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ORIGINAL RESEARCH ARTICLE

NUMERICAL AND EXPERIMENTAL STUDIES ON THE CUTTING ENERGY REQUIREMENTS OF OKRA *(ABELMOSCHUS ESCULENTUS L.)*

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ABSTRACT

Cutting energy requirements for vegetable crops is a prerequisite in the engineering design of appropriate cost effective cutting systems consuming minimum amount of energy while still providing high quality products. This study attempts the development of predictive equations describing the cutting energy for okra *(Abelmoschus esculentus L.)*. Dimensional analysis based on the Buckingham pi theorem was used to obtain the functional relationship between the cutting energy of the selected vegetable and the independent variables such as 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 was validated with experimental data. A high coefficient of determination of R^2 value of 0.973 between the predicted and measured energy values showed that the method is good. Hence the obtained predictive model is appropriate for determining the cutting energy requirements of okra up to 97%.

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1.0 Introduction

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. Cutting, which is a size reduction activity, is an energy consuming operation. However, the cutting energy requirements of vegetables have been estimated using different cutting systems and approaches (McGorry *et al.,* 2003, Blahovec, 2007; McCarthy *et al.,* 2007 and Atkins, 2009) with the following objectives; to know the most efficient cutting conditions necessary for optimization of the cutting process; to determine the optimal energy required to cut and to achieve an overall efficient cutting operation. Ciulica and Rus 2011, Elżbieta and Agnieszka, 2012; and Singh *et al.,* 2016 have identified blade sharpness, slicing angle, contact area, depth of cut, cutting speed, and the engineering properties of vegetables such as crop variety, maturity stage, moisture content, orthogonal dimensions and fiber orientation as some of the parameters affecting the energy requirements for cutting of vegetables.

Okra *(Abelmoschus esculentus L.)* is a fruit vegetable of interest in this work. Okra or lady's finger, deriving its name from the 'Igbo' word '´ k` r` ' (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, improves the shelf life and also forestalling seasonal wastage. This manual cutting operation is a most laborious, time consuming one with the challenges of contamination 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, 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.

Furthermore, extensive documentation on the properties of foods and food products exist, however data related to the cutting energy of different vegetables such as okra 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, Hence the need to intensify research activities in this post harvest area of cutting and determining the energy requirements for cutting vegetables such as the (*ìlá-ìròkò)* variety of okra.

1.1 Modeling Agricultural Processes

Modeling, simply defined 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). 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 theorems 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 (π_1, π_2, ..., π_p) constructed from the original variables (Hart, 1995), (Here k is the number of physical dimensions involved; which in this situation, (K = 3 i.e. Mass, Length and Time).

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) , modeling the drying process of a hybrid convective vegetable crop dryer (Nwakuba*,* 2018) 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).

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), much is left undone on modeling the energy requirement for cutting vegetables.

Some researchers used the dimensional analysis based on the Buckingham's pi theorem as veritable instrument in establishing a prediction equation of various systems which include 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); a mathematical model for predicting the cracking efficiency of vertical-shaft centrifugal palm nut cracker (Ndukwu and Asoegwu, 2011); and modeling flow rate of egusi-melon (*Colocynthis citrullus*) through circular horizontal hopper orifice (Asoegwu *et al.,* 2010).

The size reduction operation by cutting in most postharvest processes is a most laborious, time wasting and energy consuming task which deserves research attention. These 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 a mathematical model using dimensional analysis based on the Buckingham's pi theorem to predict the cutting energy requirements for okra *(Abelmoschus esculentus L.).* 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.

2. Materials and Methods

2.1 Theoretical Development

Factors affecting the cutting energy requirements of vegetables obtained from literature include tool parameters like (materials of construction, sharpness, rigidity of cutting tools, knife speeds, etc.) and physical properties of the plant material like (crop variety, size, maturity stage, crop moisture content , crop density, fibre orientation, etc.) (Nadulski, 2001; Szot *et al.,* 1987; Atkins, 2009; Blahovec, 2007; McCarthy *et al.,* 2007; and McGorry *et al.,* 2003). In the development of the model, dimensional analysis based on the Buckingham pi theorem was employed which is a technique used in identifying factors involved in a physical situation and forming a relationship among them. 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).

i.e. if N = number of variables involved in a physical situation

x = number of dimensions in which quantities may be expressed = (3), M, L, T

M = Mass; L = Length; T = Time

n =number of dimensionless groups as given in Equation 1.
Hence, n = N - x (1)

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

2.2 Assumptions made in Model Development

i. Variables that are design parameters which are measurable were considered.

ii. 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.

iii. The fiber orientation, textural properties (inner hollow texture) and crop variety are considered negligible in the model development, since only the horizontal orientation of the okra fruit is considered.

