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Estimation of Mass Indexes (B-Values) for Use in Predicting the Minimum Energy and Power Requirements for Mass-Size Reduction Operations of Some Cereals

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ABSTRACT

In an attempt to predict easily the minimum energy and power requirements necessary to achieve the expected size reduction of materials using the recently developed Orua Antia's energy and power equations; it is essential that constant(s) in the equation should be readily available for usage. Therefore in this study, the evaluation of a constant termed mass index (B- Value) for mass-size reduction operations was carried out on cereals such as corn, wheat, sorghum, and millet that find various applications in food industries. Equations 17 and 18b were employed to evaluate mass indexes using the principles of static impact force. Relative errors (RE) of mass indexes obtained from these two equations were assessed. Results revealed that Equation 17 or 18b could be used to evaluate the mass indexes. More so, for each selected cereal the mass index was observed to vary slightly with moisture content %wb. Hence, the average mass index per cereal type per moisture content range may be used in Orua Antia's energy Equations 5 to 9 to predict the minimum energy and power requirements of the selected cereal when subjected to mass-size reduction operations. The average mass-indexes obtained were 20.9915± 0.4198; 27.6679± 0.6506; 24.9379±20.5454 and 24.523±3.7571Kg$^{(1/2)}$ m^{2}s^{-2}for corn, wheat, sorghum, and millet respectively.

INTRODUCTION

To achieve various goals such as mixing, drying, adsorption, dissolution rate, expression, extraction, blanching, cooking, etc during food processing, it is necessary to have the material size reduced. It may involve cutting or breaking solid particles into smaller pieces. Generally, size reduction operations may be referred to as comminution. Some of the size reduction operations are crushing, milling, grinding, dicing, etc (SudSushant *et al.*, 2013; Mulla *et al*, 2016; Kumar and Yedhu Krishnan, 2020). The size reduction creates a new surface area of the material. Cereals are some of the common food materials frequently subjected to comminution for various applications. Cereals are edible seeds or grains that belong to the Gramineae grass family. Various varieties of cereals such as rye, oats, maize, millets, wheat, rice, barley, triticale, and sorghum are grown by different nations. In cereals, the endosperm is filled with starch and embryo (or germ). The outer bran and aleurone layers are concentrated with fiber , vitamins, and minerals. Generally, cereals are an essential source of energy, protein, and fiber . They contain varieties of micronutrients such as vitamin E, magnesium, zinc, and several B vitamins (Bender & Bender 1999; Brigid, 2004). In most nations, cereals are one of the main staple food as they are significant sources of nutrients. The processing of these materials in wet or dried form into powder to increase its surface areas to volume ratio and flow characteristics is essential. This is because large particles may take a longer time to achieve mixing, dissolution, etc. More so, in biological processes, biomaterial physiochemical properties are mostly influenced by the size of particles (Kumar *et al.*, 2009; Song *et al.*, 2014). To quantify the energy and power requirements per size reduction operations, some major grinding equations have been used such as Kick's, Rittinger's, and Bond's equations given respectively (Antia, 2021, MohdRozalli *et al.*, 2015, Fellows, 2009) as:

$$E_k=C_k\ [\ln (d_1/d_2)] \quad (1)$$

$$E_R=C_R\ [1/d_2 -1/d_1] \quad (2)$$

$$E_B=C_B\ [1/\sqrt{(d_2)}-1/\sqrt{(d_1)}] \quad (3)$$

Where, E=Energy, kWh/Kg or Ws/Kg or J/Kg
d=diameter of particle,m
subscript 1,2 are initial (feed) and final (product) size while K,R,B and C denotes Kicks,Rittinger,Bonds and constant.

