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Mass-Indices (B-Values) of Legumes, Tuber and Sea Food for Mass-Size Reduction Operations

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Authors' contributions

This work was carried out in collaboration among all authors. Author AOO design the study and wrote protocol. Author AAJ carried out experimental runs and wrote the first draft of the manuscript. Author OWA carried out literature searches and managed analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

In an effort to easily use the Orua Antia's energy and power equations to determine the minimum comminution energy and power requirements of a given material; the mass Index being a constant in these equations is necessary to be provided for materials that could be subjected to comminution. 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 using static impact force technique coupled with graphical and computational approaches. In graphical method Equation 17 obtained from energy expression for mass-size reduction Equation 14 was employed; while Equation 16 which is a combination of Equation 14 and the potential energy Equation 15 was used in the computational method. Also the relative errors of mass indices obtained from these two methods were evaluated. Results showed that computational or graphical

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method could be used to obtain the mass index of each selected material. It was observed that moisture content had little influence on the value of mass index. Hence, the average mass index per selected food type within its percentage moisture content wet basis range could be utilized in the minimum comminution energy and power Equations 4 to 6 and 12 to 13 respectively, via the equations constants as applicable and expressed as Equations 9, 10 and 11. Further analysis revealed that the average mass indices were 1.7123±0.5835, 1.8915±0.6377,20.2704±3.0846, 18.1960±1.0337 and 23.7791±2.3094 $kg^{1/2}m^2s^{-2}$ for cassava, yam, crayfish, beans and soy beans respectively.

Keywords: Food material; mass index; comminution; moisture content; energy.

1. 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 feats, it is essential to reduce the sizes of materials for easy processing. Particle size reduction is a 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 [1,2]. In Nigeria, some of the food materials that require size reduction via utilization in various applications are legumes, seafood and tubers.

Legumes are domesticated plants and one of the richest suppliers of protein, carbohydrates, minerals, and vitamins [3]. Legumes may be classified into grains and forage. The grain legumes such as chickpeas, cowpeas, kidney beans, lentils, peanuts, pigeon peas, soybeans etc are useful as food for human and animals while forage legumes such as Alfalfa, vetches are mostly used as feed for animal [4,5].

Seafood is sourced from marine life. They are jointed-footed invertebrates and belong to the Decapoda order (ten legs) and the Crustacea group (shell) [6]. 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. [7].

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 tubers are aroids, potatoes, cassava, sweet potatoes, yam, etc [8].

Generally, legumes, seafood and tubers may be subjected to size reduction through milling to produce powder and paste of increase fitness such as flours, 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 [9]. To achieve size reduction, some energy equations have been used such as Kick's, Rittinger's and Bond's energy equations. These equations may be expressed [10, 11, 12] as:

$$E_k = K_k[\ln(x_1/x_2)] \quad (1)$$

$$E_R = K_R[(1/x_2) - (1/x_1)] \quad (2)$$

$$E_B = K_B[(1/\sqrt{x_2}) - (1/\sqrt{x_1})] \quad (3)$$

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 [13] as:

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

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

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

Where,

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

$$D_1\ and\ D_2\ are\ initial\ and\ final\ diameter\ of\ the\ particle.$$

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

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

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

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

$S_p = sphericity$

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

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

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

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

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

C_f= Crushing efficiency

M_f = Mechanical efficiency

ρ_m= density of the material, kg/m^3

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

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

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

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

The minimum power requirements was also given as:

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

$$P_m = K_{A_3}\dot{m}\left[(1/D_2{}^{3/2}) - (1/D_1{}^{3/2})\right] \tag{13}$$

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

The Equations 4 to 13 were derived analytically based on empirically developed equation given [14] 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. 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 [15, 16, 17, 18] as:

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

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:

$$B = \tfrac{1}{2}[(Mgh)/\sqrt{m}] \tag{16}$$

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

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

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

3. 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 wet basis (MC_{wb}) of ten samples of each type of selected food material was determined at bone dry mass (constant mass) using Equation 19 [19, 20].

