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Modeling Flow rate of Egusi-Melon (*Colocynthis citrullus*) through Circular Horizontal Hopper Orifice

S.N. Asoegwu[1*], L.A.S. Agbetoye[2] and A.S. Ogunlowo[2]
[1.] Agricultural Engineering Department, Federal University of Technology, PMB 1526, Owerri, Nigeria.
[2.] Agricultural Engineering Department, Federal University of Technology, Akure, Nigeria
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Abstract

Information on the flow rate of grains through various sizes and shapes of orifices is needed to properly size the opening for flow control during transfer of grains and seeds. Prediction equations were developed describing the flow rate of egusi-melon seeds using mathematical models based on the crop and hopper parameters. Dimensional analysis was used to obtain the functional relationships between the flow rate of egusi-melon and the independent variables such as seed particle size, acceleration due to gravity, orifice diameters (equivalent and hydraulic), orifice area, etc. The developed flow rate models were verified and the power and polynomial regression equations had the highest coefficients of determination, while the power and exponential regression equations gave the least variation from the actual flow rate of less than 30% for $Q_1 = 0.75A_e g^{0.5} D_e^{0.5}$ and less than 3% for $Q_2 = 0.2277(D_e^2/A_e)^{2.9902}(D_e^{2½}g^{½})$. The model equation $Q_{actual} = 0.0008D_h^{2.6589}$ (R^2 0.988) is appropriate for the flow rate of egusi-melon through horizontal hopper orifice.

Keywords: Modeling, egusi-melon (*Colocynthis citrullus*), flow rate, dimensional analysis, hopper orifice, orifice diameter.

1.0 Introduction

For the proper sizing of bin, hopper, or other grain handling opening, information on the flow rate is necessary in order to control grain flow to and from storage and holding bins (Chang *et al*., 1984). Flow of some other granular materials, not yet egusi-melon, from orifices in flat bottomed bins has been investigated by a number of researchers (Mankoc *et al*., 2007; Kusiñska, 2005; Morsey *et al*., 1988; Gregory and Fedler, 1987; Beverloo *et al*., 1961). Granular flow occurs in industries and used in food processing, silos, plastic pipe manufacturing and in pharmaceutical plants.

Ketchum (1919) and Stahl (1950) suggested that granular flow rate varies with the cube of the orifice diameter. However, Beverloo *et al*. (1961) and Morsey *et al.* (1988) correlated flow rate with orifice diameter raised to the power of 2.5, while Franklin and Johanson (1955), Fowler and Glastonburg (1959) and Chang *et al*. (1984) found that the power exponent on the orifice diameter varied between 2.5 and 2.84.

Because of the range of values for the exponent and that most researchers agree that the relationship between flow rate and orifice size is a power function, the American Society of Agricultural and Biological Engineers developed a standard (ASAE D274.1 FEB03) that gives equations and graphs that can be used to estimate the flow rate of specific grains and oilseeds through horizontal and vertical orifices. Equation 1 gives the ASAE Standard Equation:

$$Q = C_o A D^n \qquad ...1$$

where Q = volume flow rate (m^3/h); A = area of the orifice (cm^2); D = hydraulic diameter of the orifice (cm); C_o = coefficient (varying according to grain and its moisture content); n = exponent with a value between 0.5 and 1.0.

However, Ewalt and Buelow (1963) reported that the flow rate can be estimated from the following equations 2 and 3:

$$Q = \alpha D^{\beta} \qquad ...2$$

$$Q = \lambda L^{k_1} W^{k_2} \qquad ...3$$

[*]Corresponding Author's Email: asosab49@yahoo.com

where Q = volume flow rate (m^3/h); D = diameter of orifice (m); L = length of orifice (m); W = width of orifice (m); $\alpha, \beta, \lambda, k_1$ and k_2 are constants.

