Energy requirements for cutting of selected vegetables: a review

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Abstract: This work presented a review of energy requirements for cutting different vegetables in order to obtain products that can easily lend themselves to further processing. From the review, the role of some parameters related to cutting tool geometry such as blade sharpness, slicing angle, blade edge geometry, contact length, depth of cut, cutting speed, blade shape and the engineering properties of the vegetables such as crop variety, maturity stage, moisture content, average diameter, average length, average width and fibre orientation were seen to affect the operation of cutting in terms of energy consumption and the overall efficiency of the cutting operation. Works on the estimation of energy requirements for cutting different agricultural products by adopting various methods such as universal testing machine having the cutting tool attached for potato (2.36 J), carrot (4.55 J), raddish (1.23 J), cucumber (1.19 J), bitter gourd (4.56 J), pointed gourd (1.28 J), bell pepper (1.83 J), onion (2.36 J), aubergine (7.72 J); cutting with a texture analyzer for different pepper cultivars (0.085J-0.471 J); cutting with special equipment like Zwick/Roell stand for carrot (1.82J-10.13 J) etc. and the factors affecting their energy requirement were reported. Generally, obtained results showed that with cutting speed ranging from 20 mm min^{-1} to 50 mm min^{-1} on a cutting tool and sharpening angle ranging between 0^{o} to 45^{o}, the minimum energy requirement for cutting the selected vegetables under review was found to be between 0.085 J and 10.13 J. One major prospect for future work from the findings of this review work will be extensive studies on the energy requirement for cutting vegetables (leaf, fruit and root) with known physical characteristics and parameters of the cutting tool and the development of their mathematical models.

Keywords: cutting, energy requirement, vegetables, cutting speed, blade shape

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1 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. This size reduction operation can be divided into two major categories depending on whether the material is a solid or a liquid. If it is solid, the operations are called grinding and cutting; if it is liquid, it is called emulsification or atomization. Cutting has been and continues to be a major operation in food processing, involving the breakdown of large pieces of agricultural products into smaller pieces suitable for further processing. 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 or sliced 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. Two stages are distinguished in the cutting process which involve preliminary compaction 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. 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

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al., 2005), or cutting blade, whose operating parameters affect the values of operating drag of the machines and the quality of cutting (Frączek and Mudryk, 2007). Kader (2002) observed that the development of new technologies aimed at reducing the cost of production and at limiting the yield losses (ratio of the mass of cut products to the mass of intact products) permitted the improvement of fragmentation techniques. In the case of agricultural and food materials, the process of cutting depends primarily on the design of the cutting assembly, the shape of the cutting edge, the parameters of operation of the device and on the physical properties of the plant material, 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 and Goaacki, 1987).

2 Estimation of energy for cutting

Energy generally has been defined as the capability of an object or system to do work on another system or object. Energy requirement for cutting agricultural products 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 products with known physical characteristics. ii) to estimate the optimum amount of energy, cutting speed and cutting time most suitable for a particular group of products. iii) to simulate and mathematically model cutting processes; this is aimed at improving the process and reducing the energy demand, while still providing high quality products. 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; this is so because harder foods absorb higher energy and consequently require greater energy input to create fractures (Frigg, 1976). 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. Materials of construction, sharpness, rigidity of cutting tools and knife speeds are effective parameters in cutting operations and strongly influences the energy required, production rate and final surface finish of the cut vegetables (Atkins, 2009; Blahovec, 2007; McCarthy et al., 2007; and McGorry et al., 2003). Dowgiallo (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 in line with the study on the determination of the optimum cutting angle using single edge knife (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. Cutting resistance is related to blade angle and sharpness of the knife blade (Bolin and Huxsoll, 1991), as well as the various cutting action mechanisms and blade movements which are categorized as horizontal and vertical type (Jiang, 2013). Researchers like Yee et al. (2012), Saravacos et al. (2011) and Singh et al. (2016) observed that cutting resistance depends upon the intrinsic texture of the material and the cutting rate for vegetables were decreased with increasing hardness. Cutting energy, which is a function of cutting resistance also depends upon the characteristic intrinsic texture of the material (homogenous or heterogenous body) (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) demonstrates that change in moisture content affect 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. However, for Gorny et al. (1998), firmness varies with the size of the fruits, and generally smaller fruits are harder than larger ones.