$C_B=W_i \times 0.3162$

W_i=Bond's work index, kWh/t

Usually, the mass (m) of any material especially those with irregular shapes could be measured effectively as against measuring its size. In this regard, the most recent evaluation is the mass-size reduction operation concept. This concept in addition seeks to quantify the minimum comminution energy and power requirements of materials. Hence, may enhance the conservation of any excess energy and power that would have been applied in the reduction operation. It is essential to note that the minimum energy and power requirements equations were developed to accommodate size reduction operations based on the equation given for mass reduction operation (Antia*et al.*, 2014(a)) as:

$$E_{min}=2Bm^{(1/2)} \quad (4)$$

Where m is the mass of material in kg, B is a constant referred to as mass index with the unit in Kg$^{(1/2)}$m^{2}s^{-2} and E is the minimum energy for mass reduction, J.

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By employing empirical and analytical approaches the Equation 4 was incorporated to develop mass-size reduction operation equations (Antia, 2020). These equations seem to be an improvement of the existing major grinding equations and are given as:

$E_{OA}=K_{OA1}\,[1/(D^{1/2}_{vsp})-1/(D^{1/2}_{vsf})]$ (5)

$E_{OA}=K_{OA2})\,[1/(D^{1/2}_{vsp})-1/(D^{1/2}_{vsf})]$ (6)

$E_{OA}=K_{OA3}\,[1/(D^{3/2}_{vsp})-1/(D^{3/2}_{vsf})]$ (7)

EnergyE_{OA} in Equations 5, 6, and 7 could be expressed in terms of kWh/Kg or Ws/Kg or J/Kg

$P_{cp}=K_{OA2}\,\bar{m}\,[1/(D^{1/2}_{vsp})-1/(D^{1/2}_{vsf})]$ (8)

$P_{cp}=K_{OA3}\,\bar{m}\,[1/(D^{3/2}_{vsp})-1/(D^{3/2}_{vsf})]$ (9)

Power in Equations 8 and 9 may be expressed in terms of J/s or kW

Where, E_{OA}=Orua Antia's Energy Equation

K_{OA1}, K_{OA2} and K_{OA3} are Orua Antia's energy equation constants with units as $Jm^{(1/2)}/Kg$, $Jm^{(1/2)}/Kg$ and $Jm^{(3/2)}/Kg$ respectively

P_{cp}=minimum power required for size reduction operation, J/s or kW

$D_{vsp}=D_{pa}\,S_p$ (10)

$D_{vsf}=D_{fa}\,S_p$ (11)

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

D_{vsp} and D_{vsf} are final diameter of the particle (final product) and initial diameter of the particles (initial feed)

S_p=sphericity

D_{pa}=diameter of the product,m

D_{fa}=diameter of the feed,m

The constants in these Equations 5 to 9 take care of variables that may apply to the processing materials involved in the mass-size reduction operation. These constants are expressed as:

$K_{OA1}=(2B\varrho m^{½})/(C_f\,M_f)\,(0.2304)\,S_A$ (12)

$K_{OA2}=(2B\varrho m^{½})/(C_f\,M_f)\,(0.2304)\,(u^2\,t)/\,\bar{m}$ (13)

$KOA3=(2B\varrho m^{(-½)})/(C_f\,M_f)\,(0.2304)$ (14)

Where, ϱ_m= density of the material, Kg/m^3

u=velocity of particle m/s

t = time required for the mass-size reduction process

C_f= Crushing efficiency

M_f = Mechanical efficiency

S_A=specific surface area,m^2/Kg

K_{OA1}, K_{OA2} and K_{OA} depends primarily on the efficiency of the machine, density, and mass index of the material.

It is suggested that the minimum energy and power requirements may be achieved if the combined efficiency (product of crushing and mechanical efficiency) of the operation is at least within the range of 70 to 75% with an approximate average of 73% (Antia, 2021). To apply the OruaAntia's energy equations, the mass index (B-value) of the expressions must be evaluated for various materials. Therefore, this study seeks to generate mass indexes (B-values) for some selected cereals (sorghum, millet, corn, and wheat) to enable easy evaluation of the minimum energy and power requirements for mass-size reduction operation of these materials.

