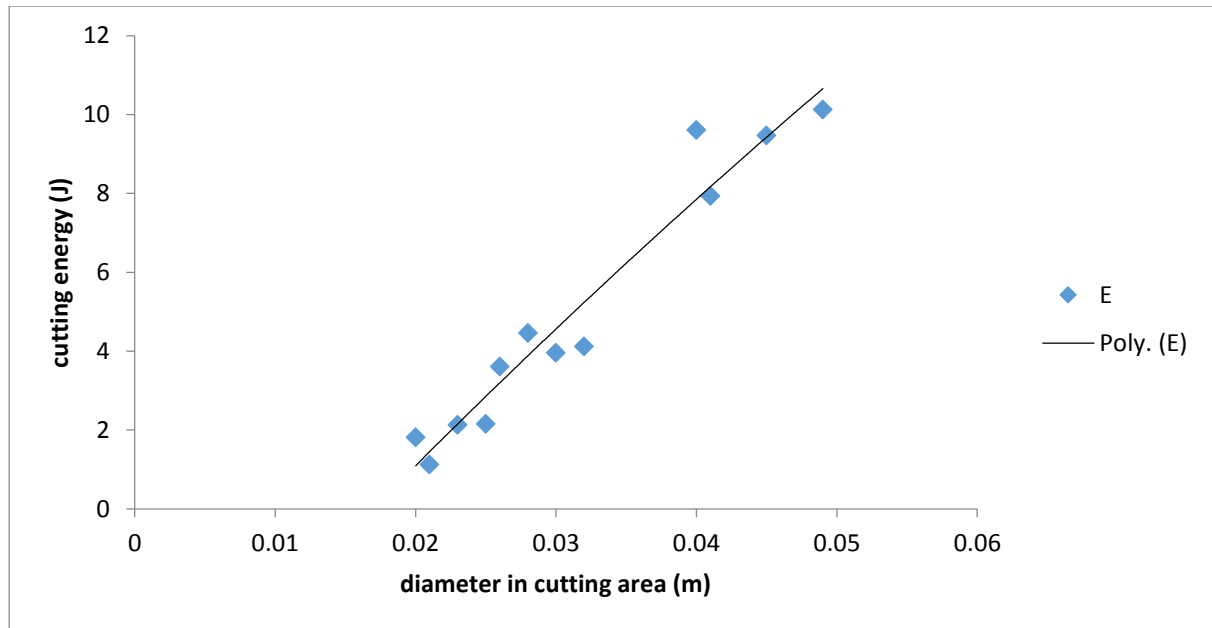


Figure 2.14: Graph representing relation between cutting energy and diameter in cutting area. Source: Lurie and Crisosto (2005)

$$y = -892.9x^2 + 391.2x - 6.37; R^2 = 0.95 \quad 2.10$$

2.9 Modeling the Energy for Cutting Vegetables Using Dimensional Analysis

Modeling is a representation in mathematical terms of the behavior of real devices and objects, or a system of postulates, data and inferences presented as a mathematical description of an entity or state of affairs. It could be descriptive, explanatory or predictive. In the prediction part, which can be envisaged as organized thinking of the possible, models are exercised to give information on a yet-to-be-conducted experiment. These predictions are then followed by observations that serve either to validate the model or to suggest reasons that the model is inadequate (Dym and Ivey, 1980; Dym, 1994 and Cha *et al.*, 2000).

The first step in modeling any physical phenomena is the identification of the relevant variables (Asonye *et al.*, 2018a) and then relating these variables by means of known physical laws. For sufficiently simple phenomena, we can usually construct a quantitative relationship among these

variables from first principles; however, for many complex phenomena which often occur in Agricultural engineering applications, it is often difficult. In these situations, modeling methods are indispensable. Various mathematical modeling techniques that are in use include: dimensional homogeneity and analysis, abstraction and scaling, conservation and balance principles and consequences of linearity.

However, Dimensional analysis has become a widely applicable and very powerful technique that is adopted in mathematical modeling. This is due to its simplicity in planning, presentation, and interpretation of experimental data, providing an organised way to plan and carry out experiments, and enables one to scale up results from model to prototype (Bahrami *et al.*, 2006). The dimensional analysis is a mathematical technique used in identifying the factors involved in a physical situation or phenomenon and forming a relationship between them. It offers a method for reducing complex physical problems to the simplest form prior to obtaining a quantitative answer (Andrzej, 2015). Although there are other methods of performing dimensional analysis, notably the indicial method, the method based on the Buckingham pi theorem gives a well-organized procedure for obtaining a solution.

The Buckingham pi theorem states that the number of dimensionless and independent quantities required to express a relationship among variables in any phenomenon is equal to the number of quantities involved minus the number of dimensions in which those quantities may be measured' (Fox and McDonald, 1992). Mathematically speaking, if there is a physically meaningful equation involving a certain number (n) of physical variables, then the original equation can be rewritten in terms of a set of $p = n - k$ dimensionless parameters ($\pi_1, \pi_2, \dots, \pi_p$) constructed from the original variables (Hart, 1995), (Here k is the number of physical dimensions involved i.e. Mass, Length and Time which in this study, $k = 3$).

The application of mathematical models in different aspects of agricultural engineering including tillage operations (Fielke, 1999), spraying machines (Teske *et al.*, 1991), crop handling machines (Gorial and O'Callaghan, 1991), harvesting (Baruah and Panesar, 2005*a and b*) and many versatile topics on post harvesting aspects have been successfully attempted such as; modeling flow rate of egusi-melon (*Colocynthis citrullus*) through circular horizontal hopper orifice (Asoegwu *et al.*, 2010); modeling the grain cleaning process of a stationary sorghum thresher (Simonyan *et al.*, 2006), experimental and numerical study of the drying process and energy requirements of a hybrid convective vegetable crop dryer (Nwakuba, 2017) and development of a model to describe infrared radiative and convective drying characteristics of onion slices for optimum management of operation parameters (Jain and Pathare, 2004).

A critical step to optimize agricultural processing is to characterize, understand and predict it by analysis and modeling. With predictive analysis, useful data like cost, energy consumption, efficiency, and profit could be obtained, and models regarding agricultural processing operations such as energy for cutting vegetables could be established. Cantos *et al.* (2001) developed an induction modeling method to predict and characterize the increase of resveratrol (a type of natural phenol, produced by several plants in response to injury) content within table grapes by applying Ultra Violet irradiation pulses, in a study conducted to establish the basis for a potential usefulness of UV irradiated grapes to develop an enriched red wine. A combined respiration rate model for predicting and optimizing the shelf life of apples has been developed and verified based on the principles of enzyme kinetics, for dependence of oxygen and carbon dioxide and also based on the Arrhenius equation, for dependence on storage temperature (Mahajan and Goswami, 2001).

For the specific agricultural processing such as drying, Jain and Pathare (2004) have developed a model to describe infrared radiative and convective drying characteristics of onion slices for optimum management of operation parameters and prediction of performance of a thin layer drying system. Sabarez and Price (1999) have tested a model which is a numerical solution based on Fick's law. With the model, high quality drying data was obtained for the dehydration of plums as a function of temperature. Other research has been conducted to study the drying kinetics of apples in a tunnel dryer as affected by various pretreatments, and to predict drying rates of apple by evaluating a time-dependent model of drying process (Goyal and Bhargava, 2008). Also, Nwakuba (2017) developed prediction models for determining the drying process and energy requirements of a hybrid convective vegetable crop dryer. Tomato, pepper and okra were used in validating the developed models.

Additionally, a simplified plate drying model has been used to simulate the intermittent drying of mushroom and to determine the optimum tempering duration for the drying process (Cao *et al.*, 2004). For storage and packaging, by utilizing the relationship between the rate of oxygen uptake and oxygen concentration for tomato fruit at different stages of ripening, which was described as a continuous mathematical function, novel prediction models for optimization of oxygen concentration in the package have been developed (Cameron *et al.*, 1989). Talasila and Cameron (1997) have developed a mathematical model to predict the influence of packaging and storage variables on the rate of free volume change. The model predictions were used to suggest methods for controlling the rate of free-volume change of a flexible, hermetic storage and packaging system for tomatoes. Other study has been conducted to predict the effect of temperature fluctuations on oxygen and carbon dioxide levels in passive and active modified atmosphere packaging (Charles *et al.*, 2005). On energy requirement for cutting agricultural crops, few researchers like Somsen *et*

al. (2004), Ferraz *et al.* (2007) and Emadi *et al.* (2007) have attempted studies on the numerical and experimental measurements of the energy needed for cutting crops.

Emadi, *et al.* (2007) attempted the modeling of mechanical peeling of two varieties of pumpkin (Jap and Jarrahdale) on the basis of energy consumption. An energy consumption model of peeling process is required to optimize the main factors influencing the process as well as to limit peeling waste and consumed energy. The mechanical peeling process using an abrasive-cutter brush which applies both abrasive and cutting forces was modeled. Three variables, namely, angular velocities of abrasive-cutter brush (ω_p), the degree of unevenness of produce surface (ϕ), and the shape of the abrasive-cutter brush (λ), were chosen as independent variables.

In the development of the model, the assumptions applied were: a) Removing peel is assumed to occur in layers and in the form of chips. b) Peeling rate is in linear proportion to peeling energy. c) The angular velocity of product is assumed to be zero. d) The size and the weight of products for each variety are assumed to be the same and constant. Since mechanical peeling is carried out mostly on the basis of applying abrasive and cutting forces, the peeling process was split into two main stages i.e. fracturing of the skin and scratching along removing the peel as formed chips which are the main energy expenditures in mechanical peeling using abrasive-cutter brush.

The total energy expenditure (P_t) during the peeling process by abrasive-cutter brush is the sum total of the power required for cutting and scratching skin as given in Equation 2.11.

$$P_t = \frac{1}{\eta_c} (p_1 + p_2) \quad 2.11$$

Source: (Emadi *et al.*, 2007)

Where, P_1 and P_2 are the required power for fracturing and scratching skin respectively, in N.mm/min and η_c is total peeling efficiency.

The output of the model is kept as P_{rate} which is function of P_t and integrating all components using factorial technique on the basis of those three independent variables gave the general format of the model as expressed in Equation 2.12.

$$P_{rate} = C_0 + C_1 W_p + C_2 \phi + C_3 \lambda \quad 2.12$$

Source: (Emadi *et al.*, 2007)

where, C_0 to C_3 are the model coefficients; W_p =angular velocities of abrasive-cutter brush; ϕ = the degree of unevenness of produce surface; λ =shape of the abrasive-cutter brush.

The developed model was verified using the experimental results of peeling by abrasive-cutter brush for the two varieties of pumpkin named Jarrahdale and Jap. The experiments were conducted on three independent variables including coarseness of abrasive-cutter brush (coarseness: very coarse, coarse, mild, and fine expressed in Figure 2.15a), the rotational velocity of the peeler head (speed: 400, 550, 700, and 850 rpm), and the peeling location on the product (location: top, top-side, bottom-side, bottom as shown in Figure 2.15b). The rotational velocity of the produce was kept fixed at 5 rpm. Also, the overlap of the brush and produce was considered fixed and equal to 10 mm for all runs. The running time of the experiments was 5 minutes and this was long enough to cover the necessary peeling time. The results in Figure 2.16 showed that coefficients of determination between predicted and experimental values of the Jap (0.9669) and Jarrahdale (0.9372) were statistically significant as indicative of high R^2 values as expressed by (Equations 2.14 and 2.15). It is concluded that the relationship among different parameters of the product and peeling tool and their effect on the peeling rate would be industrially applicable.

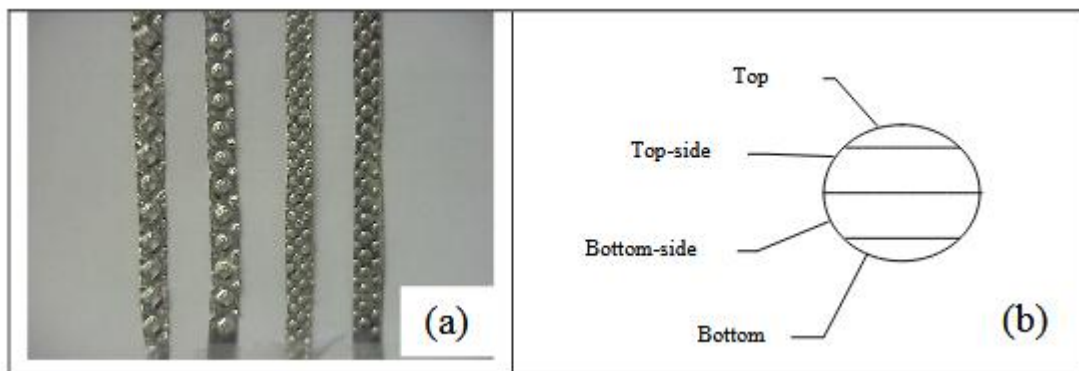


Figure 2.15: a) The strips with different type of coarseness used for fabrication of the abrasive-cutter brush (from left: very coarse, coarse, mild, fine) b) Different parts of produce's location.

Source: Emadi *et al.* (2007)

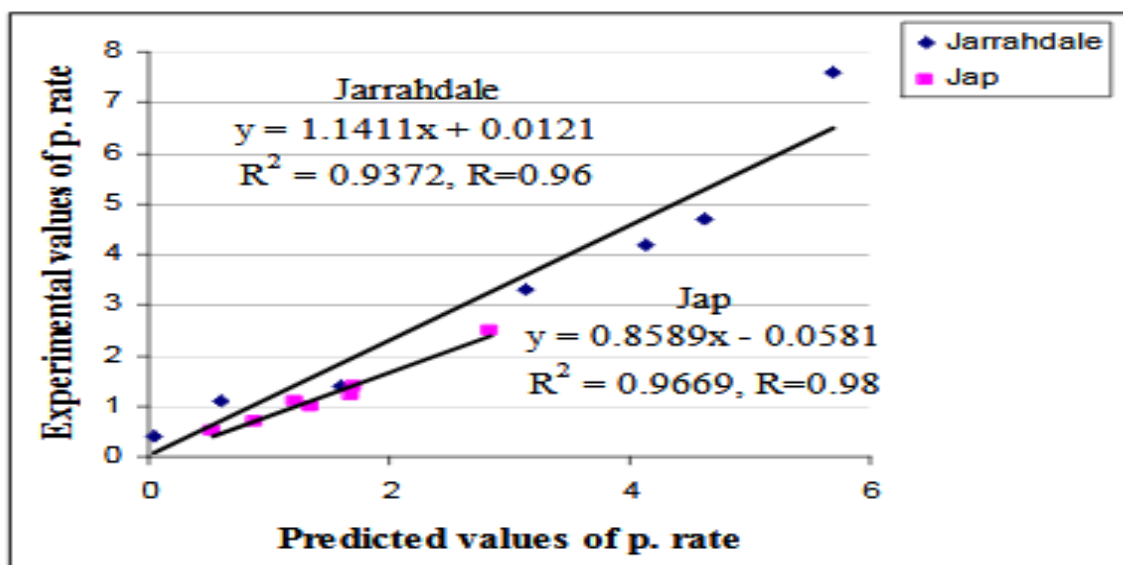


Figure 2.16: Experimental versus predicted values of p. rate (gr/min). Source: Emadi *et al.* (2007)

$$Y = 1.1411x + 0.0121; \quad R^2 = 0.9372, \quad \text{Jarradale variety} \quad 2.14$$

$$Y = 0.8589x - 0.0581; \quad R^2 = 0.9669, \quad \text{Jap variety} \quad 2.15$$

Where; Y = Experimental value of peeling rate; x = Predicted value of peeling rate

Asonye *et al.* (2019) developed a mathematical model for the cutting energy requirement of cocoyam using dimensional analysis based on the Buckingham pi theorem. Information on the optimum energy requirements for cutting cocoyam cormels is useful in order to estimate the amount of energy needed for the cutting operation with knowledge of some physical characteristics of the crop and machine factors. The independent variables involved in the model development were tool weight (w), height of tool drop (H_d), tool edge thickness (t), cutting speed (v), crop size(s), crop moisture content (ϕ), crop contact area(A) and crop density (σ). The developed model expressed in Equation 2.16 was validated with experimental data and a high coefficient of determination of $R^2 = 0.982$ between the predicted and measured values was established. The obtained predictive model proved appropriate for determining the cutting energy required for cocoyam cormels up to 98%.

$$0.658 \frac{tswH_d}{A} - 0.255 \frac{\sigma v^2 s^2 H_d}{\phi} + 10.62 \quad 2.16$$

Asonye *et al.* (2019).

Where: w = Tool weight (kg), H_d = Height of tool drop (m), t = Tool edge thickness (m), v = Cutting speed (m/s), s = Crop size (m), ϕ = Crop moisture content (%), A = Crop contact area (m^2) and σ = Crop density (kg/m^3).

2.10 Optimization of Agricultural Processes Using Response Surface Methodology (RSM)

Optimization literarily is defined as the action of making the best or most effective use of a resource or situation. The optimization of agricultural processing could be a valid way to relieve the problems of shortage of food and energy as well as the destructive impacts on environment. Agricultural processing, being defined as an activity which is performed to maintain or improve the quality of an agricultural product or to change its form or characteristics such as drying, storage, cutting, packaging, etc. (Sahay and Singh, 2004) could be optimized for better results.

Optimization is an essential tool for the efficient operation of processing systems and unit processes in agricultural and food technology yielding highly acceptable products. The response surface methodology (RSM) approach which is a statistical technique used by authors in most optimization studies has been found useful and efficient because it can determine the influence of various factors and their interactions on the indexes under investigation (response value) during technological operations, also it presents more excellent experimental designs and result expressions (Sarabia and Ortiz, 2009; Box and Draper, 1987).

With optimized agricultural processing, the resources needed such as energy could be reduced while the output of products such as high quality cut vegetables and finely brewed wine could be increased. Therefore, the situation of shortage of food and energy could be improved, and the impacts on environment due to energy consumption, such as greenhouse gas emissions, destruction of natural vegetation, habitat destruction, etc., could be relieved.

Optimization can be carried out in several ways. Most popular is the one-variable-at-a-time approach. This approach is however extremely inefficient in locating the true optimum when interaction effects are present. To overcome the problems with interaction effects, efficient medium will be achieved when mathematical optimization techniques in-terms of Response Surface Methodology (RSM) are applied (Hanan and Elrashied, 2011). In order to make use of generated data from important independent variables involved in a process and employ statistical techniques to develop empirical models useful in predicting optimal conditions for agricultural operations, response surface modeling is often used (Box and Draper, 2007).

Response Surface Methodology (RSM) is a powerful and efficient mathematical approach that is widely applied in the optimization of agricultural processes (Baş and Boyacı, 2007) such as in product quality improvement through RSM, (Zhen *et al.*, 2013 and Francis *et al.*, 2003) and process parameter optimization for production purposes (Öktem *et al.*, 2005).

Olusola *et al.* 2017 optimised the processing conditions of ‘ogi’ (pap) produced from maize using response surface methodology. The variable factors were soaking time (12–36 h) and sedimentation time (6–18 h) while the response factors were potential of Hydrogen (pH), Total titrable acidity (TTA), Viscosity at 60 rpm and sensory evaluation ogi (pap) were evaluated and optimized by response surface modelling. A central composite rotatable experimental design with two factors and five levels (−1.414, −1, 0, 1 and 1.414) was used. The results revealed that the pH, TTA and viscosity at 60 rpm reduced with increase in soaking and sedimentation time. There was no significance difference ($p > 0.05$) in the value obtained for sensory evaluation, however, these ranged from 2.60–3.87 (Aroma), 2.47–3.87 (Taste), 2.60–4.67 (Colour) and 2.60–4.07 (Consistency), respectively. The predicted optimum soaking and sedimentation time were 16 and 8 h, respectively. The desirability value was 0.99. The researchers suggested that ogi production with desired qualities is achievable at total time of 24 h. Also, varying the soaking and sedimentation time have tendency to affect the quality of ogi.

Edmondson (1991) provided an interesting application of Response Surface Methodology (RSM) to greenhouse experiments and presented some valuable insights into the use of RSM in an

agricultural setting versus an industrial one. Schmidt, *et al.* (1979) investigated the effects of cysteine and calcium chloride on the textural and water-holding characteristics of dialyzed whey protein concentrates gel systems. These characteristics were measured by hardness (y_1), cohesiveness (y_2), springiness (y_3), and compressible water (y_4). The researchers used a central composite design with five center-point replications and fitted a second-degree model to each of the four responses. Khuri and Cornell, (1996) applied a multi response optimization technique to the simultaneous maximization of the four responses, namely y_1 , y_2 , y_3 and y_4 in Schmidt, *et al.* (1979) experiment. Evans *et al.* (1982) considered data of seed-germination percentages after four weeks incubation of four plant species in response to 55 alternating and constant-temperature regimes in dark laboratory germinators and fitted a second-degree model to the data from each of the four species.

2.11 Major Findings from Literature

From the literatures reviewed on the science of cutting agricultural crops and the energy required for the operation of cutting vegetables, major findings by the researcher can be summarized into the under listed.

- Agricultural products in general often occur in sizes too large to be used, and therefore they need to be reduced and put into different sizes and shapes like cubes, thin slices or rings to facilitate further processing which include drying, packaging, extraction, expression, reduction in heat treatment periods, transportation and storage. The size reduction operations include grinding and cutting if the material is a solid (Nwakuba *et al.*, 2016; Wilhelm *et al.*, 2004; Sitkei, 1986; Arinze *et al.*, 1990; IFPA, 2000; Mohsenin, 1980).
- Cutting is a size reduction operation as well as an energy consuming activity. It involves the breakdown of large pieces of agricultural products into smaller pieces, representing the operation of reducing geometrical dimensions of particles following some exterior mechanical actions. Cutting of agricultural materials is one of the most frequent operations carried out during agricultural technological processes and is always applied during harvesting, separation and subsequent processing of plant components (Fellows, 1996; Hui, 2006). Also, in the preparation of fodder, cutting, with significant energy consumption is the main operation. During cutting, a cutting edge penetrates into a material, overcoming its strength and resistance, thereby separating it. During this process, various deformations occur within the material, and energy is being consumed in relation to such factors as the physical characteristics of the vegetable crops, machine parameters, the cutting edge and the kinematics of cutting (Dempsey and McGorry, 2014; Panainte *et al.*, 2017).

- Blade sharpness, slicing angle, contact area, depth of cut, cutting speed, height of tool drop, knife construction material, tool weight etc. and the engineering properties of vegetables such as moisture content, average diameter, orthogonal dimensions and fibre orientation etc. have been identified as some of the parameters affecting the energy requirements for cutting agricultural crops (Szabo *et al.*, 1987; Zhou and McMurray, 2011; Szot *et al.*, 1987; Beirne, 2000; Nadulski, 2001; Ciulica and Rus, 2011; Fraczek and Mudryk, 2007; Sykut *et al.*, 2005).
- Different researchers have worked on either the development of new cutter or modification of existing cutters for agricultural crops. These were done in order to reduce time and energy consumption, eliminate drudgery or improve overall efficiency of the cutting process. Such cutters include works done by (Tony *et al.*, 2014; Ogbobe *et al.*, 2007; Shittu *et al.*, 2017; Hrishikesh *et al.*, 2013; Manjunath and Kalyaniradha, 2017; Sonawane *et al.*, 2011, Anyanwu *et al.*, 2018; Aremu *et al.*, 2017; Kamaldeen and Awagu, 2013).
- Data related to the cutting energy of different Agricultural crops is scarce, even though such data is important in the design of cutters. Less work has been performed on energy involved for cutting of different food materials and limited published literatures on specific energy requirement in cutting of fruits and vegetables are available. Furthermore most of the available works on cutting are on exotic vegetables, very little work has been carried out on indigenous crops i.e. crops of African and Nigerian origin (Saravacos and Kostaropoulos, 2002; Brown *et al.*, 2005; Mitcham *et al.*, 1996).
- Some researchers have studied the post-harvest operation of cutting Agricultural crops with a view to estimating the energy involvement during the cutting operation; such works include; Singh *et al.* (2016) (potato, raddish, carrot, pepper, onion, pointed gourd, bitter gourd, cucumber and aubergine); Abdullah *et al.* (2015) (grape varieties); Elzbieta and Agnieszka (2012) (pepper varieties); Agnieszka and Elzbieta (2016) (black raddish); Ciulica and Rus (2011) (Carrots) and Lurie and Crisosto (2005) (Carrot).
- The application of mathematical models in different aspects of agricultural engineering including tillage operations (Fielke, 1999), spraying machines (Teske *et al.*, 1991), crop handling machines (Gorial and O'Callaghan, 1991), harvesting (Baruah and Panesar, 2005a and b) and many versatile topics on post harvesting aspects have been successfully attempted, with a few attempts made at modeling cutting processes (Somsen *et al.*, 2004; Ferraz *et al.*, 2007). Also, some researchers used the dimensional analysis based on the Buckingham's pi theorem as veritable instrument (Bahrami *et al.*, 2006) in establishing prediction equations of various systems such as; the development of screw-conveyor performance models using dimensional analysis, (Degrimencioglu and Srivastava, 1996); a mathematical model for predicting output capacity of selected stationary grain threshers, (Ndirika, 2006); modeling flow rate of Egusi-melon (*Colocynthis citrullus*) through circular horizontal hopper orifice, (Asoegwu *et al.*,

2010); a mathematical model for predicting the cracking efficiency of vertical-shaft centrifugal palm nut cracker, (Ndukwu and Asoegwu, 2011) and a mathematical model for predicting the cutting energy requirement for cocoyam, (Asonye *et al.*, 2019)

- Optimization of agricultural processes using Response Surface Method (RSM) has been successfully utilized in different agricultural processes by different researchers aimed at maximizing resources such as energy and producing highly efficient processes and products. (Sarabia and Ortiz, 2009; Box and Draper, 1987; Olusola *et al.*, 2017; Edmondson, 1991; Schmidt *et al.*, 1979; Khuri and Cornell, 1996; Khuri and Conlon, 1981 and Evans *et al.*, 1982).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

The materials used in the course of this study include the selected agricultural crops, instruments and equipment involved in the experimentations.

3.1.1 Selected agricultural crops.

Four crops of distinct characteristics were chosen for this study. These crops were selected because they are indigenous to the area of study. Also, they are listed among crops with least research attention. The selected crops are; cocoyam (*Colocasia esculenta*), okra (*Abelmoschus esculentus* L.), onion (*Allium cepa.*) and garden egg fruit (*Solanum macrocarpon*). Plate 3.1 shows the pictures of the cross-sectional cut-views of the selected crops.

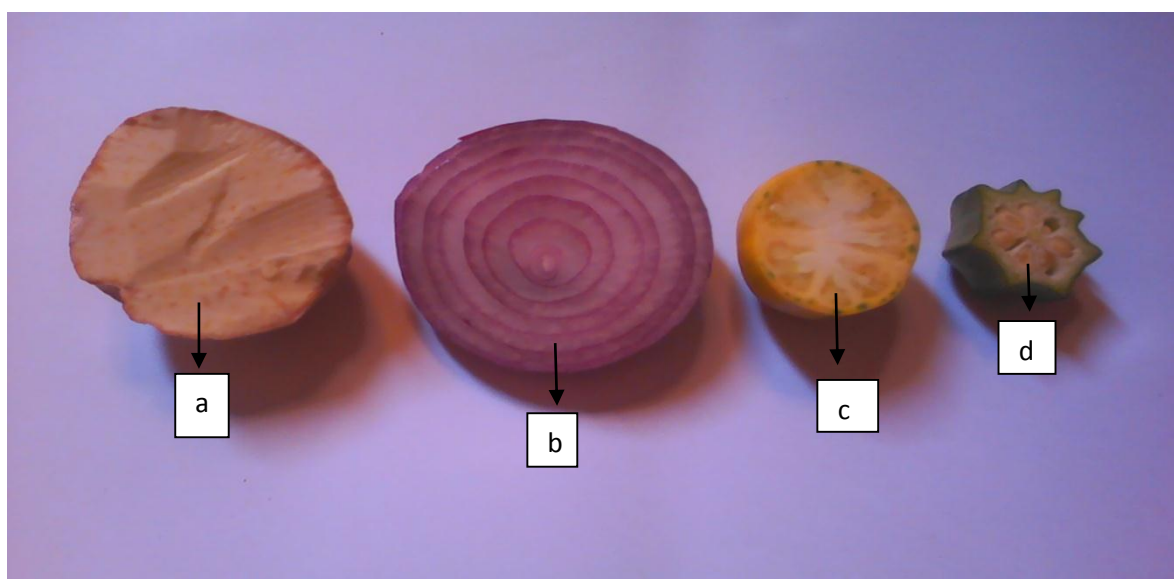


Plate 3.1: Cross-sectional cut views of experimental samples:

a = cocoyam; b = onion; c = garden egg; d = okra

3.1.2 Materials, instruments and equipment

Materials and instruments used in the course of the study include: a developed automated cutter, a digital hardness tester (Model FHT 1122, Landtek) (range 0.1 – 200N), a bench laboratory oven (Model DHG – 9101) (sensitivity 50 – 300^oc) shown in Plate 3.2, moisture cans, a digital vernier caliper (Mitutoyo, RDDC 706) (range 0 – 150mm), A digital weighing balance (Model EHA 251, Camry) (range 0.01 – 4100g), Stainless steel knives of different cutting angles ranging from 20^o to 48^o, Masking tape and markers, A clean towel, A pair of scissors and hand gloves. Plate 3.3 shows the picture of some of the materials used in the course of the study.



Plate 3.2: A bench laboratory oven (Model DHG – 9101) (range 50 – 300^oc) for the moisture content test



Plate 3.3: Other materials used in the course of the study.

a = pair of dividers, b = marker; c = metre rule (range 1 -30cm); d = hand gloves; e = digital weighing scale (range 0.01 – 4100g)

3.1.3 Study area

Nigeria is a country situated along the Gulf of Guinea. Most of the country is tropical and receives a lot of rainfall, but the very northeast part of the country located in the Sahel savannah is extremely dry. This allows the country to have some contrast in the plants and crops that are being grown (Adeyemi *et al.*, 2015). The present study was carried out in the Owerri west local government area of Imo state, Nigeria shown on the map displayed in Figure 3.2. The Owerri west local government has an area of 295 km² and a population of 99,265 at the 2006 census. The chief occupation of the people is farming.

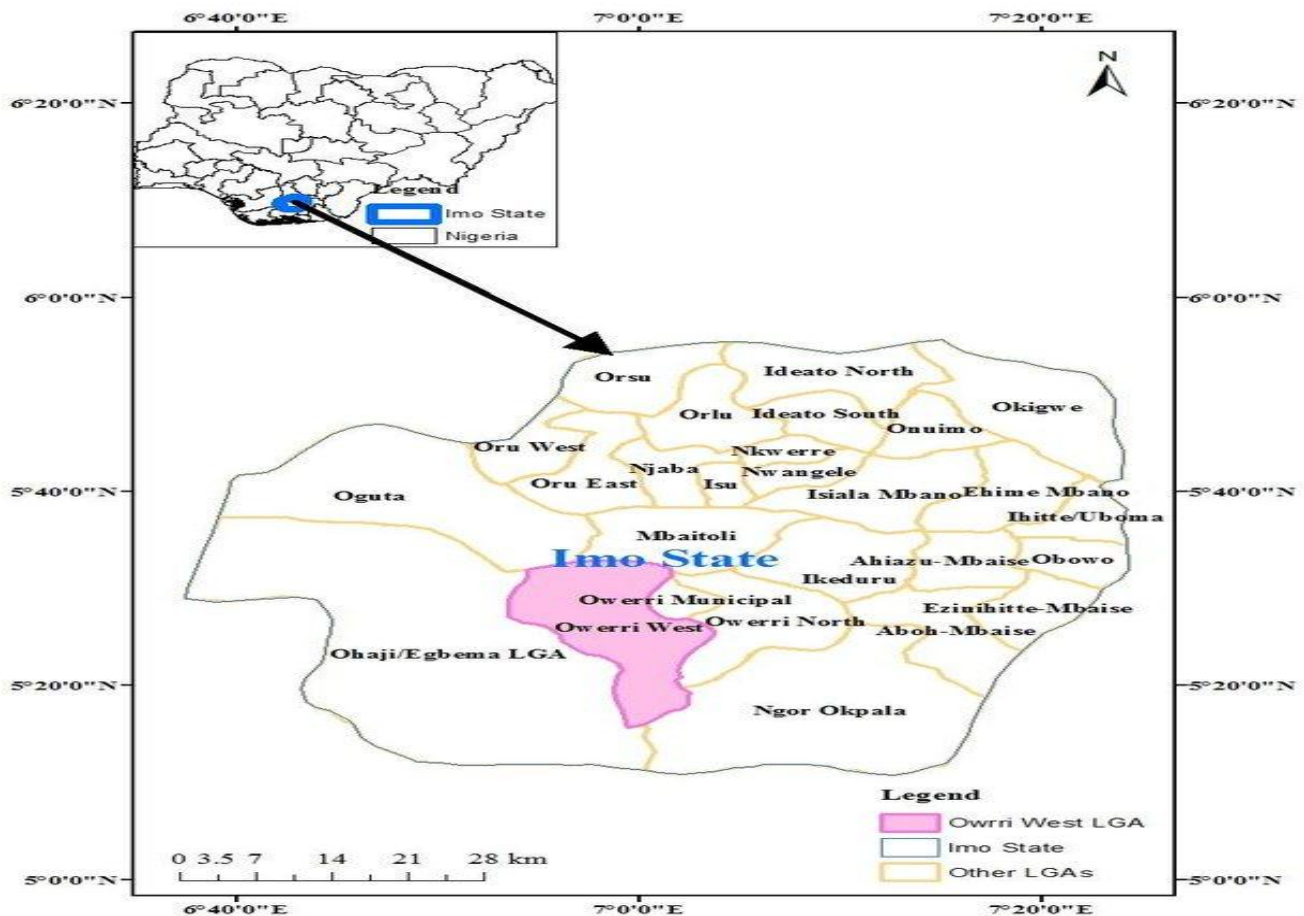


Figure 3.1: Geographical map of Nigeria showing the study area (Owerri West Local Government Area.). Source: Adeyemi *et al.* (2015).

