Development and Performance Evaluation of an Integrated Bio-degradable Kitchen Waste Comminution and Drying Machine

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ORIGINAL RESEARCH

Abstract— In this study, a kitchen waste comminution machine for converting biodegradable waste was designed, fabricated, and evaluated, using locally sourced standard materials. The machine consists of two unit operations: the comminution unit for grinding/shredding of the biodegradable domestic waste using grinding discs and the drying unit for moisture removal from the ground material using a heating element. The units were integrated and synchronized for continuous operation using a pulley-belt arrangement and powered by a single phase 2 HP electric motor. The drying unit equipped with an auger-like shaft for material stirring and conveying/evacuation was lagged for the prevention of excessive heat loss. The performance of the machine was evaluated using various kitchen wastes of tuber peels, fruit peels, vegetable stalks, and grain chaffs for shredding efficiency, throughput capacity, and dryness. The approximate values of the designed machine were established, as a force of 150 N and heat of 2 kW were required for respective grinding and drying of an average mass of 5.87 kg of the bio-waste. The machine performance analysis revealed comminution/shredding efficiency of 71.08%, drying efficiency of 32.78%, and throughput of 0.05 kg/s at an average moisture removal rate of 0.018 kg/s for bio-waste conversion. The production cost of the machine stood at N 250,000 (Two hundred and fifty thousand naira) only. Thus, the adoption of this innovation is recommended as a veritable option for the quality management of domestic kitchen waste since it reduces littering and promotes hygiene.

Keywords— Biodegradable, Comminution, Drying efficiency, Kitchen waste, Moisture removal rate, Shredding.

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1 INTRODUCTION

Food wastes are materials of organic origin, rich in calorific and nutritive values that play host to microbes responsible for methane production. Organic wastes are dumped in landfills or discarded indiscriminately in some urban areas, and most rural areas, which lead to public health hazards in many cases, as they become breeding sites for vectors causing malaria, cholera, and typhoid (Garcia *et al.*, 2005, Salemdeeb *et al.*, 2016). Inefficient management of wastes resulting from poor disposal strategies bears several adverse consequences in addition to environmental degradation and pollution (Janduir *et al.*, 2019). The methane gas generated from bio-waste does not only produce an unpleasant odor but constitutes a main greenhouse gas that leads to global warming. However, food waste when properly harnessed and processed has great potential in biomass energy utilization, agricultural production as animal feed, and farm inputs (compost manure) for crop production. This practice, in addition, promotes efficient management of organic waste through recycling for economic development and recovery (Enweremadu *et al.*, 2004; Duca *et al.*, 2014).

Agriculture, being the predominant occupation in many countries, produces a variety of wastes that require a range of treatment and management techniques. Over 70% of the Nigerian population depend basically on Agriculture as a major occupation, (FAO, 2020).

While the ultimate aim of these agricultural activities is to guarantee food security, agricultural wastes, including both natural and non-natural wastes, are generated as well (Schmidt, 2006). Traditionally, post-harvest wastages emanating from cultivated crops in Nigeria were either burnt out or discarded without regard to their energy and nutritive potential. With the increasing population, appropriate and sustainable management of these wastes aimed at stabilizing and boosting agriculture production became imminent. The prolonged use of agrochemicals such as pesticides and fertilizers in crop production has affected the soil's health status and led to a decline in yields and product quality (Orhorhoro, 2016). Hence, to maintain a natural balance in the ecosystem for the existence of life, a clear choice for the use of more naturally occurring by-products of farming activities and less of agrochemicals must be made. The conventional but one of the oldest methods of agro-waste disposal is dumping to allow degradation or decomposition in a place. While the dumped wastes degrade over time causing environmental pollution, its poor management practice undermines the huge potential that abounds in agro wastes both in terms of energy utilization and recycling potential for agricultural inputs (Smith *et al.*, 2015; Edeh *et al.*, 2020). Therefore, a system is required to break it further for easy decomposition; the comminution

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machine is suitable for such waste shredding. This shredding converts macro agriculture and bio wastes into small easily decomposable forms, usable as organic manure or animal feedstock. The shredded waste can be used in crop production to improve the growth and quality of crops in addition to improving the soil's chemical properties both in soil nutrient retention and chemical reaction promotions.