$$MC_{(wb)} = [((Initial\ weight) - (final\ wieght))/(Initial\ weight)] \times 100 \tag{19}$$

(b) Experimental Procedure

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

The mass index (B-value) of each sample per set of ten 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 [21, 22] as:

$$\mathrm{RE} = [(B_{if} - B_{ig})/B_{ig}] \tag{20}$$

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

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

4. RESULTS AND DISCUSSION

The average experimental values of E_{min} and mass index (B-value) 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 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	1.5730
	55.00	0.002322	0.1220	1.2659
	54.54	0.001624	0.1735	2.1525
	53.83	0.001514	0.1316	1.6907
	47.64	0.001230	0.1352	1.9283
Yam	66.13	0.002574	0.1596	1.5730
	54.54	0.002454	0.1242	1.2538
	53.83	0.001291	0.1771	2.4653
	53.36	0.001264	0.1360	1.9123
	47.64	0.001231	0.1360	1.9375
Crayfish	0.36	0.000169	0.5307	20.4125
	0.29	0.000156	0.4294	17.1907
	0.22	0.000142	0.4919	20.6410
	0.14	0.000129	0.4657	20.5029
	0.07	0.000115	0.5009	23.3549
Beans	5.60	0.000387	0.6752	17.1623
	4.96	0.000382	0.6741	17.2442
	4.35	0.000376	0.6802	17.5404
	2.89	0.000374	0.6814	17.6179
	1.63	0.000371	0.6948	18.0358
soybeans	14.80	0.000154	0.6079	24.4925
	13.25	0.000152	0.6433	26.0885
	11.30	0.000150	0.5683	23.2021
	8.69	0.000140	0.5081	21.4697

The intercept of the line with slope $^1/_2$ or 0.5 from plot using Equation 17 per sample per moisture content percent wet basis 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 Figs. 1 to 19