2.3 Development of the Functional Energy Equation.

These assumptions helped in reducing the number of variables involved to the underlisted as these were considered to have greater influence on the energy of cut of the selected vegetable (okra) and are measurable. The chosen variables are: 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).

Having identified the core variables influencing the energy required for cutting the selected vegetable, Equation 2 represents the functional equation of the predictive model.

i.e $E = f(w, H_{d,} t, v, s, \varphi, A, \sigma)$ (2)

Where E is the cutting energy of the okra crop (J)

w = Tool weight; 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 1 above.

i.e $n = N - x$

N = number of variables involve in the situation studied = 9
x = number of dimensions for describing these variables = 3
Hence $n = 9 - 3 = 6$ $\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6$
Hence six dimensionless groups were formed namely; Π_1, Π_2, Π_3, Π_4, Π_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 the selected vegetable were expressed in terms of their dimensions as shown in Table 1.

Table 1. List of variables and their dimensions

S/N	Variable	Symbol	Unit	Dimension
1	Energy	E	kgm^2s^{-2}	ML^2T^{-2}
2	Tool weight	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	$M^0L^0T^0$
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 2. This is needed to develop the indices of the involved variables.

Table 2. Dimensional matrix of variables

S/N	Variable	Symbol	M	L	T
1	Energy	E	1	2	-2
2	Tool Weight	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 the above matrix, 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 weight (w) and crop size (s) were selected as the major parameters (i.e. recurring set) because they contain 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, σ and A, the dimensionless groups Π_1, Π_2, Π_3, Π_4 and Π_5 are obtained as given in Equations 3 to 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.

$$\Pi_1 = \frac{E}{w^a \mathrm{v}^b \mathrm{s}^c} \quad (3)$$

$$\Pi_2 = \frac{H_d}{w^a \mathrm{v}^b \mathrm{s}^c} \quad (4)$$

$$\Pi_3 = \frac{t}{w^a \mathrm{v}^b \mathrm{s}^c} \quad (5)$$

$$\Pi_4 = \frac{\mathrm{A}}{w^a \mathrm{v}^\mathrm{b} \mathrm{s}^\mathrm{c}} \tag{6}$$

$$\Pi_5 = \frac{\sigma}{w^a \mathrm{v}^\mathrm{b} \mathrm{s}^\mathrm{c}} \tag{7}$$

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 Πs are replaced with $M^0L^0T^0$ which is a dimensionless group. 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 being expressed in terms of the dimensions on both sides becomes Equations 8

$$M^0L^0T^0 = \frac{ML^2T^{-2}}{(MLT^{-2})^a(LT^{-1})^bL^c} \tag{8}$$

Cross- multiplying Equation 8 gives Equation 9.

$$M^0L^0T^0(\left(MLT^{-2})^a\left(LT^{-1}\right)^bL^c\right) = ML^2T^{-2} \tag{9}$$

Using dimensional homogeneity for M, L and T, the exponents a, b and c are got in equations 10, 11, 12 and 13.

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

0 + a = 1

$$a = 1 \tag{10}$$

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

0+a+b+c = 2; from 3.10, a = 1

1+b+c =2

b+c = 2-1 =1

$$b+c = 1 \tag{11}$$

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

-2a – b =-2

Since a =1

-2(1) – b = -2

$$-b = -2+2 = 0,\ b = 0 \tag{12}$$

From Equation 11, b + c = 1, put b=0

$$0+c=1;\ c=1 \tag{13}$$

Hence, a = 1, b = 0, c = 1; replacing the exponents with their values,

Π_1 becomes Equation 14

$$\Pi_1 = \frac{E}{w^1\mathrm{v}^0\mathrm{s}^1} = \frac{E}{ws} \tag{14}$$

Similarly, solving for the remaining Π groups, we obtain Equations 15 to 19.