A large proportion of the waste generated in our homes, especially the kitchens is food waste (derivatives of agricultural products), they can conveniently be processed with an appropriate technology, converting them into animal feed and manure for agricultural purposes (Havlíček *et al.*, 2016). Analysis of these biodegradable kitchen wastes (usually of animal, fruit, and vegetable origin) shows that they are characterized by high moisture content of 60 % to 90 % (Garcia *et al.*, 2005). If such wastes were to be processed to a stable shelf life (20 % to 40 % moisture content), a reasonable amount of moisture has to be removed. Interestingly, such significant moisture removal causes a substantial reduction in the weight and volume of biodegradable waste but increases the energy value (Tun and Juchelkova, 2018).

Although some researchers like Polprasert (2007) and Yang *et al* (2015) have shown considerable interest in bio-waste treatment and its benefits relying on the sketchy overview of a range of treatment options, less emphasis was made on the development of a dedicated treatment technology taken into account bio-waste sources, compositions, and characterization. Therefore, with the focus of this study targeted at providing a practicable and adequate waste management solution for low and middle-income domestic settings, a kitchen waste conversion system is premeditated, designed, and fabricated for proper waste management and utilization.

2 Materials And Method

2.1 Materials

The materials used in the fabrication of the domestic waste comminution and drying machine include mild steel plates and shafts, angle iron, aluminum sheet, pulleys, belts, bearings, electric motor, heating coil, fiberglass (lagging material), air blower, switches, and grinding disc. The materials were mostly procured from Aba and Umuahia both in Abia State. A stopwatch, weighing balance, thermometer, and tachometer were employed for measurements during the evaluation. The kitchen wastes used for evaluation were sourced from Holffers and Crunches eatery kitchens in Umuahia, Abia State.

2.2 Method

2.2.1 Performance Evaluation Procedures

The designed and fabricated domestic biodegradable kitchen waste comminution and drying machine was evaluated for its performance based on shredding/ comminution efficiency, throughput capacity, and drying efficiency. The tests were carried out in nine replications. Varied quantities (mass) of biodegradable organic waste were used in the samples. The average masses of unground, ground, and dried biodegradable waste were considered and used to determine the designed machine's performance. The effect of particle size on moisture removal rate in the drying system was evaluated with one sample as ground bio-waste (fine particle sizes) and the other sample as unground bio-waste (coarse particle size).

An isometric view of the developed machine showing the components is presented in Figure 1, while Figure 2 shows the pictorial view.

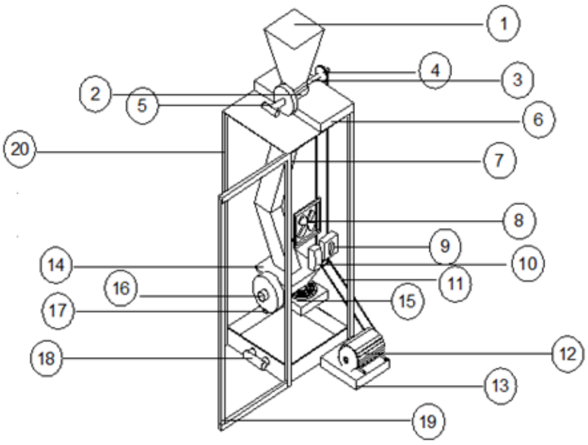

Figure 1: Isometric view of the domestic waste comminution and drying machine

1. Hopper
2. Hopper tray
3. Bearing
4. Pulley
5. Grinding Chamber
6. Vent
7. Delivery
8. Electric blower
9. Motor Switch
10. Heater/Blower Switch
11. Belt
12. Electric motor
13. Electric motor seating
14. Aluminum Sieve
15. Electric heater
16. Shaft with scoopers
17. Delivery
18. Collection tray
19. Door
20. Frame