Also Beverloo *et al.* (1961) working with flaxseed and rapeseed proposed a general equation (equation 4) for calculating the flow rate through various orifices. This equation is known as Beverloo Law.

$$Q = 0.75 A_e g^{0.5} D_e^{\,0.5} \qquad ...4$$

where Q = volume flow rate (m^3/s); g = gravitational acceleration (m/s^2); $D_e = D_h - kd$ = effective hydraulic diameter (m); D_h = hydraulic diameter (m); d = average particle size (m); A_e = effective orifice area calculated from D_e (m^2); $k = 1.3 - 1.5$, with average $k = 1.4$.

Recently, Mankoc *et al.* (2007) used experimental and numerical simulation to develop and propose a new law that correctly reproduces data for all orifice sizes, both large and small. Their law modified the Beverloo Law with a correction factor that is dependent on R = ratio of orifice diameter to particle diameter (D/d) and with k = 1.

The objective of this work is to develop some predictive equations for the flow rate of egusi-melon using dimensional analysis and then verify them with experimental and simulated data.

2.0 Theoretical Development

2.1 Flow rate approach

The physical properties affecting the flow rate of grains and seeds in a hopper obtained from literature (Ling and Wilhoit, 1999; Chang and Steele, 1996) include crop parameters (particle size, moisture content, angle of repose, bulk density, etc.) and hopper parameters (orifice size and shape, hopper side wall slope angle, coefficient of friction, etc.).

2.2 Assumptions made in model development

Because of the large number of variables that may affect the flow rate of egusi-melon seeds through hoppers, there is the need to make simplifying assumptions reducing the number involved to manageable level (Simonyan *et al.*, 2006).

- **i.** Rheological behavior of rapidly flowing grain material is ignored
- **ii.** Wedge-shaped geometry of the hopper is constant with vertical bin added on the top orifice diameter
- **iii.** Side wall slope is to the horizontal and changes as the angle of repose changes
- **iv.** Bulk flow pattern (not particle flow) is assumed to be fairly uniform and regular
- **v.** Only physical and flow (frictional) as well as hopper properties affect flow and time plays no part
- **vi.** Moisture content is implicated in most physical and flow properties and is not used in the model
- **vii.** Humidity, wall roughness, and the electric charge between particles within the flow are difficult to measure and will be neglected, even though they may affect flow rate.
- **viii.** Acceleration due to gravity is assumed constant throughout the study.

With the above simplifying assumptions, the numbers of variables to be considered are: D_e = effective diameter of the orifice (m); D_h = hydraulic diameter of the orifice (m); H = head of packing above the orifice (m); A_e = effective orifice area calculated from D_e (m^2); g = gravitational acceleration (m/s^2); d = equivalent diameter of grain (m); á = coefficient of mobility (decimal); Q = volume flow rate (m^3/h). This gives the mathematical expression in equation 5 for which dimensional analysis will be used to further reduce the number of variables in the problem, resulting in a single equation which relates all of the dimensionless physical factors involved to one another.

$$Q = f(D_e, D_h, H, A_e, d, g, \alpha) \qquad ...5$$

Using Buckingham Ï theorem (Fox and McDonald, 1992), the following dimensionless groups were determined using the following procedure:

Number of involved parameters: n = 8

Set of primary dimensions = M, L, T = 3

Table 1: List of dimensions of all the parameters in terms of the primary dimensions.

Q	D_e	D_h	H	A_e	g	d	α
L^3T^{-1}	L	L	L	L^2	LT^{-2}	L	-

Repeating parameters = D_e, g.
Number of dimensionless groups = 8 – 3 = 5
Setting up the dimensionless Π equations,

$$\Pi_1 = QD_e^{\,a} g^b = (MT^{-1})(L)^a (LT^{-2})^b = M^0L^0T^0 \quad ...6$$

Equating the exponents of *M*, *L* and *T* gives:

$$\Pi_1 = QD_e^{\,a} g^b = (L)^a (LT^{-2})^b (L^3 / T) = M^0L^0T^0 \quad ...7$$

M: 0 = 0
T: -2b – 1 = 0; b = -½
L: a + b + 3 = 0; a = -3-b = -2½

Therefore,

$$\Pi_1 = Q \Big/ D_e^{2\frac{1}{2}} g^{\frac{1}{2}} \quad ...8$$

Similarly, other trivial dimensionless groups include:

$$\Pi_2 = H/d;\ \Pi_3 = D_e^{\,2}/A_e;\ \Pi_4 = D_h/D_e;\ \Pi_5 = D_e/d \quad ...9$$