$$\Pi_2 = \frac{H_d}{s} \quad (15)$$

$$\Pi_3 = \frac{t}{s} \quad (16)$$

$$\Pi_4 = \frac{A}{s^2} \quad (17)$$

$$\Pi_5 = \frac{\sigma v^2 s^2}{w} \quad (18)$$

$$\Pi_6 = \varphi \quad (19)$$

Combining these equations gives Equation 20, whose components are dimensionless.

i.e. $\frac{E}{ws} = f\left(\frac{H_d}{s}, \frac{t}{s}, \frac{A}{s^2}, \frac{\sigma v^2 s^2}{w}, \varphi\right)$
(20)

Combining the dimensionless terms to reduce it to a manageable level (Shefii *et al.* 1996) by multiplication and/or division, we obtain Equations 21 to 23 which are dimensionless.

$$\Pi_{12} = \frac{\Pi_1}{\Pi_2} = \frac{E}{ws} \times \frac{s}{H_d} = \frac{E}{wH_d} \quad (21)$$

$$\Pi_{34} = \frac{\Pi_3}{\Pi_4} = \frac{t}{s} \times \frac{s^2}{A} = \frac{ts}{A} \quad (22)$$

$$\Pi_{56} = \frac{\Pi_5}{\Pi_6} = \frac{\sigma v^2 s^2}{w} \times \frac{1}{\varphi} = \frac{\sigma v^2 s^2}{w\varphi} \quad (23)$$

The new dimensionless functional relationship becomes Equations 24 and 25.

$$\Pi_{12} = f(\Pi_{34}, \Pi_{56}) \quad (24)$$

$$\frac{E}{wH_d} = f\left(\frac{ts}{A}, \frac{\sigma v^2 s^2}{w\varphi}\right) \quad (25)$$

From Equation 25, the Equations for E are obtained as Equations 26 and 27.

$$E = wH_d\left(\frac{ts}{A}, \frac{\sigma v^2 s^2}{w\varphi}\right) \quad (26)$$

$$E = f\left(\frac{tswH_d}{A}, \frac{\sigma v^2 s^2 H_d}{\varphi}\right) \quad (27)$$

Equation 27 gives the cutting energy E, with all the parameters in Equation 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 28.

$$E = f(P, Q) \quad (28)$$

2.4 Experimental Procedure

Green, mature and freshly harvested okra fruits (*ílá-ìròkò* variety) that were healthy and free from mechanical injuries were purchased from a local farmer in Owerri west Local government area of Imo state, Nigeria. They were thoroughly cleaned of all impurities and unwholesome fruits and thereafter sorted into four size ranges of 10 fruits each and some physical properties were obtained at an initial moisture content of 89.41± 0.4% (wb) (AOAC, 2000). With an autom... cutter, at a preset speed of 30mm/min, the cutter drops from a height of 20cm, cutt...

Electric motor

as it travels through it. The force-time relationship displayed on the monitor was used to calculate the cutting energy. Plate 1.0 shows the experimental set-up of the cutting mechanism.

Plate 1.0: Experimental set-up of the cutting mechanism

The automated vegetable cutter consists of the hardware and software components. Arduino controlled processors 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 USB port the measured values are relayed and 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.

2.5 Determination of Validation Parameters

In the determination of validation parameters, every other parameter was held constant while the crop size varied. The selected tool edge thickness (t) measured with a digital venier caliper (Model 500-196, Mitutoyo Products, America) was 0.1cm. The weight (w) of the cutting tool determined with an electronic weighing balance (Model GF-200, A & D company Ltd, Japan of an accuracy of ±0.01) was 23.1g.

The cutting tool was dropped from a pre-determined height (h) of 20cm measured with a meter rule. The crop density (σ) determined by dividing the weight of the crop by the volume of water displaced when sample is placed inside a measuring cylinder was taken as 1.107g/cm^3. The orthogonal dimensions of the sample were determined with the digital venier caliper (Model 500-196, Mitutoyo Products, America). The crop contact area (A) taken as 28.75cm^2 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

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of the crop sample determined with the method described in AOAC (2000) was taken as 89.41± 0.4% (wb).

