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Design and Development of Integrated Slurry Food Processing Machine

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Abstract
An integrated slurry food processing machine comprising an I. C. engine, water dispensing, milling and sieving units was designed and developed. The machine grinds soaked grains and separates the slurry food (starch) content of the ground grain paste from its fibrous chaff in a single flow process thereby reducing drudgery in the discharging and feeding of the paste between the milling and sieving processes. It also eliminated human contact with the ground grain paste during sieving as contained in the existing semi-mechanized and traditional slurry food processing methods. Performance analysis revealed 64.25%, 66.01% and 70.16% as the respective average extraction rate of this machine when millet, maize and soybean were processed using 2.90kg of water while 53.62kg/hr, 56.21kg/hr and 47.76kg/hr constitutes its throughputs with the respective grains. However, in the manual process, an individual processes an average of 12.62kg ground maize paste per hour using an average water of 5.62kg with extraction rate of 57.01%. In addition, unlike the manual and other mechanized slurry food sieving systems, this machine extracts the slurry food from its ground paste by compression using a horizontal screw press sieving unit, hence, its extraction rate is independent of the texture/fineness of the ground grain paste. Thus, this innovation is energy, water and time saving and also improves hygiene in the slurry food production.
Key Words: Cereals, drudgery reduction, integrated machine, milling, slurry food, sieving

1.0 Introduction

Cereal grains constitutes the most abundant source of calorie and protein in human food (Onofiok and Nnanyelugo, 1998; Osagie and Eka, 1999; Abdulrahaman and Kolawole, 2006). They can be consumed after roasting, boiled or processed into products such as bread, biscuits, pasta (from wheat) and slurry food diets (pap, tuwo, kunu, agidi, soybean meal, sorghum meal etc). The importance of food-slurry diets as adult food and weaning foods for infants in Nigeria is outstanding due to their high nutritive values and availability (Onofiok and Nnanyelugo, 1998; Osagie and Eka, 1999; Simolowo, 2011). Processing of grains to slurry food involves three major operations- soaking, wet milling and sieving (Fig. 1).

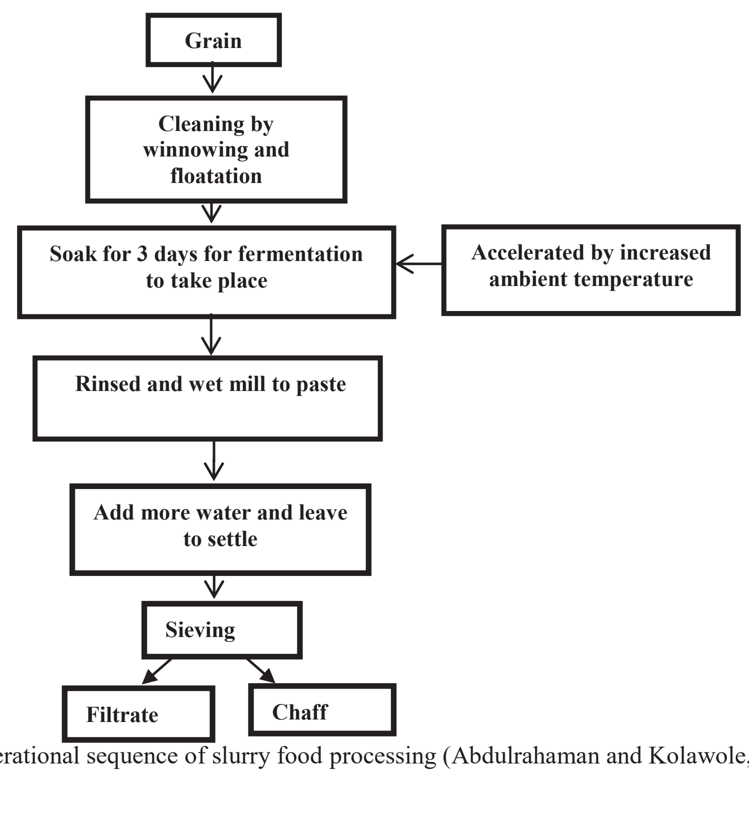

Fig.1: Operational sequence of slurry food processing (Abdulrahaman and Kolawole, 2006)