Thus, the functional relationship is:

$$\Pi_1 = f(\Pi_2; \Pi_3; \Pi_4; \Pi_5) \quad ...10$$

$$Q \Big/ D_e^{2\frac{1}{2}} g^{\frac{1}{2}} = f[H/d, D_e^{\,2}/A_e, D_h/D_e, D_e/d] \quad ...11$$

Equation 11 states that volumetric flow rate is a function of four dimensionless quantities for which Π_2 would be neglected because the head level range used with hoppers is not very large, and makes insignificant statistical influence on the volumetric flow rate. Thus, the following equations are proposed for the modeling:

$$Q_2 = \alpha(D_e^{2\frac{1}{2}} g^{\frac{1}{2}})^{n2}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...12$$

$$Q_3 = \alpha(D_h/D_e)^{n3}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...13$$

$$Q_4 = \alpha(D_e/d)^{n4}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...14$$

$$Q_5 = \alpha(D_e^{\,2}/A_e)^{n2}(D_h/D_e)^{n3}(D_e/d)^{n4}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...15$$

Solving Equations 12 to 15 simultaneously gave the following:

$$Log\ \alpha = \frac{1}{2}(\log Q_2 + \log Q_3 + \log Q_4 - \log Q_5) \quad ...16$$

$$n_2 = \frac{\frac{1}{2}(\log Q_2 - \log Q_3 - \log Q_4 + \log Q_5)}{\log D_e^{\,2} \big/ A_e} \quad ...17$$

$$n_3 = \frac{\frac{1}{2}(-\log Q_2 + \log Q_3 - \log Q_4 + \log Q_5)}{\log D_h \big/ D_e} \quad ...18$$

$$n_4 = \frac{\frac{1}{2}(-\log Q_2 + \log Q_3 - \log Q_4 + \log Q_5)}{\log D_e \big/ d} \quad ...19$$

Substituting simulated values of Qs in Equations 16 – 19, gave the following values α = 0.2277; n_2 = 2.9902; n_3 = 5.5517; n_4 = 0.3401. With the above, the model equations for the flow rate are given as:

$$Q_2 = 0.2277(D_e^{\,2}/A_e)^{2.9902}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...20$$

$$Q_3 = 0.2277(D_h/D_e)^{5.5571}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...21$$

$$Q_4 = 0.2277(D_e/d)^{0.3401}(D_e^{2\frac{1}{2}} g^{\frac{1}{2}}) \quad ...22$$

Q_5 (in equation 15) was considered superfluous and was not included as a model equation for flow rate. However, Beverloo *et al*. (1961)'s equation, equation 4 was included as a control as Q_1 in equation 23.

$$Q_1 = 0.75A_e g^{0.5} D_e^{\,0.5} \quad ...23$$

3.0 Materials And Methods

3.1 Hopper construction

Five circular hoppers of orifice diameters 10.50, 12.00, 15.00, 18.00 and 21.00 cm and total height of 20cm (15cm for hopper funnel and 5cm for bin) were constructed using mild steel of 1.5mm gauge with the hopper side wall slope angle equal to 55° to the horizontal. A sliding gate was fabricated to cover the hopper orifice while the test lot of egusi-melon seeds was transferred to the holding bin. A stand was also constructed to hold the hopper during tests.

