Determination of mass-indices (B-values) of selected legumes, tuber and sea food for utilization in minimum energy and power expressions for mass-size reduction operations.

ABSTRACT

In an effort to utilize the new concept of determining the minimum energy and power required for mass-size reduction operations of materials, it is necessary to have data bank of some parameters relevant to the equations in this regard. This is to make easy the computation of required estimate of energy and power for mass- size reduction operations of these materials. These equations in the new approach are termed as Orua Antia's energy and power equations with constants having a major parameter referred to as the mass index. In this study, the mass indices of some selected food materials such as cassava, yam, crayfish, beans and soybeans which finds applications in food industries were evaluated. The mass-index (B-Value) was obtained using two methods based on Equations 16 and 17. Relative error of these values was also evaluated. Results showed that Equation 16 or 17 could be used to obtain the mass index of the selected food materials. Also it was observed that the moisture content had little influence on the value of mass index. Hence, the average mass index per selected food type within its moisture content % wb range could be utilized in the Orua Antia's energy equations constants expressed as Equations 9, 10 and 11. The average mass indices were obtained as $1.6436 \pm\ 0.5935, 1.8915 \pm 0.6377, 20.2704 \pm\ 3.0846, 18.1960 \pm 1.0337\ and\ 23.7791 \pm 2.3094\ kg^{1/2m^2}s^{-2}$ for cassava, yam, crayfish, beans and soy beans respectively.

Keywords: Mass indices, Legumes, Tuber, Sea food, Mass-size reduction

1.0 Introduction

In processing most food materials for use as raw material or final product for consumption, it is necessary to reduce transportation cost and rate of spoilage, increase storage shelf life, solubility, size ranges of product, digestion, market margin, surface area, flow characteristics, etc of these materials. To achieve these feat, it is essential to reduce the sizes of materials for easy processing. Particle size reduction is very crucial unit operation required in determining the processing capacity of food materials, whether wet or dried form into desired form(s) as may be applicable (Mulla *et al.*, 2016; kumar and Yedhu Krishnan, 2020). In Nigeria, some of the food materials that requires size reduction via utilization in various applications are legumes, sea food and tubers.

Legumes are domesticated plants and one of the richest suppliers of protein, carbohydrates, minerals, and vitamins (Salman Ahmed. 2014). They are useful as food for humans and animals as well as agriculture. Some regular utilized legumes are Alfalfa, chick peas, clovers, cow peas, kidney beans, lentils, mung beans, peanuts, peas, pigeon peas, soy beans, and vetches (Peter and Carroll, 2003; Allen and Allen, 1981).

Seafood are sourced from marine life. They are jointed-footed invertebrates and belong to the Decapoda order (ten legs) and the Crustacea group (shell) (Helfrich & DiStefano, 2020). Some examples of sea food are skates, rays, sawfish, lampreys, sharks, crustaceans like lobster, crab, shrimp, and prawns; mollusks such as like clams, oysters, cockles, mussels, periwinkles, whelks, snails, abalones, scallops, and limpets; sea turtles, crayfish, etc. (Encyclopaedia Britannica, 2023).

Tubers are very important agricultural source of staple energy in the tropical region of the world. They are classified with other underground food and are bulky in nature with about 60-90% moisture content. Some examples of tuber are aroids, potatoes, cassava, sweet potatoes, yam, etc (Chandrasekars and Kumar 2016).

Generally, legumes, seafood and tubers may be subjected to size reduction through milling to produce powder and paste of increase fitness such as flour, starches, etc. One of the major equipment used in size reduction of material is mill such as roller, ball, impact percussion, beater bar, attrition, rod mills, etc. In grinding/milling the application of appropriate force, energy and power on the material will reduce it size through crack, crack propagation, fragmentation and further reduction in size as may be desired (Antia, 2021). To achieve size reduction, some energy equations have been used such as Kicks, Rittingers and Bonds energy equations. These equations may be expressed (Okoro, 2001, Mohd Rozalli *et al.*, 2015, Fellows, 2009) as:

$$E_k = K_k\left[\ln\frac{X_1}{X_2}\right] \qquad (1)$$

$$E_R = K_R\left[\frac{1}{X_2}-\frac{1}{X_1}\right] \qquad (2)$$

$$E_B = K_b\left[\frac{1}{\sqrt{x_2}}-\frac{1}{\sqrt{x_1}}\right] \qquad (3)$$

Where, $K_k = Kick's\ constant, {}^{Jm}/_{Kg}$

$K_R = Rittinger'sconstant, {}^{Jm}/_{Kg}$

$K_B = Bond'sconstant, {}^{Jm^{1/2}}/_{Kg} = 0.3162W_i$

$W_i = Bond's\ work\ index, {}^{Kwh}/_{t}$

$x_1 = initial\ dimension\ of\ particle, m$

$x_2 = final\ dimension\ of\ particle, m$

$E = Energy\ and\ may\ be\ expressed\ in\ terms\ of\ {}^{kWh}/_{Kg}\ or\ {}^{Ws}/_{Kg}\ or\ {}^{J}/_{Kg}$