Soaking involves sopping the grains in water for two to three days to ferment while milling constitutes grinding of the soaked grains to paste by adding water to the grains while it is being pulverised. Sieving separates the starch content (slurry food) of the ground grain paste from its fibrous content (chaff). Traditionally, milling of grains to paste is done using grinding stone while sieving involves hand stirring of the grain paste on a chiffon cloth tied firmly over a big bowl with water being added at regular intervals to wash the starch content of the paste into the bowl leaving its chaff behind on the chiffon surface. Thereafter, the filtrate is allowed to settle before its supernatant is decanted to increase the concentration of the slurry filtrate. Thus, the tedious and drudgery features of the manual milling and sieving in slurry food production yearned for their mechanization. Although, mechanization of the milling process has been successfully achieved with the present day power driven mills, development of slurry sieving machines records limited success in Nigeria and this is why the manual technique remains the only means of sieving among slurry food producers in this country (Simolowo, 2011). Apart from tedium and drudgery, Fayose (2008) stressed that manual sieving of slurry food is time wasting and unhygienic because hand stirring of the paste (human contact with the food material) involved in this process introduces germs and impurities in the product. Fayose (2008), further revealed that the offensive odour from the fermented ground paste is discouraging to the producers and this made them to drift from sieving with small mesh sized chiffon to large ones in order conserve time leading to poor products with much chaff content. Hence, the tireless efforts of Simolowo and Ndukwe (2002), Fayose (2008), Simolowo and Adeniji (2011) and Simolowo (2011) towards designing an efficient and adoptable sieving machine for slurry food extraction from grains in this country.

Simolowo, (2002) designed and fabricated a corn slurry sieving machine based on suction principle. However, the low sieving rate and interference of its filtrate flow stream with the suction line at the outlet affected the general adoption of this machine. Fayose (2008), also developed a multi-purpose sieving machine for wet agricultural products but this consumes a lot of water during operation because its performance coefficient and sieving capacity increases with low concentration of solid particles in the paste. In an attempt to improve on the shortcomings of the suction based sieving machines, Simolowo and Adeniji (2011), developed an improved prototype food slurry processing machine which employed the concept of vibration for the sieving but its extraction efficiency is poor because it depends on the particle size of the ground grain paste (i. e. milling process). In addition, this machine processes slurry food in batches like the traditional technique and other mechanized slurry food sieving systems before it. Thus, Simolowo (2011), called for an integrated grinding and sieving system for slurry food processing in order to reduce human contact with the food materials during processing. This will also eliminate drudgery in the discharging/re-loading of ground grain paste involved in the use of separate (stand-alone) milling and sieving machines. In addition, a combined three burr mills for processing ultra-fine paste (at a single grinding flow) to enable effective slurry extraction developed by Simolowo (2011), called for a sieving system whose slurry extraction efficiency will be less dependent on the milling process. As a response to Simolowo (2011), which called for improvement in the grain slurry extraction technology, a single flow process machine for milling and sieving of slurry foods from grains was designed and developed.

2.0 Design Methodology and Analysis of Integrated Slurry Food Processing Machine

2.1 Design Considerations

The integrated slurry food processing machine was designed and developed based on the following considerations:

1. A continuous sieving process whose slurry food extraction efficiency is less dependent on product from the milling process was achieved in this machine by compression using a horizontal screw press system.

2. An I. C. engine was considered as the best prime mover for this machine to enable its effective use in both rural and urban areas.

3. Average water content of the milled grain paste was assumed to be 10% by weight.

2.2 Machine Description/Manufacturing Procedure

The integrated grain slurry processing machine developed (Fig. 2) has a 5HP I. C. engine, water dispenser, discharging chutes, milling and sieving units as major components with the engine driving the mill and sieve through an intermediate primary shaft.