3.2 Crop material

Thirty kg of unshelled egusi-melon seeds (Oyo type) were bought from the Eke Onunwa Market at Owerri and were thoroughly cleaned of all impurities and unwholesome seeds.

3.3 Sample preparation

A sample was taken and the moisture content determined gravimetrically at 103°C till constant weight (Henderson *et al*., 1997). This was replicated five times and the average taken. Bulk density was determined by simply pouring the seed into a 1000ml glass cylinder from a height of 10cm, weighing the contained quantity with an electronic mettle balance (Sarturious 2355; up to 0.001g) and dividing the weight by the volume (Mohsenin, 1986). This was replicated five times and the average bulk density determined. Also, 100 seeds were selected randomly and their triaxial diameters measured using a micrometer screw gauge (Sheffied S 139 Br; up to 0.01mm) to help determine the seed equivalent diameter, using the equation given by Mohsenin (1986). The bulk egusi-melon seeds were divided into five lots for each hopper, put in high density polyethylene bags, tied and stored in a refrigerator at 5°C before the tests.

3.4 Procedure for the tests

Before each test, the bag of egusi-melon seeds was brought out from the refrigerator; the seeds were spread on a cardboard sheet and allowed to equilibrate to room temperature for 24h. The holding bin (hopper) was mounted on the stand with the sliding gate in place closing the hopper orifice. The bin was filled by pouring in the seeds from a height of 10cm. A test starts when the sliding gate is slid open to permit grain flow from the hopper through the orifice to the receiving bin. A stop watch (Precista max 60; up to 0.01sec) was used to measure the time taken for the hopper to empty. The egusi-melon seeds in the receiving bin were weighed with the electronic balance to determine the weight. This weight was divided by the bulk density of egusi-melon to obtain the volume of egusi-melon seeds that flowed through the orifice. Dividing this volume by the time taken to empty the hopper gives the volume flow rate. Each tests for each hopper was replicated five times and the averages taken.

3.5 Modeling procedure

The equivalent diameter of the orifice was determined from the hydraulic diameter using equation 24.

$$D_e = D_h - 1.4d \qquad ...24$$

where D_e = equivalent orifice diameter (cm); D_h = orifice hydraulic diameter (cm); d = seed equivalent diameter (cm). Note that A_e = equivalent orifice area is calculated from $\pi D_e^{\,2} / 4 \ (cm^2)$. The various values of D_e were used in equations 20 to 23, to determine Q_1 to Q_4. Also, model software was developed using equations 4, 12, 13 and 14. Random numbers within the range of the orifice diameters and particle sizes under study were used to evaluate the values of Q_1 to Q_4 from the model software.

3.6 Data analysis

The method of regression analysis as computed using Microsoft Excel environment was used to describe the relationships, plot the graphs and compute the coefficients of determination (R^2). R^2 is a statistic that gives some information about the goodness of fit of a model. In regression, the R^2 is a statistical measure of how well the regression line approximates the real data points. An R^2 of 1.0 indicates that the regression line perfectly fits the data.

4.0 Results And Discussion

4.1 General data

The moisture content of the bulk equsi-melon seeds before the tests were done was 10.93 ± 0.51% w.b. The other determined parameters are given in Table 1. The average values of the results of the tests are given in Table 2, showing the quantities of the seeds in each hopper, the volume of the seeds, the time taken to discharge the seeds from each hopper and the calculated flow rate. Table 3, shows the values of the data generated from the models and the actual flow rate from the tests. These were statistically evaluated to get the different regression relationships in order to identify the ones that aptly relate closely to the actual flow rate of egusi-melon seeds through

Table 1: Some physical properties of egusi-melon seeds at 10.93 ± 0.51% moisture content (w.b.)