3.2 Methods

3.2.1 Model development for the cutting energy requirement of the selected crops

In the development of the model for the predictive equations for the cutting energy requirements of the selected agricultural crops, the first step was to identify all the possible factors involved in the physical process of cutting agricultural crops, afterwards certain assumptions were made which would help in reducing the number of involving parameters in the model design for the selected crops.

3.2.1.1 Theoretical development of predictive models for cutting energy of selected crops

Factors affecting the cutting energy of crops obtained from literature include tool parameters like (sharpness, tool width, edge thickness, tool weight, height of tool drop, distance of cut, rigidity of cutting tools and knife speeds) and physical properties of the plant material like (crop variety, size, maturity stage, crop moisture content, crop density, fiber orientation) (Szot *et al.*, 1987; Nadulski, 2001; McGorry *et al.*, 2003; Blahovec, 2007; McCarthy *et al.*, 2007 and Atkins, 2009).

In the development of the model, dimensional analysis was employed which is a technique used in identifying factors involved in a physical situation and forming a relationship among them. However, dimensional analysis based on the Buckingham pi theorem was adopted (Fox and McDonald, 1992) as expressed in Equation 3.1.

$$\begin{aligned} \text{i.e. if } N &= \text{number of variables involved in a physical situation} \\ x &= \text{number of dimensions in which quantities may be expressed (3), M, L, T} \\ n &= \text{number of dimensionless groups} \\ \text{Hence, } n &= N - x \end{aligned} \tag{3.1}$$

However, due to the large number of variables influencing the energy of cut of the selected crops assumptions will be made in order to bring these large numbers to a reasonable and manageable number (Simonyan *et al.*, 2006).

3.2.1.2 Assumptions made in model development of the selected crops

- Variables that are design parameters such as crop size and tool weight which are measurable were considered.
- Variables that are functions of other variables were not considered e.g. volume which is a function of crop size. However, cutting speed which is a function of time was considered instead of time because time (T) has already been considered as one of the physical dimensions.
- The fiber orientation and crop variety are considered negligible in the model development. These variables do not have significant effect on the cutting energy requirement for the crops under study. (Emadi *et al.*, 2007; Simonyan *et al.*, 2006)

3.2.1.3 Development of the functional energy equation for the selected crops

These assumptions helped in reducing the number of variables involved to the under listed as these were considered to have greater influence on the energy of cut of the selected crops and are measurable. The chosen variables were: Tool force (w), Height of tool drop (H_d), Tool edge

thickness (t), Cutting speed (v), Crop size(s), Crop moisture content (ϕ), Crop contact area (A) and Crop density (σ).

Having identified the core variables influencing the energy required for cutting the selected crops, Equation 3.2 represents the functional equation of the predictive model.

$$\text{i.e } E = f(w, H_d, t, v, s, \phi, A, \sigma) \quad 3.2$$

where E = cutting energy (J)

w = Tool force, H_d = Height of tool drop, t = Tool edge thickness, v = Cutting speed, s = Crop size, ϕ = Crop moisture content, A = Crop contact area and σ = Crop density.

Three primary dimensions M= Mass, L= Length, T= Time were chosen in the description of the variables. From the Buckingham pi theorem (Fox and McDonald, 1992) the total number of dimensionless groups to be formed is as given in Equation 3.1 above.

$$\text{i.e. } n = N - x$$

N = number of variables involve in the situation studied = 9

x = number of dimensions for describing these variables = 3

$$\text{Hence, } n = 9 - 3 = 6$$

Hence six dimensionless groups were formed namely; $\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5$ and Π_6 . In determining the dimensionless groups, the following procedure was adopted (Fox and McDonald, 1992).

The variables utilized in the establishment of the model equation for the cutting energy of selected crops were expressed in terms of their dimensions as shown in Table 3.1.

Table 3.1: List of variables and their dimensions.

S/N	VARIABLE	SYMBOL	UNIT	DIMENSION
1	Energy	E	kgm ² s ⁻²	ML ² T ⁻²
2	Tool force	w	kgms ⁻²	MLT ⁻²
3	Height of tool drop	H _d	m	L
4	Tool edge thickness	t	m	L
5	Cutting speed	v	ms ⁻¹	LT ⁻¹
6	Crop size	s	m	L
7	crop moisture content	φ	φ	M ⁰ L ⁰ T ⁰
8	Crop contact area	A	m ²	L ²
9	Crop density	σ	kgm ⁻³	ML ⁻³

The dimensional matrix of the variables is shown in Table 3.2. This is needed to develop the indices of the involved variables.

Table 3.2: Dimensional matrix of variables

S/N	VARIABLE	SYMBOL	M	L	T
1	Energy	E	1	2	-2
2	Tool force	w	1	1	-2
3	Height of tool drop	H _d	0	1	0
4	Tool edge thickness	t	0	1	0
5	cutting speed	v	0	1	-1
6	Crop size	s	0	1	0
7	Crop moisture content	φ	0	0	0
8	Crop contact area	A	0	2	0
9	Crop density	σ	1	-3	0

From Table 3.2, it was seen that φ is dimensionless and therefore excluded from the dimensionless terms determination and is to be added later (Simonyan *et al*, 2006) while the other variables were combined to form the Π groups. Cutting speed (v), tool force (w) and crop size (s) were selected as the major parameters (i.e. recurring set) because they contained all the primary dimensions involved in this problem and their combination does not form a dimensionless group. Having selected w, v

and s as the recurring set, the exponents a , b and c are attached to them respectively so that when their product $w^a v^b s^c$ divide the remaining variables E , H_d , t , A and σ , the dimensionless groups Π_1 , Π_2 , Π_3 , Π_4 and Π_5 are obtained as given in Equations 3.3 to 3.7 (Ndirika, 2006; Simoyan *et al.*, 2006; Asoegwu *et al.*, 2010; Ndukwu and Asoegwu, 2011). This is the basis of the Buckingham pi theorem of dimensionless groups.

$$\Pi_1 = \frac{E}{w^a v^b s^c} \quad 3.3$$

$$\Pi_2 = \frac{H_d}{w^a v^b s^c} \quad 3.4$$

$$\Pi_3 = \frac{t}{w^a v^b s^c} \quad 3.5$$

$$\Pi_4 = \frac{A}{w^a v^b s^c} \quad 3.6$$

$$\Pi_5 = \frac{\sigma}{w^a v^b s^c} \quad 3.7$$

where a , b , and c are exponents needed to make the groups non-dimensional. The variables are substituted with their dimensions and the non-dimensional Π s are replaced with $M^0 L^0 T^0$ which a dimensionless group is. In order to obtain values for the exponents, the principle of dimensional homogeneity is used to equate the dimensions on each side of the equations of the Π groups.

Equation 3.3 being expressed in terms of the dimensions on both sides becomes Equation 3.8.

$$M^0 L^0 T^0 = \frac{ML^2 T^{-2}}{(MLT^{-2})^a (LT^{-1})^b L^c} \quad 3.8$$

Cross- multiplying Equation 3.8 gives Equation 3.9.

$$M^0 L^0 T^0 ((MLT^{-2})^a (LT^{-1})^b L^c) = ML^2 T^{-2} \quad 3.9$$

Using dimensional homogeneity for M , L and T , the exponents a , b and c are got in Equations 3.10, 3.11, 3.12, and 3.13.

$$\text{For } M; M^{0+a} = M^1$$

$$0 + a = 1$$

$$a = 1 \quad 3.10$$

$$\text{For } L; L^{0+a+b+c} = L^2$$

$$0+a+b+c = 2; \text{ from 3.10, } a=1$$

$$1+b+c = 2$$

$$b+c = 2-1 = 1$$

$$b+c = 1 \tag{3.11}$$

for T; $T^{0-2a-b} = T^{-2}$

$$-2a - b = -2$$

Since a = 1

$$-2(1) - b = -2$$

$$-b = -2+2 = 0, b = 0 \tag{3.12}$$

From 3.11, $b + c = 1$, put $b=0$

$$0+c=1; c=1 \tag{3.13}$$

Hence, $a = 1, b = 0, c = 1$; replacing the exponents with their values, Π_1 becomes Equation 3.14.

$$\Pi_1 = \frac{E}{W^1V^0S^1} = \frac{E}{WS} \tag{3.14}$$

Similarly, solving the Π_2 group, Equation 3.4 is expressed as Equations 3.15 and 3.16.

$$\Pi_2 = \frac{H_d}{W^aV^bS^c}$$

Substituting the variables for their dimensions

$$M^0L^0T^0 = \frac{L}{(MLT^{-2})^a(LT^{-1})^bL^c} \tag{3.15}$$

$$M^0L^0T^0((MLT^{-2})^a(LT^{-1})^bL^c) = L \tag{3.16}$$

Applying dimensional homogeneity for M, L and T, the exponents a, b and c are got in Equations 3.17 to 3.20.

$$\text{For M; } M^{0+a} = M^0 \tag{3.17}$$

$$0+a = 0; a=0 \tag{3.18}$$

$$\text{For L; } L^{0+a+b+c} = L^1 \tag{3.19}$$

$$0+a+b+c = 1$$

From 3.18, $a = 0$

$$b + c = 1 \tag{3.20}$$

for T; $T^{0-2a-b} = T^0$

$-2a-b = 0; -2a = b$

From 3.18, $a=0$

$-2(0) = b, b = 0$

From 3.20, $b + c = 1, 0+c = 1; c=1$

Hence $a=0, b= 0 c= 1$

Replacing the exponents with their values Π_2 becomes Equation 3.21.

$$\Pi_2 = \frac{H_d}{W^0V^0S^1} = \frac{H_d}{S} \tag{3.21}$$

Solving for the third dimensionless group Π_3 is expressed as Equations 3.22 and 3.23.

$$\Pi_3 = \frac{t}{W^aV^bS^c}$$

Substituting the variables for their dimensions

$$M^0L^0T^0 = \frac{L}{(MLT^{-2})^a(LT^{-1})^bL^c} \tag{3.22}$$

$$M^0L^0T^0((MLT^{-2})^a(LT^{-1})^bL^c) = L \tag{3.23}$$

Applying dimensional homogeneity for M, L, and T, the exponents a, b and c are got in Equations 3.24 to 3.27.

For M; $M^{0+a} = M^0 \tag{3.24}$

$0+a = 0; a=0 \tag{3.25}$

For L; $L^{0+a+b+c} = L^1 \tag{3.26}$

$0+a+b+c = 1$

From 3.25, $a= 0$

$b +c = 1 \tag{3.27}$

for T; $T^{0-2a-b} = T^0$

$-2a-b = 0; -2a = b$

From 3.25, $a = 0$

$$-2(0) = b, b = 0$$

From 3.27, $b + c = 1, 0 + c = 1; c = 1$

Hence $a = 0, b = 0, c = 1$

Replacing the exponents with their values, Π_3 becomes Equation 3.28.

$$\Pi_3 = \frac{t}{W^0 V^0 S^1} = \Pi_3 = \frac{t}{S} \quad 3.28$$

Solving for the fourth dimensionless group, Π_4 is expressed as Equations 3.29 and 3.30

$$\Pi_4 = \frac{A}{W^a V^b S^c}$$

Substituting the variables for their dimensions, Π_4 becomes,

$$M^0 L^0 T^0 = \frac{L^2}{(MLT^{-2})^a (LT^{-1})^b L^c} \quad 3.29$$

$$M^0 L^0 T^0 ((MLT^{-2})^a (LT^{-1})^b L^c) = L^2 \quad 3.30$$

Applying dimensional homogeneity for M, L and T, the exponents a, b and c are got in Equations 3.31 to 3.36.

$$\text{For M; } M^{0+a} = M^0 \quad 3.31$$

$$0 + a = 0; a = 0 \quad 3.32$$

$$\text{For L; } L^{0+a+b+c} = L^2$$

$$a + b + c = 2;$$

$$\text{from 3.32, } a = 0, b + c = 2 \quad 3.33$$

$$\text{For T; } T^{0-2a-b} = T^0$$

$$-2a - b = 0 \quad 3.34$$

From 3.32, $a = 0$

$$-2(0) - b = 0; b = 0 \quad 3.35$$

From 3.33, $b + c = 2$, put $b = 0$

$$0 + c = 2, c = 2 \quad 3.36$$

Hence, $a = 0, b = 0, c = 2$

Replacing the exponents with their values, Π_4 becomes Equation 3.37.

$$\Pi_4 = \frac{A}{W^0 V^0 S^2} = \Pi_4 = \frac{A}{S^2} \quad 3.37$$

Solving for the fifth dimensionless group, Π_5 is expressed as Equation 3.7 earlier stated.

$$\Pi_5 = \frac{\sigma}{W^a V^b S^c}$$

Substituting the variables for their dimensions, Π_5 becomes Equations 3.38 and 3.39.

$$M^0 L^0 T^0 = \frac{ML^{-3}}{(MLT^{-2})^a (LT^{-1})^b L^c} \quad 3.38$$

$$M^0 L^0 T^0 ((MLT^{-2})^a (LT^{-1})^b L^c) = ML^{-3} \quad 3.39$$

Applying dimensional homogeneity for M, L and T, the exponents a, b and c are got in Equations 3.40 to 3.42

$$\text{For M; } M^{0+a} = M^1$$

$$0+a = 1; a=1 \quad 3.40$$

$$\text{For L; } L^{0+a+b+c} = L^{-3}$$

$$a+b+c = -3 \quad 3.41$$

$$\text{From 3.40, } a=1$$

$$1+b+c = -3; b+c = -3-1 = -4 \quad 3.42$$

$$\text{For T; } T^{0-2a-b} = T^0$$

$$-2a-b = 0; \text{ from 3.40, } a = 1$$

$$-2(1) - b = 0; -2 = b$$

$$\text{From 3.42, } b+c = -4; \quad -2+c = -4; \quad c = -4+2 = -2$$

$$\text{Hence, } a=1, b = -2, c = -2$$

Replacing the exponents for their values, Π_5 becomes Equation 3.43.

$$\Pi_5 = \frac{\sigma}{W^1 V^{-2} S^{-2}} = \frac{\sigma V^2 S^2}{W} \quad 3.43$$

The functional relationship between the Π groups can be expressed as Equations 3.44 and 3.45.

$$\Pi_1 = f(\Pi_2 \Pi_3 \Pi_4 \Pi_5 \Pi_6) \quad 3.44$$

$$\Pi_1 = \frac{E}{wS}$$

$$\Pi_2 = \frac{H_d}{S}$$

$$\Pi_3 = \frac{t}{S}$$

$$\Pi_4 = \frac{A}{S^2}$$

$$\Pi_5 = \frac{\sigma V^2 S^2}{w}$$

$$\Pi_6 = \varphi$$

Combining these equations gives Equation 3.45, whose components are dimensionless.

$$\text{i.e. } \frac{E}{wS} = f\left(\frac{H_d}{S}, \frac{t}{S}, \frac{A}{S^2}, \frac{\sigma V^2 S^2}{w}, \varphi\right) \quad 3.45$$

Combining the dimensionless terms to reduce it to a manageable level (Shefii *et al.* 1996) by multiplication and/or division, we obtain Equations 3.46 to 3.48 which are dimensionless.

$$\Pi_{12} = \frac{\Pi_1}{\Pi_2} = \frac{E}{ws} \times \frac{s}{H_d} = \frac{E}{wH_d} \quad 3.46$$

$$\Pi_{34} = \frac{\Pi_3}{\Pi_4} = \frac{t}{s} \times \frac{s^2}{A} = \frac{ts}{A} \quad 3.47$$

$$\Pi_{56} = \frac{\Pi_5}{\Pi_6} = \frac{\sigma v^2 s^2}{w} \times \frac{1}{\varphi} = \frac{\sigma v^2 s^2}{w\varphi} \quad 3.48$$

The new dimensionless functional relationship becomes Equations 3.49 and 3.50.

$$\Pi_{12} = f(\Pi_{34}, \Pi_{56}) \quad 3.49$$

$$\frac{E}{wH_d} = f\left(\frac{ts}{A}, \frac{\sigma v^2 s^2}{w\varphi}\right) \quad 3.50$$

From Equation 3.50, the Equations for E are obtained as Equations 3.51 and 3.52.

$$E = wH_d \left(\frac{ts}{A}, \frac{\sigma v^2 s^2}{w\varphi}\right) \quad 3.51$$

$$E = f\left(\frac{tswH_d}{A}, \frac{\sigma v^2 s^2 H_d}{\varphi}\right) \quad 3.52$$

Equation 3.52 gives the cutting energy E , with all the parameters in Equation 3.2, as a function of two energy components $\frac{tswH_d}{A}$ and $\frac{\sigma v^2 s^2 H_d}{\varphi}$ which are represented as P and Q in Equation 3.53.

$$E = f(P, Q) \quad 3.53$$

3.2.1.4 Experimental procedure for cutting energy determination for selected crops

Samples of the understudied crops (cocoyam, onion, okra and garden egg) were bought from the Eke-Onunwa and Relief markets both in Owerri municipal local government area of Imo state, Nigeria. They were thoroughly cleaned of all impurities and unwholesome samples, thereafter sorted into varying size ranges for all the samples. Also, some physical properties were obtained at their initial moisture contents of $71.8 \pm 0.16\%$ (wb) (cocoyam); $89.41 \pm 0.4\%$ (wb) (okra); $86 \pm 0.4\%$ (wb) (onion) and $88.94 \pm 3.64\%$ (wb) (garden-egg) (AOAC, 2003). With the developed automated vegetable cutter, at different preset speeds and distance of cut for the different crop samples, the knife edge travels through the sample thereby cutting it. Cutting energy was calculated by measuring the surface area under the cutting force-deformation curve obtained by plotting cutting force-deformation data stored on an excel worksheet in the laptop computer. Plate 3.1 shows the experimental set-up of the cutting mechanism for the cocoyam sample. Appendices 3a, b and c show the experimental set-up for okra, onion and garden egg respectively.

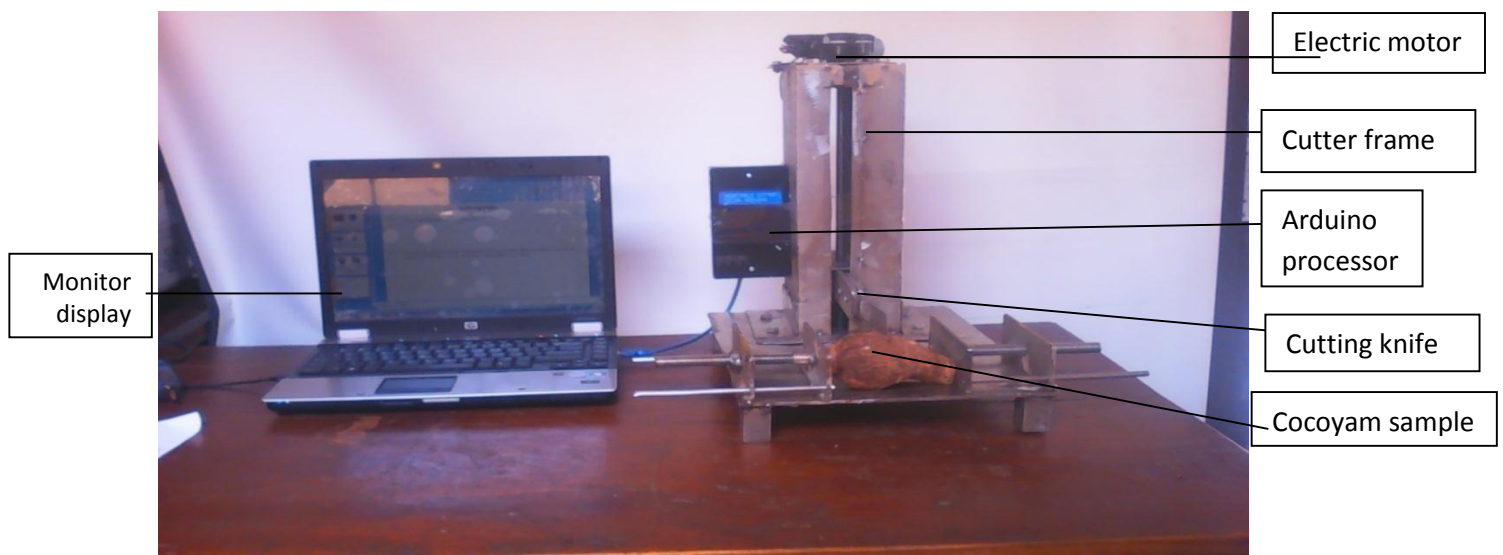


Plate 3.4: Experimental set-up of the cutting mechanism (for cocoyam)

3.2.1.5 Determination of validation parameters for predictive model of the selected crop samples

In the determination of validation parameters, every other parameter was held constant while the crop size varied. The selected tool edge thickness (t) was measured with a digital vernier caliper (Model 500-196, Mitutoyo Products, America; range 0 -150mm)). The weight (w) of the cutting tool was determined with an electronic weighing balance (Model GF-200, A & D company Ltd, Japan of an accuracy of ± 0.01 ; range 0.01 – 4100g). The distance of cut was measured with a meter rule (range 1 – 30cm). The crop density (σ) was determined by dividing the weight of the crop by the volume of water displaced when sample was placed inside a measuring cylinder. The orthogonal dimensions of the sample were determined with the digital vernier caliper (Model 500-196, Mitutoyo Products, America; range 0 – 150mm)). The crop contact area (A) was determined by multiplying the circumference at the point of cut (obtained by winding round with a tape and measuring out on the meter rule) with the major diameter of the crop sample. The moisture content of the crop samples was determined with the method described in AOAC (2003). Table 3.3 gives the values for the validation parameters for the selected crop samples.

Table 3.3: Values of validation parameters for selected crop samples

S/N	Validation parameters	Crop samples			
		Cocoyam	Okra	Onion	Garden-egg
1	Tool edge thickness (cm)	0.2	0.1	0.2	0.2
2	Weight of cutting tool (g)	300	23.1	100	100
3	Distance of cut (cm)	30	20	8.5	6.5
4	Crop density (g/cm ³)	1.35	1.107	0.97	1.11
5	Contact area (cm ²)	28.75	28.75	21.24	30.19
6	Initial moisture content (%wb)	71.8 \pm 0.4	89.41 \pm 0.4	86.0 \pm 0.4	88.9 \pm 3.64

3.2.1.6 Prediction energy equations for selected crop samples

The prediction energy equation was established by allowing one *P* or *Q* to vary at a time while keeping the other constant and observing the resulting changes in the function (Shefii *et al.*, 1996). This was achieved by plotting the experimental values of E against $P = \left(\frac{tswH_d}{A}\right)$ while keeping

Q constant. $P = \left(\frac{tswH_d}{A}\right)$ was evaluated by substituting the measured values for tool edge thickness (t), crop size(s), tool weight (w), height of tool drop (H_d) and crop contact area (A) into P . Also, E against $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ was plotted while keeping P constant. Values for $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ were obtained by substituting the measured values for crop density (σ), cutting speed (v), crop size(s), height of tool drop (H_d) and crop moisture content (ϕ).

3.2.2 Development of the automated cutter

The automated crop cutter consists of the hardware and software components. The hardware consists of the stainless base plate, the threaded shaft, bolts and nuts for joining component parts, the electric motor, the knife holder, the u-channel tube and the support stands. Arduino controlled processor automatically and effectively measures, records and stores cutting variables and other basic parameters with minimum human supervision, thus making the entire cutting process automated. Connecting to an electric power source switches on the cutter and a predetermined speed value is selected on the keypad. As the knife presses against the sample, the reactive force exerted on the load cell is amplified and measured. Connecting to a computer using Universal Serial Bus (USB) port, the measured values are relayed and Mathematical Laboratory (MATLAB) intercepts the values and plots the resulting graph of force of cut against time travelled which is used in calculating the energy of cut.

3.2.2.1: Design considerations in cutter development

A number of factors were considered in the development of the automated cutting machine. These include the food friendly properties of the materials for construction (especially the hardware component of the cutter). This is important because the agricultural products to be handled are food materials. Also, considering the function of the machine which is to cut, knife edges (sharp and thin with ability to penetrate the crop products) were prepared to be part of the cutter. Other considerations in designing the machine include, cutting resistance of the crops, speed of cut, maximum power requirement and power source.

3.2.2.2 Material selection and detailed description

The materials to be used in the course of the development of the machine were selected on the basis of the engineering properties of the materials, as well as the design considerations. All the component parts of the cutter were fabricated using stainless steel which has the following engineering properties as shown in Table 3.4.

Table 3.4: Engineering Properties of Stainless steel

Stainless steel properties	Property value
Carbon content	0.1 - 0.2%
Tensile strength	1300 MN/m ²
Thermal expansivity	$\times 10^{-6}\text{K}^{-1}$
Density	$7.7-8 \times 10^3 \text{ kg/m}^3$
Elongation	40%
Modulus of elasticity	193 GN/m ²

Furthermore, stainless steel material was selected for the design of all the component parts of the cutter(food handling equipment) because it has the following qualities among others: easy formability, exceptional mechanical strength, excellent heat resistant properties, prevents contamination and maintains freshness of food items, allows for easy cleaning, hence preventing any growth of dirt or bacteria, can withstand shock and abrasion, durable, resistant to corrosion and inert to any chemical produced during processing.

3.2.2.3 Basic design calculations

The following basic design calculations were made in developing the hardware components of the automated cutter.

3.2.2.3.1 Motor selection

In the selection of the electronic motor that will serve as the power house for the cutter, the formula for power expressed in Equation 3.52 was used to select the electronic motor for the cutter.

$$P = \frac{m(2\pi N)^3 r^2}{60} \quad (\text{Agbetoye and Balogun, 2009}) \quad 3.52$$

Where;

P = power required to operate the cutter (kW); m = mass of rotating components (kg)

N = number of revolutions of the shaft per minute (rpm); r = radius of gyration.

$$P = \frac{17.2529(2 \times 3.14 \times 1.326)^3 \times 0.01021^2}{60}$$

$$= 0.0166\text{KW} = 16.6 \text{ W}$$

Hence, an electronic windows shield motor Model ZD 1530 with a power rating of 12V, 17W was selected.

3.2.2.3.2 The base plate

This is considered the unit of the machine on which all the other components of the machine are supported. It was fabricated into 40mm x 40mm high strength Stainless steel plate of 8mm thickness (to withstand vibrations). Support stands were fabricated from 25mm² stainless steel pipe of 4cm height and welded to the four ends of the baseplate (for strength and stability). Hence, the total volume of stainless steel used for the base plates and support stand is expressed as Equation 3.53.

$$V_{TOTAL} = V_{base\ plate} + V_{support\ stands}$$

Where;

$$V_{base\ plate} = L . W . T \tag{3.53}$$

Where L = length (mm), W = width (mm), T = thickness (mm)

Hence total volume of stainless steel used for the base plate is;

$$V_{base\ plate} = 40\text{mm} \times 40\text{mm} \times 8\text{mm} = 12800\text{mm}^3 = 12.8\text{cm}^3$$

$$\text{Volume of a support stand} = 25\text{mm}^2 \times 0.4\text{m} = 10\text{mm}^3$$

$$\text{Total volume of stainless steel used for the 4 stands} = 10\text{mm}^3 \times 4 = 40\text{mm}^3$$

$$\text{therefore; } V_{TOTAL} = V_{base\ plate} + V_{support\ stands} = 12.8\text{cm}^3 + 0.04\text{cm}^3 = 12.84\text{cm}^3$$

3.2.2.3.3 U-channel tube

4 pieces of 5cm stainless steel angle iron of 5mm thickness and height 35cm was used to fabricate the U-channel along which the threaded shaft carrying the knife holder travels.

$$\text{Volumetric dimension of one angle iron} = L . W . t$$

Where L = length (mm), W = width (mm), t = thickness (mm)

$$L = 350\text{mm}, W = 50\text{mm}, t = 5\text{mm} \text{ (selected for strength and stability)}$$

$$\text{i.e. } L.W . t = 350 \times 50 \times 5 = 87500\text{mm}^3$$

For the 4 angle irons;

$$\text{Total volume of stainless steel used} = 4 \times 87500\text{mm}^3 = 350\text{cm}^3 \text{ of stainless steel for the angle irons}$$

3.2.2.3.4 Arduino

Arduino is an open-source platform used for building electronics projects shown in Plate 3.2. Arduino consists of both a physical programmable circuit board (often referred to as a microcontroller) and a piece of software, or IDE (Integrated Development Environment) that runs on your computer, used to write and upload computer code to the physical board.

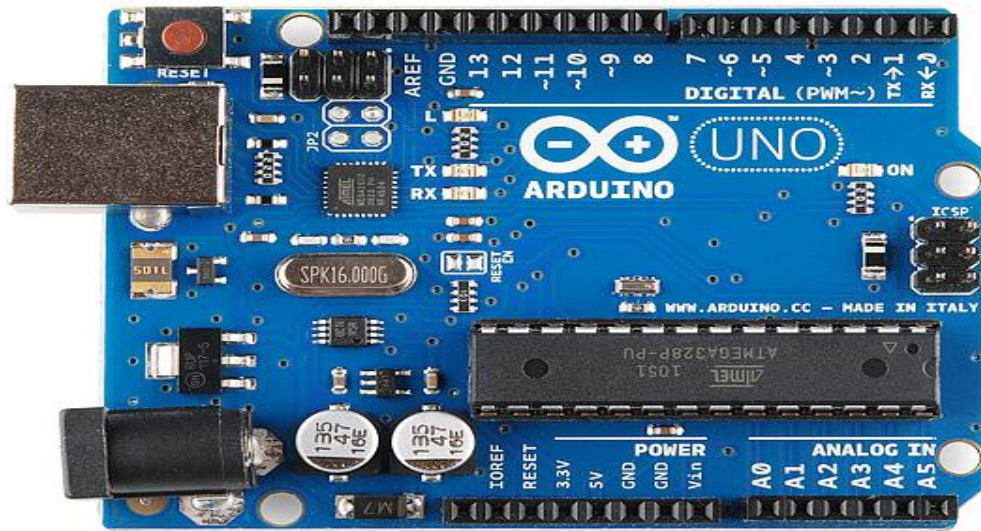


Plate 3.5: Arduino IDE (integrated Development Environment) Source: Rajakumar *et al.* (2018).

In the operations of the cutter, the Arduino serves as the heart of the controller unit. It receives signals from all sensors, processes them and saves their values.

3.2.2.3.5 Load cell (sensor)

Strain gauge load cells shown in Plate 3.4 are by far the most common type of load cell-based weighing system in recent times. Strain gauge load cell weighing systems convert weights into analog output signals that can be further conditioned to indicate weight in digital meters and control systems.

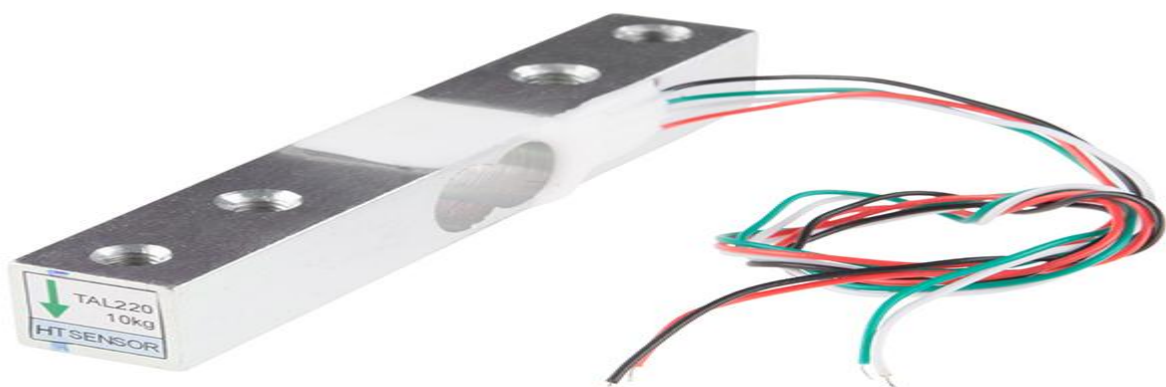


Plate 3.6: Load cell. Source: Sarah Al-Mutlag (2019)

3.2.2.3.6 Liquid crystal display (LCD)

The Liquid Crystal Display (LCD) shown in Plate 3.5 is the device through which data or information from the arduino will be viewed.