2.6 Prediction Energy Equation

The prediction energy equation was established by allowing $P or Q$ 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 = $(\frac{tswH_d}{A})$ while keeping Q constant. P = $(\frac{tswH_d}{A})$ 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 $Q = (\frac{\sigma v^2 s^2 H_d}{\varphi})$ was plotted while keeping P constant. Values for $Q = (\frac{\sigma v^2 s^2 H_d}{\varphi})$ 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. Results and Discussion

Average values and standard deviation of the measured physical parameters of the okra fruits are shown in Table 3.

Table 3. Average values for physical properties of okra fruits at 89.41± 0.4% (w.b)

S/N	Okra	Mass (g)	Diameter(mm)	Circumference (mm)	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 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 into the energy equations $P = (\frac{tswH_d}{A})$ and $Q = (\frac{\sigma v^2 s^2 H_d}{\varphi})$.

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

Table 4. Experimental values ($E_{measured}$) and calculated values of cutting energy for okra fruits.

S/N	Okra	Crop size (mm)	(E_{meas})	$P = \left(\frac{tswH_d}{A}\right)$	$Q = \left(\frac{\sigma v^2 s^2 H_d}{\varphi}\right)$
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 1 and 2 with their linear equations and R^2 values expressed in Equations 29 and 30.

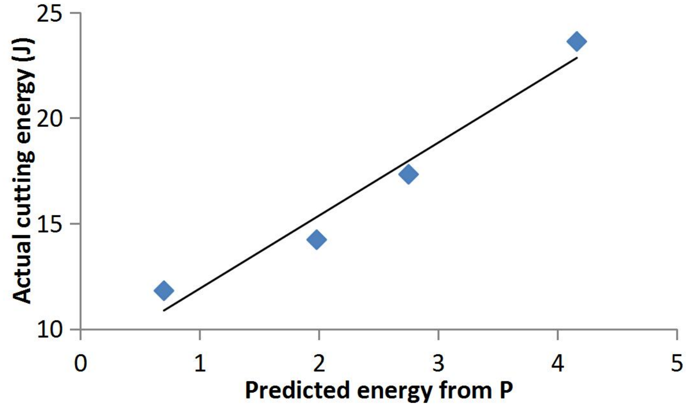

Figure 1. Variation of cutting energy against $P = \left(\frac{\mathrm{tswH_d}}{\mathrm{A}}\right)$, keeping $Q = (\frac{\mathrm{\sigma v^2 s^2 H_d}}{\varphi})$ constant.

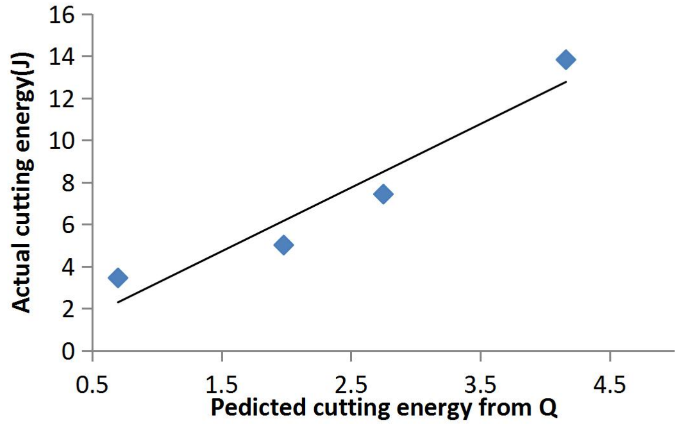

Figure 2. Variation of cutting energy with$\mathrm{Q} = (\frac{\mathrm{\sigma v^2 s^2 H_d}}{\varphi})$, keeping $P = (\frac{\mathrm{tswH_d}}{\mathrm{A}})$ constant.