Physical properties	Symbol	Maximum Value	Minimum Value	Mean Value	Standard Deviation
Major diameter, mm	A	17.50	13.00	14.84	± 2.25
Intermediate diameter, mm	B	11.00	7.20	9.01	± 1.90
Minor diameter, mm	C	2.00	1.10	1.56	± 0.05
Equivalent diameter, mm	D_e	8.60	6.53	7.25	± 0.52
Bulk density, t/m^3	P	0.444	0.409	0.426	± 0.38

Table 2: Average values of the data from the tests for each hopper orifice

Orifice Diameter (cm)	Weight of test lot (kg)	Volume of test lot (m^3)	Time taken to discharge each lot (sec)	Flow rate of each lot (m^3/h)
10.5	3.85	9.04×10^{-03}	79.0	0.412
12.0	4.16	9.76×10^{-03}	58.5	0.601
15.0	4.38	0.0103	41.5	0.893
18.0	4.53	0.0106	22.2	1.720
21.0	4.81	0.0113	15.3	2.660

Table 3: Data for flow rate of egusi-melon from the model equations and the test

D_h (cm)	10.5000	12.0000	15.0000	18.0000	21.0000
D_e (cm)	9.4850	10.9850	13.9850	16.9850	19.9850
A_e (cm^2)	70.6585	94.7742	153.6083	226.5797	313.6882
Q_1 (m^3/h)	0.5112	0.7379	1.3494	2.1936	3.2942
Q_2 (m^3/h)	0.4069	0.5874	1.0741	1.7461	2.6222
Q_3 (m^3/h)	0.3477	0.4661	0.7699	1.1707	1.6769
Q_4 (m^3/h)	0.4738	0.7189	1.4272	2.4786	3.9339
Q_{actual} (m^3/h)	0.4120	0.6010	0.8930	1.7200	2.6600

horizontal circular orifices. It was observed that the logarithmic and linear regressions had lower coefficients of determination (R^2) than the exponential, power and polynomial regressions. The regression equations are given in Table 4, for orifice hydraulic diameter, Table 5, for orifice equivalent diameter, and Table 6, for orifice equivalent area.

Table 4: The regression equations for the flow rate of egusi-melon through horizontal hopper orifice for orifice hydraulic diameter

	For D_h		
	Exponential	Power	Polynomial
Q_1	$0.086e^{0.176x}$ ($R^2 = 0.989$)	$0.0009x^{2.6878}$ ($R^2 = 1$)	$0.013x^2 - 0.153x + 0.665$ ($R^2 = 1$)
Q_2	$0.069e^{0.176x}$ ($R^2 = 0.989$)	$0.0007x^{2.6878}$ ($R^2 = 1$)	$0.010x^2 - 0.122x + 0.529$ ($R^2 = 1$)
Q_3	$0.076e^{0.149x}$ ($R^2 = 0.992$)	$0.0017x^{2.2702}$ ($R^2 = 0.999$)	$0.005x^2 - 0.047x + 0.237$ ($R^2 = 1$)
Q_4	$0.063e^{0.200x}$ ($R^2 = 0.989$)	$0.0004x^{3.0534}$ ($R^2 = 1$)	$0.02x^2 - 0.301x + 1.444$ ($R^2 = 0.999$)
Q_{actual}	$0.067e^{0.176x}$ ($R^2 = 0.993$)	$0.0008x^{2.6589}$ (R^2 0.988)	$0.016x^2 - 0.292x + 1.739$ ($R^2 = 0.996$)

Table 5: The regression equations for the flow rate of egusi-melon through horizontal hopper orifice for orifice equivalent diameter