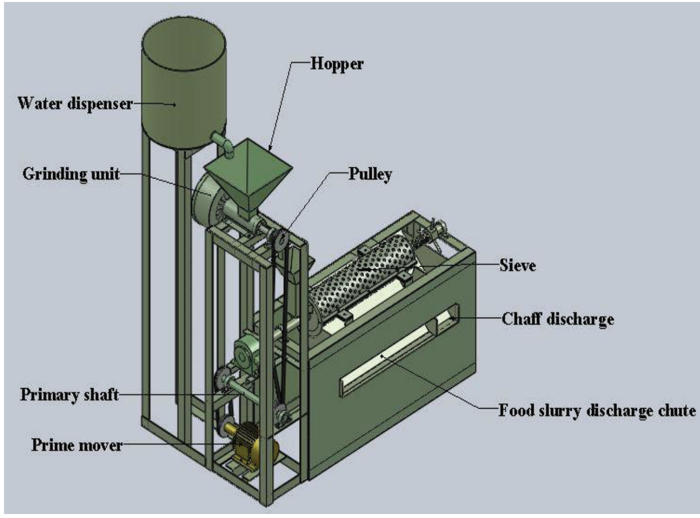

Fig. 2: Integrated Grain Slurry Processing Machine

The water dispenser is a $0.03m^3$ plastic reservoir mounted on a 1.6m high platform. The reservoir has a tap fixed at its base through which water is being supplied at a desired regular rate to the mill's hopper. The burr mill comprises of a hopper and grinder. The hopper is an inverted pyramidal funnel fabricated from a 3mm stainless steel sheet metal with top and base dimensions of $0.0915m^2$ and $0.00375m^2$ respectively which empties into the grinder through an extended aperture of 0.05m height from its base. The grinder consists of a 30mm stainless steel shaft upon which a 10mm diameter rod was scroll-welded to a length and pitch of 0.12m and 0.03m respectively for transporting the soaked grains from the hopper to the grater mounted at the end of the shaft. The grater is a pair of 6mm thick, 200mm diameter stainless steel grinding plates housed in a casing made from a 5mm thick stainless steel plate. The grinding of the soaked grains and discharging of the ground paste into the sieving unit is effected as the grater's outer plate welded to the mill shaft rotates and rubs against its inner plate fixed to the grater's barrel with the grains in between them. The fineness of the ground grain paste is regulated as desired by adjusting the gap between the plates using an adjustable locknut screw on the driving shaft. The milled grain paste discharges directly into the sieve through a $0.0026m^2$ aperture on the sieve barrel.

The sieve extracts the slurry food from the ground grain paste by compression using a horizontal screw press system comprising an assembly of screw (auger) conveyor mounted on a 30mm stainless steel shaft (1170mm long) inside a barrel with a locknut-spring operating a cone shaped stopper at its end. The conveyor was made by scroll-welding stainless steel rods in spiral form with 48mm flight and pitch of 165mm on a membrane (45mm diameter, 520mm long stainless steel pipe). Paddles (40mm x 30mm) made from 5mm thick stainless steel flat bars padded with score pads were also welded in opposite direction to the helical ridge on the membrane at an angle of 30^o to the drive axis. The paddles complements the pressing action of the screw and also wipe out the pressed grain paste/slurry matrix which tends to clog on the "eyes" of the chiffon so as to ensure continuous and effective passage of pressed slurry. The sieve barrel was made by weaving a chiffon cloth and aluminium net inside a perforated (5mm diameter holes at equal spacing of 50mm) 650mm long, 3mm thick stainless steel pipe with internal diameter of 178mm. The stopper is a cone-frustum of height 130mm made from 170mm diameter stainless steel rod lined with score pads to prevent metal to metal contact with the barrel outlet/wearing of the cone as the barrel content is being pressed and discharged at regular intervals by means of its locknut system. The slurry oozes out of its paste and discharges through the chiffon/aluminium net and barrel perforations as the screw conveyor transports ground grain paste from the left end of the barrel to the right under pressure due to the opposing stopper at the right end of the barrel. The chaff discharges at the right end of the barrel as the pressure developed (due to its weight) overcomes and pushes the stopper out of the barrel. The stopper returns to its position as the pressure drops after discharging the chaff.