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, and hence give the most efficient cutting, both in terms of quality of cut products and energy expended in the cutting process. 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). Cutting is an energy intensive process, and there is the need to conduct research on the impact of various factors on energy consumption during the cutting of plant products (Grzemski, 2013; Yan and Li, 2013; and Leonget al., 2014). By the optimal selection of knife wedge angle, the specific cutting energy can be significantly reduced. 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 et al. (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.

Singhet 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 1).

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 (Table 1).

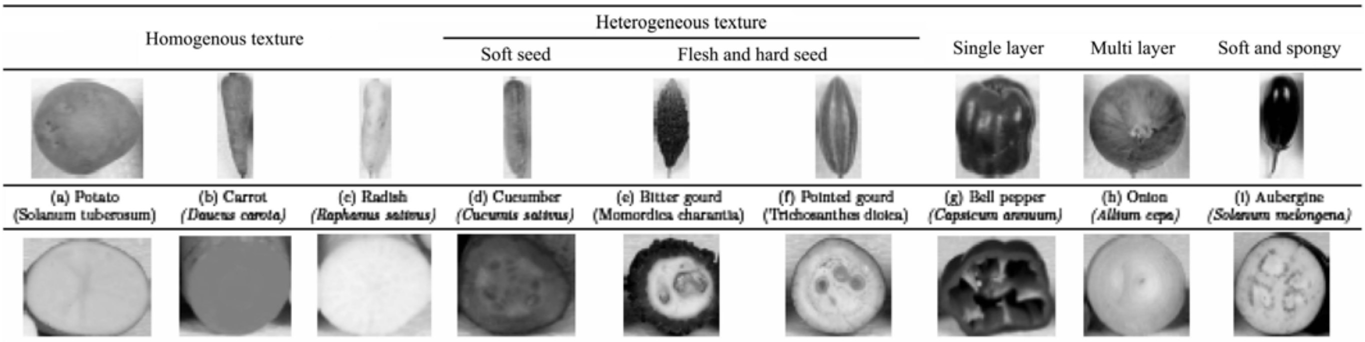


Figure 1 Whole vegetables and texture of their inner flesh (cross–sectional view) (Singhet al., 2016)

Table 1 Diameter and moisture content values for the different unpeeled vegetables studied

	Diameter (mm)#						Moisture content#	
Unpeeled Vegetable	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 54 mm and the S.D = 1.9 mm). 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). Three cutting edge angles, 15°, 20° and 25° were used in the study and three cross-head speeds, 20, 30 and 40 mm min^{-1} 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.

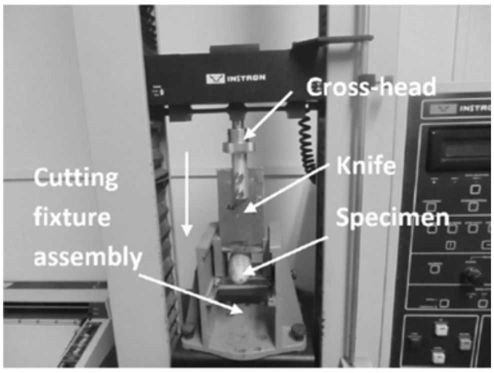


Figure 2 Knife movement within the Universal Testing Machine (Instron, UK, Model NO 1011, Load cell LVDT, Load Range 500N). Source*:* Singhet al. (2016)

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 (1) (Singh et al., 2016).

$$\text{Specific energy for cutting} = \frac{\text{total energy required for cutting}}{\text{area of cut}} (\mathrm{J\ m^{-2}}) \qquad (1)$$

The average specific energy values of all vegetables at different cutting speeds and knife-edge angles are reported in Table 2. Vegetables like potato, carrot and radish, showed a steady increase in specific energy that attained peak values of 525, 722 and 350 J m^{-2}, respectively (for knife angle of 15° and knife speed of 20 mm min^{-1}) followed by a decrease in specific energy as the knife-edge angle was increased to 25^{o} at varying knife speeds (for potato). 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 (238 J m^{-2} to 373 J m^{-2}) and bell pepper (232 J m^{-2} to 346 J m^{-2}) 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 (450 J m^{-2} to 1340 J m^{-2}).

Table 2 Average specific energy for vegetables using different knife angles and cutting speeds

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

Note: Average of five replicates, ¥=Average specific energy with standard deviation (for example, 525±30 means 525 N m^{-1} is the average specific energy and 30 N m^{-1} is the standard deviation). Source: Singh et al. (2016).

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 (526 J m^{-2} to 744 J m^{-2}) with increasing depth all through the cutting process indicating progressive cutting of layers.