Theory

The energy required to break material may be evaluated by using static impact force equipment (Asoegwu, 1995; Antia*et al.*,2012,2014(b)). This equipment could be used to assess the minimum predetermined height drop (H) of a known hammer mass (M) that will hit and cause the material to break following the impact. This minimum impact energy may be evaluated as:

$E_{min}=Mgh$ (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.

The mass index can therefore be evaluated in any of the following approaches:

a) Use of Equations 4 and 15 as:

$E_{min}=Mgh=2Bm^{(1/2)}$ (16)

$B=Mgh/2m^{(1/2)}=1/2\,[Mgh/\sqrt{m}]$ (17)

Where, g=acceleration due to gravity

B = mass index

b)Use of Equation 4 as:

$\ln_{Emin}=\ln 2B+1/2\ln m$ (18a)

$\log_{Emin}=\log 2B+1/2\log m$ (18b)

The slope of the plot of $\ln_{Emin}$ against ln m or $\log_{Emin}$ against log m should be 1/2 and the corresponding intercept will be obtained as ln2B or log2B.

Hence,

ln 2B or log 2B=intercept

$B=1/2\,[e^{intercept}]$ or $B=1/2\,[10^{intercept}]$

MATERIALS AND METHODS

Material Sourcing and Pre-Treatment

Cereals such as sorghum, millet, corn, and wheat were purchased from the local market in Uyo, Akwa Ibom state, Nigeria. Each type of cereal was cleaned to remove any dirt on it. The moisture content of each type of cereal was determined in air dried oven at 105℃; with the final drying time to achieve bone dry mass (ie when constant mass was achieved) noted. This was carried out using ten (10) samples per cereal type. The experiment was carried out in triplicate. The moisture content (MC_{wb}) per unit of each cereal type was obtained (Antia *et al.*, 2014 (a and b)) as:

$MC_{(wb)}$=(initial weight-final weight)/(initial weight) ×100 19

Experimental Procedure

Samples of each type of the selected cereal cleaned were randomly picked to obtain a total of fifty samples per cereal type. For each cereal type, the fifty (50) samples were individually weighed, labelled, and then placed in air dried oven at 105℃. The moisture content of these samples was determined at time intervals that spread from initial time t=0 to final time where constant mass was achieved (bone dry mass). At each time interval, ten (10) samples of each cereal type were removed and cooled in a dessicator. Thereafter, individually weighed, and moisture content was determined using Equation 19. The mass index was in addition evaluated per set of ten samples per moisture content per cereal type at each drying time interval using Equation 18(a) or 18(b) (graphical method) to compare the value obtained from Equation 17 (analytical method). Relative error (RE) between the mass index values (B-values) obtained from Equations 17 and 18b was evaluated (Wikipedia, 2023; Collegedunia, 2023) as:

RE=(Mass index from formular-mass index from graph)/(mass index from graph) 21

RESULTS

The values of E_{min} and mass index of the selected cereals were obtained per moisture content based on Equations 15, 16 and 17. These values are presented in Table 1.

Table 1: Average experimental values of E_min and mass index per moisture content per cereal type

	Moisture content	Mass (Kg)	E_{min} (J)	B-value ($Kg^{(1/2)}$ m^2s^{-2})
Corn	8.61	0.000285	0.700500	20.5717
	6.42	0.000284	0.701300	20.7620
	3.60	0.000282	0.708700	21.0170
	2.90	0.000274	0.701200	21.0848
	2.41	0.000268	0.700400	21.3585
Wheat	3.61	0.000055	0.400796	28.1624
	2.89	0.000055	0.402927	28.3185
	2.35	0.000055	0.400722	27.2690
	1.99	0.000054	0.397929	27.2126
	1.81	0.000054	0.400722	27.5277
Sorghum	11.94	0.000037	0.272784	22.3925
	10.60	0.000035	0.321485	27.1704
	9.51	0.000034	0.309714	26.7552
	8.10	0.000031	0.283828	25.3661
	6.94	0.000030	0.269098	24.5652
Millet	11.90	0.000016	0.204412	25.6237
	11.35	0.000015	0.204412	26.2672
	10.07	0.000014	0.205876	27.1265
	7.63	0.000013	0.150945	20.7653