2.3 Power Transmission Systems Design

The machine's prime mover drives its mill and sieve through an intermediate primary shaft. The rotary motion of the engine shaft (1440rpm) is transmitted to the primary shaft which in turn drives the mill and speed reducer of the sieve via belt drives. Due to its availability, cost and performance, mild steel pulleys were used in this machine with all the driving pulleys and engine/primary shafts' driven pulley having a diameter of 94mm each while 140mm and 150mm constitute the respective diameters of the primary/sieve and primary/mill driven pulleys. An intermediate speed reducer with 46:1 gear ratio formed part of the sieve's drive in order to achieve the required press torque with a portable design. Thus, the speed of primary, sieve and mill shafts were determined as 1440rpm, 20.29rpm, and 902.4rpm respectively from the following relation;

$$\frac{N_1}{N_2} = \frac{D_2}{D_1} \tag{1}$$

Where N_1 and N_2 constitute the driving and driven pulleys speed while D_1 and D_2 are the pulleys respective diameters. The conceptual centre distances, C, between the adjacent pulleys of engine/primary shaft, primary/sieve and primary/mill drives were determined as 188mm, 211mm and 216mm respectively from Equation (2).

$$C = \frac{D_1 + D_2}{2} + D_1 \tag{2}$$

Thus, the length of the belts, L required for engine/primary shaft, primary/sieve and primary/mill drives were computed from Equation (3) as 671.16mm, 791.89mm, and 818.71mm respectively, hence, type 'A' V-belts of standard pitch lengths of 696mm, 823mm and 823mm were selected for the respective drives since each drive transmits less than 3.75kw power (IS: 2494-1974; Khurmi and Gupta 2011). Consequently, these standard belt lengths were used to determine the actual center distances between the adjacent pulleys in this machine as 200.42mm, 226.65mm and 218.17mm respectively.

$$L = 2C + 1.57(D_2 + D_1) + \frac{(D_2 - D_1)^2}{4c} \tag{3}$$

The diameters, d of the primary, sieve and mill shafts of this machine were determined from maximum stress relations given by Khurmi and Gupta (2005) as:

$$d = \left[\frac{16}{\pi\tau}\sqrt{(k_b m_b)^2 + (k_t m_t)^2}\right]^{1/3} \tag{4}$$

Where k_b and k_t are the combined shock and fatigue factor for bending and twisting respectively while m_b constitutes the maximum bending moment on the shaft. The allowable shear stress for steel shaft with provision for keyway, τ is given as 42N/mm^2 (Khurmi and Gupta, 2005) while the respective maximum twisting moment, m_t on the primary, sieve and mill shafts were determined as 7310.85N-mm, 10759.7N-mm and 11481N-mm from Equation (5) given by Khurmi and Gupta (2005) as:

$$M_t = (T_i - T_j)\frac{D_2}{2} \tag{5}$$

Where 164.67N was determined as the tension on the tight side of each drive belt from Equation (6) while the respective tension on the slack sides of engine/primary shaft, primary/sieve and primary/mill drives' belts were determined from Equation (7) as 9.12N, 10.96N and 11.59N (Khurmi and Gupta, 2005).

$$T_i = T_{max} - T_c \tag{6}$$

$$2.3 log\frac{T_i}{T_j} = \mu\theta \operatorname{cosec}\beta \tag{7}$$

The maximum and centrifugal tensions of the belts, T_{max} and T_c are given as;

$$T_{max} = \sigma a \tag{8}$$

$$T_c = mv^2 \tag{9}$$

The coefficient of friction between the pulleys and belts (μ), maximum safe stress (σ), mass per unit length (*m*), cross sectional area (*a*) and groove angle (2β) of the belts were obtained from standard tables as 0.3, 2.1N/mm^2, 0.108kg/m, 81mm^2 and 38° respectively (Khurmi and Gupta, 2005). The angle of lap (Θ) of belt on small pulley of each drive were computed from Equation (10) as 180° (3.14rad), 168.35°(2.94rad) and 165.25° (2.88rad) for engine/primary shaft, primary/sieve and primary/mill drives respectively while 7.09m/s was determined as the speed of each drive belt Equation (11).