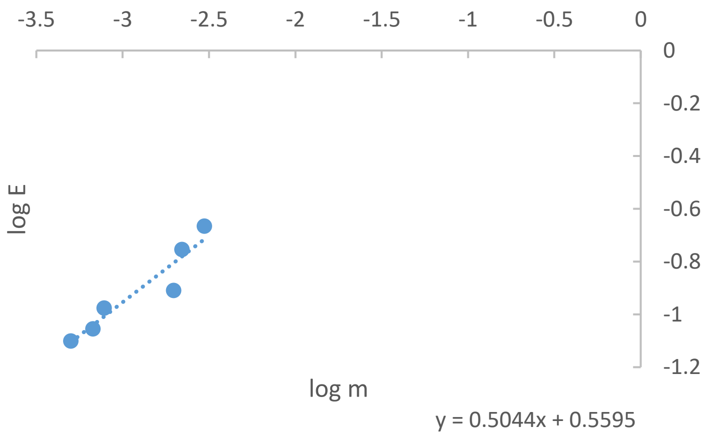

Fig. 1. Graph of log E_min against log m for cassava at 53.83 %wb

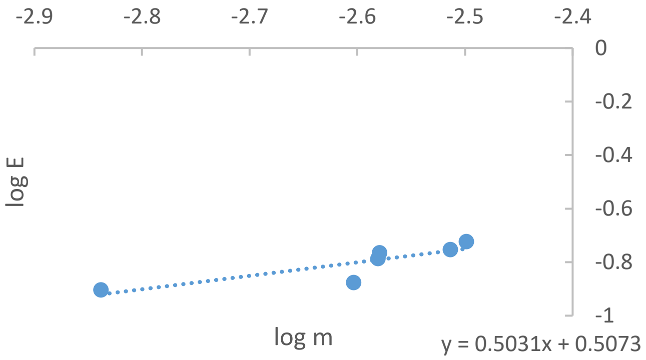

Fig. 2. Graph of log E_min against log m for cassava at 63.14 %wb

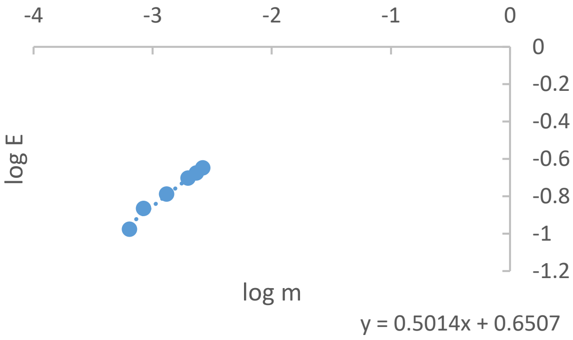

Fig. 3. Graph of log E_min against log m for cassava at 54.54 %wb

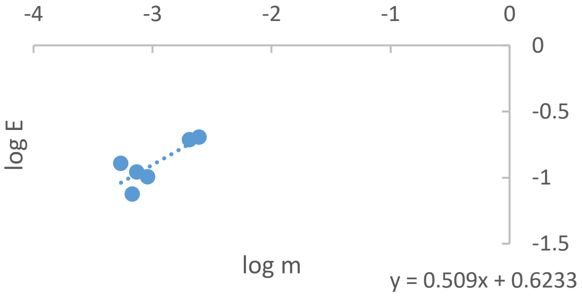

Fig. 4. Graph of log E_min against log m for cassava at 47.64 %wb

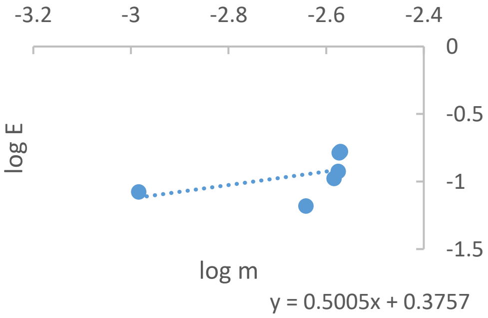

Fig. 5. Graph of log E_min against log m for cassava at 55.00 %wb