The plot is based on Equation 18(b) with the slope being 1⁄2 (0.5)corresponding to mass index (B-value) as intercept was also carried out using samples per cereal type per moisture content per drying time. The plot of the logE_minagainst logm for the selected cereals are shown in Figures 1 to 19

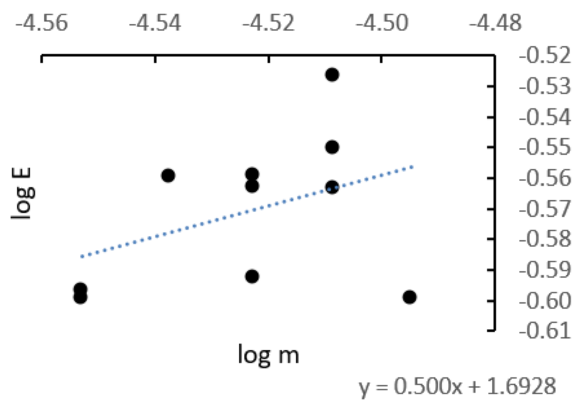

Figure 1: Graph of log E_{min} against log m for sorghum at 6.94%wb

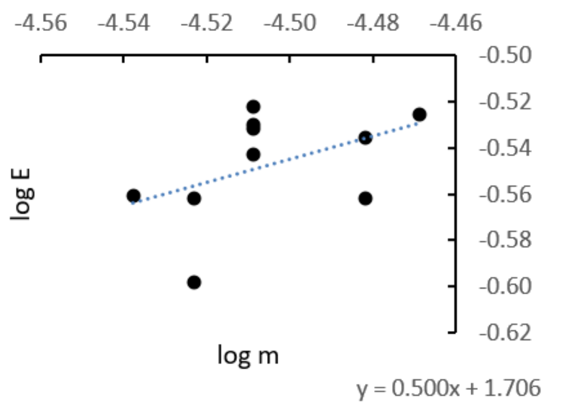

Figure 2: Graph of log E_{min} against log m for sorghum at 8.10%wb

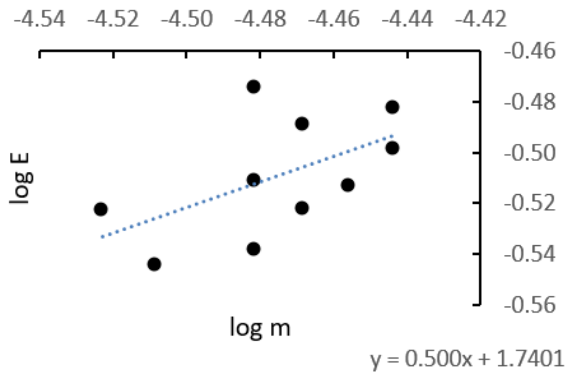

Figure 3: Graph of log E_{min} against log m for sorghum at 9.51%wb

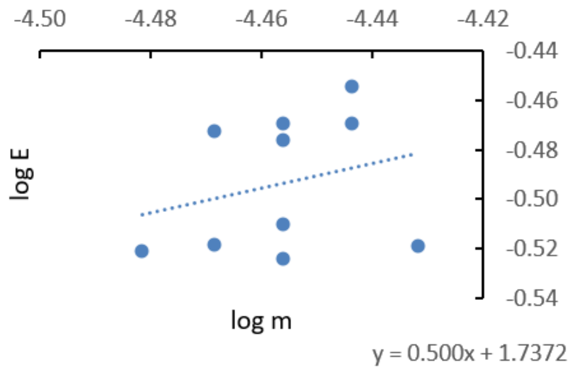

Figure 4: Graph of log E_{min} against log m for sorghum at 10.6%wb