$$\Theta = 180 - [2\sin^{-1}(\frac{D_2 - D_1}{2C})] \tag{10}$$

$$V = \pi\frac{N_2 D_2}{60} \tag{11}$$

Force analysis of the machine shafts (Figures 3, 4, and 5) revealed the maximum bending moments on the primary, sieve and mill shafts as 30483.2N-mm, 67704.86N-mm and 9664.8N-mm. Since each shaft is subjected to gradual loading, k_b and k_t were taken as 1.5 and 1.0 respectively, thus, the respective minimum diameter required of the shafts were computed from Equation (4) as 17.8mm, 23.13mm and 13.09mm (Khurmi and Gupta, 2005). Therefore, standard stainless steel shafts of 25mm diameter each were used in each drive.

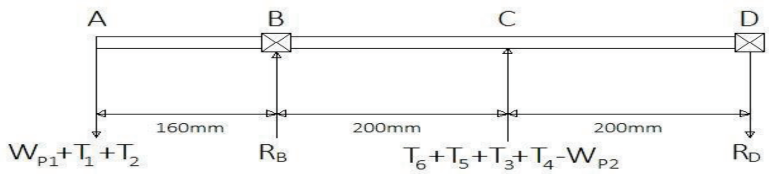

Fig. 3: Force diagram of the primary shaft

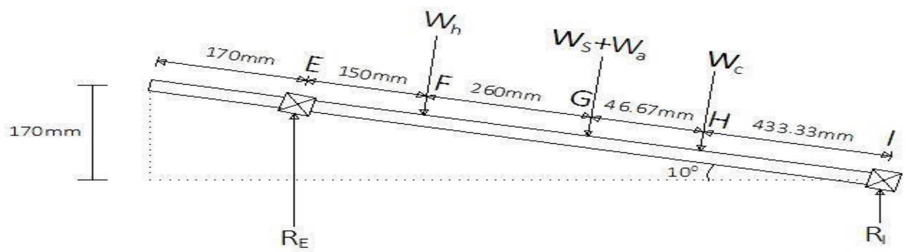

Fig.4. Force diagram of the sieve shaft

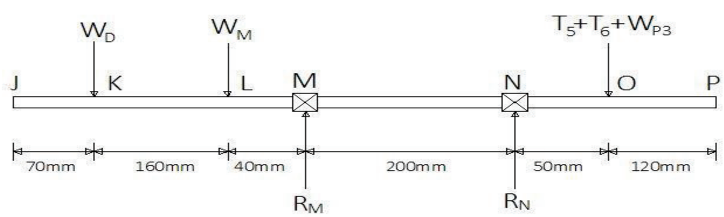

Fig.5: Force diagram of the mill shaft

Where T_1, T_3 and T_5 are tensions on the tight side of engine/primary shaft, primary/sieve and primary/mill shaft drives' belts while T_2, T_4 and T_6 constitutes the respective belts' slack side tensions. The respective weights of driven pulleys on the primary and mill shafts are $W_{p1}(16.73N)$ and $W_{p3}(17.03\text{N})$ while W_{p2} (27.23N) is the weight of double groove driving pulley mounted the primary shaft through which the sieve and mill shafts are driven. $W_h(15.28N)$, $W_c(125.50N)$, $W_a(105.15N)$ and $W_D(16.72N)$ are weights of the hopper, cone, auger conveyor and grinding disk respectively. The reaction due to bearings on the shafts, R_B, R_D, R_E, R_I, R_M and R_N were determined from the principle of moment/equilibrium as 209.91N, 344.05N 175.08N, 155.43N, 84.66N and 208.15N respectively. The effective ground grain-paste carrying capacities of the mill, w_m and sieve, w_s were designed as 82.62N each using the following derived relations;

$$w_m = g\left(0.675\rho_g + 0.075\rho_w\right)\left\{\left(\tfrac{1}{3}H_h\left(L_h B_h + L_b B_b + \sqrt{L_h B_h L_b B_b}\right)\right) + \left(L_b B_b H_b\right)\right\} \quad (12)$$

$$W_s = g\left(0.675\rho_g + 0.075\rho_w\right)\left\{\pi r_c^2 l_c - \left[\pi r_a^2 l_a + n\left(l_f B_f h_f + l_l B_l h_l\right) + 2\pi^2 r_h^2\sqrt{R^2 + \left(\tfrac{Z}{N}\right)^2} + \tfrac{1}{3}\pi\left(r_x^2 h_x - r_t^2 h_t\right)\right]\right\} \quad (13)$$