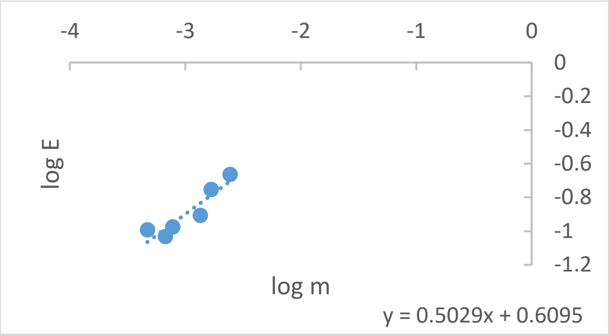

Fig. 6. Graph of log E_min against log m for yam at 47.64 %wb

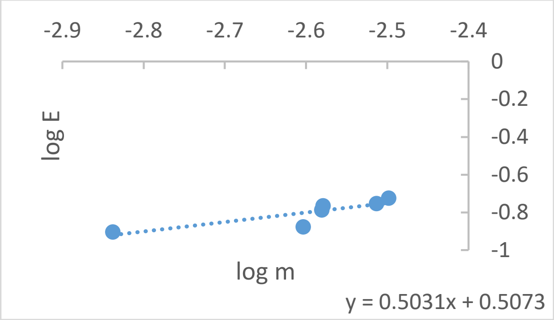

Fig. 7. Graph of log E_min against log m for yam at 66.13 %wb

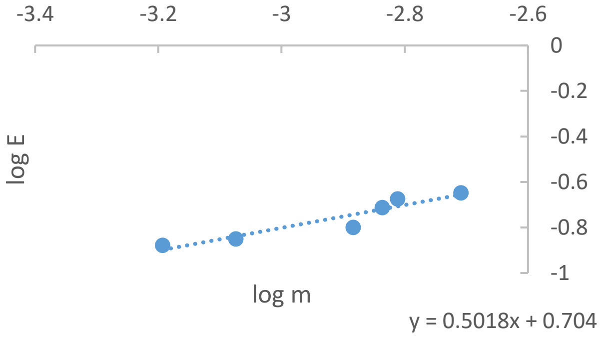

Fig. 8. Graph plot of log E_min against log m for yam at 53.83 %wb

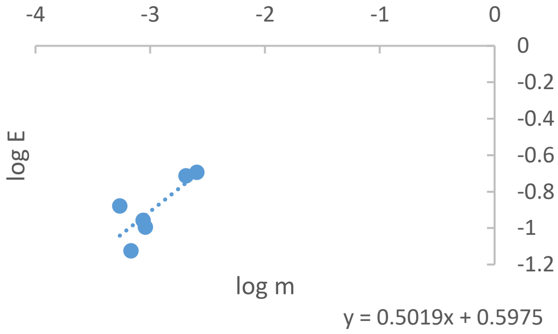

Fig. 9. Graph plot of log E_min against log m for yam at 53.36 %wb

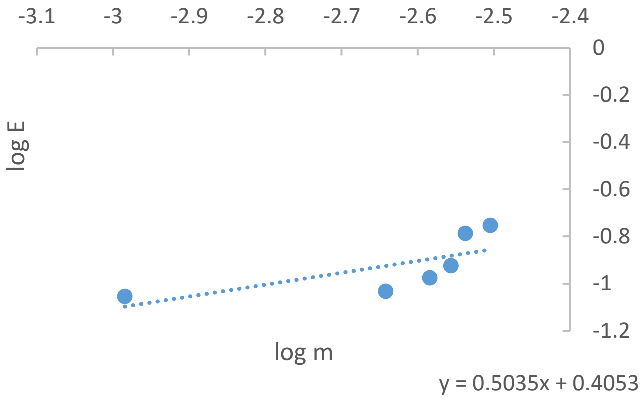

Fig. 10. Graph of log E_min against log m for yam at 54.54 %wb

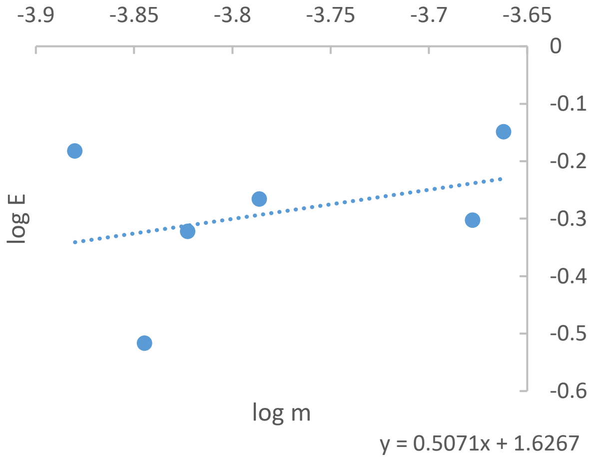