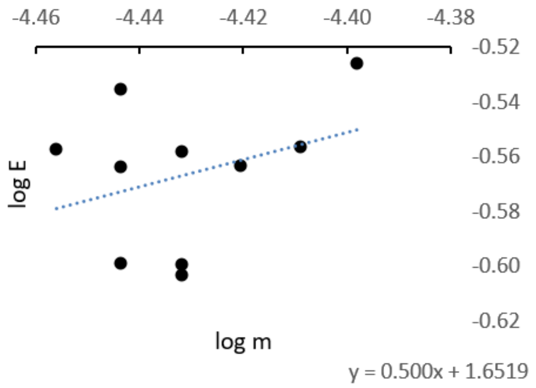

Figure 5: Graph of log E_{min} against log m for sorghum at 11.94%wb

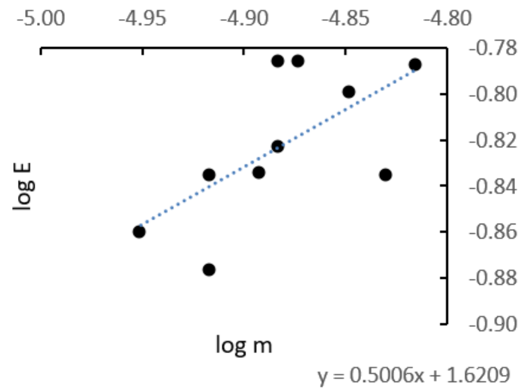

Figure 6: Graph of log E_{min} against log m for Millet at 7.63%wb

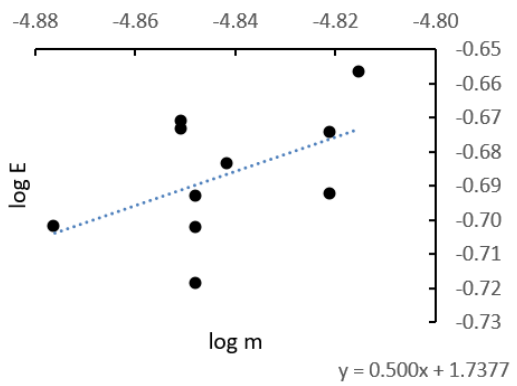

Figure 7: Graph of log E_{min} against log m for sorghum at 10.07%wb

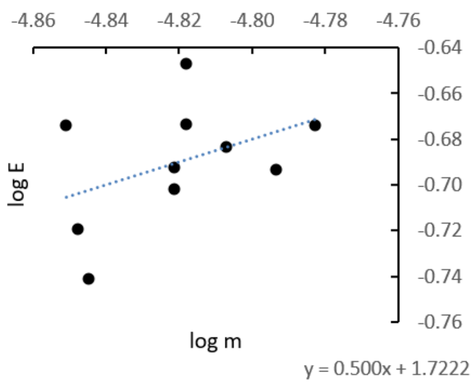

Figure 8: Graph plot of log E_{min} against log m for Millet at 11.35%wb

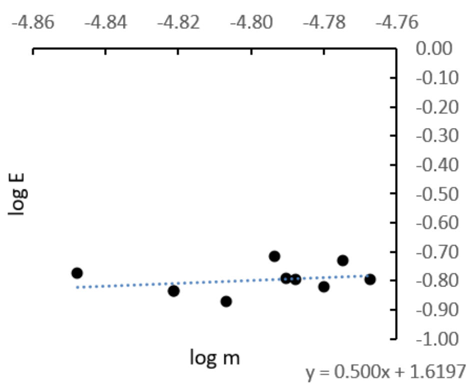

Figure 9: Graph of log E_{min} against log m for Millet at 11.9%wb

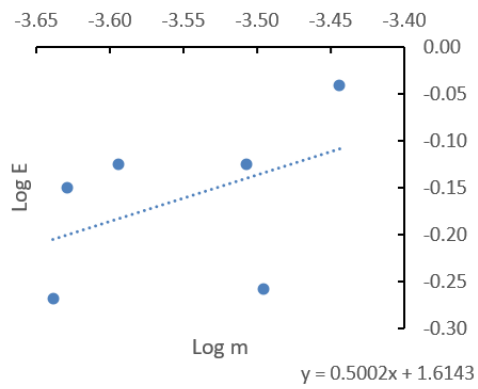

Figure 10: Graph of log E_{min} against log m for Corn at 2.41%wb