Plate 3.7: Display screen (LCDs). Source: www.circuitstoday.com

3.2.3 Detailed drawings of the automated cutter

The orthographic, isometric, pictorial, expanded and sectional views of the cutter are shown in Figures 3.2 to 3.6 respectively.

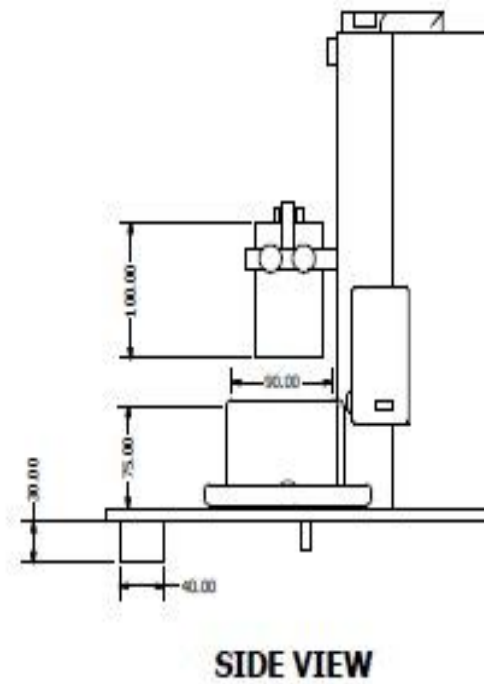
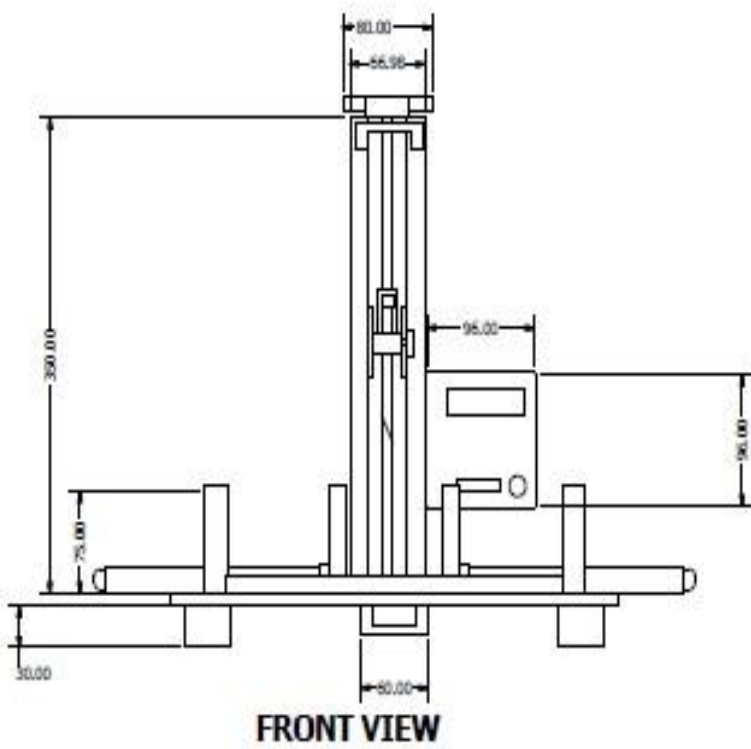
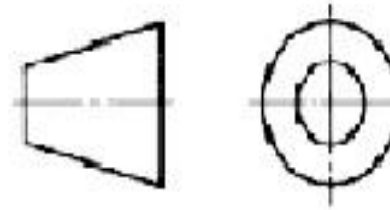
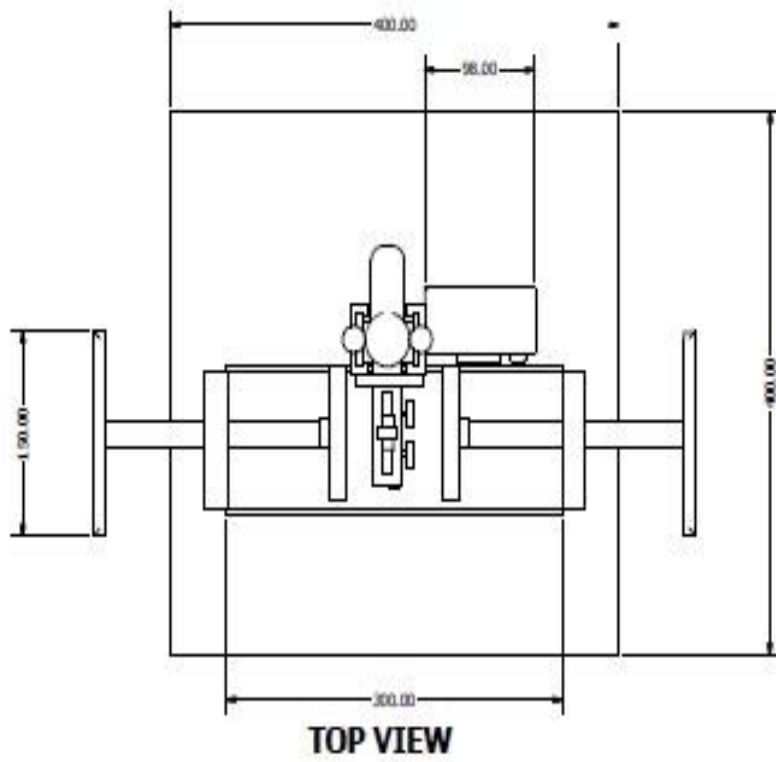


Figure 3.2: Orthographic views of the cutter

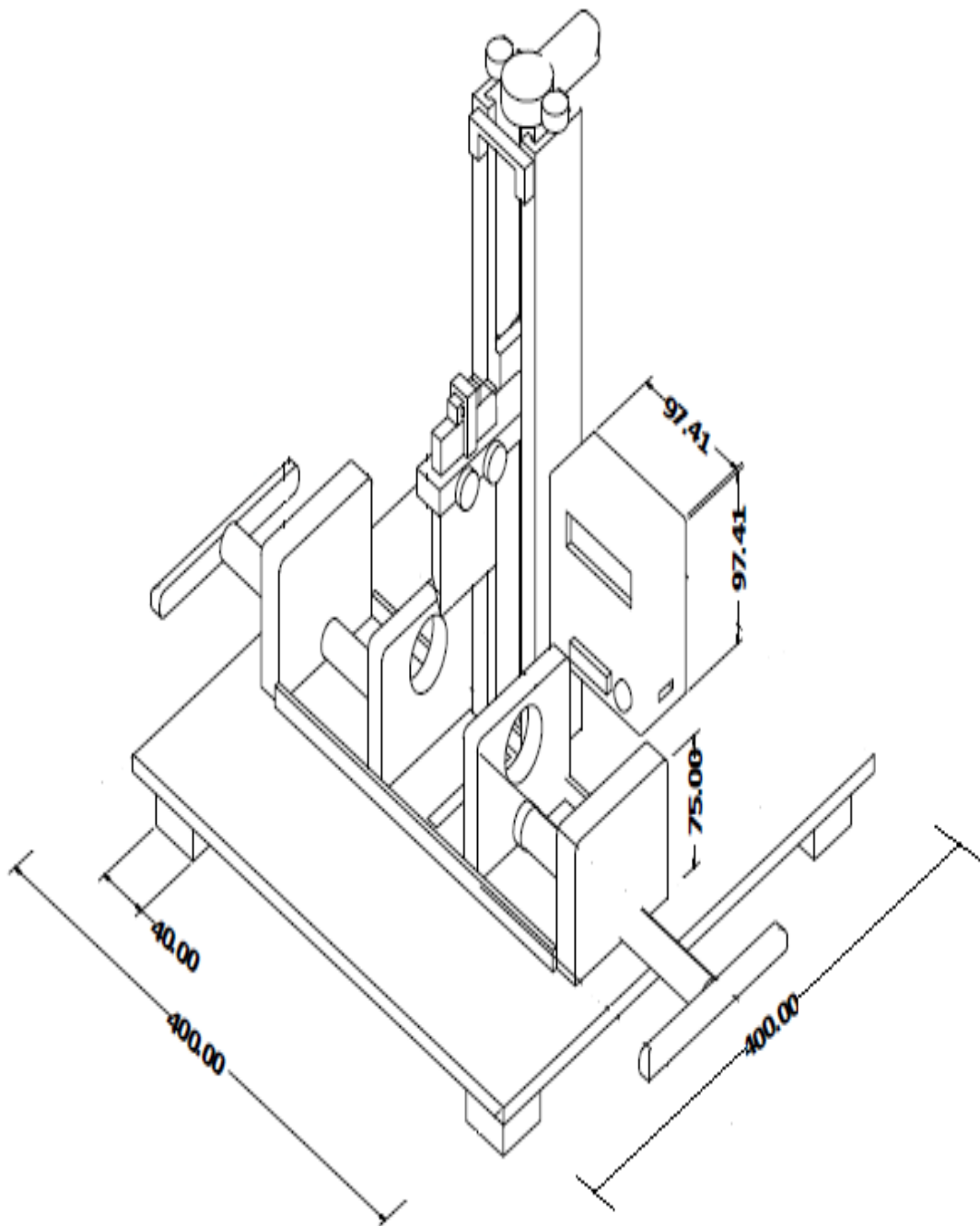


Figure 3.3: Isometric view of the automated vegetable cutter showing part dimensions

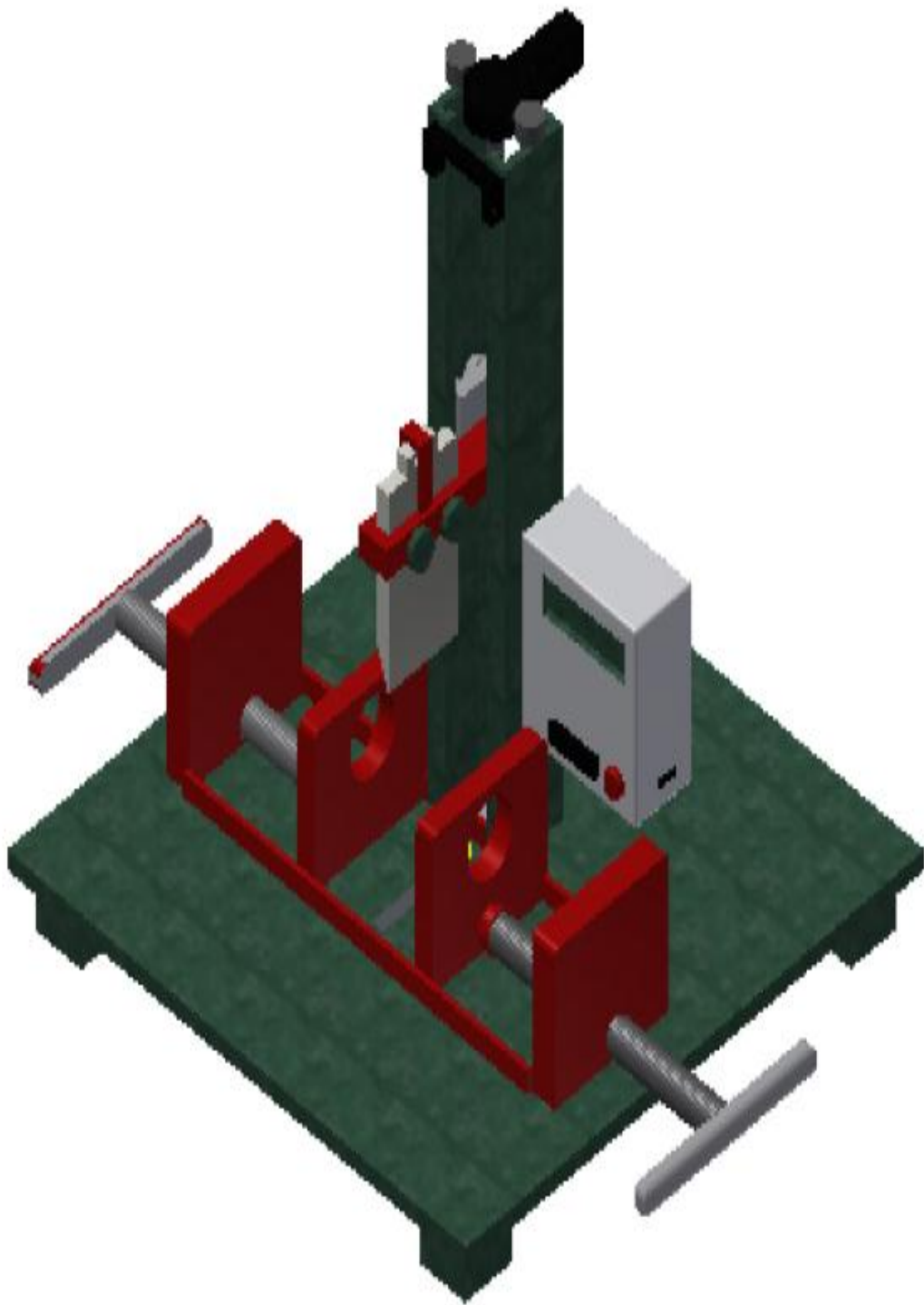
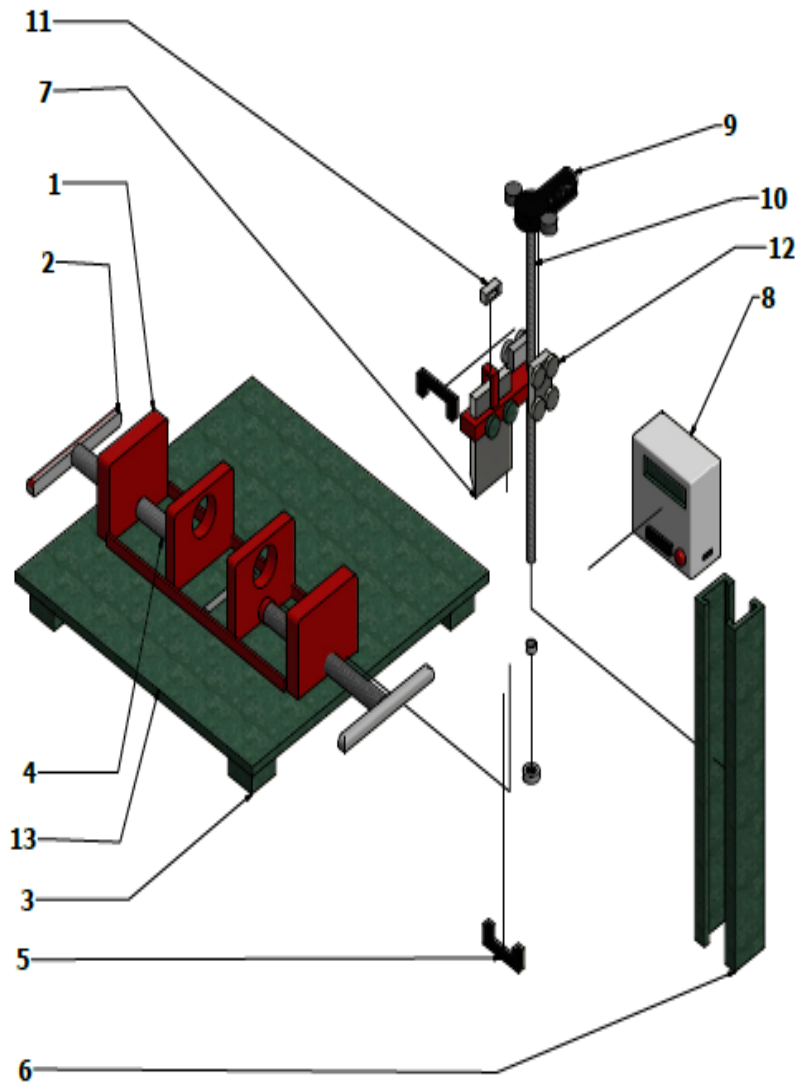


Figure 3.4: Pictorial view of the cutter



PARTS LIST			
ITEM	QTY	NAME	DESCRIPTION
1	1	VICE	FOR GRIPPING THE FOOD ITEM
2	1	HANDLE	FOR ADJUSTING THE VICE
3	1	STAND	
4	1	VICE SCREW	
5	1	OPTICAL SENSOR	FOR DETECTING THE KNIFE EDGE
6	2	RAILS	SERVES AS KNIFE EDGE SLIDE
7	1	KNIFE	FOR CUTTING THE VEGETABLE
8	2	CONTROL PANEL	FOR AQUIRING SIGNALS AND STORING DATA FOR TRANSFER TO PC
9	1	MOTOR	FOR TURNING THE SCREW THREADED ROD
10	1	SCREW THREADED ROD	FOR MOVING THE KNIFE EDGE UP AND DOWN AT HIGH TORQUE
11	1	LOAD SENSOR	FOR MEASURING THE FORCE OF CUT
12	1	BALL BEARING	ACTS AS SLIDING MECHANISM FOR THE KNIFE EDGE
13	1	BASE	SUPPORTS THE ENTIRE UNIT

EXPLODED VIEW OF DIGITAL VEGETABLE CUTTING APARATUS

Figure 3.5: Exploded view of the automated cutter showing parts description

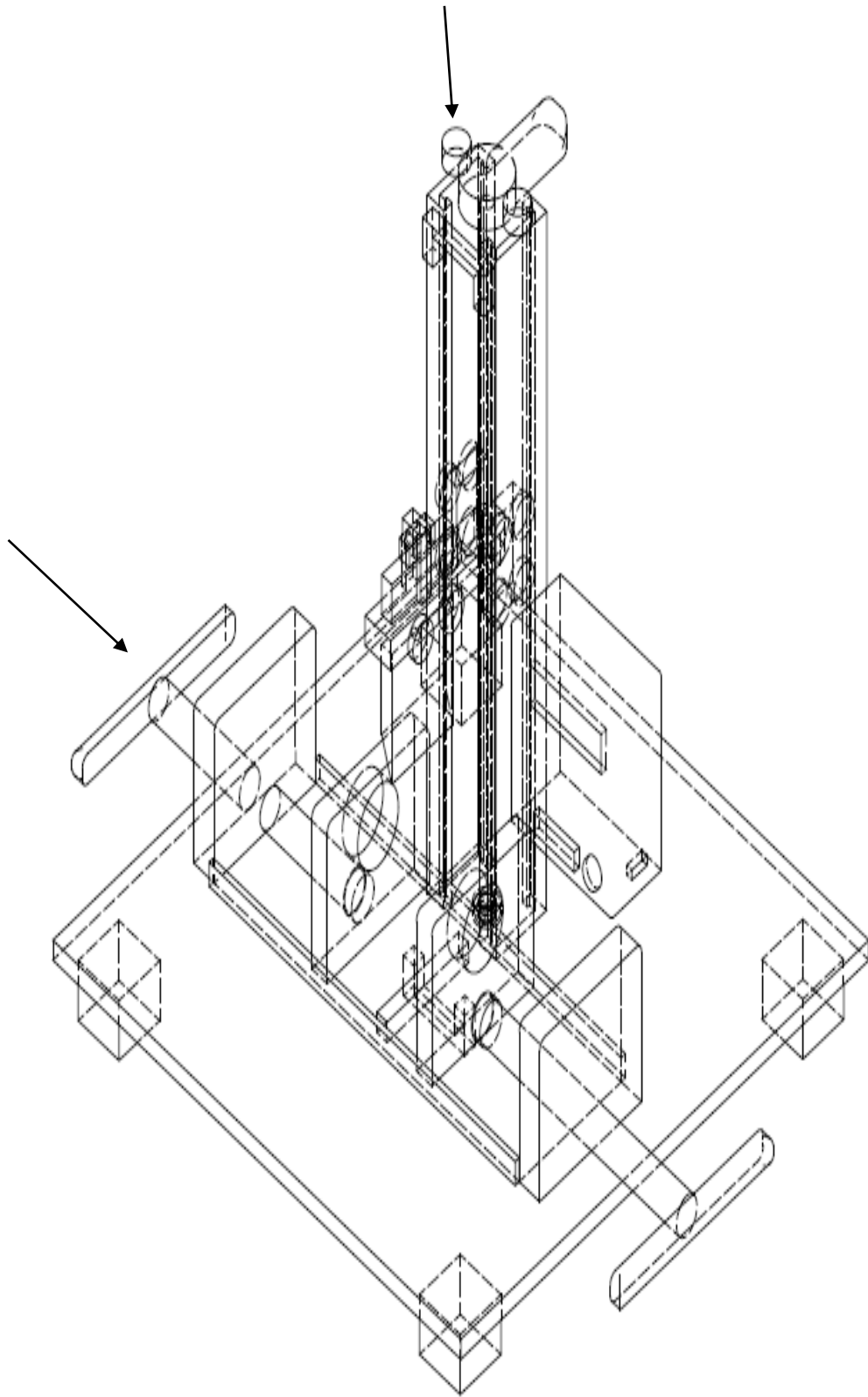


Figure 3.6 Sectional view of the automated cutter (Vertical section)

Note: —> indicates ‘direction of cut’

3.2.4 Determination of cutting energy requirement for the selected agricultural crops

The energy required to cut through selected samples of the four crops being understudied was determined experimentally by using the automated cutter. Three variables (cutting speed, knife edge angle and crop size) were chosen and their interactive effects on the cutting energy of the studies samples were observed.

3.2.4.1 Experimental design

The experiments were conducted using the Randomized Complete Block Design (RCBD) layout. The cutting speed (V), the knife edge angle (A) and crop size (equivalent diameter) (S) formed the major treatments i.e. factors (VAS). Each of the three factors has (5) levels. For cutting speed (V): 30, 35, 40, 45 and 50mm/min; knife edge angle (A): 20⁰, 27⁰, 34⁰, 41⁰ and 48⁰; equivalent crop sizes of 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 14.91, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus* L.); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa.*) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium marcrocarpon*). Each set of data was replicated three times and the average values taken. The treatments and levels were combined in a randomized set as presented in Table 3.4, and their interdependence (interaction effect) studied, hence a Randomized Complete Block Design (RCBD). The analysis of the number of the experimental (or data) points is as follows.

For each combination, VAS X 3 Replications = 5 x 5 x 5 x 3 = 375

For the four crop samples, it becomes:

375 x 4 = 1500 experimental points (treatment combinations).

The experimental layout of a factorial design shown in Table 3.5 was done for all the four crop samples (cocoyam, okra, onion and garden egg).

Table 3.5: Experimental layout of a factorial treatment design.

cutting speed mm/min	Knife Angle (deg)	Crop size mm					Total Mean
		S1	S2	S3	S4	S5	
V1	A1	V1A1S1	V1A1S2	V1A1S3	V1A1S4	V1A1S5	
	A2	V1A2S1	V1A2S2	V1A2S3	V1A2S4	V1A2S5	
	A3	V1A3S1	V1A3S2	V1A3S3	V1A3S4	V1A3S5	
	A4	V1A4S1	V1A4S2	V1A4S3	V1A4S4	V1A4S5	
	A5	V1A5S1	V1A5S2	V1A5S3	V1A5S4	V1A5S5	
	Total						
	Mean						
V2	A1	V2A1S1	V2A1S2	V2A1S3	V2A1S4	V2A1S5	
	A2	V2A2S1	V2A2S2	V2A2S3	V2A2S4	V2A2S5	
	A3	V2A3S1	V2A3S2	V2A3S3	V2A3S4	V2A3S5	
	A4	V2A4S1	V2A4S2	V2A4S3	V2A4S4	V2A4S5	
	A5	V2A5S1	V2A5S2	V2A5S3	V2A5S4	V2A5S5	
	Total						
	Mean						
V3	A1	V3A1S1	V3A1S2	V3A1S3	V3A1S4	V3A1S5	
	A2	V3A2S1	V3A2S2	V3A2S3	V3A2S4	V3A2S5	
	A3	V3A3S1	V3A3S2	V3A3S3	V3A3S4	V3A3S5	
	A4	V3A4S1	V3A4S2	V3A4S3	V3A4S4	V3A4S5	
	A5	V3A5S1	V3A5S2	V3A5S3	V3A5S4	V3A5S5	
	Total						
	Mean						
V4	A1	V4A1S1	V4A1S2	V4A1S3	V4A1S4	V4A1S5	
	A2	V4A2S1	V4A2S2	V4A2S3	V4A2S4	V4A2S5	
	A3	V4A3S1	V4A3S2	V4A3S3	V4A3S4	V4A3S5	
	A4	V4A4S1	V4A4S2	V4A4S3	V4A4S4	V4A4S5	
	A5	V4A5S1	V4A5S2	V4A5S3	V4A5S4	V4A5S5	
	Total						
	Mean						
V5	A1	V5A1S1	V5A1S2	V5A1S3	V5A1S4	V5A1S5	
	A2	V5A2S1	V5A2S2	V5A2S3	V5A2S4	V5A2S5	
	A3	V5A3S1	V5A3S2	V5A3S3	V5A3S4	V5A3S5	
	A4	V5A4S1	V5A4S2	V5A4S3	V5A4S4	V5A4S5	
	A5	V5A5S1	V5A5S2	V5A5S3	V5A5S4	V5A5S5	
	Total						
	Mean						

3.2.4.2 Fabrication of the cutting edges

Five knives of different cutting edge angles (single cut) were fabricated in the workshop (Machine Workshop, Centre for Industrial Studies) of the Federal University of Technology, Owerri, Nigeria using high quality stainless steel (VG 10 steel). The dimensions of the fabricated knives (length of 19.5cm, breadth of 3.5cm,) were chosen according to the provision kept in the fixture assembly of the developed automated cutting machine. Plate 3.6 shows the fabricated cutting tools. The blades were perfectly straight with smooth surface edges which were machined to varying edge angles of 20° , 27° , 34° , 41° and 48° respectively. Sharpening to the required cutting-edge angle blades was carried out with a rotary grinding wheel for a smooth finish of the cutting edges.



Plate 3.8: Fabricated cutting tools of different edge angles

3.2.4.3 Experimental procedure

The automated cutter was connected to a laptop (Dell, windows 7 operating system) with the aid of a Universal Serial Bus (USB). The laptop displays and stores relevant data such as the time of cut, cutting force and the distance of cut. The obtained data are used to calculate the energy of cut for the different experimental points from which the peak cutting energy and the average cutting energy were determined. The entire set up is connected to an electric power source. Samples to be cut (cocoyam, okra, onion and garden egg) were sorted into size ranges and labeled as shown in Plate 3.7 for cocoyam and appendices 1a, 1b, 1c for okra, garden egg and onion respectively.



Plate 3.9: Samples of cocoyam corms sorted and labeled.

Average values of some physical characteristics such as mass, major, intermediate, minor and equivalent diameters, hardness and compressive strength values of samples were measured and recorded. The hardness and compressive strength values for the selected crops are presented in appendices 2(a-d) for cocoyam corms, okra fruits, onion bulbs and garden egg fruits respectively. Moisture content tests using the oven drying method (AOAC, 2003) were carried out to determine the moisture content range of the select crop samples used for the cutting energy requirements test. The moisture content (wet basis) was determined using Equation 3.54.

$$MC_{wb} = \frac{w_1 - w_2}{w_1} \quad 3.54$$

Where: MC_{wb} = moisture content (wet basis) (%); w_1 = initial weight of sample, (g); w_2 = final weight of sample, (g).

At the start of the cutting operation, the force of cut is set to 0.00kg and the distance of cut set to 0.00mm on the control board. A preset speed (30, 35, 40, 45 and 50mm/min) is selected at a time by pressing the 'select speed' button on the control board. The knife edge is adjusted to a distance just above the sample lying in its natural rest position on the base of the cutter as displayed in Plate 3.10.



Plate 3.10: Cutting edge just above sample during cutting operation

The start button is then selected and the knife holder having the knife attached begins to make its downward movement. As the knife edge travels through the sample thereby cutting it, the arduino-controlled processor automatically records the force of cut for every 1mm of travel. The readings are displayed on the liquid crystal display (LCD) of the control unit and are subsequently transferred to the laptop computer for further statistical analysis. Cutting energy was calculated by measuring the surface area under the cutting force-deformation curve (Heidari and Chegini, 2011; Nazari *et al.*, 2008; Zareiforush *et al.*, 2010; Elzbieta and Agnieszka, 2012).

3.2.5 Optimization of the cutting energy requirement for the selected agricultural crops

Optimization, literarily is defined as the action of making the best or most effective use of a resource or situation; hence this part of the study was undertaken in order to determine the best interaction among three influencing variables - cutting speed (V), knife edge angle (A) and crop size(S) i.e. equivalent diameter that would yield high quality cut products with minimal energy consumption. Results of all the studied interactions in the cutting energy experiments were tested using standard variance analysis (ANOVA) for the randomized complete block design (RCBD). Also, response surface plots of both the dependent and independent variables were carried out. This helped to determine the optimal points of interactions i.e. best combinations of cutting speed (V), knife edge angle (A) and crop size (S) for energy maximizing cutting operations of the studied crops.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

The following sections give results of statistical analysis obtained for the model development using dimensional analysis based on the Buckingham pi theorem for the cutting energy requirements of the studied crops.

4.1.1 Statistical Analysis Obtained for the Model Development of the Cutting Energy Requirement for the studied crops.

The average values and standard deviations of the measured physical parameters of the selected crops taken in their natural rest position are presented in the following sections.

4.1.1.1 Cocoyam Cormels

Table 4.1 presents the average values and standard deviations of the measured physical parameters of cocoyam cormels at $71.8 \pm 0.16\%$ (w.b).

Table 4.1: Average values for physical properties of cocoyam cormels at $71.8 \pm 0.16\%$ (w.b)

S/N	Corms	Mass (g)	Equivalent		
			Diameter (mm)	Circumference(mm)	Cross-sectional area(mm ²)
1	C1	300±6.29	60.50±0.22	205.2±1.44	2874.75±32.89
2	C2	140±1.30	48.31± 0.62	165.7±1.02	1833.01±40.11
3	C3	100±4.53	36.20±0.60	120.5±0.84	1029.22±25.16
4	C4	70±1.24	22.15± 0.48	79.8±0.353	85.33±10.28

Note: Crop size was varied while the other factors remained constant.

Table 4.2 presents the average values for the hardness and compressive strength test results of cocoyam cormels.

Table 4.2: Average values of hardness and compressive strength results for cocoyam cormels.

	Size range 1	Size range 2	Size range 3	Size range 4	Size range 5
Equivalent diameter (mm)	64.89	50.31	45.34	41.02	33.68
Mass (g)	285.22	135.52	67.62	65.92	39.24
Hardness Value (N)	177.4	175.8	174.2	171.2	168.0
Compressive strength (N/mm²)	0.1152	0.0756	0.0512	0.0408	0.0264

Table 4.3 shows the experimental values of the cutting energy obtained with the automated cutter and the calculated values of the cutting energy obtained by substituting values of the cutting variables (the selected tool edge thickness (t) = 0.2cm; tool weight (w) = 300g; height of drop (H_d) = 30cm; crop density(σ) = 1.35g/cm³; the crop contact area = 28.75cm²; the moisture content of the crop sample = 71.8 %(wb)) into the energy equations $P = (\frac{tswH_d}{A})$ and $Q = (\frac{\sigma v^2 s^2 H_d}{\phi})$.

Table 4.3: Experimental values ($E_{measured}$) and calculated values of cutting energy for cocoyam cormels.

S/N	Corms	Crop size (mm)	(E_{meas})	$P = (\frac{tswH_d}{A})$	$Q = (\frac{\sigma v^2 s^2 H_d}{\phi})$	
1	C1	60.50±0.22	192.21	378.8	110.2	
2		C2	48.31± 0.62		170.73	302.4
						70.2
3	C3	36.20±0.60	129.25	226.65	39.4	
4	C4	22.15± 0.48	75.22	138.99	14.8	

The plots of the cutting energy ($E_{measured}$) against P and Q are shown in Figures 4.1 and 4.2 with their linear equations and R^2 values expressed in Equations 4.1 and 4.2.