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 3a and 3b. Bitter gourd has a tough and thick rind attributing for its large variation in specific energy (620 J m^{-2} to 1100 J m^{-2}) as reported by Singh et al. (2016).

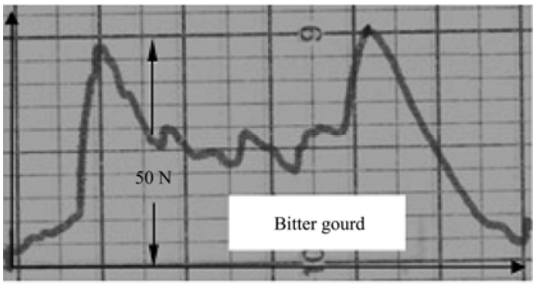


Figure 3a (Knife angle 15° and cutting speed 30 mm min^{-1}). Force-deformation graph obtained for bitter-gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine

Source: Singh et al. (2016).

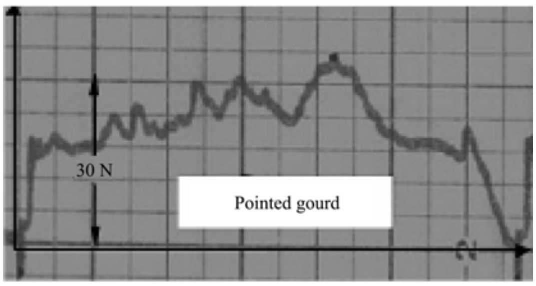


Figure 3b (Knife angle 20° and cutting speed 30 mm min^{-1}). Force-deformation graph obtained for pointed gourd on an X-Y chart for a fixed knife movement within the Universal Testing Machine

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 (40 mm min^{-1}) and large knife edge angle (25°) 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 (Table 2) showed that a combination of low speed cutting (20 mm min^{-1}) with a sharp angle cutter (15°) is favoured for low peak specific energy (least cutting energy).

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 analyzer, 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^{-1}. 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 Figures 4a are described by the Regression Equations (2) and (3) and that of Figures 4b are described by Regression Equations (4) and (5) respectively, which showed that increasing the knife wedge angle causes an increase in the values of peppers' cutting energy. The high R^2 values show strong correlation between values of the knife wedge angles and the cutting energy values.

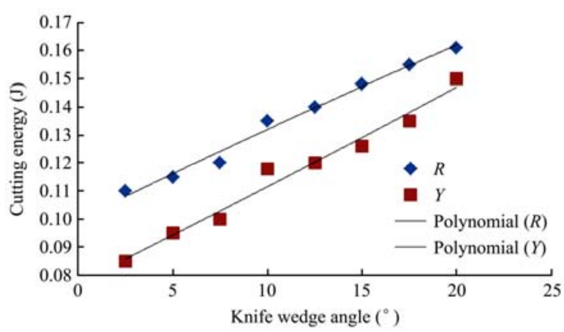


Figure 4a Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin down

Source: Elżbieta and Agnieszka (2012).

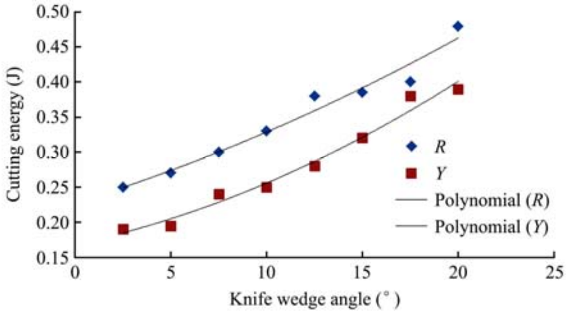


Figure 4b Graph showing relationship between cutting energy of red and yellow peppers to knife wedge angle with the material positioned skin up

Source: Elżbieta and Agnieszka (2012).

$$yR = -1E\text{-}5x^2 + 0.003x + 0.099 \quad R^2 = 0.99 \tag{2}$$

$$yY = 7E\text{-}6x^2 + 0.003x + 0.077 \quad R^2 = 0.98 \tag{3}$$

$$yR = 0.000x^2 + 0.008x + 0.227 \quad R^2 = 0.96 \tag{4}$$

$$yY = 0.000x^2 + 0.005x + 0.168 \quad R^2 = 0.98 \tag{5}$$

Source: Elżbieta and Agnieszka (2012).