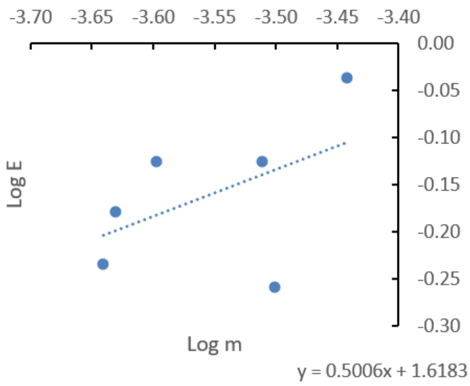

Figure 11: Graph of log E_{min} against log m for Corn at 2.9%wb

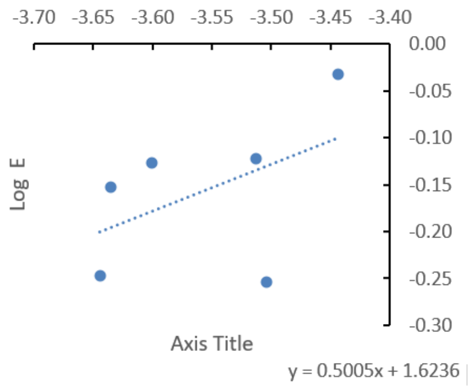

Figure 12: Graph of log E_{min} against log m for Corn at 3.60%wb

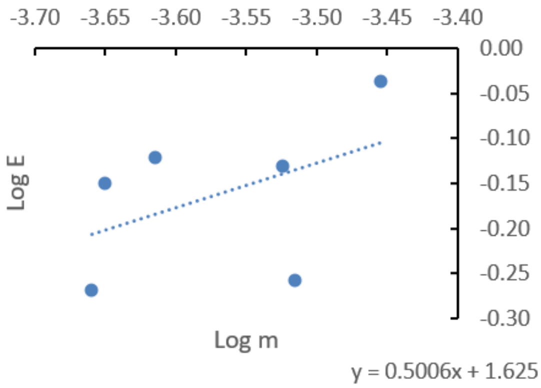

Figure 13: Graph of log E_{min} against log m for Corn at 6.42%wb

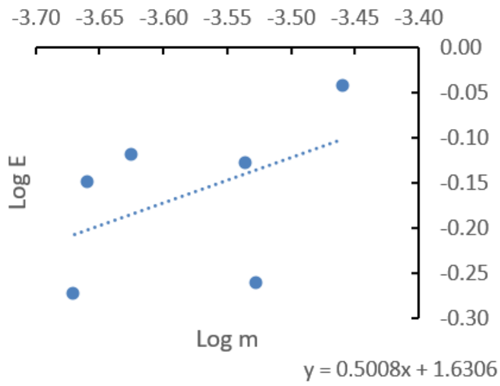

Figure 14: Graph of log E_{min} against log m forCorn at 8.61%wb

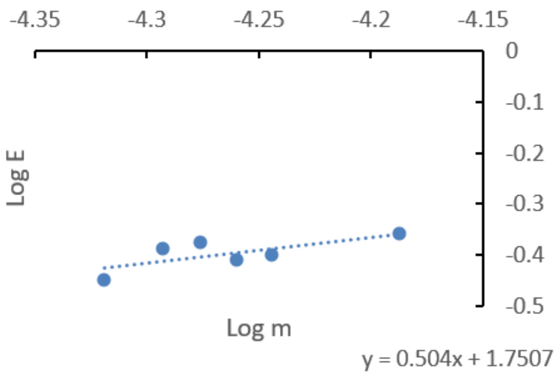

Figure 15: Graph of log E_{min} against log m for Wheatat 1.81%wb

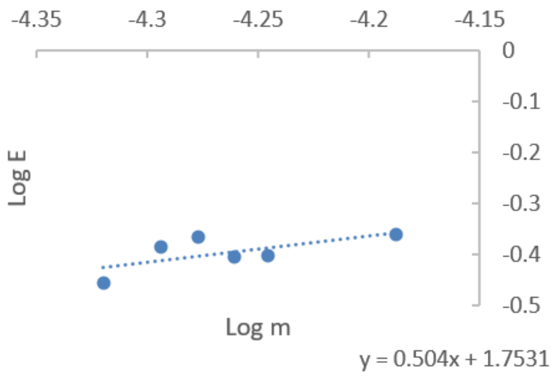

Figure 16: Graph of log E_{min} against log m for Wheatat 1.99%wb

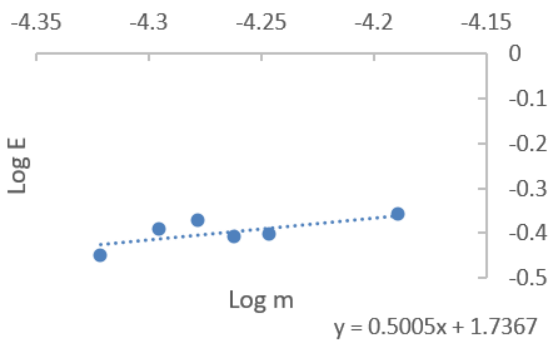