Fig. 11. Graph of log E_min against log m for crayfish at 0.36 %wb

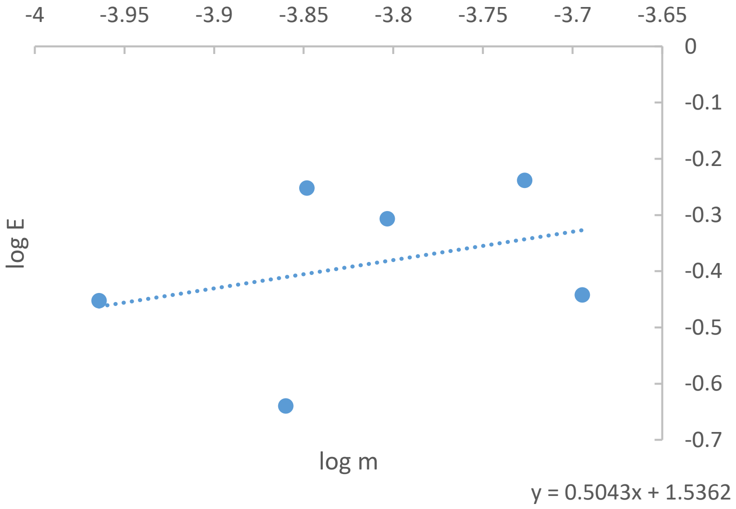

Fig. 12. Graph of log E_min against log m for crayfish at 0.29 %wb

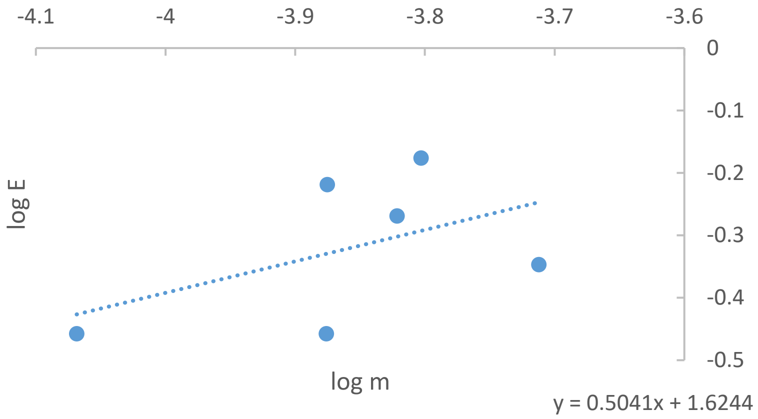

Fig. 13. Graph of log E_min against log m for crayfish at 0.22 %wb

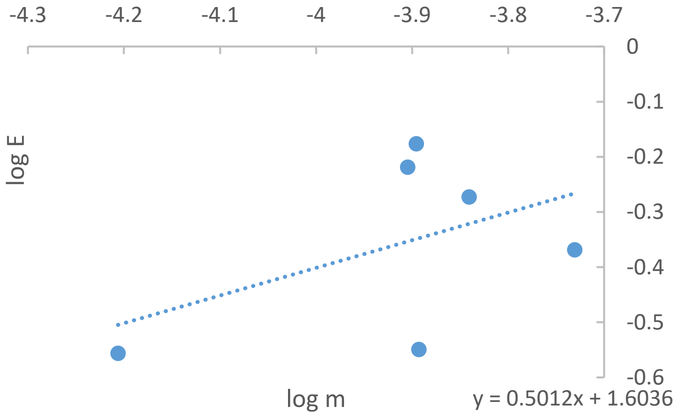

Fig. 14. Graph of log E_min against log m for crayfish at 0.14 %wb

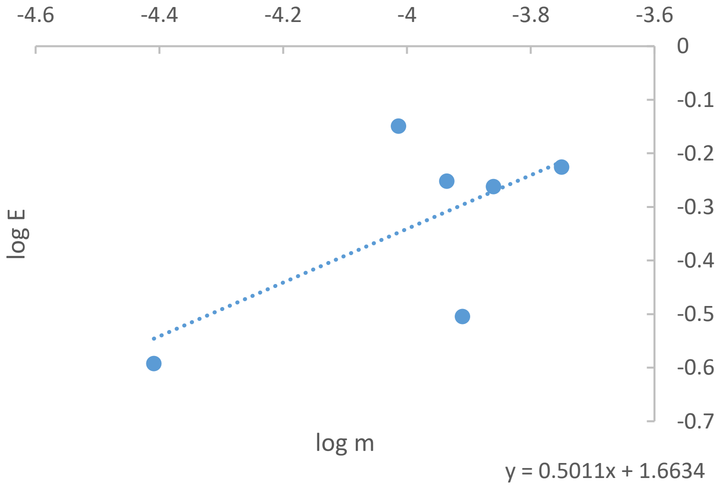

Fig. 15. Graph of log E_min against log m for crayfish at 0.07 %wb

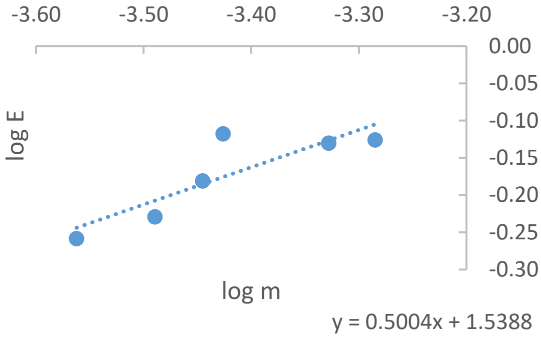