E = 3.462P + 8.448 $\quad \mathrm{R^2} = 0.961$ (29)

E = 3.026Q + 0.170; $\quad \mathrm{R^2} = 0.921$ (30)

The plot of the P and Q terms in Figures 1 and 2 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 29 and 30 give Equations 31 and 32 respectively.

$$E = f_1(P,Q) - f_2(P,Q) + K \quad (31)$$

$$E = f_1(P,Q) + f_2(P,Q) + K \quad (32)$$

It must be noted that;

at $\mathrm{f_1}$, Q was kept constant while P varied

at $\mathrm{f_2}$, P was kept constant while Q varied

Substituting Equations 29 and 30 into Equation 31 and performing some algebraic manipulations yields Equation 33.

$$E = 3.462P - 3.026Q + 8.278 \quad (33)$$

Also, Substituting Equations 29 and 30 into Equation 32 and performing some algebraic manipulations yields Equation 34.

$$E = 3.462P + 3.026Q + 8.618 \quad (34)$$

A further manipulation as permitted under the rules of the Burkingham pi theorem (Shefii *et al.,* 1996) is manipulating with a constant factor. Hence, Equations 33 and 34 were divided with a constant factor of 10 which yields the predicted model equations expressed in Equations 35 and 36 respectively. Dividing equations 33 and 34 with the constant factor of 10 yielded predicted values close to the actual ones.

$$E = 0.3462P - 0.3026Q + 0.8278 \quad (35)$$

$$E = 0.3462P + 0.3026Q + 0.8618 \quad (36)$$

Substituting the variables for P and Q into Equations 35 and 36 yield Equations 37 and 38 respectively.

$$E = 0.3462\frac{tswH_d}{A} - 0.3026\frac{\sigma v^2 s^2 H_d}{\varphi} + 0.8278 \quad (37)$$

$$E = 0.3462\frac{tswH_d}{A} + 0.3026\frac{\sigma v^2 s^2 H_d}{\varphi} + 0.8618 \quad (38)$$

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

3.1 Model Validation

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 37 and 38 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 3 and 4 respectively. Equations 39 and 40 express the relationship between the predicted cutting and experimental cutting energy with R^2 values of 0.973 and 0.945 respectively.

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. Table 4 presents values of the predicted and experimental cutting energy and Figure 3 presents the graphical relationship between the experimental and predicted cutting energy. Equation 35 expresses the relationship between the predicted cutting and the experimental cutting energy with a very high correlation with R^2 value of 0.973.

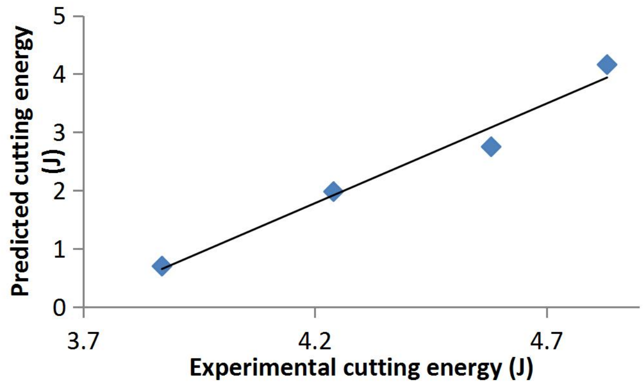

Figure 3. The graph of the relationship between experimental and predicted cutting energy (for subtraction of component energy equations)

E_{pred} = 3.423 E_{exp} – 12.59; R^2 = 0.973 (39)

Where E_{pred} = predicted cutting energy

E_{exp} = experimental cutting energy

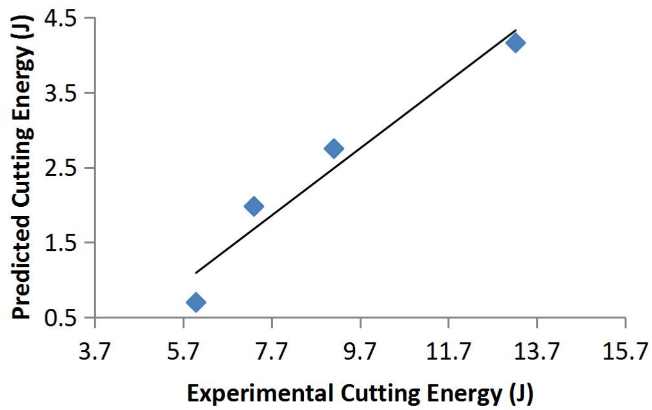

Figure 4. The graph of the relationship between experimental and predicted cutting energy. (for summation of component energy equations)