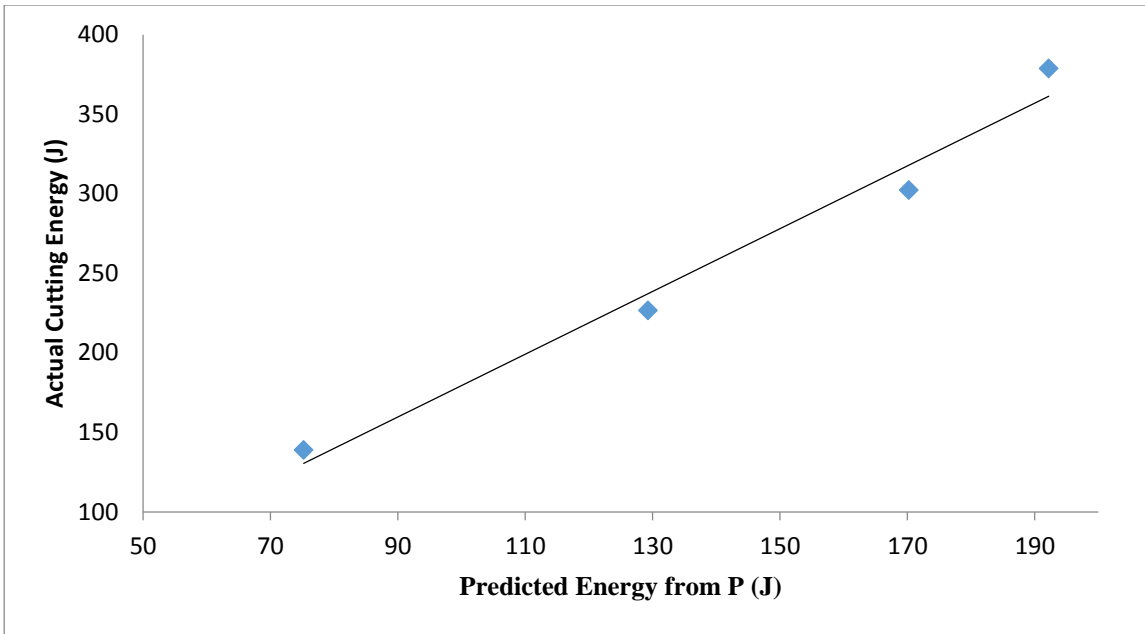


Figure 4.1: Variation of cutting energy against $P = \left(\frac{tswH_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant for cocoyam cormels

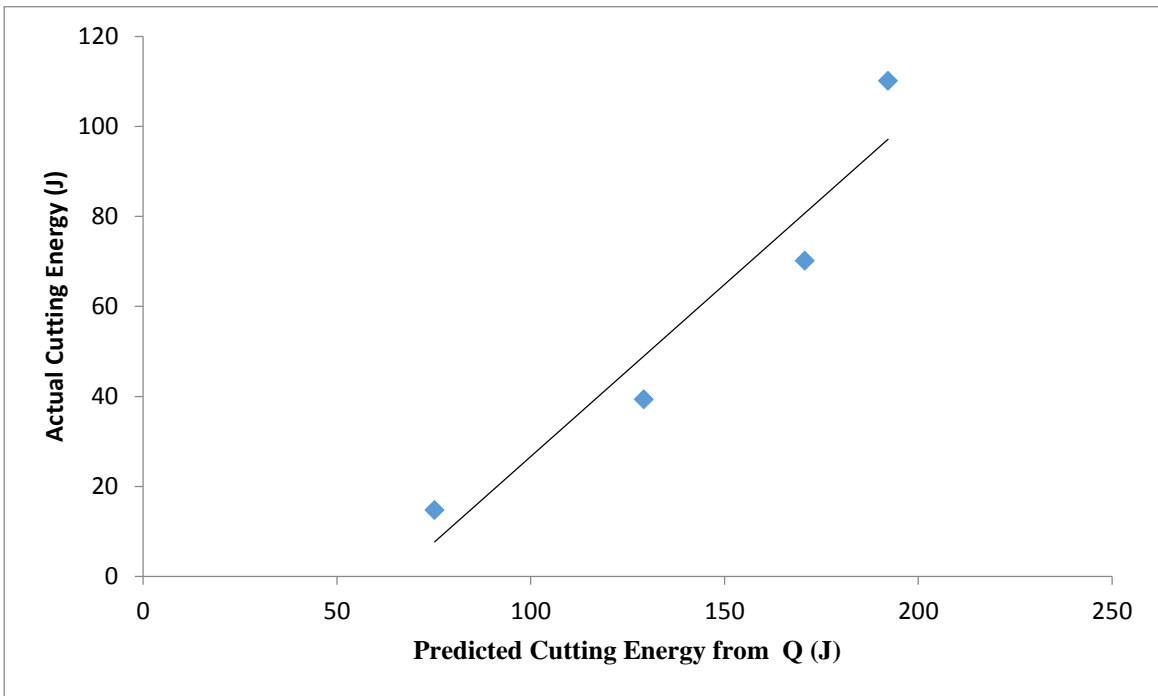


Figure 4.2: Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{tswH_d}{A}\right)$ constant for cocoyam cormels

$$E = 1.973P - 17.96; \quad R^2 = 0.977 \quad 4.1$$

$$E = 0.764Q - 49.83; \quad R^2 = 0.916 \quad 4.2$$

The plot of the P and Q terms in Figures 4.1 and 4.2 for cocoyam cormels forms a plane surface in linear space and according to Mohammed (2002), it implies that their combination favors summation or subtraction. Therefore, the component equations formed by the subtraction and summation of Equations 4.1 and 4.2 give Equations 4.3 and 4.4 respectively.

$$E = f_1 (P, Q) - f_2 (P, Q) + K \quad 4.3$$

$$E = f_1 (P, Q) + f_2 (P, Q) + K \quad 4.4$$

It must be noted that;

at f_1 , Q was kept constant while P varied

at f_2 , P was kept constant while Q varied

Substituting Equations 4.1 and 4.2 into Equation 4.3 and performing some algebraic manipulations yields Equation 4.5.

$$E = 1.973P - 0.764Q + 31.87 \quad 4.5$$

Also, Substituting Equations 4.1 and 4.2 into Equation 4.4 and performing some algebraic manipulations yields Equation 4.6.

$$E = 1.973P + 0.764Q - 67.79 \quad 4.6$$

A further manipulation as permitted under the rules of the Buckingham pi theorem (Shefii *et al.*, 1996) is manipulating with a constant factor. Hence, Equations 4.5 and 4.6 are divided with a constant factor of 3 which yields the predicted model Equations expressed in Equations 4.7 and 4.8 respectively. Dividing the prediction equations 4.5 and 4.6 with the constant factor of 3 yielded predicted values close to the actual ones obtained from experiment.

$$E = 0.658P - 0.255Q + 10.62 \quad 4.7$$

$$E = 0.658P + 0.255Q - 22.60 \quad 4.8$$

Substituting the variables for P and Q into Equations 4.7 and 4.8 yield Equations 4.9 and 4.10 respectively.

$$E = 0.658 \frac{tswH_d}{A} - 0.255 \frac{\sigma v^2 s^2 H_d}{\phi} + 10.62 \quad 4.9$$

$$E = 0.658 \frac{tswH_d}{A} + 0.255 \frac{\sigma v^2 s^2 H_d}{\phi} - 22.60 \quad 4.10$$

However, the final predicted model equation will be either of the above two equations that gives the better statistical inference.

The mathematical model was validated using the data generated from the vegetable cutter. The model validation was done at four ranges of crop sizes (20-23mm, 35-38mm, 45-49mm and 60-63mm) and a constant cutting speed of 40mm/min. The method of regression analysis as computed using Microsoft Excel environment was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2). Measured values of parameters were substituted into Equations 4.9 and 4.10 to yield the predicted cutting energy values which were plotted against the experimental energy values on a regression curve in order to obtain the coefficients of determination. Equations 4.11 and 4.12 express the relationship between the predicted cutting and experimental cutting energy with R^2 values of 0.982 and 0.970 respectively. However, Equation 4.11 which gives the higher R^2 value of 0.982 with a standard error of 0.97 between the experimented and predicted cutting energy values which is less than 1% of the average value of the experimental cutting energy is taken as the predicted model equation for the cutting energy of cocoyam corms. Figures 4.3 and 4.4 present the regression curves between the predicted and experimental cutting energies respectively with their linear equations and R^2 values given in Equations 4.11 and 4.12 respectively.

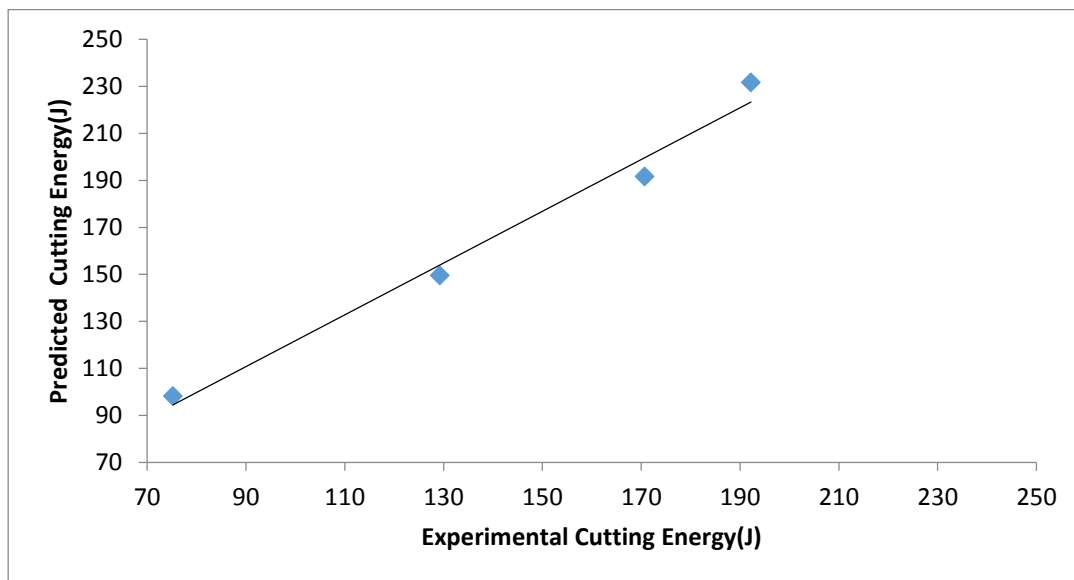


Figure 4.3: The graph of the relationship between experimental and predicted cutting energy (for subtraction of component energy equations) for cocoyam cormels.

$$E_{pred} = 1.100E_{exp} + 11.74; \quad R^2 = 0.982 \quad 4.11$$

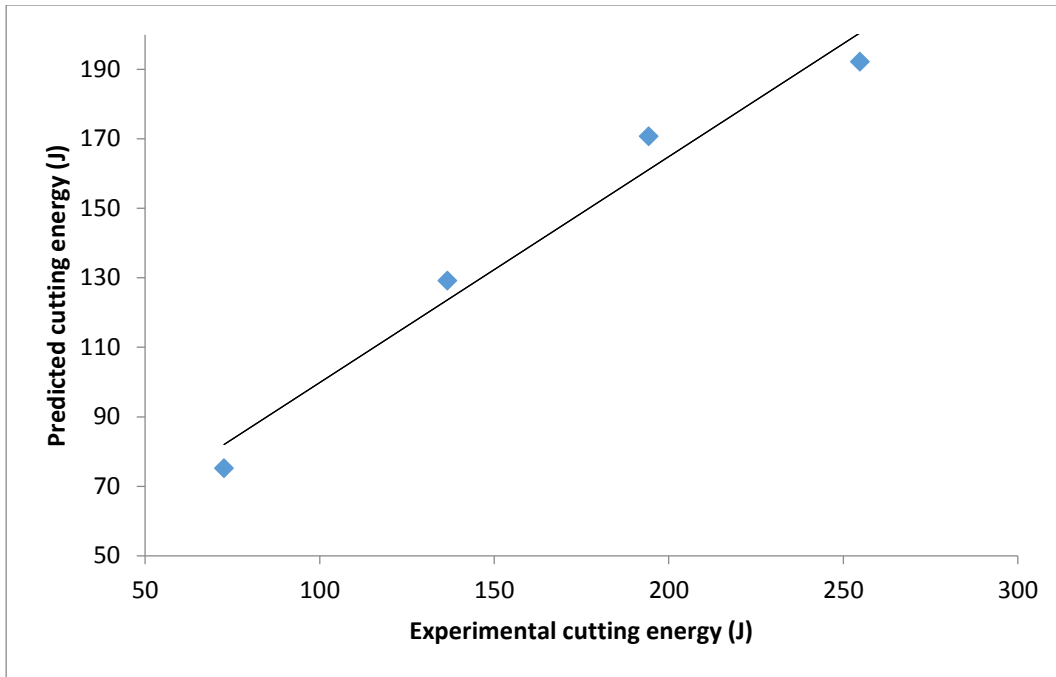


Figure 4.4: The graph of the relationship between experimental and predicted cutting energy. (For summation of component energy equations) for cocoyam cormels

$$E_{pred} = 0.650 E_{exp} + 34.75; \quad R^2 = 0.970 \quad 4.12$$

From the results of the correlation graphs, the coefficient of determination obtained when component equations were subtracted was $R^2 = 0.982$ with a standard error of 0.97 between the experimental and predicted cutting energy which is less than 1% of the average value of the experimental cutting energy. Also, the coefficient of determination obtained when component equations were summed was $R^2 = 0.970$ with a standard error of 1.06 between the experimental and predicted cutting energy which is more than 1% of the average value of the experimental cutting energy. However, a higher coefficient of determination of $R^2 = 0.982$ and a lower standard error of 0.97 were obtained with subtraction of the component energy equations as compared to coefficient of determination ($R^2 = 0.970$) and standard error of 1.06 obtained by the summation of the component energy equations. Hence, the prediction model equation for the cutting energy requirement for cocoyam (*Colocasia esculenta*) cormels will be the equation which gives a higher value of coefficient of determination of $R^2 = 0.982$ and a lower value of standard error (0.97) expressed as Equation 4.13.

$$0.658 \frac{tswH_d}{A} - 0.255 \frac{\sigma v^2 s^2 H_d}{\varphi} + 10.62 \quad 4.13$$

4.1.1.2 Okra Fruits.

The average values and standard deviation of the measured physical parameters of the okra fruits at $89.41 \pm 0.4\%$ (w.b) are shown in Table 4.4.

Table 4.4: Average values for physical properties of okra fruits at 89.41± 0.4% (w.b)

S/N	Okra	Mass (g)	Equivalent Diameter (mm)	Circumference (mm)	Cross-sectional Area(mm ²)
1	Ok ₁	18.16±2.17	24.90±0.66	89.75±4.76	487.3±26.15
2	Ok ₂	8.70±0.94	18.26±0.86	67.5±3.64	262.39±24.79
3	Ok ₃	5.15±0.07	14.99±1.02	59.5±2.29	177.35±24.90
4	Ok ₄	1.72±0.14	12.44±0.84	47.75±1.92	121.99±15.71

Table 4.5 presents the average values for the hardness and compressive strength test results for okra fruits at 89.41± 0.4% (w.b).

Table 4.5: Average values for the hardness and compressive strength test results for okra fruits

	Size range 1	Size range 2	Size range 3	Size range 4	Size range 5
Equivalent diameter (mm)	24.47	20.52	17.82	14.91	11.23
Mass (g)	18.18	13.56	14.32	10.04	4.62
Hardness Value (N)	93.80	87.32	80.32	62.40	33.44
Compressive strength (N/mm²)	0.1276	0.0846	0.0707	0.0698	0.0653

Table 4.6 shows the experimental values of the cutting energy obtained with the automated vegetable cutter and the calculated values of the cutting energy obtained by substituting values of the cutting variables(selected tool edge thickness (t) = 0.1cm; The weight (w) = 23.1g. height of tool drop (H_d) = 20cm; crop density (σ) = 1.107g/cm³; The crop contact area (A) = 28.75cm²; The moisture content of the crop sample = 89.41± 0.4% (wb)) into the energy equations $P = \left(\frac{tswH_d}{A}\right)$ and $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$.

Table 4.6: Experimental values (E_{measured}) and calculated values of cutting energy for okra fruits.

S/N	okra	Crop size (mm)	(E _{meas})	$P = \left(\frac{tswH_d}{A}\right)$	$Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$
1	Ok ₁	24.90±0.66	4.16	23.63	13.82
2	Ok ₂	18.26±0.86	2.75	17.33	7.43
3	Ok ₃	14.99±1.02	1.98	14.23	5.01
4	Ok ₄	12.44±0.84	0.70	11.81	3.45

The plots of the cutting energy (E_{measured}) against P and Q are shown in Figures 4.5 and 4.6 with their linear equations and R^2 values expressed in Equations 4.14 and 4.15 respectively.

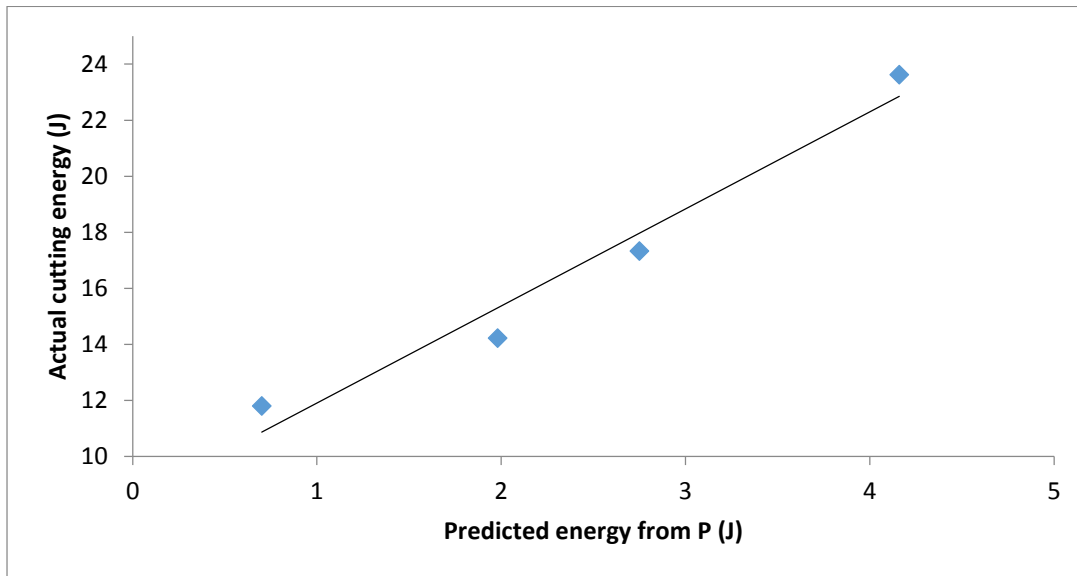


Figure 4.5: Variation of cutting energy against $P = \left(\frac{tswH_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant for okra fruits.

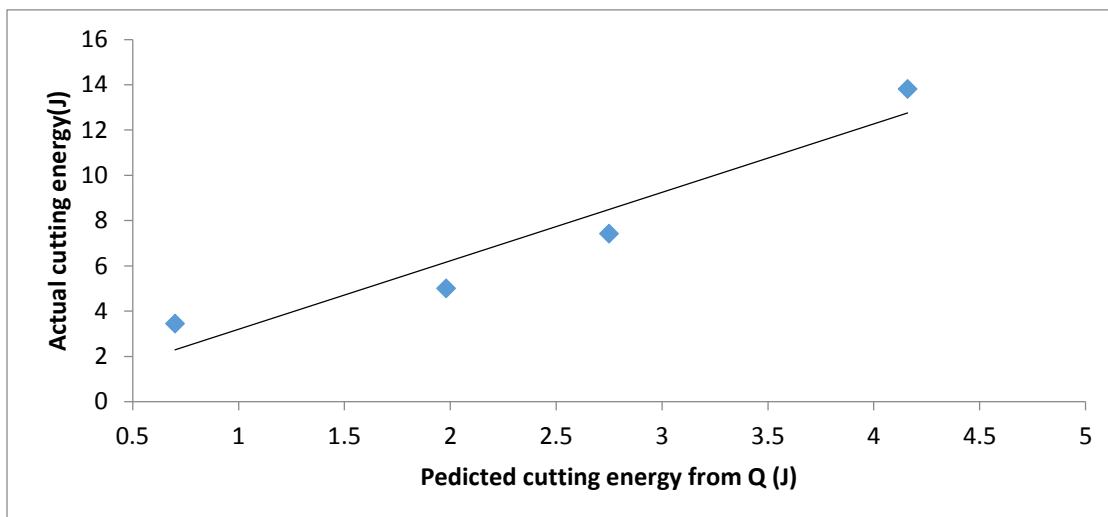


Figure 4.6: Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{tswH_d}{A}\right)$ constant okra fruits.

$$E = 3.462P + 8.448 \qquad R^2 = 0.961 \qquad 4.14$$

$$E = 3.026Q + 0.170; \qquad R^2 = 0.921 \qquad 4.15$$

The plot of the P and Q terms in Figures 4.5 and 4.6 for okra fruits forms a plane surface in linear space and according to Mohammed (2002), it implies that their combination favors summation or subtraction. Therefore, the component equations formed by the subtraction and summation of Equations 4.14 and 4.15 give Equations 4.16 and 4.17 respectively.

$$E = f_1 (P, Q) - f_2 (P, Q) + K \quad 4.16$$

$$E = f_1 (P, Q) + f_2 (P, Q) + K \quad 4.17$$

It must be noted that;

at f_1 , Q was kept constant while P varied

at f_2 , P was kept constant while Q varied

Substituting Equations 4.14 and 4.15 into Equation 4.16 and performing some algebraic manipulations yields Equation 4.18.

$$E = 3.462P - 3.026Q + 8.278 \quad 4.18$$

Also, Substituting Equations 4.14 and 4.15 into Equation 4.17 and performing some algebraic manipulations yields Equation 4.19.

$$E = 3.462P + 3.026Q + 8.618 \quad 4.19$$

A further manipulation as permitted under the rules of the Buckingham pi theorem (Shefii *et al.*, 1996) is manipulating with a constant factor. Hence, Equations 4.18 and 4.19 were divided with a constant factor of 10 which yields the predicted model equations expressed in Equations 4.20 and 4.21 respectively. Dividing equations 4.18 and 4.19 with the constant factor of 10 yielded predicted values close to the actual values.

$$E = 0.3462P - 0.3026Q + 0.8278 \quad 4.20$$

$$E = 0.3462P + 0.3026Q + 0.8618 \quad 4.21$$

Substituting the variables for P and Q into Equations 4.20 and 4.21 yield Equations 4.22 and 4.23 respectively.

$$E = 0.3462 \frac{tswH_d}{A} - 0.3026 \frac{\sigma v^2 s^2 H_d}{\phi} + 0.8278 \quad 4.22$$

$$E = 0.3462 \frac{tswH_d}{A} + 0.3026 \frac{\sigma v^2 s^2 H_d}{\phi} + 0.8618 \quad 4.23$$

However, the final predicted model equation will be either of the above two equations that gives the better statistical inference.

The mathematical model was validated using the data generated from the vegetable cutter. The model validation was done at four ranges of crop sizes (23-26mm, 17-20mm, 14-17mm and 10-13mm) and a constant cutting speed of 30mm/min. The method of regression analysis as computed using Microsoft Excel environment was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2).

Measured values of parameters were substituted into Equations 4.22 and 4.23 to yield the predicted cutting energy values which were plotted against the experimental energy values on a regression curve in order to obtain the coefficients of determination as shown in Figures 4.7 and 4.8 respectively. Equations 4.24 and 4.25 express the relationship between the predicted cutting and experimental cutting energy with R^2 values of 0.973 and 0.945 respectively.

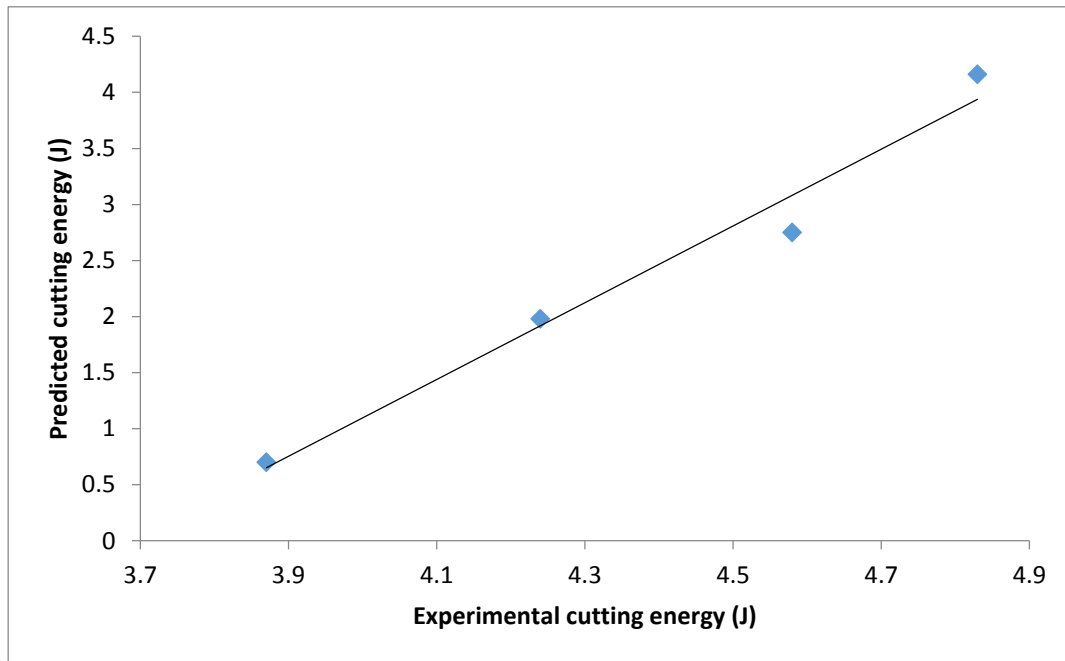


Figure 4.7: The graph of the relationship between experimental and predicted cutting energy (for subtraction of component energy equations) for okra fruits.

$$E_{\text{pred}} = 3.423E_{\text{exp}} - 12.59; \quad R^2 = 0.973 \quad 4.24$$

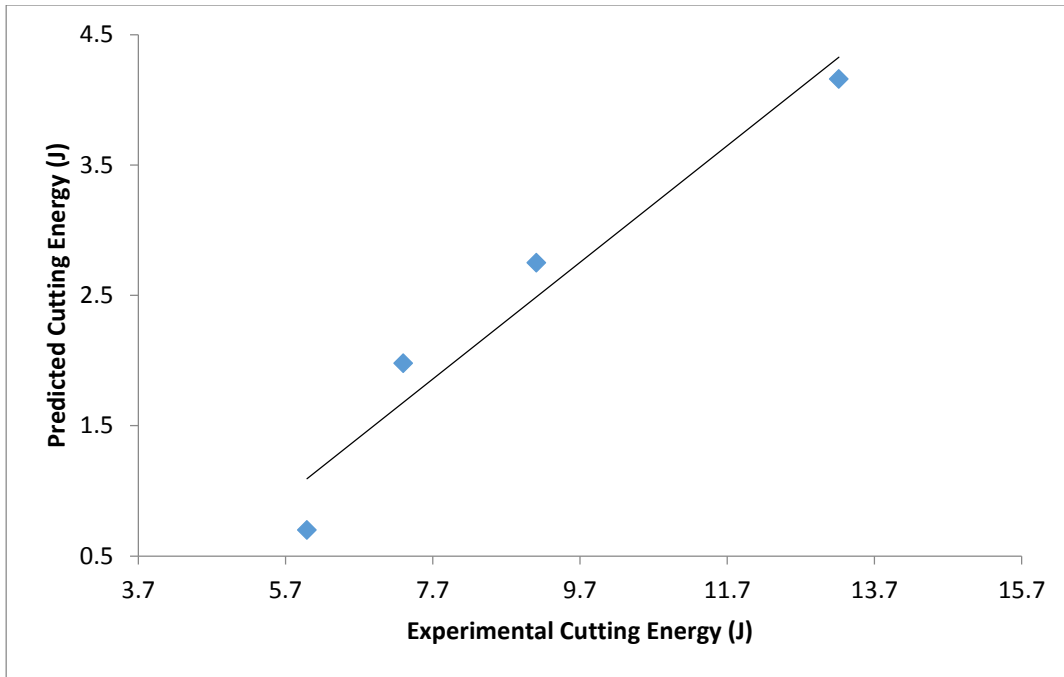


Figure 4.8: The graph of the relationship between experimental and predicted cutting energy. (for summation of component energy equations) for okra fruits

$$E_{\text{pred}} = 0.447E_{\text{exp}} - 1.584; \quad R^2 = 0.945 \quad 4.25$$

From the statistical inference carried out, the predictive model equation derived from the subtraction of component energy equations gave a higher coefficient of determination (R^2) value of 0.973, a lower mean difference of 1.983 between the predicted and experimental energy values and a lower standard error of 0.127 as compared to an R^2 value of 0.945 obtained from the summation of component energy equations, a mean difference of 6.508 between the predicted and experimental energy values and a standard error of 0.199. Hence, the predicted model equation which gives the better statistical inference of a higher R^2 value of 0.973 and lower values of 1.983 and 0.127 for mean difference and standard error respectively is chosen as the predicted model equation for the cutting energy requirement for okra (*Abelmoschus esculentus L.*) 'Ila-iroko' variety and is given as Equation 4.26.

$$E = 0.3462 \frac{tswH_d}{A} - 0.3026 \frac{\sigma v^2 s^2 H_d}{\varphi} + 0.8278 \quad 4.26$$

Also, the high R^2 values of 0.961, 0.921 and 0.973 obtained for the individual predictions equations and the Equation for subtraction of component equations is an indication that the method adopted in the development of the mathematical models is acceptable and can be translated in the development of the other varieties of the okra fruit in particular and other vegetables in general.

4.1.1.3 Onion Bulbs.

The average values and standard deviations of the measured physical parameters of the onion bulbs are given in Table 4.7.

Table 4.7: Average values for physical properties of onion bulbs at $86 \pm 0.4\%$ (w.b)

S/N	Bulbs	Mass (g)	Equivalent		
			Dia. (mm)	Circumference(mm)	Cross-sectional area(mm ²)
1	O ₁	361.44±18.06	84.10±1.31	264.20±4.10	7754.8±736.42
2	O ₂	258.02±20.58	77.35±2.77	242.99±8.71	6075.6±229.23
3	O ₃	132.54±8.68	61.36±1.20	192.77±3.78	3935.36±300.56
4	O ₄	75.14±7.95	51.78±1.08	162.67±3.40	2504±297.26
5	O ₅	45.42±3.09	42.84±1.33	134.58±4.19	2010.4±353.78

Table 4.8 presents the average values for the results of hardness and compressive strength investigations carried out on onion bulbs.

Table 4.8: Average values for the hardness and compressive strength test results for onion bulbs

	Size range 1	Size range 2	Size range 3	Size range 4	Size range 5
Equivalent diameter (mm)	84.10	77.35	61.36	51.78	42.84
Mass (g)	361.44	258.02	132.54	75.14	45.42
Hardness Value (N)	169.0	166.4	160.8	154.7	124.8
Compressive strength (N/mm²)	0.0612	0.0550	0.0416	0.0226	0.0266

Table 4.9 shows the experimental values of the cutting energy obtained with the automated vegetable cutter and the calculated values of the cutting energy obtained by substituting values of the cutting variables (the selected tool edge thickness (t) = 0.2cm; weight of cutting tool (w) = 100g; height of tool drop (H_d) = 8.5cm; crop density(σ) = 0.97g/cm³; crop contact area 21.24cm²; moisture content of the crop sample = $86 \pm 0.4\%$ (wb)) into the energy equations $P = \left(\frac{tswH_d}{A}\right)$ and $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$

Table 4.9: Experimental values (E_{measured}) and calculated values of cutting energy for Onion bulbs.

S/N	Onion	Crop size (mm)	(E_{meas})	$P = \left(\frac{tswH_d}{A}\right)$	$Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$
1	On ₁	42.84±1.33	32.20	34.29	43.99
2	On ₂	51.78±1.08	41.40	41.45	64.27
3	On ₃	61.36±1.20	64.60	49.11	90.25
4	On ₄	77.35±2.77	91.50	61.91	143.41
5	On ₅	84.10±1.31	123.90	67.31	169.54`

The plots of the cutting energy (E_{measured}) against P and Q are shown in Figures 4.9 and 4.10 with their linear equations and R^2 values expressed in Equations 4.27 and 4.28 respectively.

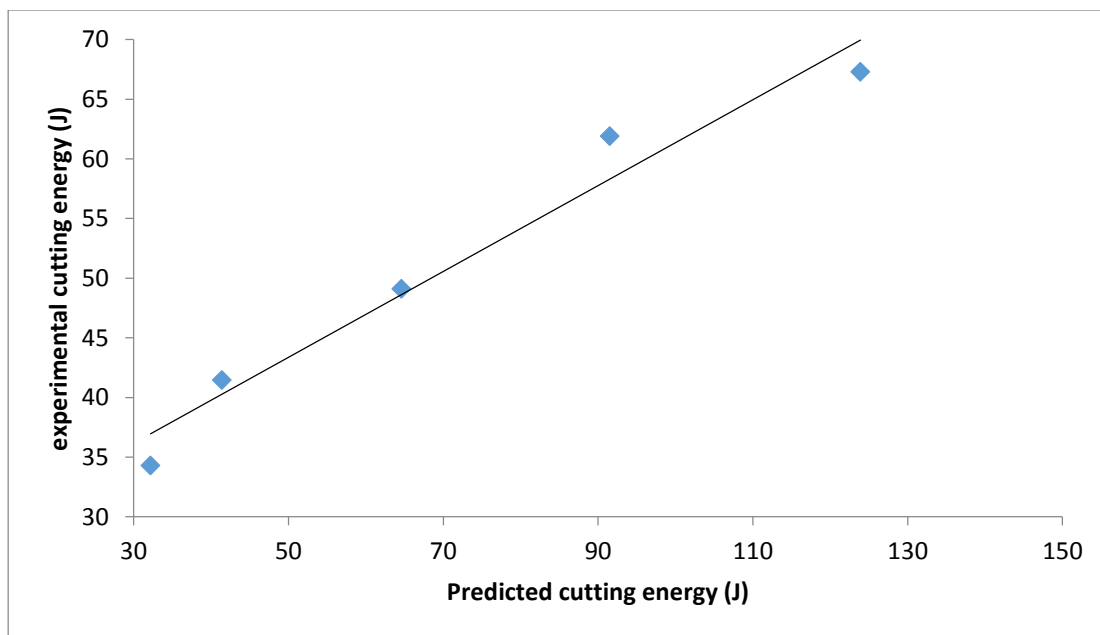


Figure 4.9: Variation of cutting energy against $P = \left(\frac{tswH_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant for onion bulbs.