Fig. 16. Graph of log E_min against log m for beans at 5.60 %wb

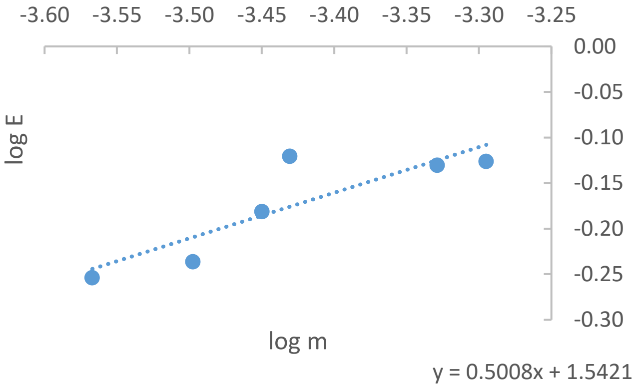

Fig. 17. Graph of log E_min against log m for beans at 4.96 %wb

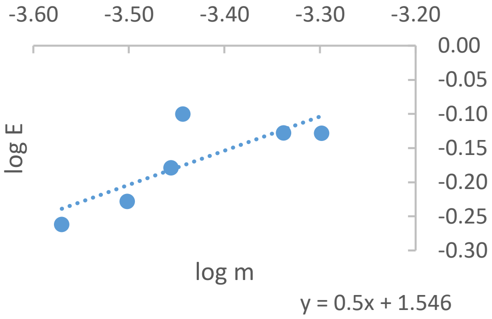

Fig. 18. Graph of log E_min against log m for beans at 4.35 %wb

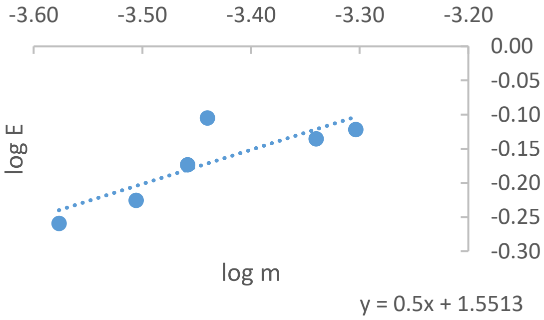

Fig. 19. Graph of log E_min against log m for beans at 2.89 %wb

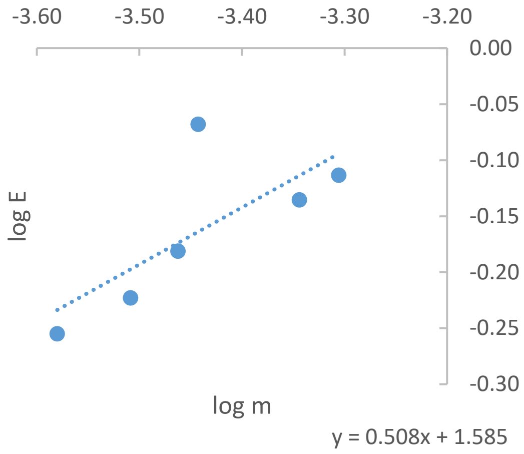

Fig. 20. Graph of log E_min against log m for beans at 1.63 %wb

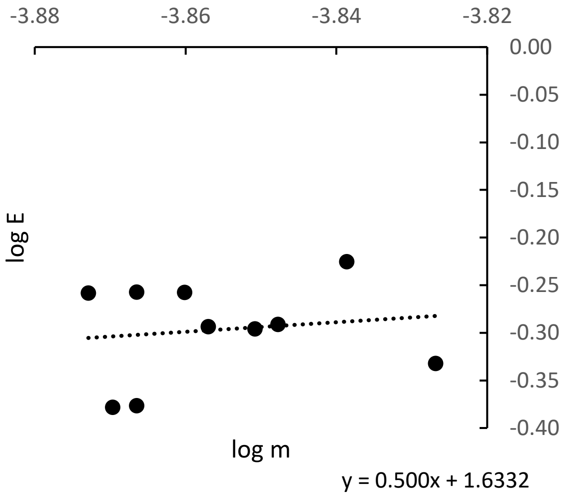