In an effort to improve on these major size reduction energy equations, another approach was carried out through the use of the relationship between energy, mass and size. In this regard, the mass-size reduction operation concept was expressed for minimum energy and power requirements as Orua Antia’s energy and power equations given (Antia, 2020) as:

$$E_A = K_{A_1}\left[\frac{1}{D_2^{1/2}}-\frac{1}{D_1^{1/2}}\right] \qquad (4)$$

$$E_A = K_{A_2}\left[\frac{1}{D_2^{1/2}}-\frac{1}{D_1^{1/2}}\right] \qquad (5)$$

$$E_A = K_{A_3}\left[\frac{1}{D_2^{3/2}}-\frac{1}{D_1^{3/2}}\right] \qquad (6)$$

Where, $E_A = Minimum\ energy\ and\ may\ be\ expressed\ in\ terms\ of\ {}^{kWh}/_{Kg}\ or\ {}^{W.s}/_{Kg}\ or\ {}^{J}/_{Kg}$

D_1 *and* D_2 *are initial and final diameter of the particle.*

$$D_1 = D_p S_p \tag{7}$$

$$D_2 = D_f S_p \tag{8}$$

$D_p = diameter\ of\ the\ product, m$

$D_f = diameter\ of\ the\ feed, m$

$S_p = sphericity$

K_{A_1}, K_{A_2} *and* K_{A_3} *are constants termed as Orua Antia's energy equation constants and may be expressed in terms of* ${Jm^{1/2}}/{Kg}$, ${Jm^{1/2}}/{Kg}$ *and* ${Jm^{3/2}}/{Kg}$ *respectively.*

$$K_{A_1} = \frac{2B\rho_m{}^{1/2}}{C_f M_f}(0.2304)S_A \tag{9}$$

$$K_{A_2} = \frac{2B\rho_m{}^{1/2}}{C_f M_f}(0.2304)\frac{u^2 t}{\bar{m}} \tag{10}$$

$$K_{A_3} = \frac{2B\rho_m^{-1/2}}{C_f M_f}(0.2304) \tag{11}$$

Where, $B = mass\ index,\ kg^{1/2}m^2s^{-2}$

C_f = Crushing efficiency

M_f = Mechanical efficiency

ρ_m = density of the material, kg/m^3

$S_A = specific\ surface\ area, {m^2}/{kg}$

$u = velocity\ of\ particle, m/s$

$t = time\ required\ for\ the\ mass - size\ reduction\ process, s\ or\ \min\ or\ hr$

$\bar{m} = mass\ flow\ rate\ of\ particles, kg/s$

The minimum power requirements was also given as:

$$P_m = K_{A_2}\bar{m}\left[\frac{1}{D_2^{1/2}} - \frac{1}{D_1^{1/2}}\right] \tag{12}$$

$$P_m = K_{A_3}\bar{m}\left[\frac{1}{D_{vsp}^{3/2}} - \frac{1}{D_{vsf}^{3/2}}\right] \tag{13}$$

$P_m = minimum\ power, J/s\ or\ KW$

These Equations 4 to 13 were derive analytically based on empirically developed equation given (Antia, 2014) as:

$$E_{min} = 2Bm^{1/2} \tag{14}$$

Where, $m = mass\ of\ material,\ kg$
$E_{min} = minimum\ energy, J$

The parameters in these Equations 9, 10, 11 and 14 are required to be obtained for use on the materials that are likely to be subjected to mass-size reduction operations. One of the major parameters in these expressions is the mass index (B-value). The availability of this parameter value would help to quickly use these expressions. Therefore, in this study, the mass indices (B-values) of selected legumes (soybeans, beans), tubers (cassava, yam) and seafood (crayfish) were investigated as these materials find application as powder, paste, etc. in various food processes.

2.0 Theory

Materials can crack followed by its reduction in size. This may occur when the material is subjected to impact such that the energy absorbed by this material is enough to cause crack followed by propagation and further fragmentation. Depending on the type of material, the energy required to cause size reduction may be evaluated by allowing such material to be subjected to impact force of hammer mass at a certain appropriate predetermined height drop. The minimum height drop of a known hammer mass to cause fragmentation of a material may be expressed using the relationship given (Antia, *et al.,* 2012, Asoegwu, 1995, Esua *et al.,* 2015 Antia, 2019(a)). as:

$$E_{min} = Mgh \tag{15}$$

Where, $h = H - d_1$
$d_1 = height\ of\ material\ from\ its\ placed\ point\ to\ its\ top\ surface.$
$H = predetetrmined\ hammer\ height\ drop\ to\ commence\ breakage\ of\ the\ material.$

$$M = mass\ of\ hammer$$

Based on Equations 14 and 15, the mass index (B-value) may be evaluated in any of the following expressions:

$$B = \frac{Mgh}{2m^{1/2}} = \frac{1}{2}\left[\frac{Mgh}{\sqrt{m}}\right] \tag{16}$$

$$\log E_{min} = {}^{1}/_{2} \log m + \log 2B \tag{17}$$

$$\ln E_{min} = \ln 2B + {}^{1}/_{2} \ln m \tag{18}$$

Where, B is evaluated directly from Equation 16 or evaluated from graph using Equation 17 or 18 with slope as ${}^{1}/_{2}$ corresponding to intercept of which