	For D_e		
	Exponential	Power	Polynomial
Q_1	$0.103e^{0.176x}$ ($R^2 = 0.989$)	$0.0018x^{2.5}$ ($R^2 = 1$)	$0.013x^2 - 0.126x + 0.523$ ($R^2 = 1$)
Q_2	$0.082e^{0.176x}$ ($R^2 = 0.989$)	$0.0015x^{2.5}$ ($R^2 = 1$)	$0.010x^2 - 0.100x + 0.416$ ($R^2 = 1$)
Q_3	$0.089e^{0.149x}$ ($R^2 = 0.989$)	$0.0030x^{2.1113}$($R^2 = 0.999$)	$0.005x^2 - 0.036x + 0.195$ ($R^2 = 1$)
Q_4	$0.077e^{0.200x}$ ($R^2 = 0.989$)	$0.0008x^{2.8401}$ ($R^2 = 1$)	$0.02x^2 - 0.260x + 1.159$ ($R^2 = 0.999$)
Q_{actual}	$0.080e^{0.176x}$ ($R^2 = 0.993$)	$0.0015x^{2.4717}$ (R^2 0.986)	$0.016x^2 - 0.259x + 1.459$ ($R^2 = 0.996$)

Table 6: The regression equations for the flow rate of egusi-melon through horizontal orifice for equivalent orifice area

	For A_e		
	Linear	Power	Polynomial
Q_1	$0.011x - 0.351$ ($R^2 = 0.997$)	$0.002x^{1.25}$ ($R^2 = 1$)	$8E{-}06x^2 + 0.008x - 0.127$ ($R^2 = 1$)
Q_2	$0.009x - 0.279$ ($R^2 = 0.997$)	$0.002x^{1.25}$ ($R^2 = 1$)	$6E{-}06x^2 + 0.006x - 0.101$ ($R^2 = 1$)
Q_3	$0.005x - 0.053$ ($R^2 = 0.999$)	$0.003x^{1.055}$ ($R^2 = 0.999$)	$2E{-}06x^2 + 0.004x + 0.010$ ($R^2 = 1$)
Q_4	$0.014x - 0.640$ ($R^2 = 0.993$)	$0.001x^{1.42}$ ($R^2 = 1$)	$2E{-}05x^2 + 0.008x - 0.177$ ($R^2 = 1$)
Q_{actual}	$0.009x - 0.334$ ($R^2 = 0.982$)	$0.002x^{1.235}$ (R^2 0.986)	$2E{-}05x^2 + 0.003x + 0.112$ ($R^2 = 0.995$)

Table 7: The regression equations for the flow rate of egusi-melon through horizontal hopper orifice for particle size of seed

	For d		
	Linear	Exponential	Polynomial
Q_1	$-0.0043x + 0.6078$ ($R^2 = 0.924$)	$0.6081e^{-0.007x}$ ($R^2 = 0.924$)	$0.4618x^2 + 0.0399x - 0.0033$ ($R^2 =0.975$)
Q_2	$-0.0023x + 0.0.4766$ ($R^2 = 0.970$)	$0.4768e^{-0.005x}$ ($R^2 = 0.969$)	$0.4387x^2 + 0.0092x - 0.0009$ ($R^2 = 0.987$)
Q_3	$0.000x + 0.238$ ($R^2 = 0.069$)	$0.238e^{0.002x}$ ($R^2 = 0.070$)	$0.2321x^2 + 0.2255x - 0.0280$ ($R^2 = 0.512$)
Q_4	$-0.0604x + 1.4743$ ($R^2 = 0.995$)	$1.5586e^{-0.056x}$ ($R^2 = 0.993$)	$0.9889x^2 + 0.0873x - 0.0112$ ($R^2 = 0.999$)

4.2 Effect of Orifice Hydraulic Diameter

In Table 4, the power and the polynomial regressions had the same coefficients of determination higher than for the exponential except for the Q_{actual}. Also, the exponents of D_h in the power equations lie between 2.5 and 2.8 as found in literature (Beverloo *et al*., 1961; Morsey *et al*., 1988; Franklin and Johanson, 1955; Fowler and Glastonburg, 1959; and Chang *et al*., 1984) except for Q_3 and Q_4 which seem to under and over estimate flow rate respectively. Again, it is observed that the exponents for Q_1 and Q_2 are the same and very close to that of Q_{actual}. For the polynomial, the coefficients of D_h^2 for Q_1, Q_2 and Q_{actual} are again similar, showing that Q_1 and Q_2 closely estimates the actual flow rate of egusi-melon seeds through horizontal hopper orifice. For the exponential regression equations, the exponentials for Q_1, Q_2 and Q_{actual} are the same, showing close correlation. The regression equations for Q_1 and Q_2 (whether exponential, polynomial or power) may then be said to correlate closely with Q_{actual}. The exponent on D_h in Q_4 is very close to 3.0 as suggested by Ketchum (1919), Leva (1952), Elwalt and Buelow (1963) and Gregory and Fedler (1987).