Figure 2: Pictorial view of the domestic waste comminution and drying machine

2.2.2 Principle of Operation

The machine comprises two units: the comminution/ shredding and the drying units. The two units are driven by a single phase 2 HP electric motor through pulley and belt drive configuration properly synchronized to achieve continuous operation (Shigley, 1986). From the hopper

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through the auger-like/screw shaft (with constant pitch), the materials are conveyed to the grinding unit where the aid of two opposing discs (one rotating and one stationary) breaks down the material into smaller particles by comminution principle (Screenivas *et al*., 2017). The grinding power varies in line with the power of the electric motors. The drying unit, properly lagged with fiberglass material to reduce heat loss, is equipped with a perforated zigzag rectangular cross-section aluminum funnel, a semi-circular trough that houses a stirring/conveying shaft, and a hot air blower (for circulation of heat).

The electrical section of the machine was connected to an electric source; as the switch of the electric motor was turned on and the change-over switch that turns on the heater and electric blower were equally turned on. The rotation of the rotor of the electric motor transmits motion and power to the shafts of the grinder and the heating chamber (Pothi, 2016). The biodegradable kitchen waste to be processed was introduced through the hopper. Once the waste was due for crushing/grinding as determined by the volume of the hopper, a feeding control tray beneath the hopper was opened allowing the loaded waste to be fed by gravity into the chamber and conveyed by the auger shaft as it rotates (Sanjay and Kumar, 2015). It goes to the grinding chamber where the pair of grinders reduce them into smaller particles which are dropped on the vibrating aluminum sieve/funnel through which they fall by gravity to the trough and dried at the drying chamber till the desired moisture condition is achieved. The material is afterward evacuated and collected at the collection chamber. Heat transfer through conduction and convection is initiated as the ground material is introduced in the aluminum funnel (designed with a maximum angle of repose of biomaterials and staggered to increase resident time) and continues throughout the material path to the exit spout. The moisture removal rate was used to determine the resident time of material which informed the design of the material paths. (Finlay *et al*., 2008)

2.3 DESIGN ANALYSES

2.3.1 DESIGN CONCEPT AND CONSIDERATIONS

The biodegradable kitchen waste comminution and drying machine was designed and fabricated based on mechanical, operational, and economic considerations. Service requirements, availability, ease of fabrication, durability, cost, and maintenance were among the factors considered. The acceptability of the machine by households who would be the end users was also the main focus. Design considerations observed are:

i. Availability of materials (components) for ease of construction without compromise to service requirements. This entails the properties (hardness, strength, stiffness, toughness, corrosion resistance, heat resistance) possessed by material that satisfies the designed purpose. Therefore, materials such as angle bars, mild steel shafts, and metal sheets are readily accessible and satisfy the service requirements.
ii. The size and moisture content of the shredded waste of about 20 to 40% for optimal drying efficiency, which is less than 25mm in diameter and moisture content of twigs. (Oladejo, 2020).
iii. The inclination of the hopper surface at 100 for easy introduction (by gravity) of the unshreded waste.
iv. Economic requirement considers the affordability of fabrication materials and consequent commercialization. It is expected that the benefits derived from the machine outweigh the manufacturing and investment costs.
v. The components were designed to allow easy dismantling and assembling for maintenance

2.3.2 DETERMINATION OF VOLUME OF HOPPER

The volume of the hopper, V_{sh}, through which the waste materials were fed shredding was obtained using equation 1;

$$V_{sh} = \frac{1}{3}(BH - bh) \qquad (1)$$

Where:
V_{sh} = volume of the hopper
B = the rectangular base area of the big pyramid,
H = the height of the big pyramid,
b = the rectangular base area of the small truncated pyramid, and
h = the height of the small truncated pyramid.
The angle of inclination of hopper Ø = 10°