Fig. 21. Graph of log E_min against log m for soybeans at 8.69 %wb

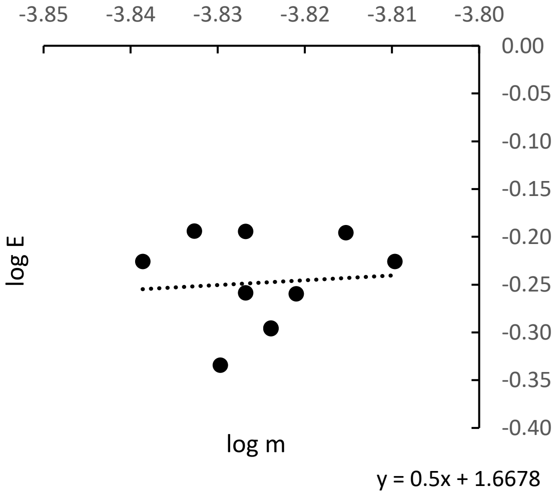

Fig. 22. Graph of log E_min against log m for soybeans at 11.30 %wb

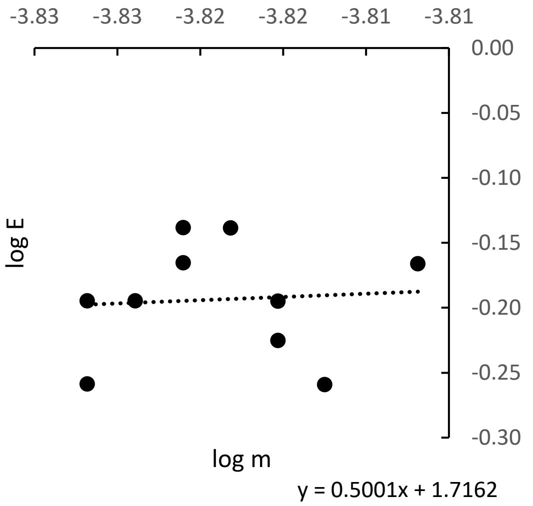

Fig. 23. Graph of log E_min against log m for soybeans at 13.25 %wb

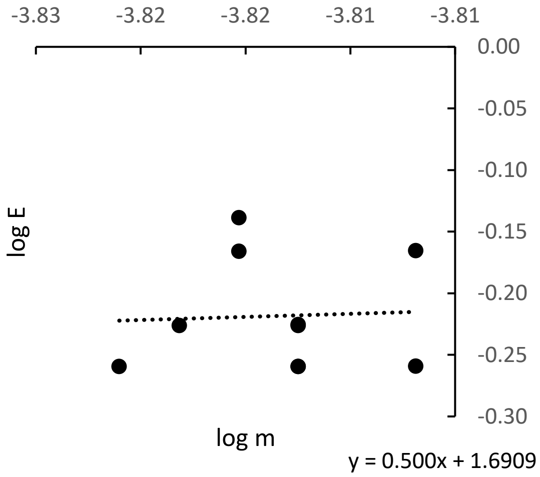

Fig. 24. Graph of log E_min against log m for soybeans at 14.80 %wb

The relative errors between the mass indices obtained using Equations 16 and 17 (based on graph) were computed using Equation 20 and are presented in Table 2.