Figure 17: Graph of log E_{min} against log m for Wheatat 2.35%wb

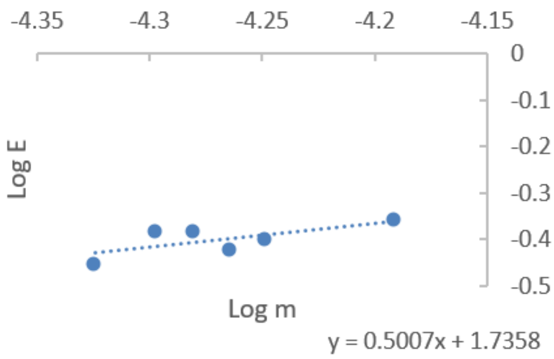

Figure 18: Graph of log E_{min} against log m for Wheatat 2.89%w

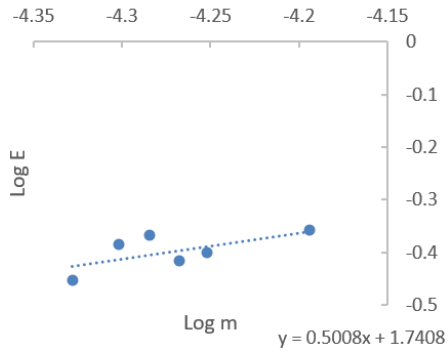

Figure 19: Graph of log E_{min} against log m Wheatat 3.61%wb

The mass indexes were obtained from these plots as intercepts. The relative errors between the mass indexes from Equations 17 (analytical method) and 18(b) (graphical method) were evaluated using Equation 21. These values are presented in Table 2. From Table 2, it was observed that the relative error of both values was low, thus any of the two methods could be used to find the B-value of samples. The effect of moisture content on mass indexes per cereal type