Where, $\rho_g(800.923kg/m^3)$ and $\rho_w(1000kg/m^3)$ are the densities of soybean grain and water respectively; Density of soybean was used in this design because it is highest among the three grains used in this investigation. L_h (0.351m), L_b(0.1m), l_c (0.65m), l_a(0.52m), l_f (0.03m) and l_l (0.065m) constitute lengths of hopper's top, hopper's base, barrel, screw membrane, paddles flat bar and score pad respectively. B_h(0.350m), B_b (0.07m), B_f (0.005m) and B_l (0.003m), are the width of hopper's top, hopper's base, paddles flat bar and score pad. H_h (0.251m), H_b (0.05m), h_f (0.04m), h_l (0.03m), Z (0.52m), h_x (0.150m), and h_t (0.002m) various normal heights of hopper's frustum, hopper's base funnel, paddles flat bar, score pad, helix, complete and cut cones. r_c(0.089m), r_a(0.0225m), r_t(0.047m), r_x(0.085m), R(0.048m), and r_h(0.01m) are respective radius of barrel, screw membrane, cone's top, cone's base, helix and rod used for the press screw formation. The number of press screw turns, N and paddles, n are 3 and 5 respectively.

2.4 Sieving Screw and Barrel Design

The sieve conveyor is a decreasing depth and pitch screw thread conveyor. The difference between its successive screw depths d_p was determined as -1.5mm from the following relation;

$$U_n = a_f + (N-1)d_p \tag{14}$$

Where the screw depth at the feed (a_f) and discharge (U_n) ends are 48mm, and 45mm respectively. This implies that the screw depth would be decreased consistently by 1.5 mm from the feed end to the discharge end of the barrel. The pressure developed by the screw thread which expels the slurry filtrate from its grain paste was determined as 1.39N/mm^2 from the following relations;

$$P_r = \frac{T(d_m \cos\alpha \tan\theta + 2\mu)}{2\pi n d_m U_n \cos\alpha(1-\mu\tan\theta\cos\alpha)} \tag{15}$$

Where the helix angle, α is given as;

$$\alpha = \tan^{-1}(\tan\theta_n \cos\theta) \tag{16}$$

The torque transmitted by the screw shaft, T = 10759.7Nmm; the mean thread diameter, d_m = 90mm; Coefficient of friction, μ = 0.12; thread lift angle, θ_n = 15° and tapering angle, θ = 6°. The maximum allowable pressure of the barrel was determined as 1.82N/mm^2 from the relationship given by Khurmi and Gupta (2005) as;

$$P_b = \frac{0.54t\delta_o}{d_i} \tag{17}$$

Where the thickness of the barrel, t = 3mm; inside diameter of the barrel, d_i =178mm, and maximum yield stress of steel, δ_o =200 N/mm^2. Hence, the barrel is suitable since its pressure bearing capacity of 1.82N/mm^2 is greater than the pressure (1.39N/mm^2) developed by the screw thread.

2.5 Selection of Prime Mover

The power, P required at the milling and the sieving units of this slurry processing machine were determined as 1.09kW and 1.09kW respectively using Equation (18) given by Khurmi and Gupta (2005) as.

$$P = (T_i - T_j)\,V \tag{18}$$

Accounting for possible 10% power loss due drive friction, a total power of 2.40kw (3.21 HP) is required for the operation of this integrated machine, hence, a 3.5 HP I. C. engine was selected.