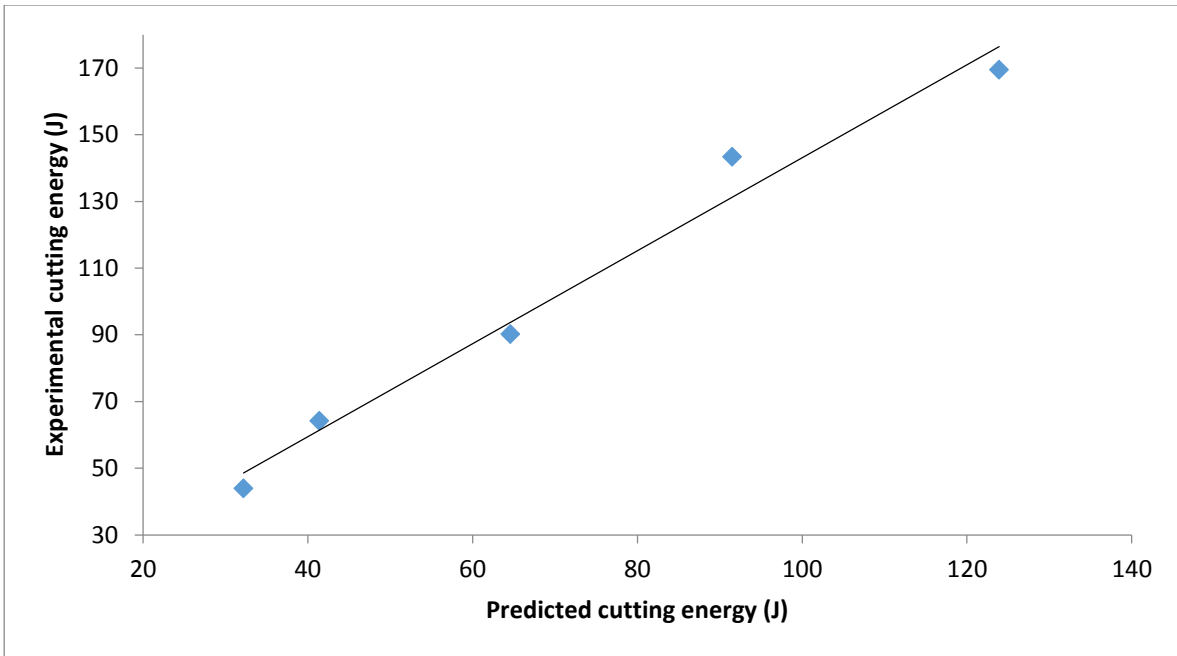


Figure 4.10. Variation of cutting energy with $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{tswH_d}{A}\right)$ constant for onion bulb.

$$E = 0.359P + 25.37; \quad R^2 = 0.962 \quad 4.27$$

$$E = 1.394Q + 3.687; \quad R^2 = 0.978 \quad 4.28$$

The plot of the P and Q terms in Figures 4.9 and 4.10 forms a plane surface in linear space and according to Mohammed (2002), it implies that their combination favors summation or subtraction. Therefore, the component equations formed by the summation and subtraction of Equations 4.27 and 4.28 give Equations 4.29 and 4.30 respectively.

$$E = f_1 (P, Q) + f_2 (P, Q) + K \quad 4.29$$

$$E = f_1 (P, Q) - f_2 (P, Q) + K \quad 4.30$$

It must be noted that;

at f_1 , Q was kept constant while P varied

at f_2 , P was kept constant while Q varied

Substituting Equations 4.27 and 4.28 into Equation 4.29 and performing some algebraic manipulations yields Equation 4.31 (for summation of the energy components).

$$E = 0.359P + 1.394Q + 29.057 \quad 4.31$$

Also, Substituting Equations 4.27 and 4.28 into Equation 4.30 and performing some algebraic manipulations yields Equation 4.32 (for subtraction of the energy components)

$$E = 0.359P - 1.394Q + 21.683 \quad 4.32$$

A further manipulation as permitted under the rules of the Buckingham pi theorem (Shefii *et al.*, 1996) is manipulating with a constant factor. Hence, Equations 4.31 and 4.32 were divided with a constant factor of 3 which yields the predicted model equations expressed in Equations 4.33 and 4.34 respectively. Dividing Equations 4.31 and 4.32 with the constant factor of 3 yielded predicted values close to the actual values.

$$E = 0.120P + 0.465Q + 9.686 \quad 4.33$$

$$E = 0.120P - 0.465Q + 7.228 \quad 4.34$$

Substituting the variables for P and Q into Equations 4.33 and 4.34 yield Equations 4.35 and 4.36 respectively.

$$E = 0.120 \frac{tswH_d}{A} + 0.465 \frac{\sigma v^2 s^2 H_d}{\phi} + 9.686 \quad 4.35$$

$$E = 0.120 \frac{tswH_d}{A} - 0.465 \frac{\sigma v^2 s^2 H_d}{\phi} + 7.228 \quad 4.36$$

However, the final predicted model equation will be either of the above two equations that gives the better statistical inference.

The mathematical model was validated using the data generated from the vegetable cutter. The model validation was done at five ranges of crop sizes (80-86mm, 72-79mm, 58-64mm, 49-54mm and 40-45mm) and a constant cutting speed of 50mm/min. The method of regression analysis as computed using Microsoft Excel environment was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2).

Measured values of parameters were substituted into Equations 4.35 and 4.36 to yield the predicted cutting energy values. However, the predicted cutting energy for subtraction of the energy component gave negative energy values. Hence the equation for the summation of the energy components is taken and a graph of experimental cutting energy is plotted against the predicted cutting energy as shown in Figure 4.11 to obtain the high coefficient of determination (R^2) value of 0.978. Equation 4.37 express the relationship between the predicted cutting and experimental cutting energy for summation of energy components with R^2 value of 0.978.

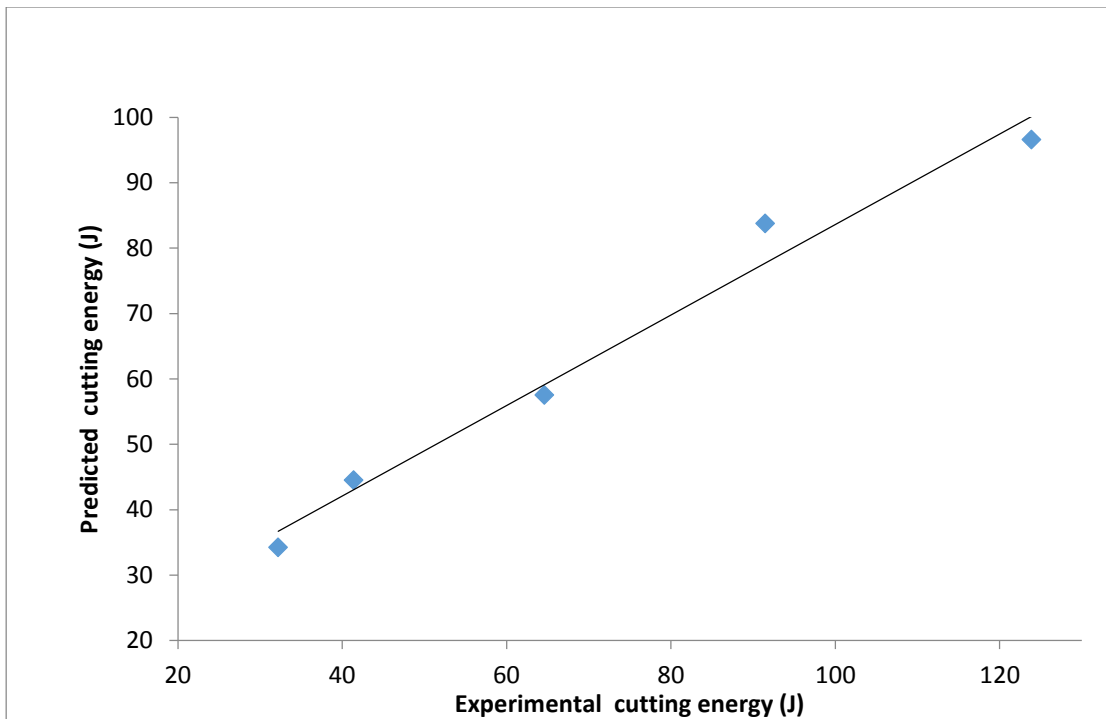


Figure 4.11: The graph of the relationship between experimental and predicted cutting energy (for summation of component energy equations) for onion bulbs.

$$E_{\text{pred}} = 0.691E_{\text{exp}} - 14.45; \quad R^2 = 0.978 \quad 4.37$$

Where E_{pred} = predicted cutting energy

E_{exp} = experimental cutting energy

From the statistical inference, the high R^2 value of 0.978, a low mean difference of 7.37 and a least significance difference of 0.755 between the experimental and predicted cutting energy values for the summation of component energy values is an indication that the method adopted in the development of the model equation is good. Also, the method is acceptable in the development of mathematical model equations for other crops in general. Equation 4.38 gives the mathematical model equation for the cutting energy for onion bulbs.

$$E = 0.120 \frac{tswH_d}{A} + 0.465 \frac{\sigma v^2 s^2 H_d}{\phi} + 9.686 \quad 4.38$$

4.1.1.4 Garden egg fruits.

The average values and standard deviations of the measured physical parameters of garden egg fruits are given in Table 4.10.

Table 4.10: Average values for physical properties of garden egg fruits at $88.94 \pm 3.64\%$ (w.b)

S/N	Garden		Equivalent		Cross-sectional
	eggs	Mass (g)	Diameter (mm)	Circumference (mm)	area(mm ²)
1	GE ₁	70.42 ± 3.67	52.73±1.08	165.65±3.40	2296.8±302.38
2	GE ₂	54.34±2.73	47.69±1.09	149.83±3.44	2127.2±120.65
3	GE ₃	34.20±3.89	41.46±1.73	130.24±5.44	1466.0±88.41
4	GE ₄	32.80±3.58	37.31±1.78	117.21±8.55	1431.2±143.07
5	GE ₅	18.92±1.24	32.87±1.44	103.25±4.54	964.0±87.23

Table 4.11 presents results of the average values for the hardness and compressive strength investigations on garden egg fruits.

Table 4.11: Average values for hardness and compressive strength test for garden egg fruits.

	Size range 1	Size range 2	Size range 3	Size range 4	Size range 5
Equivalent diameter (mm)	166.85	149.83	130.24	117.11	103.25
Mass (g)	70.42	54.34	34.06	32.80	18.92
Hardness Value (N)	163.2	175.4	166.8	171.0	157.8
Compressive strength (N/mm²)	0.666	0.331	0.483	0.288	0.456

Table 4.12 shows the experimental values of the cutting energy obtained with the automated vegetable cutter and the calculated values of the cutting energy obtained by substituting values of the cutting variables (the selected tool edge thickness (t) = 0.2cm; weight of cutting tool (w) = 100g; height of tool drop (H_d) = 6.5cm; crop density(σ) = 1.11g/cm³; crop contact area = 30.19cm²; moisture content of the crop sample = $88.94 \pm 3.64\%$ (wb) into the energy equations $P = \left(\frac{tswH_d}{A}\right)$ and $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$.

Table 4.12: Experimental values (E_{measured}) and calculated values of cutting energy for garden egg fruits.

S/N	Garden egg	Crop size (mm)	(E_{meas})	$P = \left(\frac{tswH_d}{A}\right)$	$Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$
1	GE ₁	52.73±1.08	12.43	12.49	36.09
2	GE ₂	47.69±1.09	10.67	11.29	29.52
3	GE ₃	41.46±1.73	8.85	9.82	22.31
4	GE ₄	37.31±1.78	7.54	8.84	18.07
5	GE ₅	32.87±1.44	6.35	7.78	14.02

The plots of the cutting energy (E_{measured}) against P and Q are shown in Figures 4.12 and 4.13 with their linear equations and R^2 values are expressed in Equations 4.39 and 4.40 respectively.

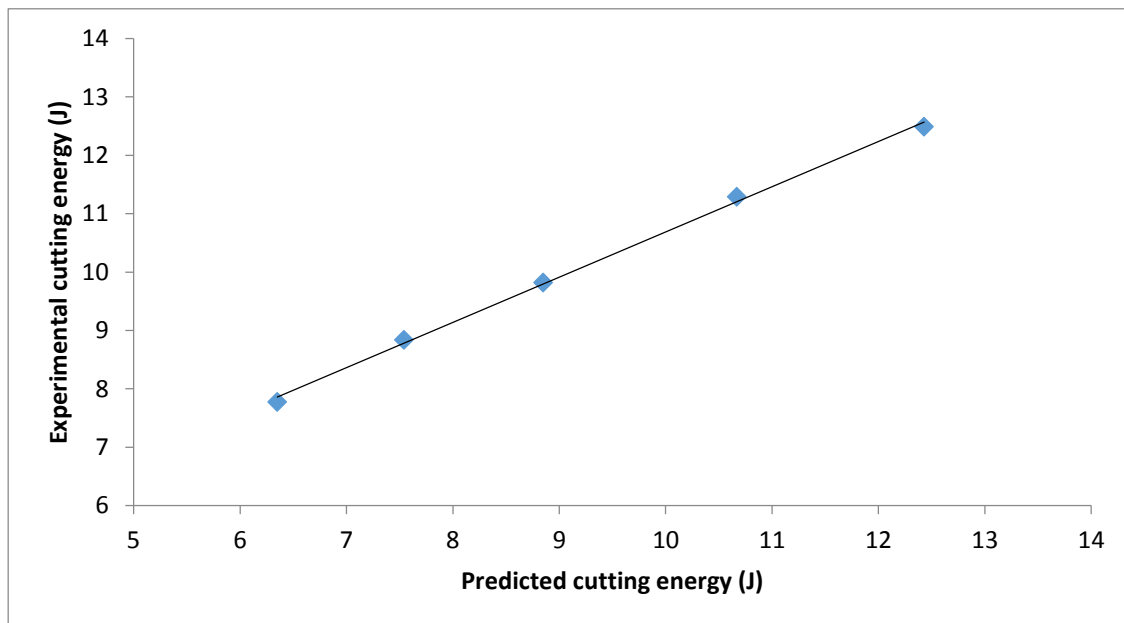


Figure 4.12: Variation of cutting energy against $P = \left(\frac{tswH_d}{A}\right)$, keeping $Q = \left(\frac{\sigma v^2 s^2 H_d}{\phi}\right)$ constant for garden egg fruits.

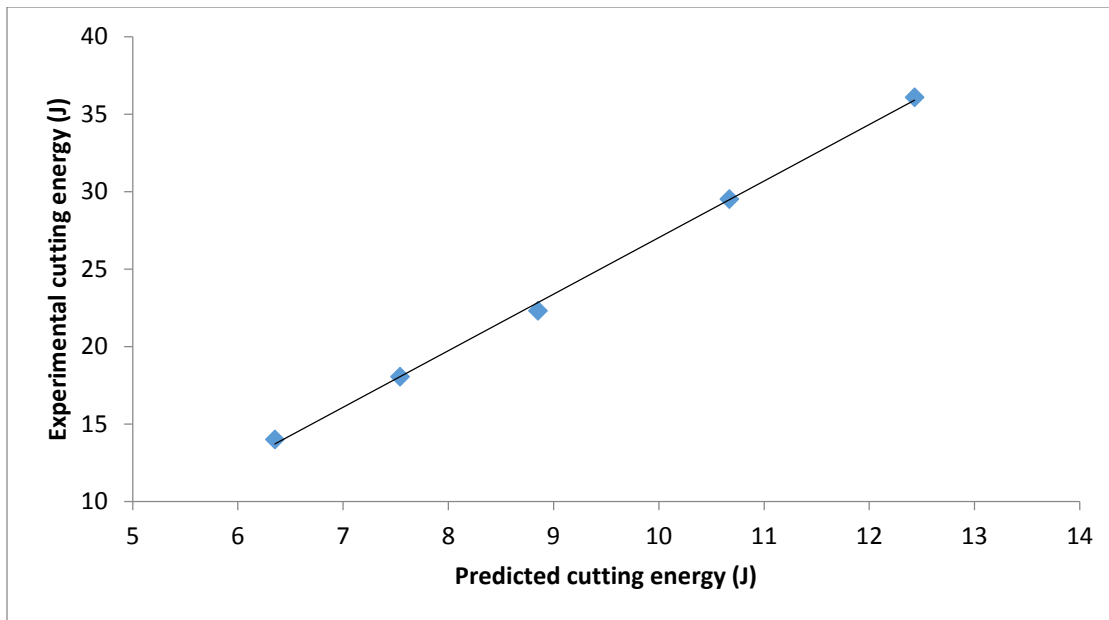


Figure 4.13: Variation of cutting energy with $Q = \left(\frac{\sigma_v^2 s^2 H_d}{\phi}\right)$, keeping $P = \left(\frac{t_{sw} H_d}{A}\right)$ constant for garden egg fruit.

$$E = 0.774P + 2.946; \quad R^2 = 0.998 \quad 4.39$$

$$E = 3.647Q - 9.439; \quad R^2 = 0.998 \quad 4.40$$

The plot of the P and Q terms in Figures 4.12 and 4.13 forms a plane surface in linear space and according to Mohammed (2002), it implies that their combination favors summation or subtraction. Therefore, the component equations formed by the summation and subtraction of Equations 4.39 and 4.40 give Equations 4.41 and 4.42 respectively.

$$E = f_1 (P, Q) + f_2 (P, Q) + K \quad 4.41$$

$$E = f_1 (P, Q) - f_2 (P, Q) + K \quad 4.42$$

It must be noted that;

at f_1 , Q was kept constant while P varied

at f_2 , P was kept constant while Q varied

Substituting Equations 4.39 and 4.40 into Equation 4.41 and performing some algebraic manipulations yields Equation 4.43 (for summation of the energy components).

$$E = 0.774P + 3.647Q - 6.493 \quad 4.43$$

Also, Substituting Equations 4.39 and 4.40 into Equation 4.42 and performing some algebraic manipulations yields Equation 4.44 (for subtraction of the energy components).

$$E = 0.774P - 3.647Q + 12.385 \quad 4.44$$

A further manipulation as permitted under the rules of the Buckingham pi theorem (Shefii *et al.*, 1996) is manipulating with a constant factor. Hence, Equations 4.43 and 4.44 were divided with a constant factor of 10 which yields the predicted model equations expressed in Equations 4.45 and 4.46 respectively. Dividing Equations 4.43 and 4.44 with the constant factor of 10 yielded predicted values close to the experimental values.

$$E = 0.0774P + 0.365Q - 0.649 \quad 4.45$$

$$E = 0.0774P - 0.365Q + 1.239 \quad 4.46$$

Substituting the variables for P and Q into Equations 4.45 and 4.46 yield Equations 4.47 and 4.48 respectively.

$$E = 0.0774 \frac{tswH_d}{A} + 0.365 \frac{\sigma v^2 s^2 H_d}{\varphi} - 0.649 \quad 4.47$$

$$E = 0.0774 \frac{tswH_d}{A} - 0.365 \frac{\sigma v^2 s^2 H_d}{\varphi} + 1.239 \quad 4.48$$

However, the final predicted model equation will be either of the above two equations that gives the better statistical inference.

Data generated from the automated cutter was used to validate the predicted model equations. This validation was done at five ranges of crop size (55-62mm, 50-58mm, 43-49mm, 37-44mm, 34-39mm) and a constant cutting speed of 40mm/min.

Measured values of parameters were substituted into Equations 4.47 and 4.48 to yield the predicted cutting energy values. However, the predicted cutting energy for subtraction of the energy component gave negative energy values. Hence the equation for the summation of the energy components is taken and a graph of experimental cutting energy is plotted against the predicted cutting energy as shown in Figure 4.14 to obtain the high coefficient of determination (R^2) value of 0.998. Equations 4.49 express the relationship between the predicted cutting and experimental cutting energy for summation of energy components with R^2 value of 0.998.

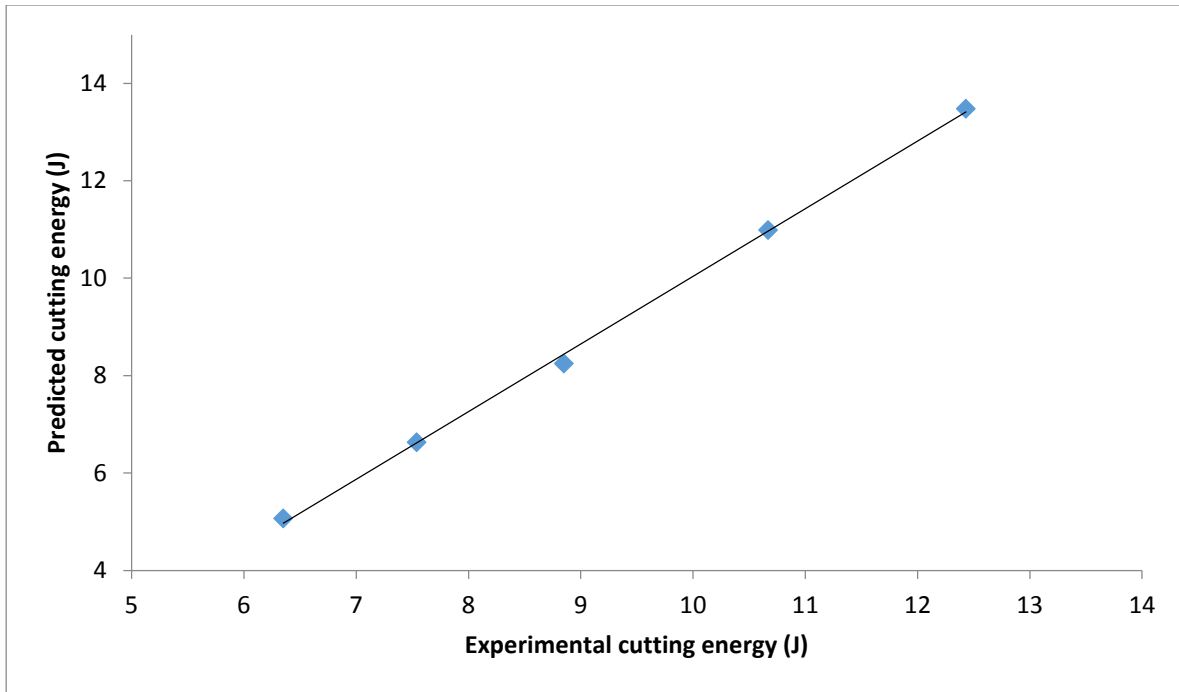


Figure 4.14: The graph of the relationship between experimental and predicted cutting energy (for summation of component energy equations) for garden egg fruits.

$$E_{\text{pred}} = 1.389E_{\text{exp}} - 3.853; \quad R^2 = 0.998 \quad 4.49$$

Where E_{pred} = predicted cutting energy

E_{exp} = experimental cutting energy

From the statistical inference, the high R^2 value of 0.998, a low mean difference of 0.29 and a least significance difference of 0.228 between the experimental and predicted cutting energy values for the summation of component energy values is an indication that the method adopted in the development of the model equation is good. Also, the method is acceptable in the development of mathematical model equations for other vegetables in general. Equation 4.50 gives the mathematical model equation for the cutting energy equation for garden egg fruits.

$$E = 0.0774 \frac{tswH_d}{A} + 0.365 \frac{\sigma v^2 s^2 H_d}{\phi} - 0.649 \quad 4.50$$

4.1.2 Experimental Studies of the Cutting Energy Consumption of the Selected Crops

The effect of three variables (cutting speed, knife edge angle and crop size) on the cutting energy requirement of the select crops were studied. Peak cutting and average cutting energies were determined for all the experimental points and results displayed on the randomized complete block design platform.

4.1.2.1 Cocoyam cormels

The energy consumed in cutting through given samples of the cocoyam cormels by varying three variables; cutting speeds of 30, 35,40, 45 and 50mm/min, knife edge angles of 20, 27, 34, 41 and 48⁰ and crop sizes with equivalent diameters of 33.68, 41.02, 45.34, 50.31 and 64.89mm were obtained with the developed cutter controlled by an arduino microprocessor. The peak cutting and average cutting energies were recorded and displayed in Table 4.13.

Table 4.13: Experimental results of the cutting energy requirements for cocoyam cormels.

ENERGY VALUES (J)	CUTTING SPEED (mm/min)	KNIFE ANGLE (°)	CROP SIZE (mm)									
			S1 (33.68)		S2 (41.02)		S3 (45.34)		S4 (50.31)		S5 (64.89)	
			P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E
COCOYAM	V1-30	A1-20	3.5767	0.9423	5.9694	2.6650	7.5092	3.7701	9.4014	5.1251	15.6969	9.6164
		A2-27	4.0346	1.318	6.1869	2.9345	7.5852	3.9771	9.8145	5.2603	15.1325	9.5407
		A3-34	4.7336	1.7534	6.6454	3.2638	7.9022	4.2440	9.5688	5.4552	14.8091	9.5248
		A4-41	5.6736	2.2486	7.3450	3.6528	8.4603	4.5705	9.8641	5.7099	14.7268	9.5686
		A5-48	6.8548	2.8036	8.2857	4.1017	9.2595	4.9569	10.5005	6.0244	14.8856	9.6722
	V2-35	A1-20	2.6684	1.0008	4.8781	2.4732	6.3103	3.4309	8.0785	4.6164	14.0106	8.6104
		A2-27	3.0312	1.279	5.0005	2.6452	6.2911	3.5404	7.8966	4.6541	13.3511	8.4372
		A3-34	3.6351	1.6169	5.3640	2.8769	6.5131	3.7098	7.9558	4.7515	12.9326	8.3237
		A4-41	4.4801	2.0146	5.9685	3.1685	6.9761	3.9388	8.2560	4.9087	12.7553	8.2701
		A5-48	5.5661	2.4721	6.8141	3.5198	7.6802	4.2277	8.7973	5.1257	12.8190	8.2762
	V3-40	A1-20	2.2888	1.2612	4.3155	2.4832	5.6400	3.2936	7.2844	4.3096	12.853	7.8062
		A2-27	2.5566	1.4419	4.3429	2.5577	5.5258	3.3056	7.0074	4.2497	12.0984	7.5355
		A3-34	3.0654	1.6823	4.6112	2.6920	5.6527	3.3774	6.9714	4.2496	11.5849	7.3246
		A4-41	3.8152	1.9825	5.1207	2.8860	6.0206	3.5090	7.1766	4.3094	11.3124	7.1734
		A5-48	4.8062	2.3425	5.8712	3.1399	6.6296	3.7004	7.6227	4.4288	11.2810	7.0821
	V4-45	A1-20	2.4379	1.7235	4.2817	2.6951	5.4984	3.3581	7.0189	4.2046	12.2241	7.2039
		A2-27	2.6106	1.8066	4.2139	2.6721	5.2891	3.2727	6.6468	4.0472	11.3744	6.8357
		A3-34	3.0243	1.9496	4.3872	2.7089	5.3209	3.2470	6.5158	3.9497	10.7658	6.5273
		A4-41	3.6791	2.1523	4.8015	2.8054	5.5938	3.2811	6.6258	3.9119	10.3982	6.2787
		A5-48	4.5749	2.4148	5.4569	2.9618	6.1077	3.3749	6.9769	3.9339	10.2718	6.0898
	V5-50	A1-20	3.1157	2.3876	4.7765	3.1088	5.8856	3.6246	7.2821	4.3015	12.1238	6.8035
		A2-27	3.1933	2.3733	4.6136	2.9884	5.5812	3.4416	6.8150	4.0466	11.1791	6.3379
		A3-34	3.5119	2.4187	4.6918	2.9276	5.5179	3.3184	6.5889	3.8516	10.4754	5.9319
		A4-41	4.0716	2.5239	5.0111	2.9267	5.6956	3.2550	6.6038	3.7163	10.0128	5.5858
		A5-48	4.8724	2.6889	5.5714	2.9855	6.1145	3.2513	6.8598	3.6408	9.7912	5.2994

Note: P.C.E – Peak cutting energy

A.C.E – Average cutting energy

4.1.2.2 Okra fruits

Experimental results obtained for the cutting energy requirement for okra fruits using the randomized complete block design layout is displayed in Table 4.14. Three variables were studied; cutting speed ranging from 30,35,40,45 and 50mm/min; knife edge angle ranging from 20, 27, 34, 41 and 48⁰; crop size with equivalent diameters of 11.23, 14.91, 17.82, 20.52 and 24.47mm.

Table 4.14: Experimental results of the cutting energy requirements for okra fruits.

		CROP SIZE(mm)										
	CUTTING SPEED (mm/min)	KNIFE ANGLE (°)	S1(11.23)		S2(14.91)		S3(17.82)		S4(20.52)		S5(24.47)	
ENERGY VALUES(J)			PCE	ACE	PCE	ACE	PCE	ACE	PCE	ACE	PCE	ACE
	V1-30	A1-20	2.3313	0.8752	1.8710	0.6837	1.4260	0.4878	0.9491	0.2707	0.1402	0.1079
		A2-27	1.2816	0.4731	1.3170	0.5056	1.2640	0.4867	1.1507	0.4339	0.8738	0.2956
		A3-34	0.7573	0.2122	1.2884	0.4686	1.6273	0.6267	1.8776	0.7382	2.1328	0.8402
		A4-41	0.7584	0.0924	1.7851	0.5727	2.5159	0.9078	3.1299	1.1836	3.9171	1.5259
		A5-48	1.2848	0.1137	2.8071	0.8179	3.9299	1.3301	4.9075	1.7701	6.2267	2.3527
OKRA	V2-35	A1-20	2.205	0.8554	1.6069	0.5877	1.0531	0.3315	0.4751	0.0585	0.4815	0.4020
		A2-27	0.8825	0.3658	0.7803	0.3221	0.6184	0.2429	0.4041	0.1342	0.0205	0.0860
		A3-34	0.0856	0.0174	0.4790	0.1975	0.7091	0.2954	0.8584	0.3509	0.9658	0.3711
		A4-41	0.1860	0.1899	0.7031	0.2141	1.3251	0.4890	1.8381	0.7089	2.4775	0.9694
		A5-48	0.0678	0.2561	1.4525	0.3719	2.4664	0.8238	3.3431	1.2079	4.5146	1.7087
	V3-40	A1-20	2.6664	1.0569	1.9310	0.7131	1.2683	0.3966	0.5893	0.0676	0.5150	0.4746
		A2-27	1.0716	0.4799	0.8317	0.3599	0.5609	0.2205	0.2457	0.0558	0.3267	0.2461
		A3-34	0.0020	0.0440	0.2578	0.1479	0.3790	0.1855	0.4274	0.1851	0.3870	0.1235
		A4-41	0.5422	0.2508	0.2093	0.0770	0.7224	0.2916	1.1344	0.4555	1.6261	0.6342
		A5-48	0.5610	0.4045	0.6861	0.1472	1.5911	0.5389	2.3668	0.8670	3.3905	1.2860
	V4-45	A1-20	3.7162	1.4799	2.8431	1.0598	2.0715	0.6830	1.2916	0.2982	0.0395	0.3259
		A2-27	1.8487	0.8153	1.4712	0.6191	1.0916	0.4194	0.6753	0.1988	0.0447	0.1849
		A3-34	0.5065	0.2919	0.6247	0.3196	0.6370	0.2969	0.5844	0.2406	0.3963	0.0972
		A4-41	0.3103	0.0904	0.3035	0.1612	0.7078	0.3156	1.0188	0.4235	1.3628	0.5204
		A5-48	0.6018	0.3315	0.5077	0.1439	1.3039	0.4753	1.9786	0.7476	2.8545	1.0848
	V5-50	A1-20	5.3540	2.1242	4.3433	1.6279	3.4629	1.1908	2.5820	0.7501	1.1822	0.0442
		A2-27	3.2139	1.3722	2.6988	1.0997	2.2103	0.8397	1.6931	0.5632	0.8253	0.0976
		A3-34	1.5991	0.7613	1.5796	0.7127	1.4831	0.6297	1.3295	0.5175	0.9937	0.2923
		A4-41	0.5096	0.2915	0.9858	0.4668	1.2813	0.5609	1.4913	0.6129	1.6875	0.6280
		A5-48	0.0545	0.0372	0.9174	0.3620	1.6047	0.6331	2.1785	0.8495	2.9067	1.1048

Note: P.C.E – Peak cutting energy

A.C.E – Average cutting energy

4.1.2.3 Onion bulbs

The energy consumed in cutting through given samples of the onion bulbs by varying three variables; cutting speeds of 30, 35,40, 45 and 50mm/min, knife edge angles of 20, 27, 34, 41 and 48⁰ and crop sizes with equivalent diameters of 42.84, 51.78, 61.36, 77.35 and 84.10mm were obtained with a developed cutter controlled by an arduino microprocessor. Peak cutting and average cutting energies were determined for all the experimental points and results displayed on the randomized complete block design platform. Table 4.15 displays result of the cutting test obtained for onion.