4.3 Effect of Orifice Equivalent Diameter

As in Table 4, the power, exponential and polynomial regression equations fitted the flow rate of egusi-melon through horizontal orifice (Table 5). The indices of all the exponential regression equations were the same for D_e and for D_h. However, the exponents of the power equations were lower than for D_h ranging from 2.111 to 2.84. The exponents for Q_1 and Q_2 are 2.5 as found in literature (Chang *et al*., 1984; Kotchanova, 1970). That of Q_{actual} = 2.471, which is close to 2.5, even though Chang and Converse (1988) got the exponents for wheat and sorghum to range from 2.461 to 2.693. However, the power exponent of 2.840 for Q_4 is still within the range found in literature (Chang *et al*., 1984; Brown and Richards, 1960). Also, since the coefficients of Q_2 and Q_{actual} are equal, it may be said that Q_2 could correlate Q_{actual} very closely. As with the exponential, the coefficients of D_e and D_h are equal (0.176) for Q_1, Q_2 and Q_{actual} (Tables 4 & 5), showing that for D_e, the three flow rate equations are close.

4.4 Effect of Equivalent Orifice Area

For A_e (Table 6), the linear regression equation replaced the exponential one because it had a higher coefficient of determination (R^2). The gradients of Q_1, Q_2 and Q_{actual} are again similar, showing the closeness of the three flow rate equations. Their exponents for the power equations are again similar, ranging between 1.235 and 1.25. However, their coefficients in the polynomial equations are not close, showing that for A_e, the actual flow rate equation for egusi-melon may be said to be close only to Q_4, with Q_1, Q_2 and Q_3 under estimating the actual flow rate.

4.5 Effect of Seed Particle Size

The effect of particle size on the flow rate of egusi-melon seeds through horizontal circular hopper orifice is shown in Table 7. The Table shows only the simulated values of flow rate as no tests were done with varying particle size of egusi-melon seeds. From the statistical analysis done on the generated data, the flow rate equation Q_3 had no relationship with particle size of egusi-melon since R^2 for all the regression equations ranged from 0.060 for power and logarithmic to 0.512 for polynomial. For the other Qs, R^2 were highest for polynomial, linear, and exponential regression equations. That Q_4 had the highest coefficient of determination ($R^2 = 1$) may be because it contains the particle size in its equation. It is observed that flow rate decreased as the particle size increased and that the linear and polynomial regression equations for Q_4 may best describe the relationship between flow rate and egusi-melon seed size.

4.6 Relationships Between Q_1, Q_2 and Q_{actual} for Equivalent Orifice Diameter

Figure 1 shows the relationship between the flow rate of egusi-melon and the equivalent diameter of the circular orifice. The closeness of the Q_{actual} to Q_2 is not in doubt and that while Q_1 over estimates the actual flow rate by about 28%, Q_2 does the same by about 2.6%. For the five regression equations of the flow rate of egusi-melon through circular horizontal orifice, given in Table 5 for D_e, Table 8 shows how they over estimate Q_{actual} for $D_e = 12$ cm. It is clear that the power regression equation gave the least difference (Q_1 = 28.95%; Q_2 = 2.65%) followed by exponential (Q_1 = 29.35%; Q_2 = 2.92%). The polynomial regression equation gave the largest overestimation (Q_1 = 40.39%; Q_2 = 7.65%).