2.3.2 DETERMINATION OF THE SHREDDING SHAFT SPEED

Motor speed was transmitted to the crank, with the help of V-belt drive, and calculated using equation 2, given the speed of the electric motor as 1430 rpm;

$$\frac{N1}{N2} = \frac{D_2}{D_1} \qquad (2)$$

Where;
N_1 = Motor speed, rpm
N_2 = Speed of the shaft, rpm
D_1 = Diameter of the driver pulley
D_2 = Diameter of the driven pulley

2.3.3 DETERMINATION OF DIAMETER OF THE SHAFTS

In estimating the machine shaft diameters, the maximum shear stress theory as expressed by Khurmi and Gupta, (2005) was considered appropriate for shafts subjected to combined bending and twisting moments. The shafts used in the machine were made of tough mild steel. Two shafts were used in the design; the shredding shaft and the drying unit shaft.

i. Shredding Shaft

The shaft was subjected to both bending and twisting load as shown by the free body diagram in Fig 3

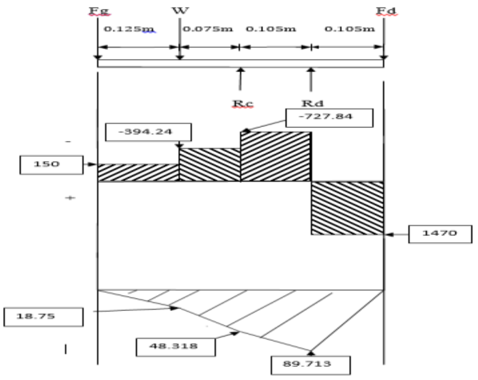

Figure 3: Shredding Shaft Loading

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Where;
F_g = grinding force, 150N
W = weight of the food waste, 244.24N
F_d = Driving force, 1270N
R_c and R_d are reactions at the bearings as R_c = -615.76N and R_d = 2480N

The shaft diameter was determined as 50 mm, using the maximum stress theory (Hall *et al.*, 1980).

$$d = \left[\frac{16}{\pi s}\sqrt{(k_b M_b)^2 + (k_t M_t)^2}\right]^{\frac{1}{3}} \quad (3)$$

$$M_t = F_d \times \frac{D}{2} \quad (4)$$

Where;
M_b = maximum bending moment on the shaft, 89.713 Nm (determined from BM diagram)
M_t = maximum torsional moment on the shaft, (1470 × 0.1)
s = allowable shear stress for steel, (2480 N)
K_t and K_b are fatigue and shock factors for torsion and bending moments (K_t = 1.0, K_b = 1.5)

The maximum shear force of 1470 N occurred between R_d and F_d while the maximum bending resulted in R_d with a peak value of 89.71 Nm as shown in Fig. 3. This value of BM is exploited with a combined effect of twisting moment in equation (3) to determine the minimum shaft diameter required to withstand such loading without failure.

ii. Drying chamber shaft

This shaft is loaded as shown by the free body diagram in Fig 4

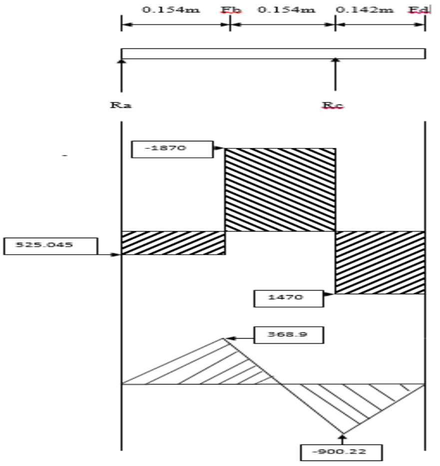

Figure 4: Drying Shaft Loading

F_b = weight of the ground food waste, 2396 N
F_d = Driving force, 1470 N
R_c = 3340N and R_a = 525.045 N

Similarly, the shaft diameter is determined as 20 mm, using equation (3),
Where;
M_b = −900.22 Nm
M_t = 1470 N
s = 2480N
K_t = 1.0 and K_b = 1.5

The maximum shear force of 1870 N occurred between F_b and R_c while the maximum bending resulted at R_c with a peak value of 900.22Nm as shown in Fig. 3. Similarly, these values help in determining the minimum shaft diameter (20 mm) of the drying shaft under the loading conditions.