Table 4.15: Experimental results of the cutting energy requirements for onion bulbs.

ENERGY VALUES (J)	CUTTING SPEED (mm/min)	KNIFE ANGLE (°)	CROP SIZE (mm)									
			S1 (42.84)		S2 (51.78)		S3 (61.36)		S4 (77.35)		S5 (84.10)	
			P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E	P.C.E	A.C.E
ONION	V1-30	A1-20	2.8860	3.5579	5.7131	6.1388	8.3449	8.7167	11.8212	12.5869	12.9445	14.0582
		A2-27	4.1573	2.9732	6.9088	5.4991	9.4595	8.0182	12.8004	11.7902	13.8666	13.2201
		A3-34	5.8251	2.3885	8.5009	4.8595	10.9705	7.3197	14.1761	10.9935	15.1852	12.3819
		A4-41	7.8893	1.8037	10.4894	4.2199	12.8780	6.6212	15.9482	10.1968	16.9002	11.5438
		A5-48	10.3500	1.2190	12.8744	3.5802	15.1819	5.9228	18.1168	9.4001	19.0117	10.7057
	V2-35	A1-20	5.0316	6.784	7.3846	9.2341	9.5083	11.6720	12.1365	15.3083	12.9019	16.6810
		A2-27	5.9762	5.9862	8.2536	8.3814	10.2962	10.7603	12.7891	14.2985	13.4974	15.6297
		A3-34	7.3174	5.1883	9.5191	7.5286	11.4806	9.8487	13.8382	13.2887	14.4893	14.5784
		A4-41	9.0550	4.3904	11.1810	6.6758	13.0615	8.9371	15.2837	12.2789	15.8777	13.5272
		A5-48	11.1890	3.5926	13.2394	5.8231	15.0388	8.0255	17.1257	11.2691	17.6625	12.4759
	V3-40	A1-20	7.0166	10.0101	8.8955	12.3295	10.5111	14.6272	12.2913	18.0298	12.6987	19.3037
		A2-27	7.6347	8.9991	9.4379	11.2636	10.9724	13.5025	12.6173	16.8068	12.9675	18.0393
		A3-34	8.6492	7.9881	10.3767	10.1977	11.8302	12.3778	13.3397	15.5839	13.6329	16.7749
		A4-41	10.0601	6.9771	11.7120	9.1318	13.0844	11.2530	14.4586	14.3610	14.6946	15.5106
		A5-48	11.8676	5.9661	13.4438	8.0659	14.7351	10.1283	15.9740	13.1381	16.1528	14.2462
	V4-45	A1-20	8.8411	13.2362	10.2458	15.4249	11.3534	17.5825	12.2856	20.7512	12.3350	21.9265
		A2-27	9.1325	12.0121	10.4616	14.1458	11.4881	16.2446	12.2849	19.3152	12.2772	20.4490
		A3-34	9.8204	10.7880	11.0738	12.8668	12.0192	14.9068	12.6807	17.8791	12.6159	18.9715
		A4-41	10.9048	9.5638	12.0825	11.5878	12.9468	13.5689	13.4730	16.4431	13.3510	17.4939
		A5-48	12.3856	8.3397	13.4876	10.3088	14.2709	12.2311	14.6617	15.0070	14.4826	16.0164
	V5-50	A1-20	10.5050	16.4623	11.4356	18.5202	12.0352	20.5378	12.1193	23.4727	11.8107	24.5492
		A2-27	10.4699	15.4623	11.3248	17.0281	11.8432	18.9868	11.7920	21.8235	11.4263	22.8586
		A3-34	10.8311	13.5878	11.6104	15.5359	12.0477	17.4358	11.8612	20.1743	11.4383	21.168
		A4-41	11.5888	12.1505	12.2924	14.0438	12.6487	15.8848	12.3268	18.5251	11.8469	19.4773
		A5-48	12.7430	10.7133	13.371	12.5516	13.6461	14.3339	13.1889	16.876	12.6518	17.7867

Note: P.C.E – Peak cutting energy

A.C.E – Average cutting energy

Results of the experimental test carried out on the cutting energy requirements for onion bulbs as displayed in the above Table 4.10 showed three variables were studied during the test and the peak and average energy of cut values obtained.

4.1.2.4 Garden egg fruits

Result of the cutting energy requirement test carried out on the garden egg fruit is presented in the randomized complete block design as displayed out in Table 4.16.

Table 4.16: Experimental results of the cutting energy requirements for garden egg fruits.

		CROP SIZE (MM)		S ₁ (25.69)		S ₂ (32.87)		S ₃ (40.31)		S ₄ (47.69)		S ₅ (52.73)	
ENERGY VALUES(J)	CUTTING SPEED mm/min	KNIFE ANGLE (°)	PCE	ACE	PCE	ACE	PCE	ACE	PCE	ACE	PCE	ACE	
	V ₁ -30	A1-20	1.4514	1.0294	1.4653	0.6579	1.1980	0.3174	0.6495	0.0242	0.1128	0.1505	
		A2-27	1.8372	1.0163	2.2347	0.6448	2.3648	0.3042	2.2106	0.0111	1.9431	0.1636	
		A3-34	2.0160	1.1152	2.7970	0.7438	3.3246	0.4032	3.5645	0.1100	3.5663	0.0646	
		A4-41	1.9877	1.3263	3.1523	0.9548	4.0773	0.6143	4.7115	0.3211	4.9824	0.1464	
		A5-48	1.7524	1.6494	3.3005	1.2779	4.6229	0.9374	5.6513	0.6442	6.1915	0.4696	
GARDEN EGG	V ₂ -35	A1-20	1.277	1.3021	1.2838	0.9021	1.0096	0.5320	0.4543	0.2095	0.0871	0.0148	
		A2-27	1.4440	1.2867	1.8348	0.8867	1.958	0.5166	1.7969	0.1941	1.5248	0.0006	
		A3-34	1.4044	1.3833	2.1788	0.9833	2.6994	0.6132	2.9326	0.2907	2.9296	0.0960	
		A4-41	1.1577	1.5920	2.3156	1.192	3.2337	0.8219	3.8611	0.4994	4.1274	0.3047	
		A5-48	0.7040	1.9128	2.2455	1.5128	3.5610	1.1427	4.5826	0.8202	5.1181	0.6256	
	V ₃ -40	A1-20	1.2791	1.6274	1.2797	1.1989	0.9986	0.7992	0.4365	0.4474	0.1096	0.2327	
		A2-27	1.2281	1.6097	1.6124	1.1811	1.7287	0.7815	1.5608	0.4296	1.2839	0.2149	
		A3-34	0.9702	1.7040	1.7379	1.2754	2.2517	0.8758	2.478	0.5240	2.7040	0.3092	
		A4-41	0.5051	1.9104	1.6564	1.4818	2.5676	1.0822	3.1882	0.7304	3.4498	0.5156	
		A5-48	0.1670	2.2289	1.3679	1.8003	2.6765	1.4007	3.6913	1.0488	4.2221	0.8341	
	V ₄ -45	A1-20	1.4590	2.0053	1.4531	1.5483	1.1651	1.1191	0.5961	0.7379	0.0454	0.5032	
		A2-27	1.1898	1.9852	1.5673	1.5282	1.6768	1.0990	1.502	0.7178	1.2205	0.4831	
		A3-34	0.7134	2.0772	1.4745	1.6202	1.9814	1.1909	2.2009	0.8098	2.1886	0.575	
		A4-41	0.0300	2.2813	1.1746	1.8242	2.0790	1.3950	2.6927	1.0139	2.9496	0.7791	
		A5-48	0.8605	2.5975	0.6677	2.1404	1.9695	1.7112	2.9774	1.3300	3.5036	1.0953	
	V ₅ -50	A1-20	1.8165	2.4359	1.8038	1.9503	1.5090	1.4915	0.9332	1.081	0.3778	0.8262	
		A2-27	1.3288	2.4134	1.6997	1.9278	1.8023	1.4690	1.6207	1.0586	1.3345	0.8038	
		A3-34	0.6341	2.5031	1.3885	2.0175	1.8885	1.5587	2.1012	1.1482	2.0843	0.8935	
		A4-41	0.2677	2.7048	0.8703	2.2192	1.7677	1.7604	2.3746	1.3500	2.6269	1.0952	
		A5-48	1.3766	3.0187	0.1450	2.5331	1.4398	2.0743	2.4410	1.6638	2.9625	1.409	

Three variables were studied and their effect on the cutting energy values reported. The variables were cutting speed with a range of 30,35,40,45 and 50mm/min; knife edge angle of 20, 27, 34, 41 and 48°, equivalent crop diameters of 25.69, 32.87, 40.31, 47.69 and 52.73mm.

The elastic nature of the garden egg fruit can be seen in Figures 4.15 a-c showing the graph of the energy of cut against distance of cut at different experimental points (variables interaction). The pattern of the graph shows an upward rise in energy value, then a sudden drop in the cutting energy. This shows the high energy demand in compression of the elastic skin as the cutting edge tries to penetrate through the garden egg fruit, then a sudden drop indicating a soft inner texture of the garden egg fruit.

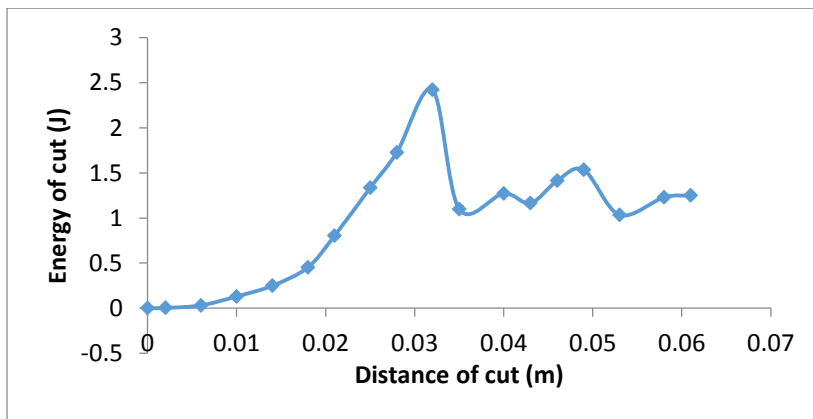


Figure 4.15a: Energy- displacement curve at experimental point (35mm/min, 27°, 77.35mm) for garden egg fruit

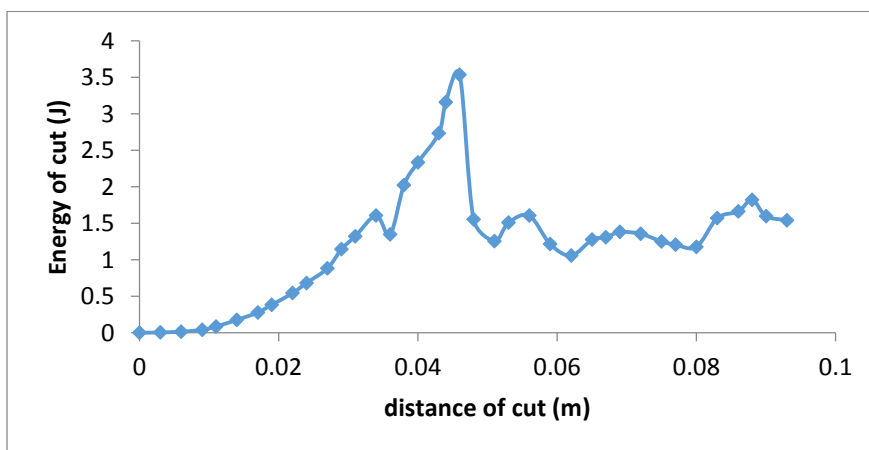


Figure 4.15b: Energy- displacement curve at experimental point (40mm/min, 34°, 61.36mm) for garden egg fruit

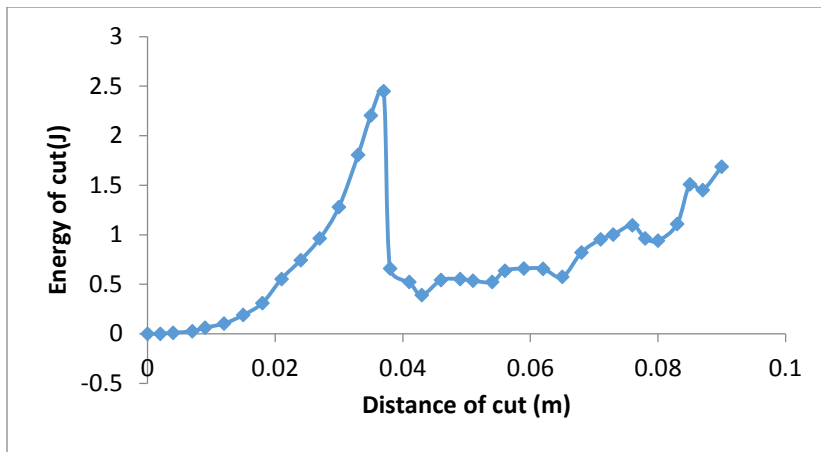


Figure 4.15c: Energy- displacement curve at experimental point (35mm/min, 27°, 51.78mm) for garden egg fruit.

4.1.3 Development of Predictive Models from Cutting Energy Tests

With the aid of a statistical software (Design expert version 7.0, Stat {Ease INC., 2009, USA), the experimental values obtained were used to generate predictive model equations for the cutting energy requirements of the four agricultural crops studied. Significance of the effects of all the independent variables (cutting speed, knife edge angle and cutting speed) on the peak and average cutting energy were evaluated using analysis of variance (ANOVA). Quadratic regression equations gave the best fit for the variables and were adopted in the analysis.

4.1.3.1 Cocoyam cormels

Experimental values obtained for the cutting energy consumption for cocoyam cormels were used to generate a quadratic regression equation as given in equations 4.51 and 4.52 respectively.

$$PE = +6.69 + 4.26A - 1.39B + 0.24C + 0.64A^2 + 1.06B^2 + 0.48C^2 - 0.78AB - 1.02AC - 0.38BC;$$

$$R^2 = 0.905 \quad 4.51$$

$$ACE = +4.06 + 2.82A - 0.73B + 0.089C + 0.44A^2 + 0.40B^2 + 0.12C^2 - 1.06AB - 0.45AC - 0.39BC$$

$$R^2 = 0.900 \quad 4.52$$

A and B and C are cocoyam crop size, cutting speed and knife edge angle respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively).

4.1.3.2 Okra fruits

Quadratic regression curves which gave the best fit was used to develop predictive models for the cutting energy requirement for okra. Equations 4.53 and 4.54 are the predictive models of the peak and average cutting energy for okra fruits.

$$PE = +0.38 - 0.073A + 0.17B + 0.19C + 1.18A^2 + 1.05B^2 - 0.19C^2 - 1.09AB - 0.49AC + 1.78BC;$$

$$R^2 = 0.788 \quad 4.53$$

$$ACE = +0.19 + 3.323 * 10^{-4}A + 0.075B + 0.040C + 0.44A^2 + 0.28B^2 - 0.10C^2 - 0.35AB - 0.27AC + 0.81BC;$$

$$R^2 = 0.745 \quad 4.54$$

A and B and C are cutting speed, knife edge angle and okra crop size respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively).

4.1.3.3 Onion bulbs

Quadratic regression equations generated for the cutting energy requirements for onion bulbs are shown in equations 4.55 and 4.56.

$$PE = +5.48 + 2.80A - 0.63B + 2.50C - 0.70A^2 - 0.19B^2 + 0.75C^2 - 1.37AB - 0.30AC - 1.00BC;$$

$$R^2 = 0.999 \quad 4.53$$

$$ACE = +2.89 + 1.91A - 0.41B + 1.63C - 0.66A^2 - 0.059B^2 + 0.80C^2 - 0.88AB - 0.16AC - 0.71BC;$$

$$R^2 = 0.984 \quad 4.54$$

A and B and C are onion crop size, cutting speed and knife edge angle respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively).

4.1.3.4 Garden egg fruits

Quadratic regression curves which gave the best fit was used to develop predictive models for the cutting energy requirement of garden egg. Equations 4.57 and 4.58 are the predictive models of the peak and average cutting energy for garden egg fruit.

$$PE = +2.59 - 0.72A + 0.89B + 0.89C + 0.35A^2 - 0.41B^2 - 0.47C^2 - 0.87AB - 0.025AC + 1.50BC;$$

$$R^2 = 0.632 \quad 4.57$$

$$ACE = +0.88 - 0.11A + 0.28B + 0.25C + 0.11A^2 + 0.22B^2 + 0.075C^2 - 0.30AB - 0.11AC + 0.39BC;$$

$$R^2 = 0.600 \quad 4.58$$

A and B and C are cutting speed, knife edge angle and garden egg crop size respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively).

4.1.4 Optimization of Cutting Energy Consumption and Interactions.

The optimum energy required for cutting the studied crop samples was obtained using the response surface methodology (RSM). The independent variables were cutting speed (30, 35, 40, 45 and 50mmmin⁻¹), knife edge angle (20, 27, 34, 41 and 48 deg) and crop size. The selected crop sizes (equivalent diameter) were 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 14.91, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus* L.); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa.*) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium marcrocarpon*) while the dependent variable (response) is the cutting energy (peak and average cutting energy). To facilitate the relative study of the effect of two significant variables simultaneously on the cutting energy requirement for the selected crops, response surface methodology (RSM) was adopted (Singh *et al.*, 2016). Response surface methodology (RSM) is a statistical procedure used for optimization of multivariate problems. It helps in determining the relationship between one or more measured responses and multiple input variables. Also, it provides statistically acceptable results with fewer numbers of experiments (Kaur *et al.*, 2009).

A second order polynomial equation was used to analyze the obtained experimental data and to relate response function to coded variables so as to generate three dimensional (3D) responses and contour plots with the help of a statistical package, Design-Expert, version 7.0 (Jain *et al.*, 2011; Giri and Prasad 2007; Balusu *et al.*, 2005). Numerical optimization process variables based on the multiple responses for each of the input factors: cutting speed (V), Knife edge angle (A) and crop size (S) was performed using the Design- Expert 7.0 version. The optimum conditions for cutting cocoyam, okra, onion and garden egg were determined to obtain the criteria for minimum and maximum energy consumed during the cutting operation of the samples. Applying desirability functions (Giri and Prasad, 2007; Kumar *et al.*, 2011), the optimum conditions (maximum and minimum) for cutting the crop samples were observed.

4.1.4.1 Cocoyam cormels

The surface response plots for the interaction effects between cutting speed, knife edge angle and the crop size for cocoyam cormels are detailed in the sections below.

4.1.4.1.1 Cutting speed and crop size

The effect of cutting speed and crop size on the energy consumption for cutting cocoyam cormels is as shown in Figures 4.16a and 4.16b.

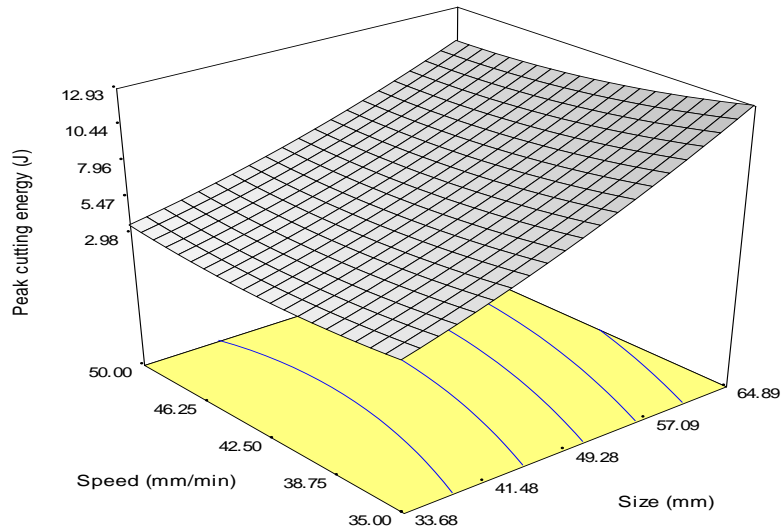


Figure 4.16a: Surface response plot of the interaction effect between speed and size on the peak cutting energy requirement of cocoyam samples.

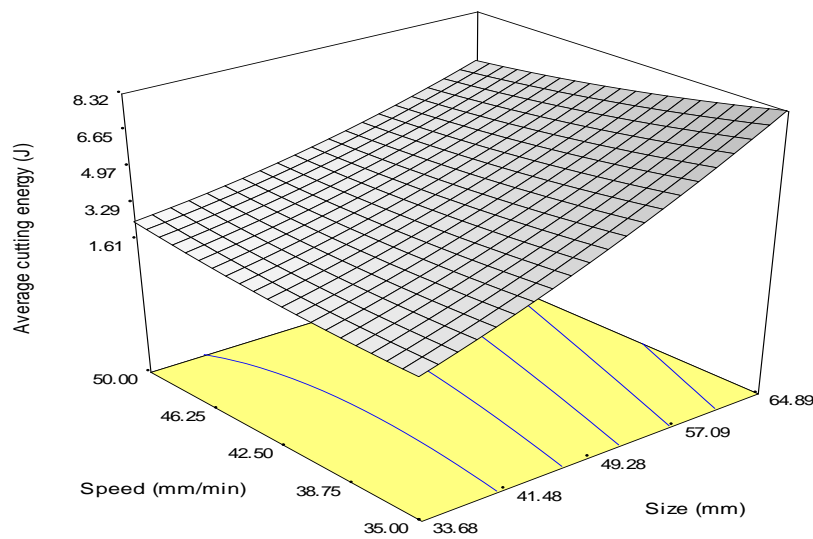


Figure 4.16b: Response surface plot of the interaction effect between speed and size on the average cutting energy of Cocoyam.

4.1.4.1.2 Knife edge angle and crop size

Figures 4.17a and 4.17b shows the interactive effect between knife edge angle and crop size for cocoyam cormels using the response surface methodology. Statistical analysis show significant effects of these independent variables on the responses.

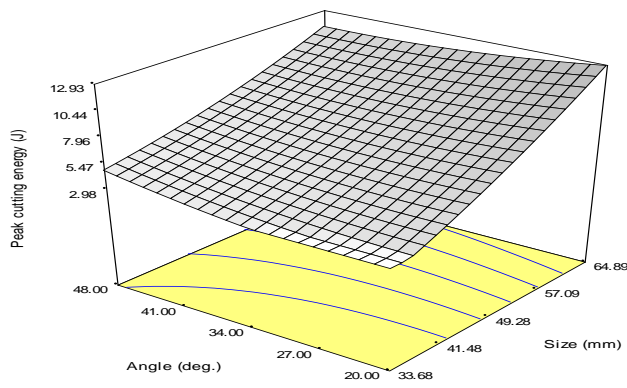


Figure 4.17a: Response surface plot of the interaction effect between angle and size on the peak cutting energy of cocoyam cormels.

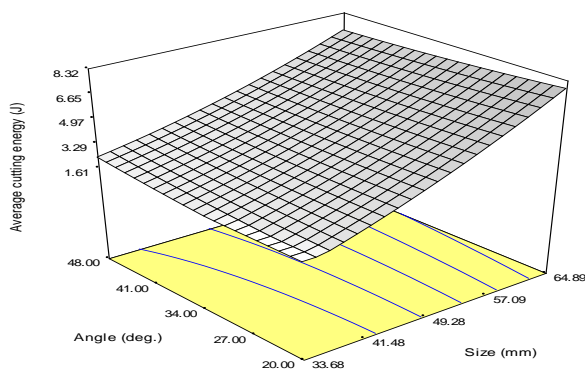


Figure 4.17b: Response surface plot of the interaction effect between angle and size on the average cutting energy of cocoyam cormels.

4.1.4.1.3 Knife edge angle and cutting speed

Figures 4.18a and 4.18b are response surface plots of the interactive effect between the knife edge angle and the cutting speed on the peak and average cutting energy of cocoyam cormels.

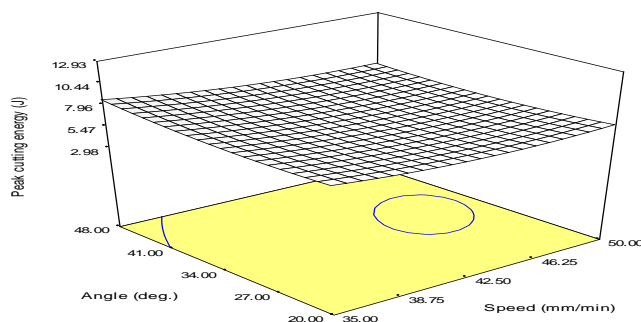


Figure 4.18a: Response surface plot of the interaction effect of angle and speed on the peak cutting energy of cocoyam.

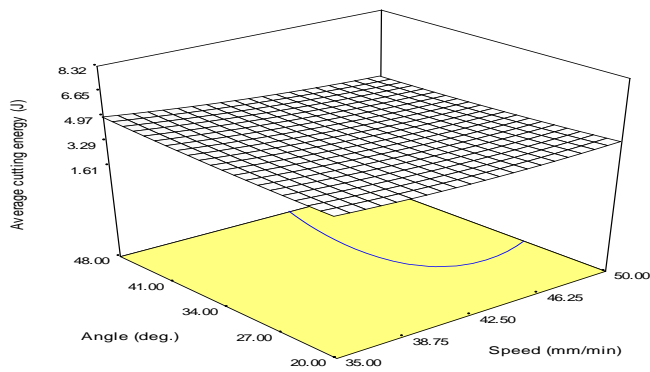


Figure 4.18b: Response surface plot of the interaction effect of angle and speed on the average cutting energy of cocoyam cormels.

4.1.4.2 Okra fruits

The interactive effects of knife edge angle, cutting speed, and crop sizes on the peak and average cutting energy of okra fruits are discussed in the sections below.

4.1.4.2.1 Crop size and cutting speed

The effect of the interaction between the crop size and cutting speed on the peak and average cutting energy requirement for okra fruits bulbs are shown with the response surface plots in Figures 4.19a and 4.19b.

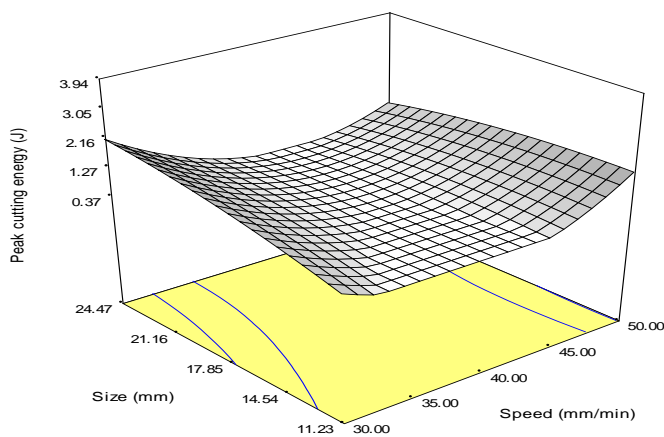


Figure 4.19a: Response surface plot of the interaction effect between size and speed on the peak cutting energy for okra fruits.

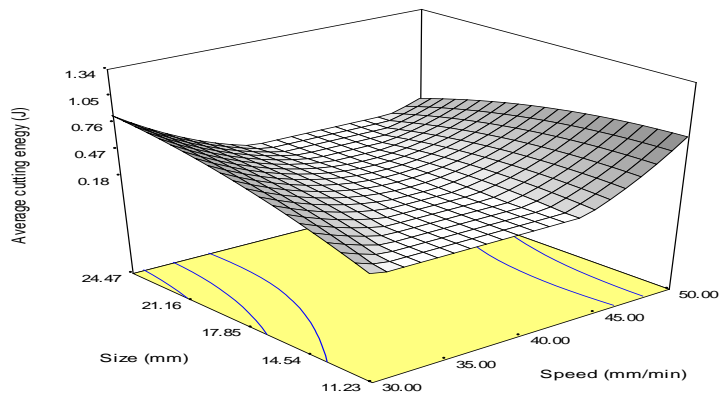


Figure 4.19b: Response surface plot of the interaction effect between size and speed the average cutting energy for okra fruits.

Statistical inference using the coefficient estimate as indicators showed significant effect with a coefficient estimate of -0.49 and -0.27 respectively for the peak and average cutting energy.

4.1.4.2.2 Knife edge angle and cutting speed

The effect of the interaction between the knife edge angle and cutting speed on the peak and average cutting energy requirement for okra fruits are shown with the response surface plots in Figures 4.20a and 4.20b.

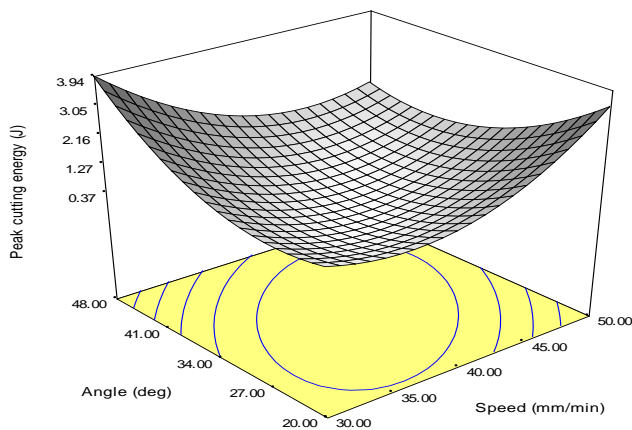


Figure 4.20a: Response surface plot of the interaction effect between angle and speed on the peak cutting energy for okra fruits.

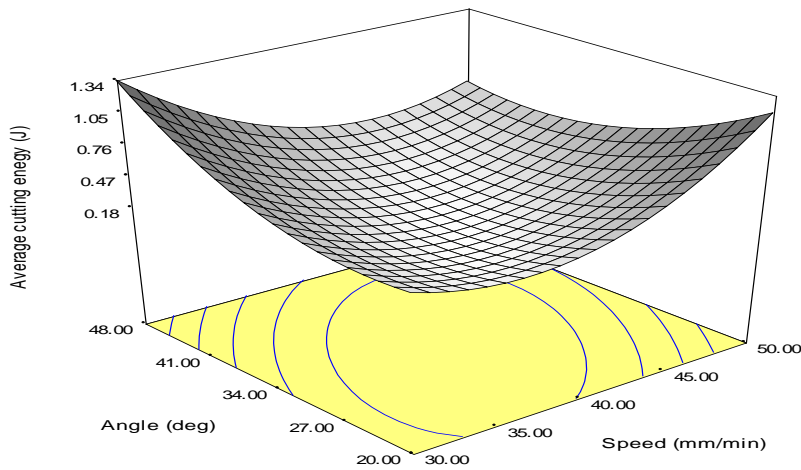


Figure 4.20b: Response surface plot of the interaction effect between angle and speed on the average cutting energy for okra fruits.

4.1.4.2.3 Knife edge angle and crop size

The effect of the interaction between the knife edge angle and crop size on the peak and average cutting energy requirement for okra fruits are shown with the response surface plots in Figures 4.21a and 4.21b.

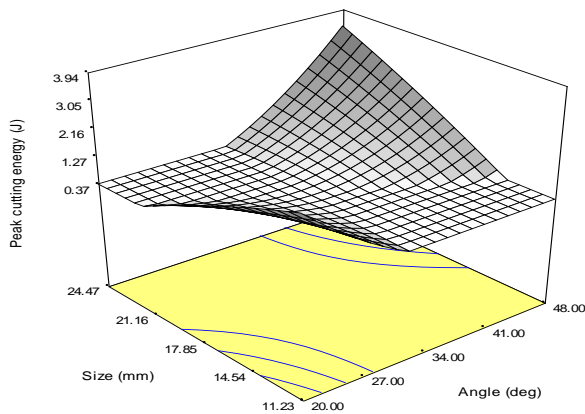


Figure 4.21a: Response surface plot of the interaction between knife angle and crop size on the peak cutting energy of okra fruits.