$B = {}^{1}/_{2}\left[e^{intercept}\right]$ $using\ Equation$ 18 or $B = {}^{1}/_{2}\left[10^{intercept}\right]$ $using\ Equation$ 17.

3.0 Materials and Methods

(a.) Material Sourcing and Pre-treatment

Legumes (soybeans, beans) and seafood (cray fish) were purchased from the local market while tubers (yam and cassava) were harvested from a local farm all in Uyo, Akwa Ibom state, Nigeria. Each type of legume and sea food were cleaned to remove any dirt on it while the yam and cassava was peeled, washed and cut into desired sizes. The cleaned samples were weighed and dried till it reach a constant mass using an air dried oven operated at temperature of 105°C. The moisture content (MC_{wb}) of ten (10) samples of each type of selected food material was determined at bone dry mass (constant mass) using Equation 19 (Antia, *et al.*, 2019 (b) & (c)).

$$MC_{(wb)} = \frac{initial\ \ weight - final\ \ weight}{initial\ \ weight} \times 100 \tag{19}$$

(b.) Experimental Procedure

Ten (10) samples of each type of selected food materials were dried at five (5) different time intervals that span from time $t = 0$ to time when dry bone mass was achieved. A total of fifty (50) samples per selected food material were used. At each time interval, ten (10) samples of each selected food material type were removed and cooled in dessicator. Each of the ten (samples) cooled was thereafter weighed and Equation 19 employed in determining its moisture content (%wb).

The mass-index (B-value) of each sample per set of ten (10) samples per moisture content per type of selected food material at each drying time interval was carried out based on Equation 16 and the value compared with the value obtained from Equation 17 or 18. Relative error between these values was computed (Wikipedia, 2023; Collegedunia, 2023) as:

$$RE = \frac{\boldsymbol{B_{if}} - \boldsymbol{B_{ig}}}{\boldsymbol{B_{ig}}} \qquad (20)$$

Where, $\boldsymbol{B_{if}} = Mass\ index\ from\ formular\ (Equation\ 16)$

$\boldsymbol{B_{ig}} =\ mass\ index\ from\ graph\ (based\ on\ equation\ 17\ or\ 18$

3.1 Results and Discussion

The average experimental values of E_{min} and mass index of the selected type of food materials obtained per moisture content using Equations 14, 15 and 16 are presented in Table 1

Table 1: Average experimental values of $\boldsymbol{E_{min}}$ and mass index per moisture content per food type

	Moisture content(%w.b)	Mass of material (kg)	Minimum Energy (E_{min}) (J)	Mass index (B value) ($kg^{1/2}m^2s^{-2}$)
cassava	63.14	0.002574	0.1596	1.6079
	55.00	0.002322	0.1176	1.1876
	54.54	0.001624	0.1735	2.2370
	53.83	0.001514	0.1316	1.8133
	47.64	0.001230	0.1352	2.1002
yam	66.13	0.002574	0.1596	1.6079

	54.54	0.002454	0.1242	1.2714
	53.83	0.001291	0.1771	2.5291
	53.36	0.001264	0.1360	1.9791
	47.64	0.001231	0.1360	2.0346
crayfish	0.36	0.000169	0.5314	21.1675
	0.29	0.000156	0.4292	17.1858
	0.22	0.000142	0.4925	21.0557
	0.14	0.000129	0.4653	20.0710
	0.07	0.000115	0.4969	23.9646
beans	5.60	0.000387	0.6751	17.2890
	4.96	0.000382	0.6739	17.4209
	4.35	0.000376	0.6802	17.5780
	2.89	0.000374	0.6811	17.7939
	1.63	0.000371	0.6949	19.2296
soybeans	14.80	0.000154	0.6079	24.5397
	13.25	0.000152	0.6433	26.0118
	11.30	0.000150	0.5683	23.2686
	8.69	0.000140	0.5081	21.4867

The intercept of the line with slope $^{1}/_{2}\ or$ 0.5 from plot using Equation 17 per sample per moisture content %wb per drying time correspond to a value evaluated as mass index of that sample. These plots of log E_{min} against log m are presented per selected type of food material per moisture content %wb in Figures 1 to 19