2.3.4 DETERMINATION OF V–BELT LENGTH

To determine the belt length used in operating the shredder and dryer conveyor, equation 5 (Khurmi and Gupta, 2005) was employed;

$$L = \frac{\pi}{2}(Ds + Dm) + 2C + \left(\frac{Ds + Dm}{4c}\right)^2 \quad (5)$$

Where;
L = Belt Length
C = Center length between two pulleys
Ds= Pitch diameter of the first pulley
Dm= Pitch diameter of the second pulley

2.3.5 DETERMINATION OF POWER REQUIREMENT

The power requirement of the shredder was considered one of the important factors in the design of the machine and was computed using equations 6, 7, and 8 (Shigley, 1986).

$$P = F \times V \quad (6)$$

$$P = \frac{(2\pi NT)}{60} \quad (7)$$

$$S = V = \frac{(\pi DN1)}{60000} \quad (8)$$

Where;
P = power, (Nms−1)
F = Shredding force, N
V = Velocity (ωr), ms^{-1}

The required force for shredding was computed, using equations 9 and 10;

$$F = m\omega^2 r \quad (9)$$

$$\omega = 2\pi N/60 \quad (10)$$

Where;
F = force required to shred waste material
m = mass of shredding discs,
ω= angular velocity of shaft.
N = speed of shredding (rev/m).

The power delivered to the machine by the shaft was calculated using equation (11);

$$P = F \times \omega \times r = m\omega^3 r^2 \quad (11)$$

2.3.6 SHREDDING/COMMINUTION EFFICIENCY

To determine the comminution efficiency, the total weight of the unprocessed waste materials was measured and recorded before shredding in the machine. Similarly, the weight of both shredded and unshredded materials was measured and recorded with time. All measurements were made in kilograms (kg).

The shredding/comminution efficiency of the machine was then determined using equation 12;

$$S_E = \frac{W_c}{W_t} \times 100 \quad (12)$$

$$W_c = W_t - W_u \quad (13)$$

Where;
S_E = Shredding efficiency, %
W_c = Weight of shredded materials (kg), M_2
W_t= Total weight of the waste (kg), M_1
W_u= Total weight of un-shredded materials (kg).

2.3.7 THROUGH-PUT CAPACITY

Through-put is simply the rate of the production, and was calculated using equation 14;

$$T_{PC} = \frac{M_1}{t_g} \quad (14)$$

Where,
T_{PC} = Through-put Capacity, kg/s
M_1 = Total weight of the biodegradable waste, kg
t_g = Time of grinding, s

2.3.8 DRYING EFFICIENCY

This is determined by the moisture content of the ground/shredded food waste before and after drying.

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The moisture content was determined by oven dry method (evaporation method) on a wet basis using equation 15 (Komilis *et al.*, 2012);

$$M_C = \frac{M_2 - M_3}{M_2} \times 100 \qquad (15)$$

Where;

M_C = Moisture content
M_2 = Mass of ground food waste
M_3 = Mass of dried food waste

An average moisture removal rate (MRR) was determined by equation 16 (Aravindan *et al.*, 2017)

$$MRR = \frac{M_2 - M_3}{t} \qquad (16)$$

Where t is the average drying time.

3 RESULTS AND DISCUSSION

The performance analysis of the fabricated biodegradable kitchen waste comminution and drying machine shown in Table 1 depicts the machine throughput capacity, shredding/comminution, and drying efficiencies. Thus, with average masses, M_1 (total mass of unshredded waste), M_2 (shredded waste), and M_3 (dried waste) of 5.87kg, 5.17 kg, and 3.49 kg and an average processing time of 91.70 s, the developed machine attained an average through-put, shredding efficiency and drying efficiency of 0.057 kg/sec, 71.08 %, and 32.78 % respectively. It was observed that average moisture removal from the ground samples (at constant heat and air speed) is dependent on the resident time in the drying chamber hence the need for reduction in material conveying speed. It therefore implies that approximately 2 minutes (91.70s) is required for processing and drying (32.78 % moisture content) of 5.87 kg biodegradable kitchen waste to 3.49 kg at an average moisture removal rate (MRR) of 0.018 kg/s.