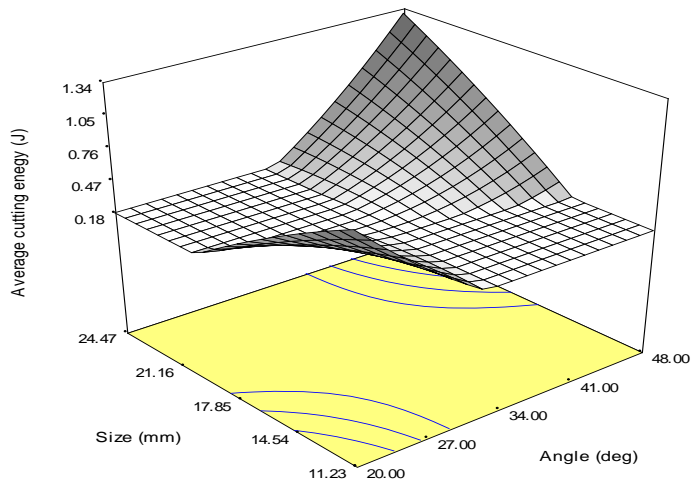


Figure 4.21b: Response surface plot of the interaction between knife angle and crop size on the average cutting energy of okra fruits.

4.1.4.3 Onion bulbs

The response surface plots for the interaction effects between cutting speed, knife edge angle and the crop size for onion bulbs are detailed in the sections below.

4.1.4.3.1 Cutting speed and crop size

Figures 4.22a and 4.22b are response surface plots of the interactive effect between cutting speed and crop size on the peak and average cutting energy of onion bulbs.

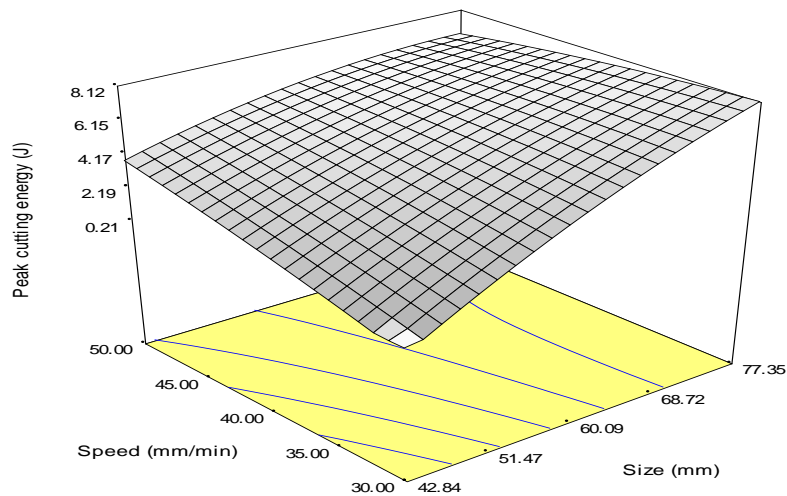


Figure 4.22a: Response surface plot of the interaction effect of speed and size on the peak cutting energy of onion bulbs.

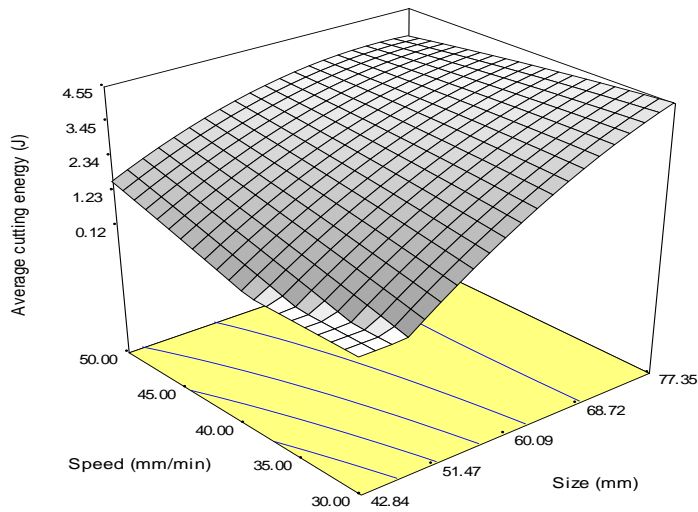


Figure 4.22b: Response surface plot of the interaction effect of speed and size on the average cutting energy of onion bulbs.

4.1.4.3.2 Knife edge angle and crop size

The effect of the interaction between the knife edge angle and crop size on the peak and average cutting energy requirement for onion bulbs are shown with the response surface plots in Figures 4.23a and 4.23b.

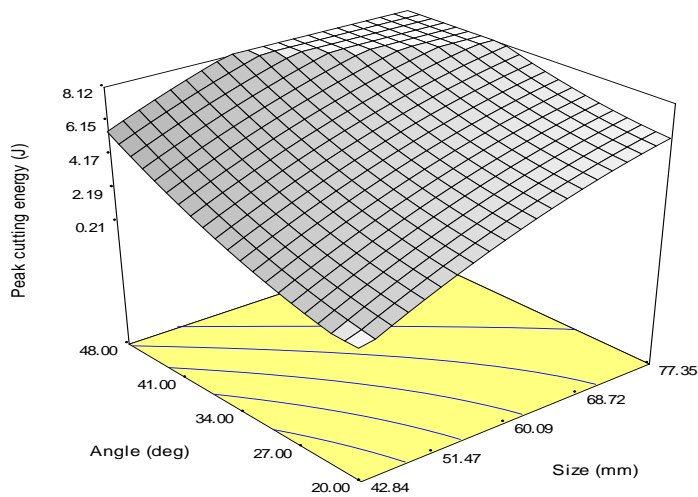


Figure 4.23a: Response surface plot of the effect of angle and size on the peak cutting energy of onion bulbs.

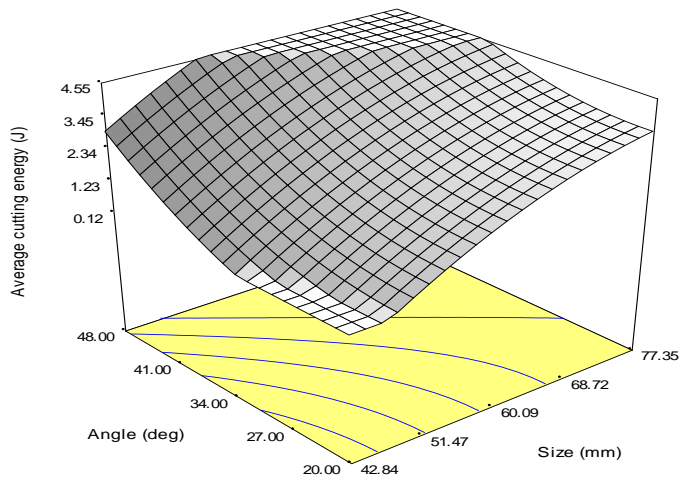


Figure 4.23b: Response surface plot of the effect of angle and size on the average cutting energy of onion bulbs.

4.1.4.3.3 Knife edge angle and cutting speed

The effect of the interaction between the knife edge angle and cutting speed on the peak and average cutting energy requirement for onion bulbs are shown with the response surface plots in Figures 4.24a and 4.24b.

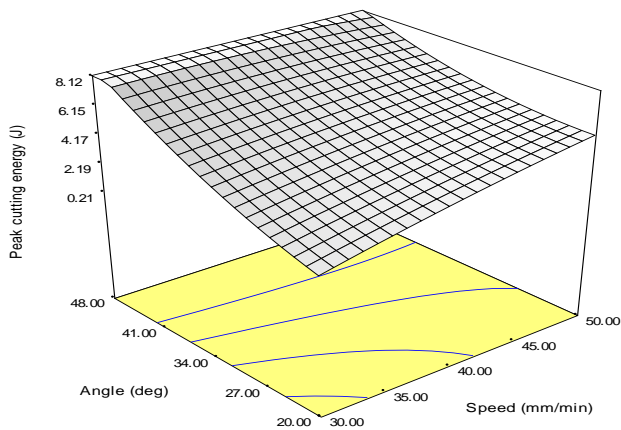


Figure 4.24a: 3D plot of the effect of knife angle and cutting speed on the peak cutting energy of onion bulbs.

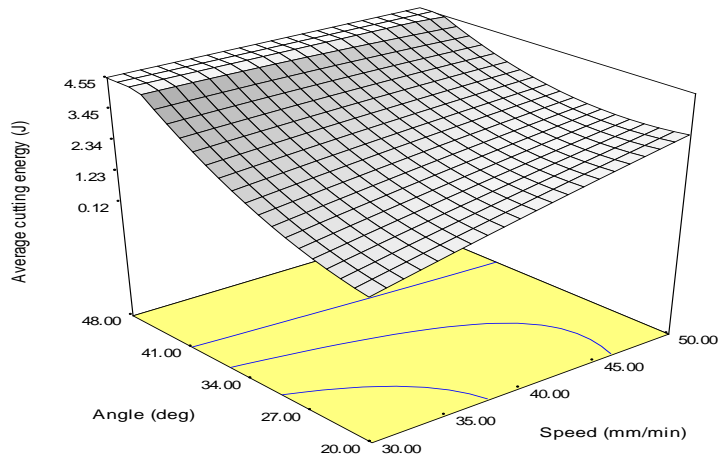


Figure 4.24b: 3D plot of the effect of knife edge angle and cutting speed on the average cutting energy of Onion.

4.1.4.4 Garden egg fruits

The results of the interactive effects of knife edge angle, cutting speed, and crop sizes on the peak and average cutting energy of garden egg fruits are shown in the figures below.

4.1.4.4.1 Crop size and cutting speed

The effect of the interaction between crop size and cutting speed on the peak and average cutting energy requirement for garden egg fruits are shown with the response surface plots in Figures 4.25a and 4.25b.

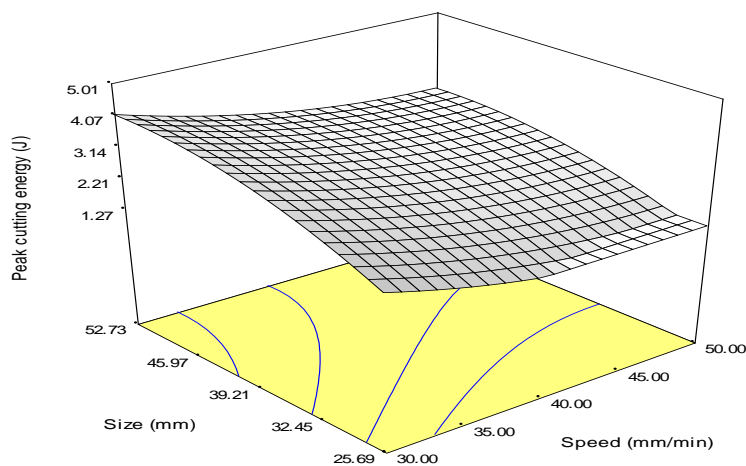


Figure 4.25a: Response surface plot of the interaction effect between size and speed on Peak cutting energy for garden egg fruits.

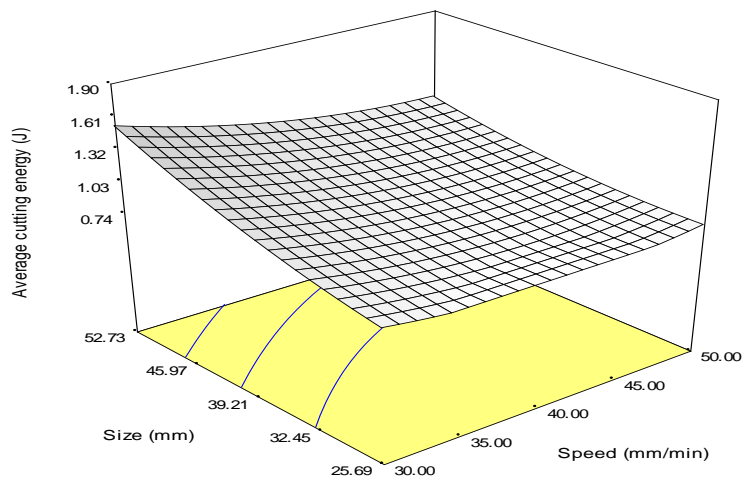


Figure 4.25b: Response surface plot of the interaction effect between size and speed on average cutting energy for garden egg fruits.

4.1.4.4.2 Knife edge angle and cutting speed

The effect of the interaction between knife edge angle and cutting speed on the peak and average cutting energy requirement for garden egg fruits are shown with the response surface plots in Figures 4.26a and 4.26b.

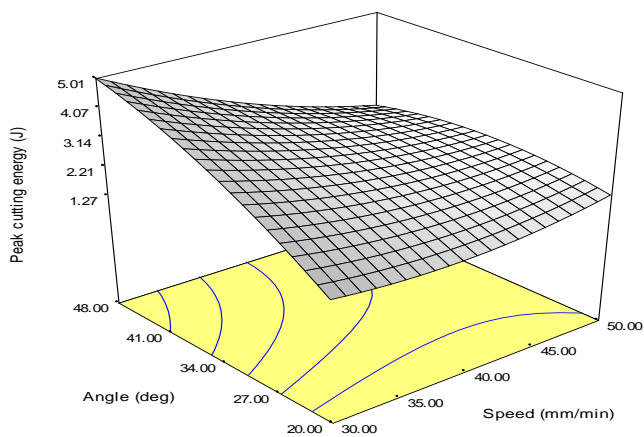


Figure 4.26a: Response surface plot of the interaction effect between angle and speed on Peak cutting energy for garden egg fruits.

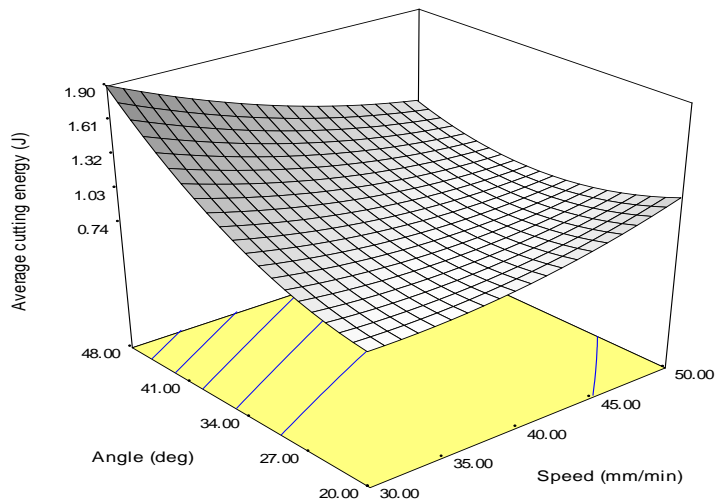


Figure 4.26b. Response surface plot of the interaction effect between angle and speed on average cutting energy for garden egg fruits.

4.1.4.4.3 Knife edge angle and crop size

The effect of the interaction between knife edge angle and crop size on the peak and average cutting energy requirement for garden egg fruits are shown with the response surface plots in Figures 4.27a and 4.27b.

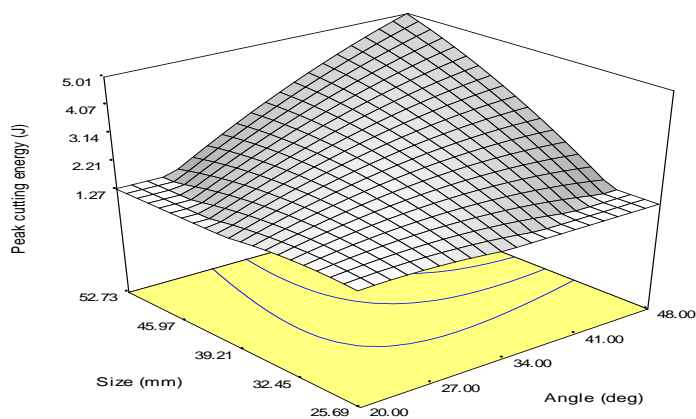


Figure 4.27a: Response surface plot of the interaction effect between size and angle on Peak cutting energy for garden egg fruits.

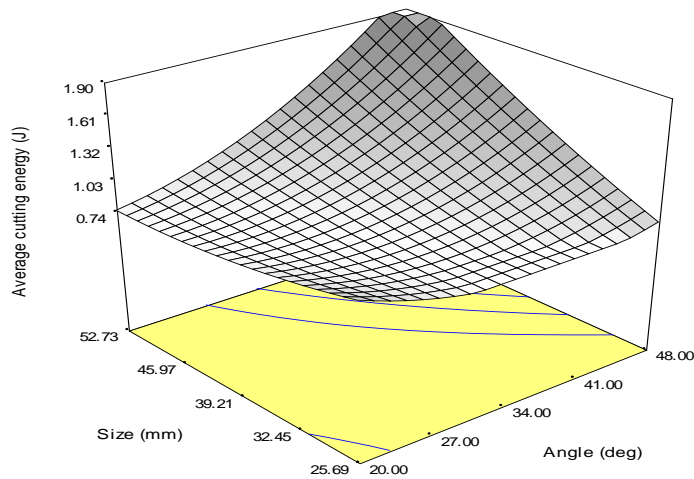


Figure 4.27b: Response surface plot of the interaction effect between size and angle on average cutting energy for garden egg fruits.

4.2 DISCUSSION

4.2.1 Discussion on Statistical Analysis Obtained for the Model Development and Validation.

The following sections discuss the results of tests carried out on the physical characteristics, harness and compressive strength test for the studied crops.

4.2.1.1 Cocoyam cormels

The obtained values for the physical properties of cocoyam cormels support the findings by researchers such as Balami *et al.* (2014) while working on central tendencies of some physical properties of cocoyam. Their obtained values of 65.48mm, 35.75mm, 50.18mm and 8.30 for maximum equivalent diameter, minimum equivalent diameter, arithmetic mean diameter and standard deviation respectively falls within the range of values obtained for the cocoyam cormels studied in this research work in which the maximum and minimum equivalent diameters were observed to be 60.5 ± 0.22 mm and 22.15 ± 0.18 mm respectively. These results show that the cocoyam cormels studied in this research work falls within the generally acceptable physical properties for the crop.

The result of the hardness and compressive strength test for cocoyam cormels as presented in Table 4.2 shows a steady decrease in the obtained values for hardness and compressive strength as the equivalent diameters decrease. This implies that the larger the size of the cormels, the greater the force needed to penetrate through the tissues of the cormels. The highest hardness value of 177.4N was obtained for the largest equivalent diameter of 64.89mm and the lowest hardness value of 168N was obtained for the smallest cormel of equivalent diameter 33.68mm. This observation was made by Ciulica and Rus (2011a) in their study on the influence of maturity degree of vegetables on their cutting

resistance force. Following the experimental measurements, their results showed that carrot cutting operation was influenced by the diameter in cutting area. It was equally observed that there was an increase in the cutting force with increasing cutting section in which the highest cutting forces of 90.89N, 137.55N and 240.3N were observed for diameters 20mm, 26.28mm and 40mm respectively.

4.2.1.2 Okra fruits

From the results of the average values for physical properties of okra fruits as presented on Table 4.3, the average value of the largest samples studied was 24.9 ± 0.66 mm in equivalent diameter and has a mass of 18.16 ± 2.17 g while the average values of the smallest samples studied was 12.44 ± 0.84 mm and 1.72 ± 0.14 g in mass. In comparison with results obtained by researchers such as Sahoo and Srivastava (2002) in their study on the physical properties of okra fruit as a function of moisture content obtained average values of 35.17 ± 7.97 mm and 13.27 ± 4.07 for equivalent mean and mass respectively. Hence the obtained values for the physical properties of okra in this research work are relevant in post-harvest operation of okra fruits such as cutting.

From the values obtained for hardness and compressive strength of okra fruits, it was observed that the hardness and compressive strength of okra fruits increases with increasing equivalent diameter and mass showing a direct proportionality relationship. The largest values of 93.8N and 0.1276Nmm for hardness and compressive strength respectively corresponds to the largest equivalent diameter of 24.47mm. these results are supported by findings by Asonye *et al.* (2018b) in their work on the numerical and experimental studies of the cutting energy requirements of okra (*Abelmoschus esculentus L.*). They reported that the highest cutting energy of 23.63J was observed for the largest range of okra fruits tested and the lowest cutting energy of 3.45J was recorded for the least range of okra fruits tested. These results will enhance the appropriate handling and further processing of okra fruits.

4.2.1.3 Onion bulbs

The results of the average values for the physical properties of onion bulbs as presented in Table 4.5 is typical with results obtained by other researchers such as Karthik and Correll (2015). The range of values of 10.28 ± 2.74 g to 66.16 ± 18.4 g for unit mass of onion bulbs obtained in their study falls within the range of values for the mass of onion bulbs in this study (45.42 ± 3.09 to 361.44 ± 18.07 g). Also, onion bulbs in this study are red in colour and spherical in shape as observed by Karthik and Correll (2015). Furthermore, Singh *et al.* (2016) in their study on the effect of knife edge angle and speed on the specific energy requirement when cutting vegetables varying in their textural characteristics of rind and flesh measured the diameter and moisture content of onion which is a multilayered textural vegetable. Values obtained for the moisture content (%wb), major, minor and intermediate diameters

were $86.05 \pm 2.19\%$ wb, 51 ± 5.5 mm, 42 ± 3.1 mm and 40 ± 5.2 mm respectively. These values fall within the range of measured values for the physical properties of onion bulbs used in this study as presented in Table 4.5. These results are indicative of the effect of size on the physical properties of onion bulbs and equally serve as important data for designers of post-harvest machines such as cutters.

The obtained results for the hardness and compressive strength test for onion bulbs show a progressive increase in value as the equivalent diameter and mass increases. The largest mass and highest equivalent diameter of 361.44g and 84.09mm respectively was observed to have the highest hardness value of 169N and compressive strength of 0.0612N/mm^2 . These observations were also made by Ciulica and Rus (2011a) in their study on the influence of maturity degree of vegetables on their cutting resistance force. The values registered at the cutting test showed a steady increase in the maximum cutting strain as the diameter in cutting area increases. The lowest diameters in cutting area of 20mm, 21mm and 25mm had maximum cutting strain of 90.89N, 53,80N and 84.62N respectively while the largest diameters in cutting areas of 49.02mm, 41mm and 32.16mm had maximum cutting strain of 206.62N, 193.7N and 128.2N respectively. This shows that the size of onion bulbs has a considerable effect on their hardness and compressive strength. This finding is of relevance to designers of post-harvest handling equipment and systems.

4.2.1.4 Garden egg fruits

Results of some of the physical properties of the garden egg fruit needed for post-harvest handling operations such as cutting which are presented in Table 4.10 shows the range of equivalent diameters obtained to be 32.87 ± 1.44 mm to 52.73 ± 1.08 mm, range of mass as 18.92 ± 1.24 g to 70.42 ± 3.67 g and cross-sectional area as $964.0 \pm 87.23 \text{mm}^2$ to $2296.8 \pm 307.38 \text{mm}^2$. These results obtained for the studied garden egg fruits which are spherical in shape and greenish in colour support the findings by Ikrang and Okoko (2014) in their study of some engineering properties of the garden egg fruit. The results of their experiment revealed the shape of the garden egg fruit as prolate spheroid, geometric mean diameter ranged between 15.0mm and 28.0mm, average mass and surface area as 8.77g and 2658mm^2 respectively. This shows universal acceptability of the garden egg fruits in this study. Designers of systems and equipment to handle garden egg fruits will find these results of great importance.

The hardness and compressive strength values of the garden egg fruit presented on Table 4.11 shows increase in hardness value and compressive strength with increasing equivalent diameters and mass of the garden egg fruits. However, the increase is not steady as observed in the other crops studied. The highest value of 175.4N for the hardness value was observed for size range 2 and the lowest value of 0.288N/mm^2 for the compressive strength was obtained for size range 4. This could be as a result of the presence of multiple seeds in the garden egg fruit. This observation was also made by researchers such as Singh *et al.* (2016) in their study on the effect of knife edge angle and speed on the specific

energy requirement when cutting vegetables varying in their textural characteristics of rind and flesh. Their findings revealed that vegetables with multiple seeds such as bittergourd and pointed gourd showed typical force depth of cut characteristics having peaks and ripples as shown in Figures 2.9a and 2.9b.

4.2.2 Discussion on Experimental Studies of Cutting Energy Consumption

The following sections discuss the result of the experimental test conducted on the studied crops. Three variables were studied during the test (crop size, cutting speed and knife edge angle) and the peak and average cutting energy were obtained

4.2.2.1 Cocoyam cormels

From the results displayed in Table 4.9, it is observed that both the peak energy of cut and the average cutting energy showed steady increase as the crop size increased for all the cutting speeds. For the cutting speed of 30mm/min, the highest peak energy of cut and the average cutting energies of 15.6969J and 9.6164J respectively were obtained for crop size 5 which is the largest crop size with equivalent diameter of 64.89mm. Also, the lowest peak energy of cut and the average cutting energy of 3.5767J and 0.9423J respectively were obtained for the lowest crop size of 33.68mm. This indicates a direct relationship between the cutting energy values and the size of the cocoyam crop samples. This could be as a result of the greater distance of travel as the cutting edge penetrates through the sample and since energy is a function of the force of cut and distance travelled by the force, hence greater distance of cut gave larger energy of cut.

Furthermore, results as seen from the Table 4.5 showed that as the knife edge angle increases, there is an increase in both the peak and average cutting energies for all the cutting speeds. For the cutting speed of 50mm/min, the peak and average energies of cut were observed to be 3.1157J and 2.3876J respectively for knife edge angle 20° while the peak and average cutting energies for knife edge angle 48° for same cutting speed of 50mm/min gave 4.8724J and 2.6889J respectively. This also shows a direct relationship between the cutting energy requirement and the cutting edge angles. This could be as a result of the large area of the cutting-edge penetrating through the sample i.e. greater area of contact between the cutting edge and the sample, hence greater force concentration is needed on this contact area leading more energy been expended while low knife edge angles define smaller area leading lower force of concentration on this contact area and hence lower energy of cut

A more investigative look at the experimental result showed a decrease in the cutting energy values as the cutting speed increases. The peak and average cutting energy values obtained for the cutting speed of 30mm/min for the largest crop size of 64.89mm were 14.8856J and 9.6722J respectively while the peak and average cutting energy values obtained for the cutting speed of 50mm/min for the

largest crop size of 64,89mm gave 9.7912J and 5.2994J. This could be as a result of less time utilized as the speed increases. Since speed is a function of time, greater distance is covered in less time with an increased speed; hence more work is done within a shorter time resulting in less energy expended as the speed of cut increases.

4.2.2.2 Okra fruits

From the cutting energies results shown on Table 4.8, there is an observable increase in the cutting energy values as the crop sizes increase for all the cutting speeds. For cutting speed of 35mm/min at the knife edge angle of 34° , the lowest energy values for both the peak and average cutting energy were recorded as 0.0856J and 0.0174J respectively for the lowest crop size i.e equivalent diameter of 11.23mm while the highest energy values of 0.9658J and 0.3711J obtained for peak and average cutting energy values were reported for the largest crop size i.e equivalent diameter of 24.47mm. This could be attributed to the increase in maturity stage of okra fruits as they increase in size, this increase in maturity stage causes a toughening of the fibres and equally reduces the moisture content of the crop. Hence for larger fruits, the cutting energy requirement is higher because of the tougher nature of the fibres than the energy consumed in cutting smaller fruits.

Furthermore, a closer observation of the test result showed a decreasing cutting energy value as the cutting speed increases, for cutting speed of 30mm/min and knife edge angle of 48° , the peak and average cutting energy values were reported as 6.2267J and 2.3527J for the largest crop size with equivalent diameter of 24.47mm while the peak and average cutting energy values for the cutting speed of 50mm/min and the knife edge angle of 48° for the largest crop size with equivalent diameter of 24.47mm were reported as 2.9067J and 1.1048J respectively. This could be as a result of the reduced time taken to travel through the product due to an increase in speed. Hence work is done at a shorter time, thereby reducing the energy consumed in the work of cutting.

In addition, there is a general display of energy increment as the knife edge angle increases. An example is the energy value obtained for the cutting speed of 40mm/min. the peak and average energy values obtained from crop size 4 with equivalent diameter of 20.52mm for knife edge 20° were 0.3966J and 0.5893J respectively while the peak and average cutting energy values obtained for same crop size of equivalent diameter of 20.52mm and same speed of 40mm/min were 2.3668J and 0.8670J for knife edge angle of 48° . This could be as a result of a larger contact area between the knife edge and the okra sample, causing a reduction in pressure exerted on the sample. Hence, more force is required to cause pressure enough required to compress and subsequently shear through the sample, more force results into more work done and this translates into more energy consumed in doing more work.

4.2.2.3 Onion bulbs

From the result displayed in Table 4.10, it is observed that there is a steady increase in the energy of cut values as the crop size increases for all the cutting speeds. For the cutting speed of 30mm/min, the highest peak and average energy of cut values of 12.9445J and 14.0582J respectively were obtained for crop size 5 (largest crop size) with equivalent diameter of 84.10mm while the lowest peak and average cutting energy values of 2.886J and 3.5579J respectively were obtained for crop size 1 (lowest crop size) with equivalent diameter of 42.84mm for the same knife edge angle of 20°. This is an indication that a direct relationship exists between the energy requirement for cutting and the size of the onion bulbs. This could be as a result of the larger distance of cut as the crop sizes increases, hence the knife edge travels a longer distance during penetration through larger samples than through smaller samples. Energy is a function of force of cut and distance travelled by the force; hence longer travel distance gives greater energy expended and vice-versa.

Furthermore, results of the cutting energy test as displayed in Table 4.10 showed an increase in the cutting energy value as the knife edge angle increases. Considering the cutting speed of 40mm/min and knife edge angle of 20° for size range 1 with equivalent diameter of 42.84mm, the peak cutting energy is recorded as 7.0166J and the value for 48° knife edge angle was recorded as 11.8676J. Also, for size range 5 with equivalent diameter of 84.10mm, the peak cutting energy for 20° knife angle is 12.6987J while the peak cutting energy value for 48° is 16.1528J. This could be as a result of larger area of the knife edge penetrating through the sample i.e. as contact area increase, pressure on the sample reduces and more energy is needed to overcome the resistive force exerted by the sample on the knife edge in order to cause compression and shearing. Lower knife edges have little contact area and pressure is spread over a small area, hence lower energy consumption to cause shearing.

4.2.2.4 Garden egg fruits

Results obtained showed a steady reduction in the average cutting energy values for the crop samples as the crop size increases (a shift from results obtained from the other three crops). Observations for the cutting speed of 45mm/min and knife edge angle of 20° showed that the highest average cutting energy of 2.0053J was obtained for crop size range of equivalent diameter of 25.69mm and the least average cutting energy value of 0.5032J was observed for the largest garden egg crop size with equivalent diameter of 52.73mm. Also, for the same cutting speed of 30mm/min and knife edge angle of 48°, the highest average cutting energy value of 1.6494J was observed for the least crop size of 25.69mm and the least average cutting energy value of 0.4696 was observed for the largest crop size of 52.73mm equivalent diameter. This could be attributed to the highly elastic nature of the outer skin of the garden egg fruit. Perhaps the skin gets softer as the crop gets larger, hence reduction in energy consumed for cutting as the crops gets larger.

Furthermore, the results of the cutting energy requirement test for the garden egg fruit show a general decrease in the average cutting energy values as the cutting speed increases. The highest peak cutting energy value of 6.1915J was observed for cutting speed of 30mm/min for the largest crop size of equivalent diameter 52.73mm and knife edge angle 48° while the lowest peak cutting energy value of 0.0300J was observed for cutting speed of 45mm/min for crop size of equivalent diameter 25.69mm and knife edge angle of 41° . This could be attributed to the less time utilized for the higher speed values, hence a reduction in energy expended in carrying out the work of cutting.

4.2.3 Discussion on Development of Predictive Models for Cutting Energy Tests

4.2.3.1 Cocoyam cormels

The peak and average cutting energy requirement models for cocoyam cormels were described by polynomial functions of the second order with R^2 -values of 0.904 and 0.900 respectively. These R^2 values which indicate high goodness of fit showed close correlation between the actual experimental values obtained and the values predicted by the design expert software. Statistical inference from the analysis of variance at 95% confidence level ($P < 0.05$) showed that the interaction between crop size and knife edge angle and interaction between crop size and cutting speed gave the least energy demand for the peak and average cutting energy respectively. Hence increasing the values for the crop size and knife edge angle resulted in a decrease in the peak energy consumed in the cutting of cocoyam cormels while an increase in the crop size and cutting speed resulted to a decrease in the average cutting energy for cocoyam cormels.

4.2.3.2 Okra fruits

A and B and C are cutting speed, knife edge angle and okra crop size respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively). The high values obtained for the coefficient of determination $R^2 = 0.788$ and $R^2 = 0.745$ for the peak and average cutting energy for okra fruit is a good indication of the correlation between the actual experimental values and the predictive values by the design expert software. The analysis of variance also showed that the interactive effect between knife edge angle and crop size constitutes the greatest influence on the peak and average cutting energy of okra fruits.

4.2.3.3 Onion bulbs

The high coefficient of determination of $R^2 = 0.999$ and $R^2 = 0.984$ obtained for the predictive model equations is an indication of the high correlation between the actual experimental values and the predicted values. Also, the statistical inference from the analysis of variance at 95% confidence level

($P < 0.05$) showed that an increase in the interaction effect between crop size and knife edge angle will result in an increase of both the peak and average cutting energy requirement for onion bulbs.