E_{pred} = 0.447E_{exp} – 1.584; R^2 = 0.945 (40)

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 41.

$$E = 0.3462\frac{tswH_d}{A} - 0.3026\frac{\sigma v^2 s^2 H_d}{\varphi} + 0.8278 \quad (41)$$

4.0 Conclusion

A mathematical model for predicting the cutting energy of okra *(Abelmoschus esculentus L)* was presented using dimensional analysis based on the Buckingham's Π theorem. The model equation expressed as $E = 0.3462\frac{tswH_d}{A} - 0.3026\frac{\sigma v^2 s^2 H_d}{\varphi} + 0.8278$ was validated with data from an automated vegetable cutter. Results obtained showed a high coefficient of determination (R^2 = 0.973), a low mean difference of 1.983 between the predicted and experimental energy values and a low standard error of 0.127. This is an indication that the method adopted in the development of the mathematical model is acceptable and can be translated in the development of predictive models for the other varieties of the okra fruit in particular and other vegetables in general. Also, this expression will also help designers of the cutting equipment for okra (*ilá-ìròkò)* variety to avoid the rigors of experimentations and at the same time obtain efficient cutters. Hence, the developed model could be used to predict the cutting energy for okra (*ilá-ìròkò)* variety up to 97%.

References

Adeboye, OC. and Oputa, CO. 1996. Effect of galex on growth and fruit nutrient composition of okra. *Ife Journal of Agriculture*. 18 (12): 1-9.

Adom, KK., Dzogbefia, VP., Ellis, WO. and Simpson, BK. 1996. Solar drying of okra- effects of selected package materials on storage stability*. Food Research International.*29(7):589–593.

Agarwal, M., Rajani, S., Mishra, A. and Rai, JSP. 2003. Utilization of okra gum for treatment of tannery effluent. *International Journal of Polymeric Materials and Polymeric Biomaterials*.52(11):1049–1057.

AOAC, 2000. Official Methods of Analysis. 17th Edition. The Association of Official Analytical Chemists, Gaithersburg, MD, USA. (6):200-220.

Andras, CD., Simandi, B., Orsi, F., Lambrou, C. and Tatla, DM. 2005. Supercritical carbon dioxide extraction of Okra (*Hibiscus esculentus L*.) seeds. *Journal of Food and Agricultural Science*. 85:1415-1419.

Andrzej, F. 2015. Basic principles and theorems of dimensional analysis and the theory of model similarity of physical phenomena, *Technical Transactions in Civil Engineering* (2B). Cracow University of Technology. Pp 242-272.

Asoegwu, SN., Agbetoye, LAS. and Ogunlowo, AS. 2010. Modeling flow rate of Egusi- melon (*Colocynthis citrullus*) through circular horizontal hopper orifice. *Advances in Science and Technology.* 4(1): 35-44.

Atanda, SA., Pessu, PO., Agoda, S., Isonga, IU. and Ikotun, I. 2011. The concepts and problems of postharvest food loss in perishable crops. *African Journal of Food Science*. 5(11):603-613.

Atkins, T. 2009. *The Science and Engineering of Cutting: the Mechanics and Process of the Separating, Scratching and Puncturing Biomaterials Metals and Non-Metals.* pp 283-284. UK Butterworth, Heinemann Elsevier.

Bahrami, M., Yovanovich, MM. and Culham, JR. 2006. Pressure drop of fully developed laminar flow in rough microtypes*. Journal of Fluid Engineering. Transaction of the American Society of Mechanical Engineers.* 128: 632-637.

Baruah, DC. and Panesar, BS. 2005a. Energy requirement model for combine harvester, Part 1:Development. *Biosystems Engineering,* 90 (1): 9 - 25.

Baruah, DC. and Panesar, BS. 2005b. Energy requirement model for combine harvester, Part 2: Integration of component models. *Biosystems Engineering*, 90 (2): 161-171.

Blahovec, J. 2007. Role of water content in food and product texture. *International Agrophysics*. 21(3): 209-215.

Brown, T., James, SJ. and Purnell, GL. 2005. Cutting force in foods: experimental measurements. *Journal of Food Engineering.* 70 (2):165-170.