Table 2: Relative error of mass index obtained using Equation 17 (formula) and 18(b) (graphical method)

	Moisture content (%wb)	Mass index (B value) from graph($Kg^{(1/2)}$ m^2s^{-2})	Mass index (B value) from formula($Kg^{(1/2)}$ m^2s^{-2})	Relative error
Corn	8.61	20.5717	20.7396	0.00816
	6.42	20.7620	20.8145	0.00252
	3.60	21.0170	21.1071	0.00428
	2.90	21.0848	21.1867	0.00483
	2.41	21.3585	21.4113	0.00247
Wheat	3.61	28.1624	27.0627	-0.03905
	2.89	28.3185	27.2314	-0.03839
	2.35	27.2691	27.1320	-0.00503
	1.99	27.2126	27.0173	-0.00718
	1.81	27.5277	27.3079	-0.00799
Sorghum	11.94	22.4321	22.3925	-0.00177
	10.60	27.3005	27.1704	-0.00476
	9.51	27.4834	26.7552	-0.02649
	8.10	25.4080	25.3661	-0.00165
	6.94	24.6473	24.5652	-0.00333
Millet	11.90	20.8291	25.6237	0.23018
	11.35	26.3736	26.2672	-0.00404
	10.07	28.2794	27.1265	-0.04077
	7.63	20.8867	20.7653	-0.00582

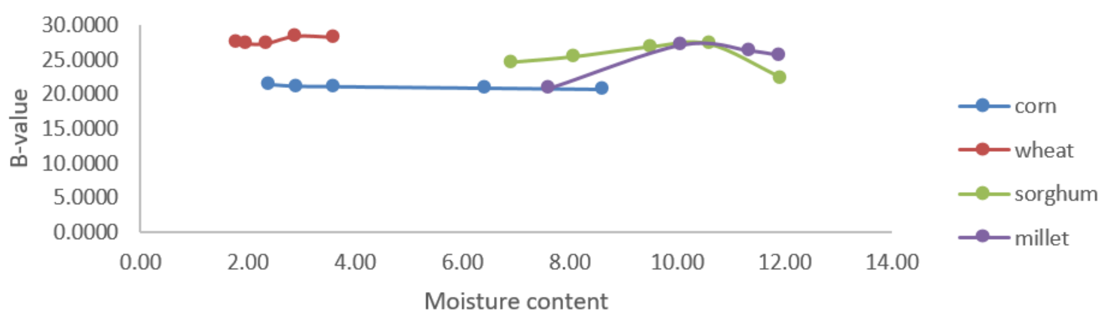

Figure 20: Graph of B-value against moisture content per cereal type

was examined as shown in Figure 20.
From this plot, it was observed that the B-value (mass index) increased to a certain level and decreased at a point. This could be due to the nature of the food

sample, the hardness after drying of the food sample, and the porosity or air space in the sample after drying. However, since the mass index value obtain per cereal type are close to the moisture content range per cereal type; it may be considered that an average value of the mass index is used in evaluating the Orua Antia's energy equation constants. The average values of the mass index of each cereal type were computed within its moisture content range and are presented in Table 3

Table 3: Average mass index of selected cereal type within its moisture content range

Cereal type	Moisture Content range (%wb)	Average Mass index (B value)($Kg^{(1/2)}\ m^2s^{-2}$)
Corn	8.61-2.41	20.9915±0.4198
Wheat	3.61 -1.81	27.6679±0.6506
Sorghum	11.94-6.94	24.9379±2.5454
Millet	11.90-7.63	24.5223±3.7571

CONCLUSION

The mass index (B-values) of cereals evaluated using Equations 17 and 18b were slightly affected by their moisture content. The average mass index value obtained within each cereal type and moisture content (%wb) range may be used to predict from Equations 5 to 9 via Equations 12 to 14, the minimum energy and power required to cause the expected reduction in the size of the material.

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