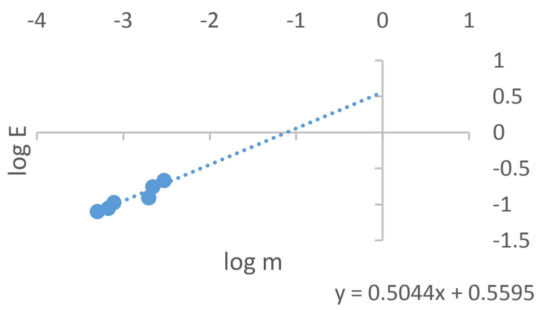

Figure 1: Graph of log E_{min} against log m for cassava at 54.54 %wb

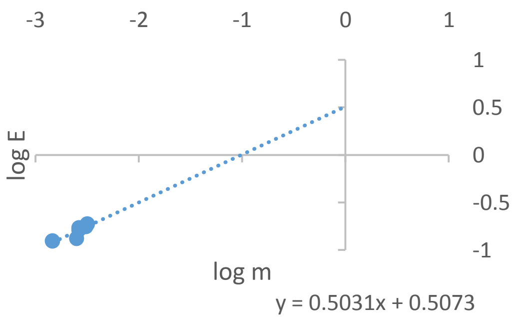

Figure 2: Graph of log E_{min} against log m for cassava at 47.64 %wb

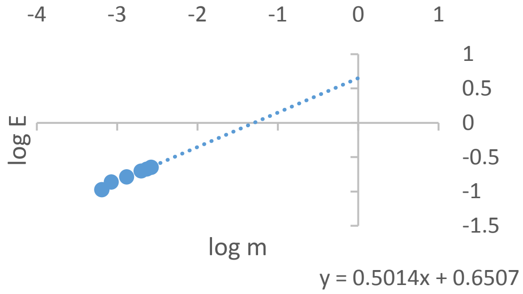

Figure 3: Graph of log E_{min} against log m for cassava at 53.83 %wb

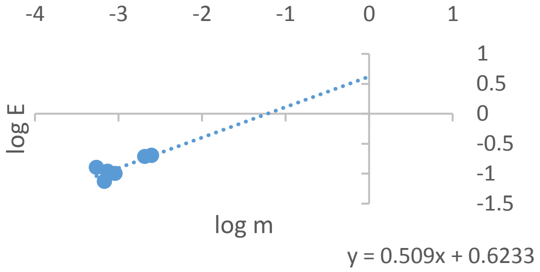

Figure 4: Graph of log E_{min} against log m for cassava at 55.00 %wb

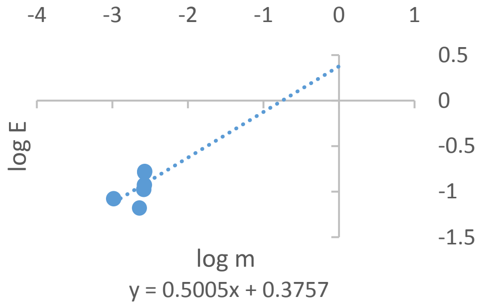

Figure 5: Graph of log E_{min} against log m for cassava at 63.14 %wb

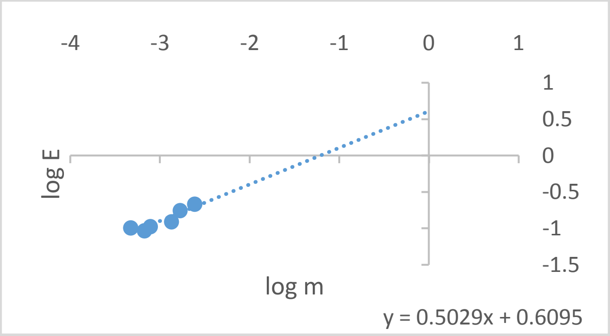

Figure 6: Graph of log E_{min} against log m for yam at 54.54 %wb

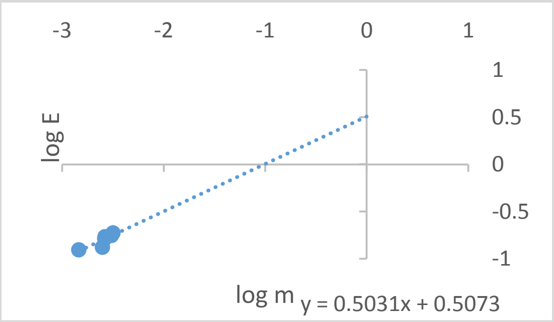

Figure 7: Graph of log E_{min} against log m for yam at 47.64 %wb

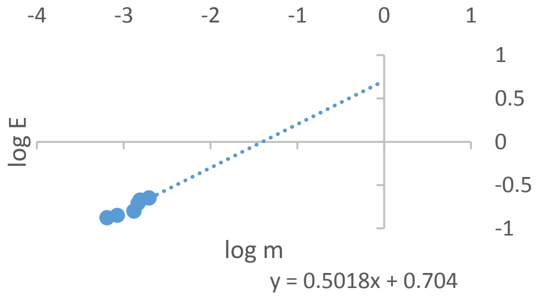

Figure 8: graph plot of log E_{min} against log m for yam at 53.83 %wb

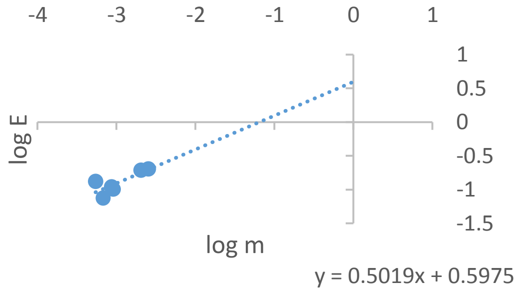

Figure 9: graph plot of log E_{min} against log m for yam at 53.36 %wb

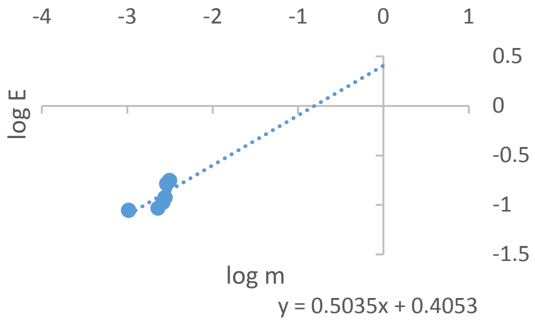