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 was 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 0.471 J was obtained (from the report of Elzbieta and Agnieszka, 2012) 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 0.085 J obtained when cutting with wedge angle of α=2.5° (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 (Elzbieta and Agnieszka, 2012). 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, (0.246-0.471 J), compared to yellow pepper cv. Bell (0.188-0.392 J) 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 3).

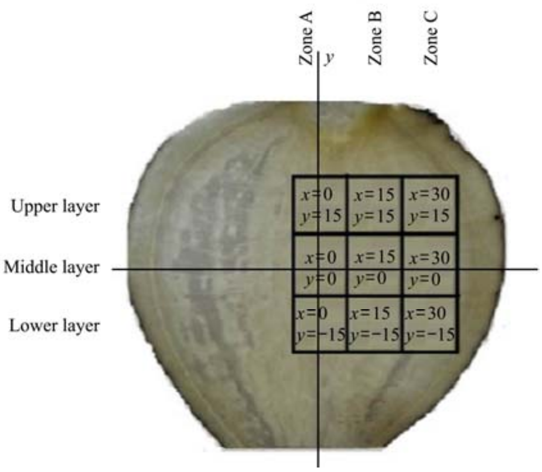
Table 3 Texture properties of red peppers (cultivar King Arthur) and yellow peppers (Cultivar Bell)

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

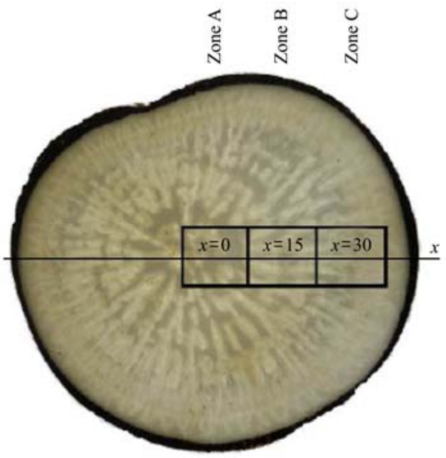
Source: Elżbieta and Agnieszka (2012).

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^{-1}) and contact area of 200, 300, 400 and 500 mm^2 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 10 mm resulting into a contact area of 200 mm^2 (20 mm×10 mm)). 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 0.175 J was observed for least contact surface area (200 mm^2) and minimum knife speed (20 mm min^{-1}), and the highest cutting energy of 1.296 J was observed for highest contact surface area (500 mm^2) at maximum knife speed (40 mm min^{-1}) respectively. Low speed (20 mm min^{-1}) 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. 0.175 J, 0.1978 J, and 0.208 J) for contact area of 200 mm^2 at 20, 30 and 40 mm min^{-1} respectively, indicating the homogeneous texture of potato.

Agnieszka and Elżbieta (2016) in their study on the impact of the wedge angle on the specific cutting energy of black radish (variety *Murzynka*), consideredthe 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 (shown in Figure 5) at the knife wedge angles: 2.5°, 5°, 7.5°, 10°, 12.5°, 15°, moving at the speed of 0.83 mm s^{-1} (about 50 mm min^{-1}).



(a) Longitudinally



(b) Transversely to the fibers

Figure 5 The structure of black radish parenchyma and place of sampling after cutting (Agnieszka and Elżbieta, 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) as shown in (Figure 6).

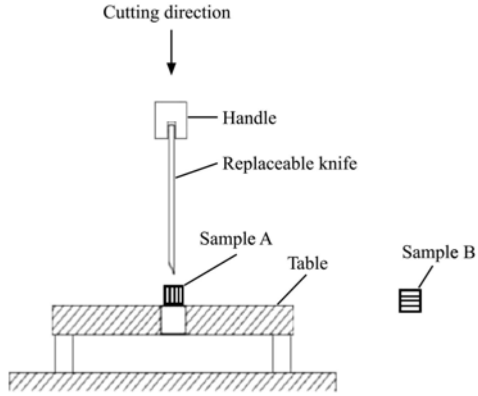


Figure 6 Sample orientation ((longitudinally (sample A) and transversely (sample B) to knife direction (Agnieszka and Elżbieta, 2016)

Measurement graphs were obtained showing the relationship between the force and displacement of the cutting knife, and using Equation (2), the specific cutting energy, was calculated, defined as the labor required to cut the specific area of the material (Agnieszka and Elżbieta, 2016):

$$Ej = \frac{L}{A} \tag{6}$$

where, Ej – specific cutting energy, J m^{-2}; L – Work of cutting, J; A – Surface area of the sample, m^2.