Analysis of particle size revealed an increase in moisture removal rate as particle size reduces from coarse to fine particles since more surfaces are made available for effective heat transfer in smaller particles.

Table 1: Machine throughput capacity (MTC), Machine efficiency, and drying efficiency with variation in Masses and Time

S/N	M_1 (Kg)	M_2 (Kg)	M_3 (Kg)	t (sec)	MTC (Kg/sec)	S_E (%)	M_C (%)
1	5.45	4.81	3.05	98	0.056	88.26	36.59
2	4.45	3.81	2.74	86	0.052	85.62	28.08
3	5.43	4.00	2.83	93	0.058	73.66	29.25
4	7.01	5.21	3.27	101	0.069	74.32	37.23
5	4.49	3.27	2.11	88	0.051	72.83	35.47
6	6.00	4.32	2.97	99	0.061	72.00	31.25
7	9.51	7.33	5.17	121	0.079	77.08	29.47
8	6.31	5.11	3.17	102	0.062	80.98	37.96
9	10.05	8.65	6.08	129	0.078	86.07	29.71
∑	58.70	46.51	31.39	917	0.566	710.82	295.01
AVE	**5.87**	**5.17**	**3.49**	**91.70**	**0.057**	**71.08**	**32.78**

3.1 DRYING KINETICS

The kitchen waste was dried to a thin layer using the heating chamber by introducing hot air. The variation in the moisture ratio of the wastes is a function of the drying time, at different inlet air velocities as presented in the graph in Figure 5. The airflow was varied at 50, 60, and 70^{0}C, with velocity flow rates of 1, 1.5, and 2m/sec respectively. It was observed that as the moisture ratio decreases the time taken increases with a reduction in the intensity of air and its flow rate (consistent with a similar observation by Nzioka *et al.*, 2016), and this can be attributed to non-characterization of the waste.

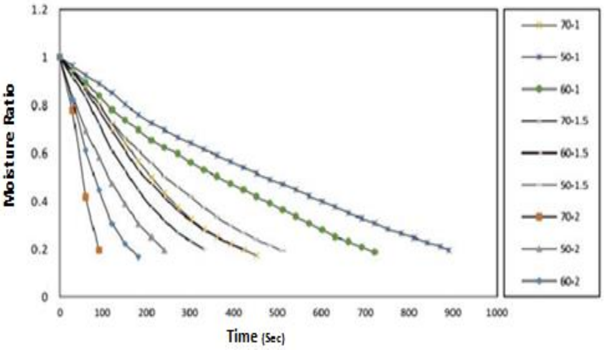

Fig. 5: Chart showing the Drying curves of moisture ratio over time per second.

4 CONCLUSION

The fabricated domestic kitchen waste comminution and drying machine powered by an electric motor, satisfied the general and functional requirements of converting biodegradable kitchen waste into disposable form. This mechanized method of grinding and drying kitchen waste has an average through-put, comminution, and drying efficiencies of 0.057kg/s, 71.08%, and 32.78 % respectively, which effectively aided the conversion process of organic waste and brings a transformation in the domestic waste management system. Also, it was observed that as the moisture ratio decreases the time taken increases with a reduction in the intensity of air and its flow rate, and this can be attributed to the non-characterization of the waste. The machine promotes kitchen and household hygiene while eliminating the negative effects of littering and indiscriminate dumping of organic wastes which serve as breeding sites for vectors (macro and micro-organisms) causing malaria, cholera, and typhoid. This innovation generates compost manure fast for farmers in addition to serving as an animal feed processing system, i.e. feed for poultry, piggery, and other animals. It should be embraced by Nigerians, individuals, commercial chefs, kitchen managers, catering services, and any hygienist, because of its simplicity of use, affordability, and low maintenance cost, combined with its positive impact on our domestic environment.

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