Figure 10: Graph of log E_{min} against log m for yam at 66.13 %wb

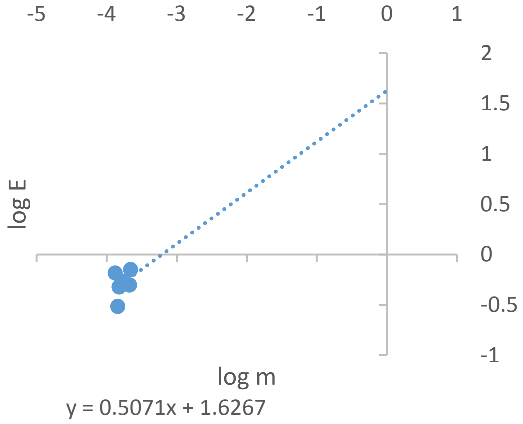

Figure 11: Graph of log E_{min} against log m for crayfish at 0.07 %wb

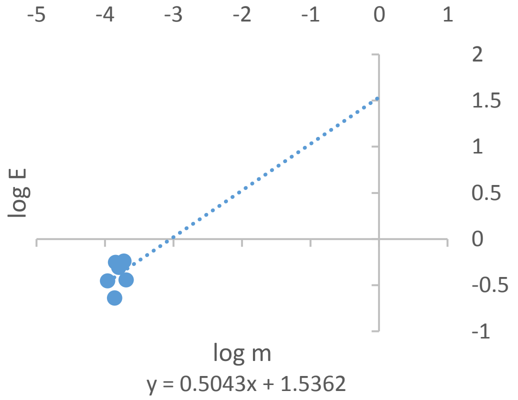

Figure 12: Graph of log E_{min} against log m for crayfish at 0.14 %wb

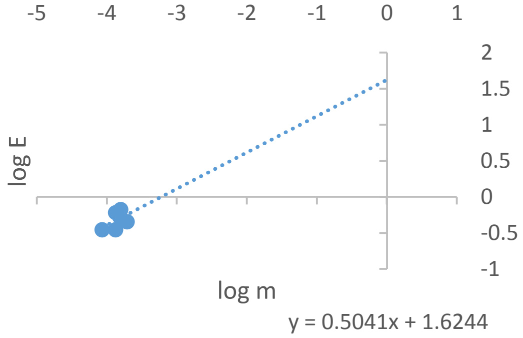

Figure 13: Graph of log E_{min} against log m for crayfish at 0.22 %wb

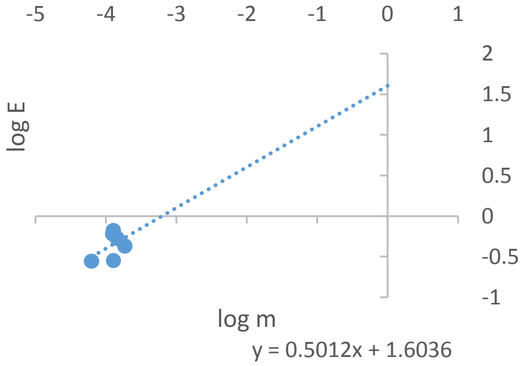

Figure 14: Graph of log E_{min} against log m for crayfish at 0.29 %wb

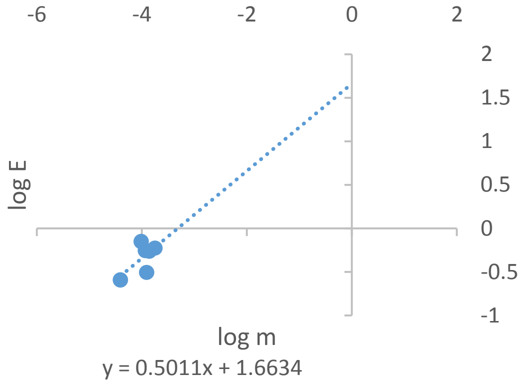

Figure 15: Graph of log E_{min} against log m for crayfish at 0.36 %wb

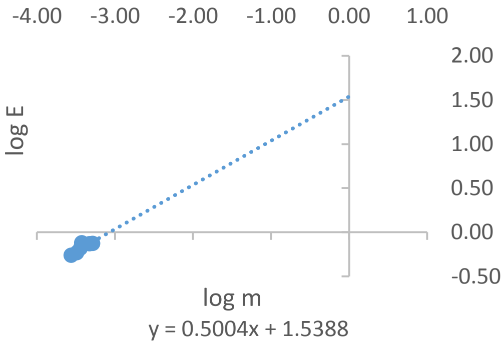

Figure 16: Graph of log E_{min} against log m for beans at 1.63 %wb

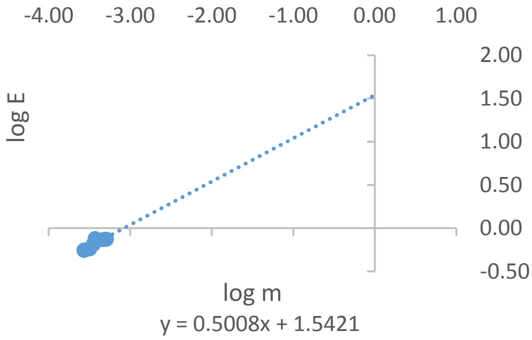

Figure 17: Graph of log E_{min} against log m for beans at 2.89 %wb

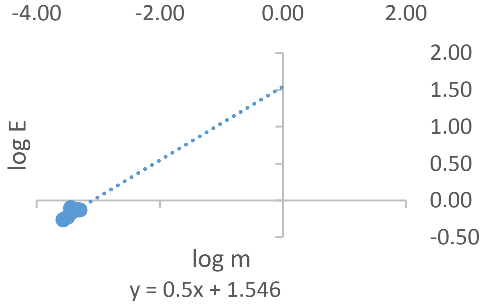

Figure :18 Graph of log E_{min} against log m for beans at 4.35 %wb

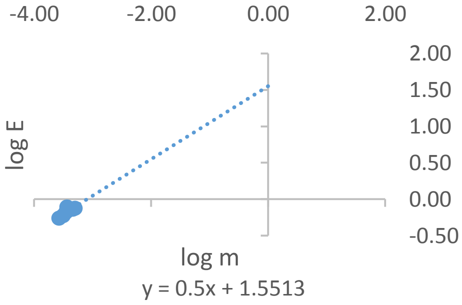