Burkil, HM. 1997. *The Useful Plants of West Tropical Africa.* Royal Botanical Gardens, Kew, UK. 4:2, pp 969.

Cha, PD., Rosenberg, JJ. and Dym, CL. 2000. *Fundamentals of Modeling and Analyzing Engineering Systems.* Cambridge University Press,New York. Pp 35 – 41.

Ciulica, LG. and Rus, F. 2011. The influence of maturity degree of vegetables on their cutting resistance force. *The 4th International Conference on Computational Mechanics and Virtual Engineering* 'COMEC 2011' 20-22 October 2011, Brasov, Romania. Pp 194 – 198.

Degirmencioglu, A. and Srivastava, A. 1996. Development of screw-conveyor performance models using dimensional analysis. *Transactions of the American Society of Agricultural Engineers.* 39(5):1757-1763.

Dym, CL. 1994. *Engineering Design: a synthesis of views*. Cambridge University Press, New York. Pp 422 – 426.

Dym, CL. and Ivey, ES. 1980. *Principles of Mathematical Modeling.* 1st Edition, Academic Press, New York. Pp 1 -12.

Elżbieta, K. and Agnieszka, S. 2012. Effect of knife wedge angle on the force and work of cutting peppers. *Teka. Commission of Motorization and Energetics in Agriculture*. 12(1):127–130.

Falade, KO. and Omojola, BS. 2010. Effect of processing methods on physical, chemical, rheological, and sensory properties of okra (*Abelmoschus esculentus*). *Food Bioprocess Technology.*3:387–394.

Farinde, AJ., Owolarafe, OK. and Ogungbemi, OI. 2007. An overview of production, processing, marketing and utilization of okra in Egbedore Local Government Area of Osun State, Nigeria. *Journal of Agricultural Engineering and Technology (JAET).* 20:1-17.

Ferraz, AC., Mittal, GS., Bilansk, WK. and Abdullah, HA. 2007. Mathematical modeling of laser based potato cutting and peeling. *BioSystems*. 90(3):602-613.

Fielke, JM. 1999. Finite element modeling of interaction of cutting edge of tillage implements with soil. *Journal of Agricultural Engineering Research*. 74: 91-101.

Fox, RW. and McDonald, AT. 1992. *"Introduction to Fluid Mechanics*," John Wiley and Sons, New York. 4^{th} Edition. pp 123-124.

Hart, GW. 1995. Multidimensional Analysis: Algebras and Systems for Science and Engineering. *Springer-Verlag.* ISBN 0-387-94417-6.

Jain, D. and Pathare, PB. 2004. Selection and evaluation of thin layer drying models for infrared radiative and convective drying of onion slices. *Biosystems Engineering*, 89(3):289-296.

Makose, BL. and Peter, KV. 1990. *Okra. Review of Research on Vegetable and Tuber Crops.* Technical Bulletin 16. Kerala Agricultural University Press Mannuthy, Kerala, pp 109.

McCarthy, CT., Hussey, M. and Gilchrist, MD. 2007. On the sharpness of straight edge blades in cutting soft solids: Part I-indentation experiments. *Engineering Fracture Mechanics.* 74(14): 2205-2224.

McGorry, RW., Dowd, PC. and Dempsey, PG. 2003. The effect of blade finish and blade edge angle on forces used in meat cutting operations. *Applied Ergonomics, Elsevier publications*. 35: 71-77.

McRandal, DM. and McNulty, PM. 1978. Impact cutting behaviour of forage crops. Mathematical models and laboratory test. *Journal of Agricultural Engineering Research,* 23 (3): 313 – 328.

McWhorter, JH. 2000. *The Missing Spanish Creoles: Recovering the Birth of Plantation Contact Languages*. University of California Press. p. 77. *ISBN 0-520-21999-6. Retrieved 2008-11-29*

Mitcham, B., Cantwell, M. and Kader, A. 1996. Methods for determining quality of fresh commodities. *Perishables Handling Newsletter*. 85:5-6.Mohammed, US. 2002. Performance modeling of the cutting process in sorghum harvesting. [PhD Thesis.] Department of Agricultural Engineering, Ahmadu Bello University, Zaria.

Nadulski, R. 2001. Wpáyw geometrii narzĊdzia tnącego na przebieg procesu ciĊcia wybranych warzyw korzeniowych. *Acta Agrophysica.* 58: 127-135.