4.2.3.4 Garden egg fruits

A and B and C are cutting speed, knife edge angle and garden egg crop size respectively, which are the independent variables while PE and ACE are the responses (peak cutting and average cutting energy respectively). The values of the coefficient of determination $R^2 = 0.632$ and $R^2 = 0.600$ obtained for the peak and average cutting energy equations for garden egg fruits are acceptable as goodness of fit indicators ($R^2 > 0.5$) of the correlation between the actual experimental values and the predicted values. However, the low values could be attributed to experimental errors.

4.2.4 Discussion on Optimization of Cutting Energy Consumption and Interactions

4.2.4.1 Cocoyam cormels

The surface response plots for the interaction effects between cutting speed, knife edge angle and the crop size for cocoyam cormels are discussed in the sections below.

4.2.4.1.1 Cutting speed and crop size

Generally, observation from the response surface plots showed that the peak and average cutting energy requirements increased as crop size increased showing a direct relationship while cutting energy requirements reduced as the cutting speed increased indicating an inverse relationship between the cutting speed and the cutting energy requirement.

Statistical analysis of the response surface plots showed that the crop size has the highest coefficient estimate of 4.26 and 2.82 respectively for the peak and average cutting energy models for cocoyam cormels. This is an indication that the crop size constitutes the greatest influence on the cutting energy requirement. However, the interaction between cutting speed and crop size will cause significant effect on the peak and average cutting energy requirements for cocoyam cormels as they gave high coefficient estimates of -0.78 and -1.06 respectively.

4.2.4.1.2 Knife edge angle and crop size

The significant effect of the interaction between knife edge angle and crop size is indicated in the coefficient estimate values of -1.02 and -0.45. this means that increasing the values of the knife angle and the crop size (i.e larger knife edge angles and bigger crop sizes) will result into high cutting energy consumption and reducing the values will greatly reduce the cutting energy consumption. (i.e. in terms of smaller crop sizes and low knife edge angles)

4.2.4.1.3 Knife edge angle and cutting speed

The interactive effect of speed and angle on the peak and average cutting energy of cocoyam cormels as shown in Figures 4.18a and 4.18b gave significant effects and the largest coefficient estimate values of -0.38 and -0.39 respectively for the models for peak and average cutting energy. This is an indication that the interaction between knife angle and cutting speed gave the highest effect on the cutting energy of cocoyam cormels.

However, Optimization result for the cutting energy requirement for cocoyam cormels were observed to occur at equivalent crop diameter of 33.68mm, cutting speed of 35mm/min and 20° knife edge angle for both the peak and average cutting energy. Hence to save energy during the cutting process of cocoyam cormels for the range of variables studied, it is recommended that these optimal values should be taken into consideration.

4.2.4.2 Okra fruits

4.2.4.2.1 Crop size and cutting speed

Statistical inference using the coefficient estimate as indicators showed significant effect with a coefficient estimate of -0.49 and -0.27 respectively for the peak and average cutting energy.

4.2.4.2.2 Knife edge angle and cutting speed

The effect of the interaction between knife edge angle and cutting speed on both the peak and average cutting energy of okra fruits showed significant result with a coefficient estimates of -1.09 and -0.35 and standard errors of 0.56 and 0.23 (< 1.0) respectively. The effects of their interaction (between knife angle and cutting speed) were however lower than the effect obtained with the interaction between the okra fruit size and the cutting speed (coefficient estimates of -0.49 and -0.27 for peak and average cutting energy).

4.2.4.2.3 Knife edge angle and crop size

Statistical inference of the interaction between knife angle and crop size on the peak and average cutting energy of okra fruits showed very significant result. Statistical inference of this interaction gave the highest coefficient estimates of 1.78 and 0.81 respectively. This is an indication that increment in the interaction between the okra crop size and the knife edge angle will cause a very significant increase in the energy consumption during the cutting process of okra fruits. This is worthy of note for designers of okra processing plants especially cutters for okra fruit.

However, optimization results for okra fruits showed energy consumption being maximized at the cutting speed of 35mm/min, knife edge angle of 20^0 and crop size with equivalent diameter of 23.80mm.

4.2.4.3 Onion bulbs

The response surface plots for the interaction effects between cutting speed, knife edge angle and the crop size for onion bulbs are discussed in the sections below.

4.2.4.3.1 Cutting speed and crop size

Result obtained for the interaction between cutting speed and crop size for both the peak and average cutting energy for onion bulbs showed significant effects. However, the effect of the interaction of these variables gave the least effect indicated by the least coefficient estimate values of -1.37 and -0.88 respectively.

4.2.4.3.2 Knife edge angle and crop size

Results obtained for the interactive effect of knife edge angle and crop size for both the peak and average cutting energy of onion bulbs indicated the highest effect. The analysis of variance (ANOVA) report showed the highest coefficient estimate values of -0.30 and -0.16 for respectively. Hence, in the design of onion cutters, very much attention should be given to the edge angle of the cutter and the onion bulb size.

4.2.4.3.3 Knife edge angle and cutting speed

Statistical analysis of the interaction between the knife edge angle and the cutting speed on both the peak and average cutting energy of onion bulbs showed significant effect with coefficient estimate values of -1.00 and -0.71. However, these estimates were lower than those of the interaction between edge angle and crop size.

Optimization of the cutting process for onion bulbs were observed to occur at crop size of 47.91mm, cutting speed of 35mm/min and knife edge angle of 20^0 . Hence, in the design of cutters for onion bulbs with an objective to maximize energy, these observations should be taken into consideration.

4.2.4.4 Garden egg fruits

The interactive effects of knife edge angle, cutting speed, and crop sizes on the peak and average cutting energy of garden egg fruits are discussed in the sections below.

4.2.4.4.1 Crop size and cutting speed

The effect of the interaction between crop size and cutting speed on the peak and average cutting energy of garden egg fruit showed significant effect. However, the significant was minimal as the coefficient estimate value of -0.025 was the least of all the values of the interactions.

4.2.4.4.2 Knife edge angle and cutting speed

The interactive effect of knife angle and cutting speed on the cutting energy of garden egg fruit showed significant effect with coefficient estimate of -0.87. However, this effect is lower than that obtained for the interaction of knife edge angle and crop size by 63% and higher than that obtained for cutting speed and crop size by 84.5%.

4.2.4.4.3 Knife edge angle and crop size

The interaction of crop size and the knife edge angle on the energy consumption during the cutting of garden egg fruits showed very significant results. The coefficient estimate of 1.50 was the largest of all the interactions. This knowledge is of importance to designers of processing equipment for okra fruits especially the development of cutters.

However, the optimization result for garden egg fruits showed energy consumption being maximized at the cutting speed of 35mm/min, knife edge angle of 20⁰ and crop size of 45.41mm.

4.2.5 Summary of Discussion

The results of this research work which were discussed and compared with the findings of other researchers are great contributions to knowledge. Results on the physical properties of the studied crops show the significant effects of crop size on the measured physical characteristics. Experimental studies carried out show the relevant effects of crop size, cutting speed and knife wedge angles on the peak and average cutting energies of the select crops. The high coefficient of determination (R² values) obtained for the developed predictive models for the cutting energy of the studied crops are indicators of good and acceptable models. The optimization process which studied the interaction of three independent variables (crop size, cutting speed and knife wedge angle) on the dependent factor (cutting energy) revealed values for optimal cutting energy consumption for the select crops.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Numerical and experimental studies of the cutting process and the cutting energy requirements for selected vegetable crops were carried out. Cutting at any stage of agricultural processing is a time and energy consuming operation. Hence this study looked at the development of prediction models using dimensional analysis based on the Buckingham's Π theorem for the cutting energy requirements for selected crops. The crops of interest are tuber crop (cocoyam) (*Colocasia esculenta*); fruit vegetable (okra) (*Abelmoschus esculentus L*); bulb vegetable (onion) (*Allium cepa.*) and fruit vegetable (garden egg leaf) (*Solanum macrocarpon*). These crops were selected because they are native to the study area and they suffer a lot of postharvest losses due to their relatively high moisture content, soft texture and high respiration rate.

Factors influencing the cutting process of the selected vegetable crops were grouped into tool parameters (materials of construction, sharpness, rigidity of cutting tools, knife speeds etc) and crop characteristics (crop variety, size, maturity stage, crop moisture content, crop density, fibre orientation etc.). With proper assumptions being made, the most important and measurable factors were used in predicting the model equations.

Mathematical model for predicting the cutting energy of cocoyam (*Colocasia esculenta*) was developed using dimensional analysis based on the Buckingham's Π theorem. The model equation expressed as $E = 0.658 \frac{tswH_d}{A} - 0.255 \frac{\sigma v^2 s^2 H_d}{\phi} + 10.62$ was validated with data from a developed automated cutter. Results obtained showed a high coefficient of determination ($R^2 = 0.982$) which implies that the model is good. Also, Mathematical model for predicting the cutting energy of okra (*Abelmoschus esculentus L*) was developed using dimensional analysis based on the Buckingham's Π theorem. The model equation expressed as $E = 0.3462 \frac{tswH_d}{A} - 0.3026 \frac{\sigma v^2 s^2 H_d}{\phi} + 0.8278$ was validated with data from an automated vegetable cutter. Results obtained showed a high coefficient of determination ($R^2 = 0.986$) which implies that the model is good. Furthermore, the cutting energy model equation for onion bulbs expressed as $E = 0.120 \frac{tswH_d}{A} + 0.465 \frac{\sigma v^2 s^2 H_d}{\phi} + 9.686$ was validated experimentally and an R^2 value of 0.978 obtained is an indication of an appropriate model. Lastly the cutting energy prediction model obtained for garden egg, expressed as $E = 0.0774 \frac{tswH_d}{A} + 0.365 \frac{\sigma v^2 s^2 H_d}{\phi} - 0.649$ and validated gave a coefficient of determination of $R^2 = 0.998$ which is a good indicator.

The developed automated cutter consists of the hardware and software components. Arduino controlled processors were used in the development of the cutter in order to automatically and effectively measure, record and store cutting variables and other basic parameters with minimum human supervision, thus making the entire cutting process automated.

Furthermore, optimization studies were carried out by studying the interaction between three independent variables namely cutting speed (30, 35, 40, 45 and 50mmmin⁻¹), knife edge angle (20, 27, 34, 41 and 48 deg) and crop size on the dependent factor (cutting energy consumption). The selected crop sizes (equivalent diameter) were 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 14.91, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus* L.); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa.*) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium macrocarpon*).

Results of the study showed that optimization of cutting energy consumption can be achieved at equivalent crop diameter of 33.68mm, cutting speed of 35mm/min and 20⁰ knife edge angle for cocoyam cormels; crop size of 47.91mm, cutting speed of 35mm/min and knife edge angle of 20⁰ for onion bulbs; cutting speed of 50mm/min, knife edge angle of 20⁰ and crop size with equivalent diameter of 23.80mm for okra fruits; cutting speed of 35mm/min, knife edge angle of 20⁰ and crop size of 45.41mm for garden egg fruits.

5.2 RECOMMENDATIONS

The following recommendations are considered for future studies:

1. Studies on cutting processes and energy requirements for cutting of different agricultural crops especially of indigenous origin should be intensified as review shows that little work has been done on energy requirement to cut agricultural crops and these data are needed for efficient design of energy saving cutters.
2. Models for predicting the amount of energy required to cut given mass of different crops using different cutting systems should be developed since individual crops behave differently as a result of their intricate characteristics.
3. In terms of varieties and stages of maturity, experimental investigations of the influence of these factors on specific and total energy consumption, cutting rate and time is of great importance for future work.

5.3 CONTRIBUTIONS TO KNOWLEDGE

This study has contributed to knowledge in the following ways:

1. Developed an automated cutter (which can be mass produced) that measures, records and displays basic cutting parameters such as cutting speed, distance of cut, force of cut and energy consumption and controls cutting operation with minimum human supervision through the use of Integrated Development Environment (IDE) and micro-processor known as arduino.
2. Developed prediction models for the cutting energy requirement for selected crops (cocoyam) (*Colocasia esculenta*); fruit vegetable (okra) (*Abelmoschus esculentus L.*); bulb vegetable (onion) (*Allium cepa.*) and fruit vegetable (garden egg fruit) (*Solanium macrocarpon*) using dimensional analysis based on the Buckingham pi theorem and validated the developed models with experimentations.
3. Cutting energy experiments carried out on the selected crops showed variability in the obtained energy values for the crops. At 30mm/min cutting speed and knife edge angle of 20⁰, the average cutting energy for the highest size range were found to be 9.6164J, 0.1079J, 14.0582J and 0.1505J for cocoyam cormels, okra fruit, onion bulb and garden egg fruit respectively. This showed uniqueness of agricultural products.
4. Optimization of the cutting process and cutting energy consumption for the select crops by studying the interaction of three independent variables on the dependent factor. The independent variables were cutting speed (30, 35, 40, 45 and 50mmmin⁻¹), knife edge angle (20, 27, 34, 41 and 48 deg) and crop size. The selected crop sizes (equivalent diameter) were 33.68, 41.02, 45.34, 50.31 and 64.89mm for cocoyam (*Colocasia esculenta*); 11.23, 14.91, 17.82, 20.52 and 24.47mm for okra (*Abelmoschus esculentus L.*); 42.84, 51.78, 61.36, 77.35 and 84.10mm for onion (*Allium cepa.*) and 25.69, 32.87, 40.31, 47.69 and 52.73mm for garden egg (*Solanium macrocarpon*). Results for optimal cutting energy consumption for the select crops were revealed as; equivalent crop diameter of 33.68mm, cutting speed of 35mm/min and 20⁰ knife edge angle (cocoyam cormels); crop size of 47.91mm, cutting speed of 35mm/min and knife edge angle of 20⁰ (onion bulbs); cutting speed of 50mm/min, knife edge angle of 20⁰ and crop size with equivalent diameter of 23.80mm (okra fruits); cutting speed of 35mm/min, knife edge angle of 20⁰ and crop size of 45.41mm (garden egg fruits).

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APPENDICES

Appendix 1a: Sorted and labeled okra samples



Appendix 1b: Sorted and labeled garden egg samples



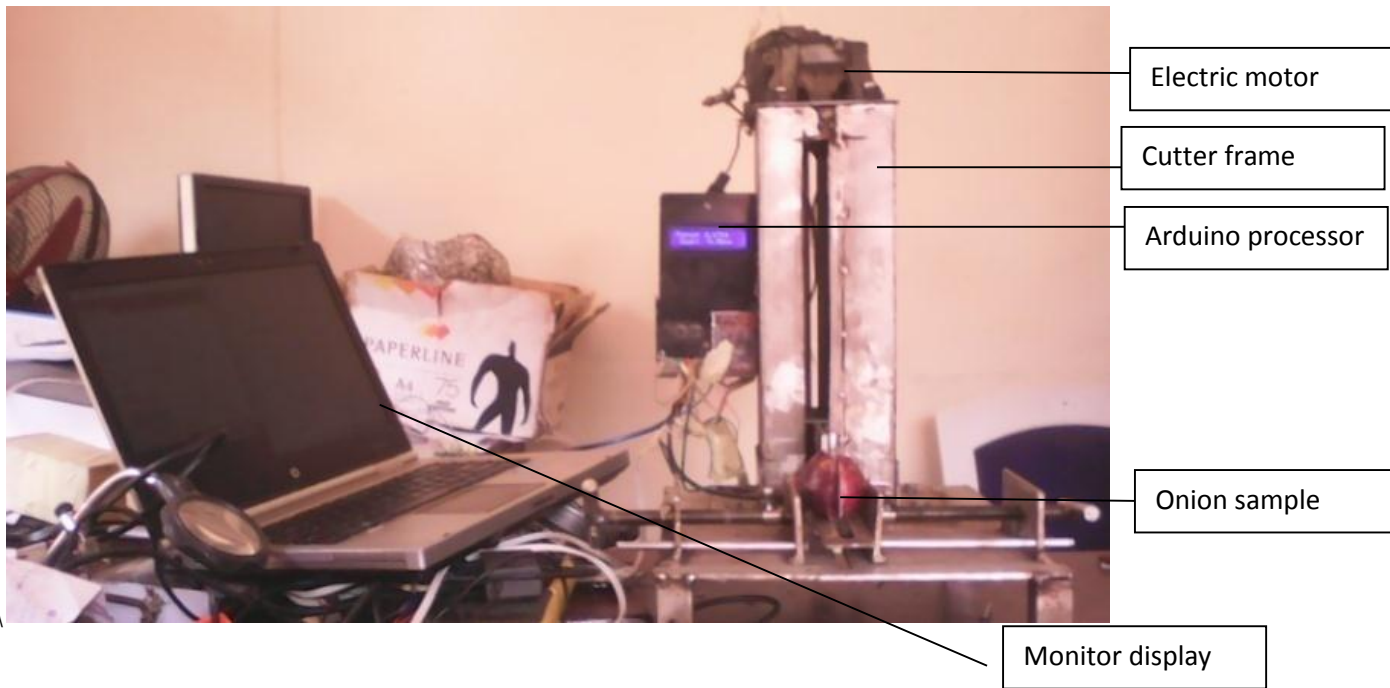
Appendix 1c: Sorted and labeled Onion bulb samples



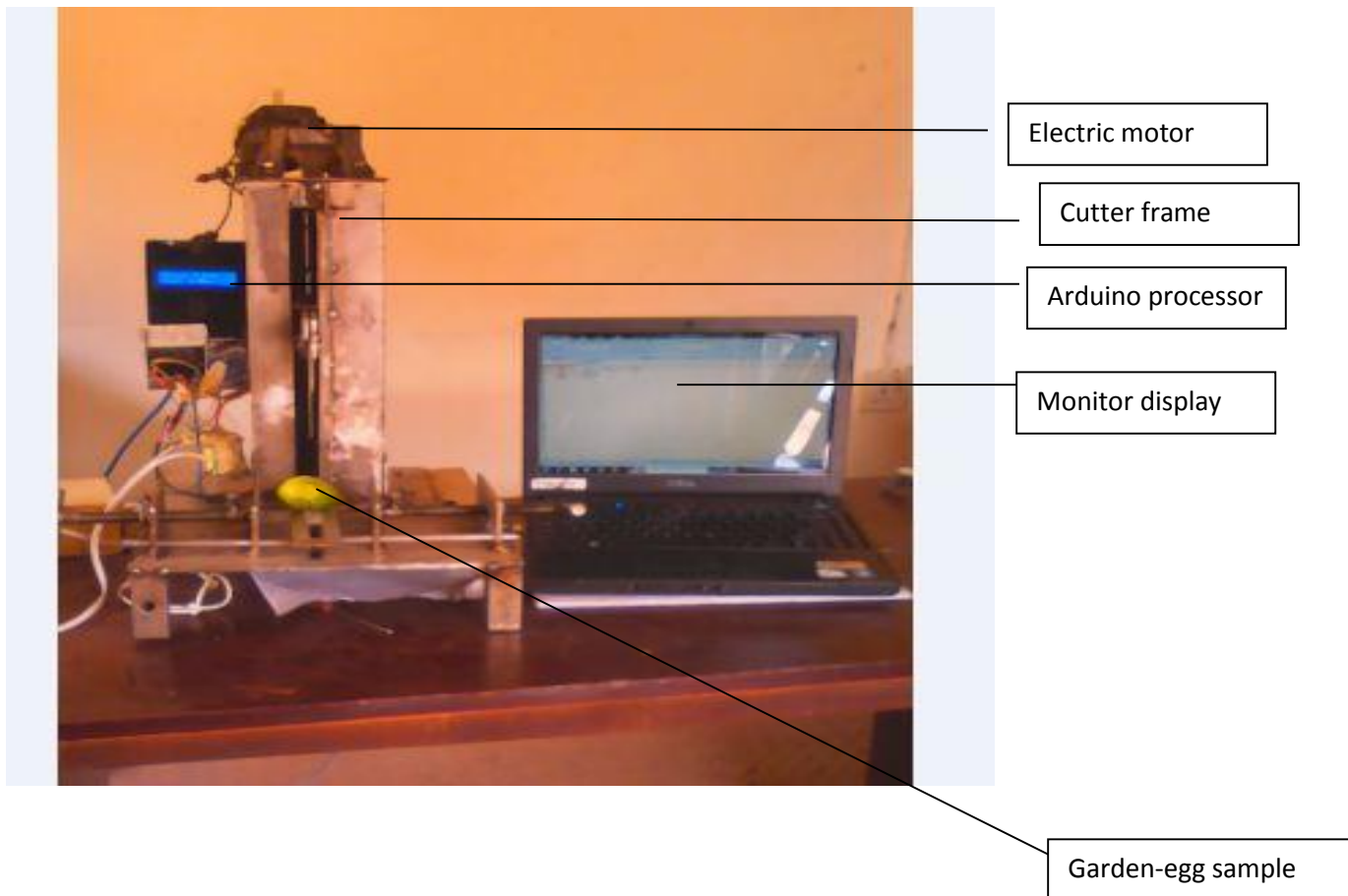
Appendix 2a: Experimental set-up of the cutting mechanism (for Okra fruit)



Appendix 2b: Experimental set-up of the cutting mechanism (for Onion bulb)



Appendix 2c: Experimental set-up of the cutting mechanism (for garden egg fruit)



**APPENDIX 3A: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
COCOYAM CORMELS**

	Size range 1					Size range 2					Size range 3				
	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e
Major Diameter (mm)	185	146	191	182	142	128.5	127.2	117.3	132.4	111.4	102.1	106.0	109.6	113.3	127.6
Intermediate Diameter (mm)	60.1	60.6	58.8	59.3	60.7	45.3	48.3	49.2	44.2	52.4	40.4	40.6	42.2	37.2	40.7
Minor Diameter (mm)	20.9	35.0	27.3	22.6	32.5	24.2	14.4	24.6	25.5	21.1	23.7	21.5	21.7	16.8	20.7
Equivalent diameter (mm)	61.48	67.65	67.43	62.48	65.43	52.03	44.56	52.17	53.04	49.75	46.07	45.23	46.47	41.37	47.55
Mass (g)	338.6	252.6	250.9	274.2	309.8	142.5	125.4	145.6	127.2	136.9	79.7	87.4	81.3	84.6	105.1
Weight (9.8) (N)	3318.28	2475.48	2458.82	2687.16	3028.2	1396.5	1228.92	1426.88	1246.56	1341.62	781.06	856.52	796.74	829.08	1029.98
Hardness Value (N)	177	177	166	170	150	172	179	179	177	180	176	175	179	171	155
Compressive strength (N/mm²)	0.023	0.031	0.026	0.027	0.025	0.041	0.041	0.039	0.041	0.042	0.054	0.054	0.054	0.055	0.043
Area (mm²)	7818	5736	6288	5328	6010	4212	4364	4592	4358	4282	3264	3220	3332	3086	3628

**APPENDIX 3A: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
COCOYAM CORMELS**

Size ranges	Size range 4					Size range 5				
	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e
Major Diameter (mm)	93.3	77.5	95.0	92.1	92.2	72.0	79.1	76.3	58.3	68.7
Intermediate Diameter (mm)	41.5	45.6	37.3	38.8	43.2	36.5	30.3	37.2	30.6	35.6
Minor Diameter (mm)	17.7	19.8	18.1	16.8	21.1	19.4	11.7	10.7	20.5	20.0
Equivalent diameter (mm)	40.92	41.21	40.03	39.16	43.80	37.08	30.38	31.20	33.19	36.57
Mass (g)	65.0	65.1	65.0	56.9	77.6	43.1	32.6	40.9	35.4	44.2
Weight (9.8) (N)	637	637.98	637	557.62	760.48	422.38	319.48	400.82	346.92	433.16
Hardness Value (N)	177	170	179	172	173	175	172	178	180	174
Compressive strength (N/mm²)	0.078	0.079	0.078	0.077	0.066	0.098	0.107	0.097	0.112	0.096
Area (mm²)	2280	2162	2298	2234	2616	1778	1604	1828	1608	1808

**APPENDIX 3B: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
OKRA SAMPLES**

Size ranges	Size range 1					Size range 2					Size range 3				
	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e
Major Diameter (mm)	75.0	77.5	68.3	67.1	77.0	59.6	64.1	66.7	59.4	56.1	74.8	69.8	63.6	62.4	62.6
Intermediate Diameter (mm)	19.5	21.0	29.0	29.0	22.5	18.0	20.0	22.4	19.2	17.1	12.2	15.3	17.0	16.2	14.1
Minor Diameter (mm)	8.0	9.0	8.7	9.0	7.4	8.0	8.0	6.8	7.2	6.7	5.2	5.7	6.2	5.9	5.6
Equivalent diameter (mm)	22.70	24.47	25.83	25.97	23.40	20.47	21.73	21.66	20.17	18.59	16.80	18.26	18.86	18.13	17.03
Mass (g)	16.6	14.3	20.1	21.1	18.8	10.5	13.8	16.0	13.2	14.3	12.8	14.4	16.2	15.6	12.6
Weight (9.8) (N)	162.68	140.14	196.98	206.78	184.24	102.9	135.24	156.8	129.36	140.14	125.44	41.12	158.76	152.88	123.48
Hardness Value (N)	93.1	88.7	103.0	89.9	94.3	62.7	83.8	100	82.2	72.9	89.1	10	84.9	55.6	107
Compressive strength (N/mm²)	0.0594	0.054	0.081	0.093	0.066	0.052	0.056	0.0896	0.073	0.056	0.061	0.093	0.0698	0.039	0.086
Area (mm²)	1568	1648	1276	964	1432	1202	1504	1116	1120	1302	1472	1186	1216	1436	1240

**APPENDIX 3B: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
OKRA SAMPLES**

Size ranges	Size range 4					Size range 5				
	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e
Major Diameter (mm)	36.6	36.1	35.5	34.6	33.5	32.0	33.4	29.2	27.0	34.0
Intermediate Diameter (mm)	16.4	19.1	17.5	15.0	13.6	11.0	13.6	13.6	13.0	14.1
Minor Diameter (mm)	6.0	6.0	5.1	5.6	6.3	2.2	3.7	4.5	3.3	4.0
Equivalent diameter (mm)	15.33	16.05	14.69	14.27	14.21	9.18	11.89	12.14	10.5	12.42
Mass (g)	10.6	11.2	9.2	8.0	1.2	3.7	4.3	4.5	4.2	6.4
Weight (9.8) (N)	103.88	109.76	90.16	78.4	70.56	36.26	42.14	44.1	41.16	62.72
Hardness Value (N)	60.3	56.0	75.0	67.5	53.2	36.8	35.1	31.7	33.2	30.4
Compressive strength (N/mm²)	0.093	0.072	0.090	0.091	0.077	0.143	0.105	0.170	0.145	0.075
Area (mm²)	974	1052	944	964	956	536	712	418	506	936

**APPENDIX 3C: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
ONION SAMPLES**

Size ranges	Size range 1					Size range 2					Size range 3				
	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e
Major Diameter (mm)	95.2	103.2	103.0	95.9	99.5	88.4	90.6	93.3	90.3	90.0	70.1	73.1	74.0	73.0	74.8
Intermediate Diameter (mm)	92.6	99.2	97.0	94.5	97.3	86.0	90.0	91.6	89.2	88.4	69.0	71.6	68.7	71.3	72.7
Minor Diameter (mm)	67.2	60.3	63.0	60.6	60.8	52.6	59.4	59.2	64.6	51.8	43.3	43.3	43.6	45.7	46.1
Circumference (mm)	263.86	267.32	269.23	257.27	263.30	231.44	246.71	250.32	252.68	233.80	186.58	191.54	192.99	194.65	198.08
Equivalent diameter (mm)	83.99	85.09	85.70	81.89	83.81	73.67	78.53	79.68	80.43	74.42	59.39	60.97	61.43	61.96	63.05
Mass (g)	339.5	379.2	384.2	343.7	360.6	234.6	255.6	287.0	237.5	275.4	116.9	142.0	134.3	130.9	138.6
Weight (9.8) (N)	3337.1	3710.16	3765.16	3368.26	3533.88	2299.08	2304.88	2812.6	2327.5	2698.92	1145.62	1391.6	1316.14	1282.82	1358.28
Hardness Value (N)	170	156	166	178	175	176	155	177	150	146	165	173	177	153	164
Compressive strength (N/mm²)	0.026	0.019	0.020	0.022	0.026	0.031	0.026	0.029	0.023	0.024	0.045	0.48	0.046	0.037	0.032
Area₄ (mm²)	6626	8492	8482	7970	7198	5716	5890	6100	6432	6180	3664.8	3642	3526	4108	4436

**APPENDIX 3C: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
ONION SAMPLES**

Size ranges	Size range 4					Size range 5				
	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e
Major Diameter (mm)	57.0	59.1	57.0	64.2	60.8	50.5	50.4	48.7	49.0	45.6
Intermediate Diameter (mm)	56.4	57.0	55.3	63.8	59.5	47.2	49.4	43.2	47.0	44.4
Minor Diameter (mm)	39.3	40.6	45.4	37.3	37.6	34.4	36.6	36.8	30.0	36.9
Circumference (mm)	157. 65	161. 85	164.3 4	167.95	161.5 7	136.4 7	141.3 7	133.8 9	128.9 0	132.29
Equivalent diameter (mm)	50.1 8	51.5 2	52.31	53.46	51.43	43.44	45.00	42.62	41.03	42.11
Mass (g)	66.5	72.9	73.6	90.2	72.5	47.1	46.2	49.9	41.8	42.1
Weight (9.8) (N)	651. 7	714. 42	721.2 8	883.96	710.3	461.5 8	452.7 6	489.0 2	409.6 4	412.58
Hardness Value (N)	180	166	91.3	177	159	149	118	117	82.9	157
Compressive strength (N/mm²)	0.07 6	0.06 2	0.043	0.059	0.066	0.074	0.064	0.069	0.046	0.091
Area x4 (mm²)	2368	2664	2110	2984	2394	2004	1820	2694	1810	1724

**APPENDIX 3D: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR
GARDEN EGG SAMPLES**

Size ranges	Size range 1					Size range 2					Size range 3				
	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e
Major Diameter (mm)	59.2	54.8	59.0	57.3	62.2	51.7	54.2	54.0	52.0	58.3	48.0	46.7	49.2	51.0	44.2
Intermediate Diameter (mm)	53.0	53.7	52.6	56.0	52.5	49.6	51.2	49.4	43.5	48.4	40.1	41.6	41.4	44.5	41.2
Minor Diameter (mm)	45.2	46.8	48.0	51.0	43.4	41.6	39.1	44.5	42.6	40.0	36.3	35.2	35.7	38.6	32.7
Circumference (mm)	52.15	51.6 4	53.0 1	54.7 0	52.14	47.43	47.70	49.15	45.85	48.33	41.19	40.89	41.74	44.41	39.0 5
Equivalent diameter (mm)	163.83	162. 23	166. 54	177. 85	163.8	149.0 1	149.8 5	154.4 1	144.0 4	151.8 3	129.4 0	128.4 6	131.1 3	139.5 2	122. 68
Mass (g)	70.3	69.6	70.5	76.6	65.1	53.2	54.7	59.4	51.5	52.9	34.1	30.4	35.7	40.7	30.1
Weight (N) *9.8	688.94	682. 08	690. 90	750. 68	637.9 8	521.3 6	536.0 6	582.1 2	504.7	518.4 2	334.1 8	297.9 2	349.8 6	398.8 6	294. 98
Hardness Value (N)	133	177	178	170	158	172	172	179	176	178	179	153	170	174	158
Compressive strength (N/mm²)	0.272	0.36 4	0.28 6	0.28 5	0.233	0.329	0.301	0.321	0.362	0.343	0.499	0.414	0.482	0.427	0.45 9
Areax4 (mm²)	489	486	622	596	678	5235	572	557.5	486.5	519.5	358.5	369.5	353	407.5	344

APPENDIX 3D: HARDNESS TEST AND COMPRESSIVE STRENGTH RESULTS FOR GARDEN EGG SAMPLES

Size ranges	Size range 4					Size range 5				
	4a	4b	4c	4d	4e	5a	5b	5c	5d	5e
Major Diameter (mm)	43.3	47.1	42.1	48.2	48.6	35.8	43.2	41.7	36.0	38.8
Intermediate Diameter (mm)	41.0	44.3	41.2	39.2	44.2	35.0	30.0	32.5	30.4	36.5
Minor Diameter (mm)	33.2	36.6	31.0	35.2	34.4	31.0	24.1	29.0	26.6	28.3
Circumference(mm)	38.92	32.43	37.74	40.52	36.94	33.87	31.49	33.99	32.76	34.22
Equivalent diameter (mm)	122.2 7	101.3 6	118.56	127.3 0	116.0 5	106.4 1	98.93	106.7 8	96.64	107.5 1
Mass (g)	32.7	38.3	27.4	31.3	34.3	19.6	19.8	17.8	17.1	20.3
Weight (9.8) (N)	320.4 6	375.3 4	268.52	306.7 4	336.1 4	192.0 8	194.4 4	174.4 4	167.5 8	198.9 4
Hardness Value (N)	177	170	157	171	180	169	144	163	178	135
Compressive strength (N/mm²)	0.481	0.407	0.467	0.480	0.579	0.701	0.537	0.685	0.877	0.529
Area (mm²)	368	418	336	356	311	241	268	238	203	255