Figure 19: Graph of log E_{min} against log m for beans at 4.96 %wb

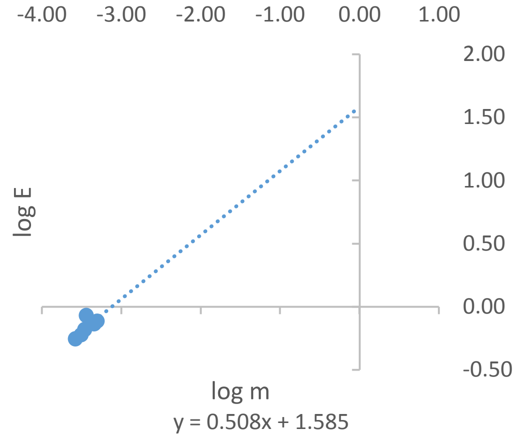

Figure 20: Graph of log E_{min} against log m for beans at 5.61 %wb

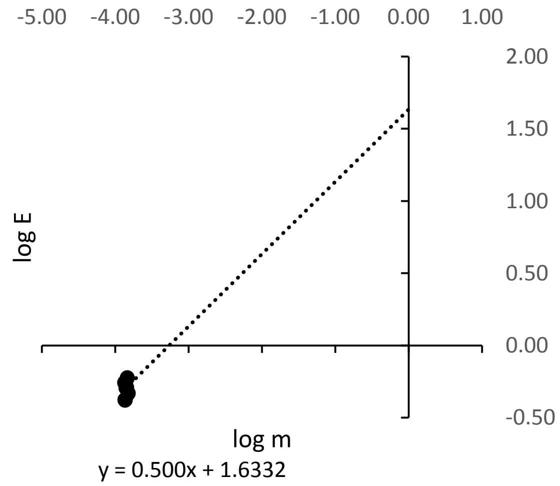

Figure 21: Graph of log E_{min} against log m for soybeans at 8.69 %wb

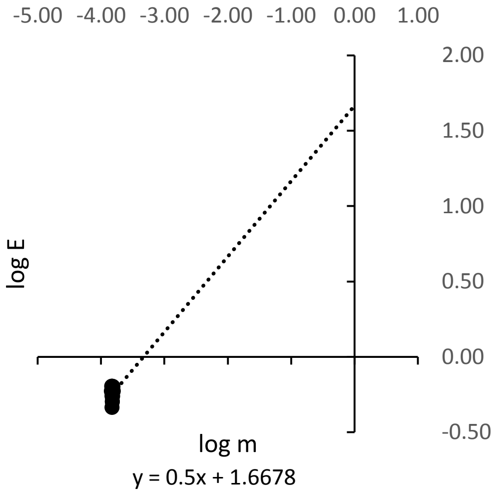

Figure 22: Graph of log E_{min} against log m for soybeans at 11.30 %wb

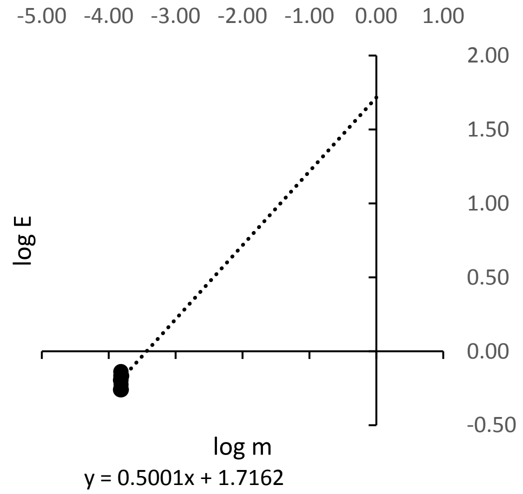

Figure 23: Graph of log E_{min} against log m for soybeans at 13.25 %wb

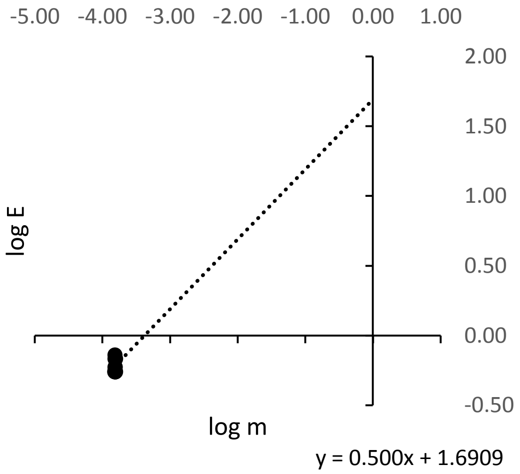

Figure 24: Graph of log E_{min} against log m for soybeans at 14.80 %wb

The computed relative error between the mass index obtained using Equations 16 and 17 (based on graph) presented in Table 2.

Table 2: Relative error using Equation 20 for mass index determined based on Equation 16 (formula) and 17 (graphical method).

	moisture content (%wb)	B-value from graph ($kg^{1/2}m^2s^{-2}$)	B-value from formula ($kg^{1/2}m^2s^{-2}$)	Relative error
Cassava	63.14	1.6079	1.5730	-0.0217020