Ndirika, VIO. 2006. A mathematical model for predicting output capacity of selected stationary grain threshers. *Agricultural Mechanization in Asia, Africa and Latin America. (AMA)*.36: 9–13.

Ndukwu, MC. and Asoegwu, SN. 2011. A mathematical model for predicting the cracking efficiency of vertical-shaft centrifugal palm nut cracker. *Research in Agricultural Engineering.* 57(3):110-115.

Nwakuba, NR. 2018. Modeling the Drying Process of a Hybrid Convective Vegetable Crop Dryer. [PhD Thesis.] Department of Agricultural and Bio-resources Engineering, Federal University of Technology, Owerri.

Ogbobe, PO., Ugwuishiwu, BO., Orishagbemi, CO. and Ani, AO. 2007. Design, Construction and Evaluation of Motorized Okra Slicer*. Nigerian Journal of Technology.* 26(2):42-49.

Okra Food. 2003. www.foodreference.com Accessed on April 10, 2003.

Owoeye AL., Lauric, MC., Allagheny, NN. and Onyezili, FN. 1990. Chemical and physical parameters affecting the viscosity of the mixed okra and tomato homogenate. *Journal of Food and Agricultural Science*. 53:283–286.

Owolarafe, OK., Muritala, OA. and Ogunsina, BS. 2007. Development of an okra slicing device. *Journal of Food Science and Technology*. 44(4): 426-429.

Owolarafe, OK. and Shotonde, HO. 2004. Some Physical Properties of Fresh Okra Fruit. *Journal of Food Engineering*. 3:299-304.

Oyelade, OJ., Ade-Omowaye, BIO. and Adeomi, VF. 2003. Influence of variety on protein, fat contents and some physical characteristics of okra seeds. *Journal of Food Engineering.* 57:111-114.

Saifullah, M. and Rabbani, MG. 2009. Evaluation and characterization of okra (*Abelmoschus esculentus L.*) genotypes. *Journal of Agriculture*. 7:91-98.

Saravacos, GD. and Kostaropoulos, AE. 2002. *Hand Book of Food Processing Equipments.* pp 138-141. New York: Kluwer Academic / Plenum Publishers.

Schippers, RR. 2000. African *Indigenous Vegetables. An Overview of the Cultivated Species.* Chatham, UK: Natural Resources Institute/ACP-EU Technical Centre for Agricultural and Rural Cooperation. Pp 103-116.

Shefii, S., Upadhyaya, SK. and Garret, RE. 1996. The importance of experimental design to the development of empirical prediction equations: A case study. *Transaction of American Society of Agricultural and Bio-resources Engineers*. 39: 377–384.

Simonyan, KJ., Yilijep, YD. and Mudiare, OJ. 2006. Modeling the grain cleaning process of a stationary sorghum thresher. *Agricultural Engineering International: the CIGR E-Journal.* 3: 1–16.

Singh, V., Madhusweta, D. and Susanta, K. 2016. Effects of knife edge angle and speed on peak force and specific energy when cutting vegetables of diverse texture. *International Journal of Food Studies*. 5: 22-38.

Sobukola, O. 2009. Effect of pre-treatment on the drying characteristics and kinetics of okra (*Abelmoschus esculentus* (L.) slices. *Internatonal Journal of Food Engineering*. 5(2):9.

Somsen, D., Capelle, A. and Tramper, J. 2004. Manufacturing of par-fried French fries, Part 2. Modeling yield efficiency of peeling. *Journal of Food Engineering.* 61(2):199-207.

Szot, B., Ċsik, TK. and Goáacki, K. 1987. Badania zmiennoĞci wáaĞciwoĞci mechanicznych korzeni marchwi w zaleĪnoĞci od cech odmianowych, czynników agrotechnicznych i okresu przechowywania. *Zeszyty Problemowe PostĊpów Nauk Rolniczych*. 316: 227-246.

Teske, ME., Barry, JW. and Ekbald, RB. 1991. Preliminary sensitivity study of aerial application inputs for FSCBG4.0. *American Society of Agricultural Engineers*, Paper No. 91 - 1052. St. Josef, Michigan.