This justifies why previous reports (ASABE, 2003; Beverloo *et al*., 1961; Chang *et al*., 1984) have continued to project the power regression equation as the only one for the flow rate of grains. However, since the disparity between the exponential and power is not much, the exponential may be added to literature as another way of expressing the flow rate of egusi-melon seeds through horizontal hopper orifices.

5.0 Conclusions

a. From the four model equations for the flow rate of egusi-melon seeds through horizontal hopper orifice, the Q_1 and Q_2 were found to be very close to Q_{actual} for D_h, D_e and A_e.

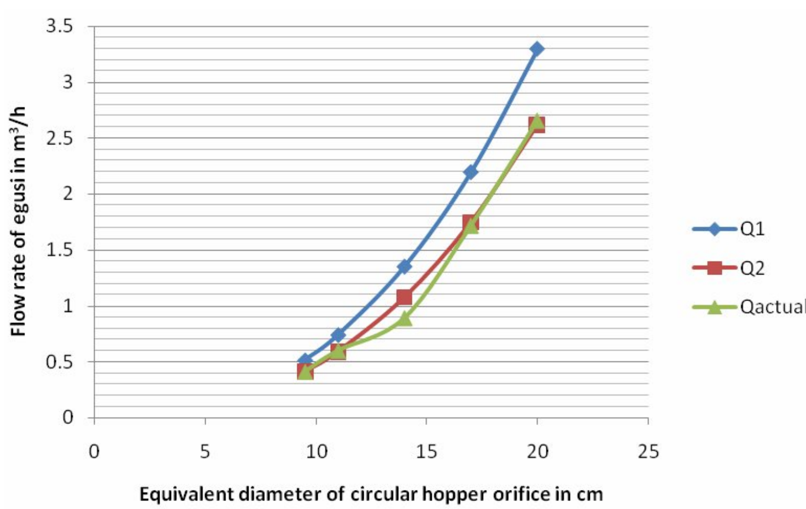

Figure 1. The graph of the relationship between egusi-melon flow rate and circular orifice equivalent diameter

Table 8. The percentage values with which Q_1 and Q_2 over estimate Q_{actual}

	Power	Exponential	Logarithmic	Linear	Polynomial
Q1	28.95	29.35	30.07	31.17	40.39
Q2	2.65	2.92	3.54	4.41	7.65

b. Because of the over estimation percentage with Q_1 and Q_2 for all the model regression equations both the power and the exponential equations may be acceptable for the flow rate of egusi-melon seeds through horizontal hopper orifice since they had the least percentage of over estimation.

c. This work suggests the following equations for egusi-melon seeds flow rate through horizontal hopper orifice:
$0.0008D_h^{2.658}$ ($R^2 = 0.988$); $0.067e^{0.176Dh}$ ($R^2 = 0.993$)
$0.001D_e^{2.471}$ ($R^2 = 0.988$); $0.080e^{0.176De}$ ($R^2 = 0.993$)
$0.002A_e^{1.235}$ ($R^2 = 0.988$); $2E\text{-}05A_e^2 + 0.003A_e + 0.112$ ($R^2 = 0.995$).

d. For egusi-melon seeds, however, it may be most appropriate to take the following equations:
$Q = 0.0008D_h^{2.658}$ ($R^2 = 0.988$);
$Q = 0.080e^{0.176De}$ ($R^2 = 0.993$);
$Q = 2E\text{-}05A_e^2 + 0.003A_e + 0.112$ ($R^2 = 0.995$);
as the ones that best describe its flow rate through horizontal circular orifice, where $Q = m^3/h$; D_h = cm; D_e = cm; and $A_e = cm^2$.

e. The R^2 value is not directly a measure of how good the modeled values are, but rather a measure of how good a predictor might be constructed from the modeled values, so the values in c and d above were suggested based on the least percentage of how the equations over estimated Q_{actual}.

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