	55.00	1.1876	1.2659	0.0659313
	54.54	2.2370	2.1525	-0.0377738
	53.83	1.8133	1.6907	-0.0676115
	47.64	2.1002	1.9283	-0.0818550
Yam	66.13	1.6079	1.5730	-0.0217020
	54.54	1.2714	1.2538	-0.0137970
	53.83	2.5291	2.4653	-0.0252410
	53.36	1.9791	1.9123	-0.0337590
	47.64	2.0346	1.9375	-0.0477060
Crayfish	0.36	21.1675	20.4125	-0.0356690
	0.29	17.1858	17.1907	0.0002850
	0.22	21.0557	20.6410	-0.0196980
	0.14	20.0711	20.5029	0.0215170
	0.07	23.0340	23.3549	0.0139310
beans	5.60	17.2890	17.1623	-0.0073310
	4.96	17.4209	17.2442	-0.0101430
	4.35	17.5780	17.5404	-0.0021390
	2.89	17.7939	17.6179	-0.0098880
	1.63	19.2296	18.0358	-0.0620830
soybeans	14.80	24.5397	24.4925	-0.0019250
	13.25	26.0118	26.0885	0.0029510
	11.30	23.2686	23.2021	-0.0028560
	8.69	21.4867	21.4697	-0.0007900

These values of relative error computed are low, hence it is suggested that Equation 16 or 17 could be used to obtain the mass indices (B-values) of the food material samples. The influence of moisture content %wb on the mass index were assessed using Figures 25 and 26.