Table 2. Relative errors between mass indices (B-values) at various moisture contents per food type

	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

	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**
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 errors computed are low, hence it is suggested that Equation 16 or 17 could be used to obtain the mass index (B-value) of a given food material sample. The influence of moisture content percent wet basis on the mass index were assessed using Figs. 25 and 26.

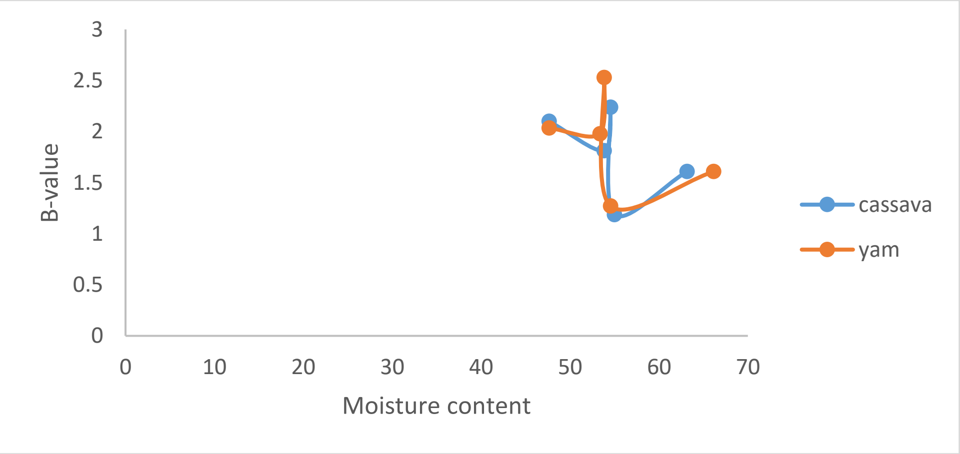

Fig. 25. Graph of B-value against moisture content per tuber

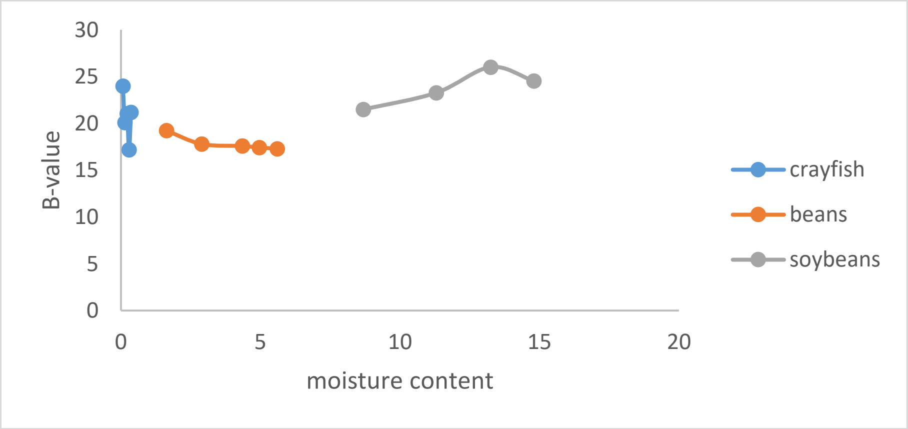

Fig. 26. Graph of B-value against moisture content per food type

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	1.7123 ± 0.5835
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

The mass indices (B-values) 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 was reasonably close. Hence, the mass index per moisture content percent wet basis range per selected type of food material could be averaged and used in computing the Orua Antia's energy and power equations 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 operations of the selected food materials. These average values of the mass indices are presented in Table 3 for the selected food materials in this study.

5. CONCLUSION

The mass indices could be obtained using Equation 16 or 17 for the selected food material. Generally, the moisture content percent wet basis 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 Equations 4 to 6 and 9 to 13 for mass-size reduction operations of these selected materials.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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