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 (2012) in their opinion that cutting resistance during knife movement is related to the sharpness of the cutting edge. Increasing the knife angle from 2.5° to 15° caused a corresponding increase of the specific cutting energy of black radish from 347 to 851 J m^{-2} (at the longitudinal orientation of fibers), and from 388 to 1033 J m^{-2} (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 (2011) 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 4.

Table 4 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 (2011).

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 5. However, results equally showed that the highest cutting forces of 90.89 N, 137.55 N and 240.3 N were recorded in the middle area of carrots (Samples 1, 2 and 3of diameters 20 mm, 26.28 mm and 40 mm, 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 larger diameters of 25 mm, 30.4 mm and 45 mm, respectively has lower values of cutting forces (84.62 N, 130.28 N and 210.4 N respectively), supporting the findings of 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) opined that the force required to penetrate carrot increases with increasing elastic behavior. Cutting forces are however, lowest at the bottom of carrots, where the section cutting area is smallest (53.80 N, 94.31 N and 128.2 N respectively). A slightly different position was observed with sample 4 (probe number 4) which shows a normal characteristic pattern of decreasing cutting forces of 206.62 N, 197.3 N and 156.8 N with decreasing cutting diameters of 49.02 mm, 41 mm and 28.4 mm respectively. The relation presented in Figure 7 is described by Equation (7) showing a high R^2 value which is indicative of a significant relationship between the diameter in cutting area and the cutting energy.

$$y = -892.9x^2 + 391.2x - 6.37 \quad R^2 = 0.95 \tag{7}$$

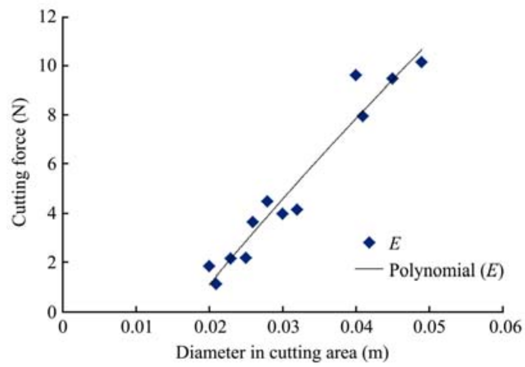


Figure 7 Graph representing relation between cutting energy and diameter in cutting area

Source: Ciulică and Rus (2011).

3 Conclusion

Cutting energy requirements of vegetables have been estimated using different cutting systems and approaches with a view to know the most efficient cutting conditions necessary for optimization of the cutting process in terms of energy required to cut and an overall efficient cutting operation. Blade sharpness, slicing angle, contact area, depth of cut, cutting speed, and the engineering properties of the vegetables such as crop variety, maturity stage, moisture content, average diameter, average length, average width, and fibre orientation have been identified as some of the parameters affecting vegetables cutting energy requirement. Cutting of vegetable products have been found advantageous in terms of obtaining products with the desired shape and size that could easily lend themselves to further processing such as drying and other heat treatments and cutting energy requirement is of importance in order to aid in the engineering design and modifications of cutting mechanisms and to investigate the effects of parameters on cutting energy.

From the review, different methods have been adopted to estimate the energy requirement for cutting to include; universal testing machine with fixture for inserting knives coupled with recorder for automatic generation of cutting energy values for potato (2.36 J), carrot (4.55 J), raddish (1.23 J), cucumber (1.19 J), bitter gourd (4.56 J), pointed gourd (1.28 J), bell pepper (1.83 J), onion (2.36 J) and aubergine (7.72 J) as obtained in the works of Singh et al. (2016). Other methods include cutting on a texture analyzer (Elżbieta and Agnieszka. 2012), type TA.XT Plus for different pepper cultivars (0.085-0.471 J) and cutting with special stands such as the Zwick/Roell stand having software called Test Expert for carrot (1.82-10.13 J) (Ciulică and Rus, 2011) etc.

Generally, from the reviewed works, obtained results showed that with cutting speed ranging from 20 mm min^{-1} to 50 mm min^{-1} on a cutting tool sharpening angle ranging between 0^o to 45^o, the minimum energy requirement for cutting the reviewed vegetables was found to be between 0.085 J and 10.13 J. It was however observed that extensive documentation on the properties of foods and food products exist, but data related to the cutting energy of different vegetables is scarce, limited published literatures on specific energy in cutting of fruits and vegetables are available even though such data are important in the design of cutters. Therefore, more studies to investigate the cutting energy requirement for vegetables should be of considerable interest.

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