3.0 Performance Test Procedure

The throughput, TP (kg/h) and extraction efficiency, ɳ (%) of the integrated grain slurry processing machine developed were evaluated using three different grains: corn, millet and soybean bought from Ubani market, Umuahia in Abia state. Each trial involves soaking of a known mass of each grain in water for three days after which it was washed in clean water before processing with the developed machine. This trial was repeated thrice as per each grain and thereafter, the processing time (t), mass of grain processed (M_g), water used (M_w), extracted slurry food (M_f) and chaff (M_c) recorded from each experimental run were used for computing the machines *TP* and ɳ with respect to each grain from the following relations.

$$\text{TP} = \frac{M_g}{t} \tag{19}$$

$$\eta = \frac{100M_f}{M_f + M_c} \tag{20}$$

In addition, the average throughput of manual processing of soaked maize grain by five individuals was also evaluated and compared with that of this integrated machine.

4.0 Result and Discussion

The integrated slurry food processing machine's performance test results shown in Table 1 revealed 64.25%, 66.01% and 70.16% as its efficiencies when millet, maize and soybean food slurries were processed respectively while 53.62kg/h, 56.21kg/h and 47.76kg/h constitutes its respective throughput with the grains. The high efficiency and low throughput associated with soybean grain processing is due to its high oil content compared to maize and millet that are more fibrous in nature. The extraction rate of this machine is independent of the milling process because it extracts the slurry food from ground grain paste by compression. Thus, this innovation is energy, water and time saving since it processes an average of 56.21kg of soaked maize grain using 2.90kg of water in one hour while manually, an individual sieves an average of 12.62kg ground maize paste per hour using an average water of 5.62kg with extraction efficiency of 57.01% (Table 2). It also improves hygiene because human contact with the food materials during sieving is eliminated.

Table1: Performance Analysis of the Integrated Slurry Food Processing Machine

S/No.	Soaked Grains (kg)	Water (kg)	Slurry Food (kg)	Chaff (kg)	Processing Time (hr)	Extraction Efficiency (%)	Throughput (kg/hr)
				MAIZE			
1	3.14	2.90	5.11	0.93	0.05	84.60	62.80
2	3.13	2.90	3.43	2.60	0.06	56.90	52.17
3	3.22	2.90	3.46	2.66	0.06	56.54	53.67
Average		**2.90**				**66.01**	**56.21**
				MILLET			
1	2.62	2.90	3.94	2.58	0.05	71.38	52.40
2	2.58	2.90	3.33	2.15	0.05	60.77	51.60
3	3.98	2.90	4.17	1.20	0.07	60.61	56.86
Average		**2.90**				**64.25**	**53.62**
				SOYBEAN			
1	3.75	2.90	4.78	1.87	0.08	71.88	46.88
2	4.35	2.90	5.04	2.21	0.09	69.52	48.33
3	3.98	2.90	5.99	2.68	0.12	69.09	48.08
Average		**2.90**				**70.16**	**47.76**

Table 2: Processing of Soaked Maize Grain to Slurry Food by Manual Method

S/No.	Soaked Grains (kg)	Water (kg)	Slurry Food (kg)	Chaff (kg)	Processing Time (hr)	Extraction Efficiency (%)	Throughput (kg/hr)
1	1.55	9.52	3.01	2.06	0.13	59.37	11.92
2	2.82	5.03	4.56	3.29	0.21	58.09	13.43
3	2.07	4.51	3.55	3.03	0.16	53.95	12.94
4	2.57	4.93	4.65	2.87	0.21	61.84	12.33
5	2.00	4.09	3.15	2.94	0.16	51.80	12.50
Average		**5.62**				**57.01**	**12.62**

5.0 Conclusion

An integrated slurry food processing machine was designed and developed using locally sourced standard materials at Michael Okpara University of Agriculture, Umudike. This machine performs with throughput of 53.62kg/hr, 56.21kg/hr and 47.76kg/hr when millet, maize and soybean food slurries were processed respectively using 2.90kg of water each while manually an individual sieves an average of 12.62kg ground maize paste per hour using an average water of 5.62kg. The extraction efficiencies of the machine are 64.25%, 66.01% and 70.16% with the respective grains while 57.01% constitutes the extraction rate of the manual process with respect to maize. This integrated machine is thus energy, water and time saving and also improved hygiene.

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