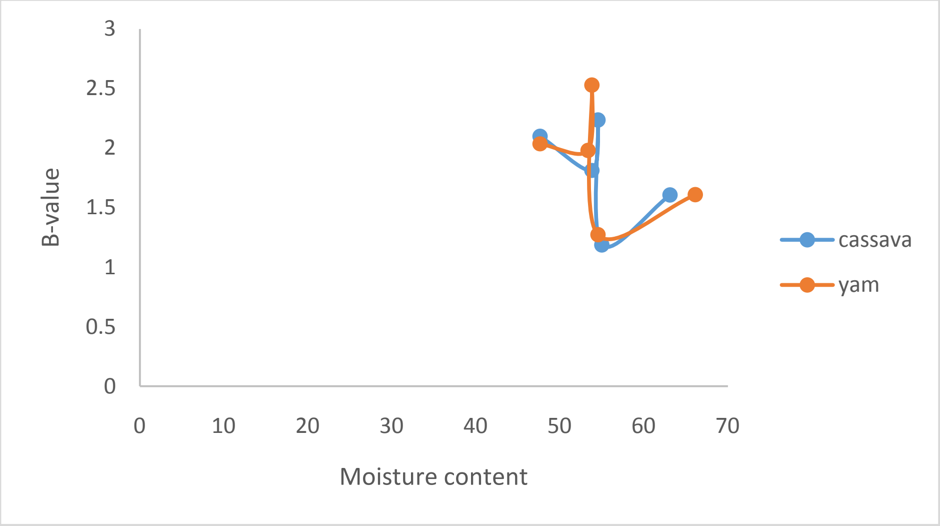

Figure 25: Graph of B-value against moisture content per tuber

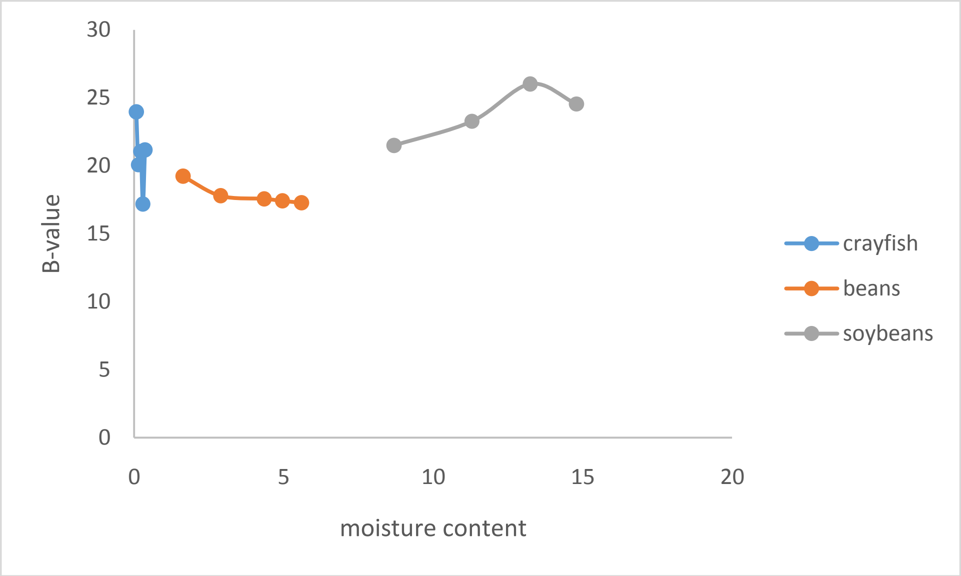

Figure 26: Graph of B-value against moisture content per food type

The B-values (mass indices) were observed to increase and decreased within the moisture content range of each selected material. This is suggested to be due to the nature of the food sample, the hardness of sample as drying time progresses and the porosity or air space available in the sample after drying. Also to note is that within the moisture content range per selected type of food material, the mass index evaluated were reasonably close. Hence, the mass index per moisture content %wb range per selected type of food material could be averaged and used in computing the Orua Antia's energy equation constants (Equations 9 to

11) for further use in determining the minimum energy and power requirements (Equations 4 to 6 and 12 to 13) for mass-size reduction operation of the selected food materials. These average values of the mass indices are presented in Table 3 for each of the selected food material in this study.

Table 3: Average mass index value for cassava, yam, crayfish, beans and soybeans.

Food type	Moisture content range %wb	Average B-value ($kg^{1/2}m^2s^{-2}$)
cassava	47.64-63.14	1.6436 ± 0.5935
yam	47.64-55.13	1.8915 ± 0.6377
crayfish	0.07-0.36	20.2704 ± 3.0846
beans	1.63-5.60	18.1960 ± 1.0337
soybeans	8.69-14.8	23.7791 ± 2.3094

5.0 Conclusion

The mass indices could be obtained using Equation 16 or 17 for the selected food material. Generally, the moisture content %wb of the selected food material was observed to have little influence on the mass index of the material. The average mass index from Table 3 may be used in determining the minimum energy and power requirements via Equation 4 to 6 and 9 to 13 for mass-size reduction operation of these selected materials.

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