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Development and performance evaluation of a mini plastic crushing machine

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Abstract

Global plastic production has seen a significant surge owing to its versatile applications resulting in a large volume of plastic waste polluting the environment. However, the high cost and size of plastic crushers have hindered efficient plastic recycling efforts. This research focused on creating a cost-effective, portable plastic crusher tailored for local use. The machine comprises four main units: the feeding, grinding, power, and framework units. A 3D model was crafted using Solid Works software (2017 version 25), and essential components were constructed from mild steel. The feeder has a capacity of 837480 mm^3, a 20 mm diameter shaft with a power rating of 2.078 kW, and an outlet volume of 748692 mm^3. Performance tests using High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), Poly Vinyl Chloride (PVC), and Polyethylene Terephthalate (PET) indicated throughput capacities of 2.83, 2.71, 6.00, and 1.60 kg/h, respectively. The machine has efficiencies of 73.3%, 53.85%, 60%, and 50% for HDPE, LDPE, PVC, and PET, respectively. Notably, the portable plastic grinding machine excels in grinding HDPE, making it highly recommended for small and medium-sized enterprises. This innovation focused on bolstering plastic recycling efforts in localized contexts.

Keywords: Plastics; Environmental Pollutants; Feeder; Grinder; Power Transmitter; Frame; Electric Motor; Plastic Grinding Machine

1. Introduction

Globally, over 2.01 billion metric tons of Municipal Solid Waste (MSW) are generated annually and this figure is anticipated to increase to 3.40 billion tons by the year 2050. However, only 9-12% is recycled while the rest end up in landfills, incinerated, or leaked into the environment (Khurmi et al. 2005). In Nigeria, approximately 3.8 million tons of the 32 million tons of MSW generated annually are plastic. However, only a fraction of plastic waste is collected and recycled (Ogechukwu et al. 2020). Recycling enables the reuse of plastic waste for the production of new products, enabling `a circular economy (Abdulkarim et al. 2016). Plastics are non-degradable and recycling is part of a global effort to reduce their global environmental impact since about eight million tons of plastics are discharged into the ocean annually (Akash et al. 2019). Because most plastics are non-biodegradable, recycling within a circular economy becomes a viable alternative to burning and burying them in landfills (Bird 2002).

The use of plastics dates back to the early 1950s, and there has been continuous growth in the production of plastics worldwide by Edke et al. (2020) due to rapid urbanization, population growth, increased consumption, low production cost and packaging trends among others. A rise in the usage of single-use plastics, personal protection equipment, and environmental trash has been caused by the global COVID-19 pandemic, further complicating the issue (Geyer et al.

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2017). They are versatile, durable, impermeable to liquids, and highly resistant to physical and chemical degradation (Jadhav et al. 2018).

Plastic waste management or recycling is a major challenge in Nigeria due to poor awareness and lack of a legal framework for its disposal. Nigeria should take a clue from countries such as Canada and Denmark which levy customers for plastic bags and have made efforts to limit plastic waste to safeguard the lives on land and below water. While it is not economically wise to completely ban plastic production in Nigeria, existing and new policies within the regulatory framework aiming at minimizing the consequential environmental effects must be vigorously pursued (Verma et al. 2016). Although the effects of plastics on human health as a result of their presence in the environment are still largely unknown, some research suggests that the leaching of endocrine disruptors from plastic can be linked to a number of human health disorders (Geyer et al. 2017).

One of the major steps in plastic recycling is crushing. Crushing reduces plastic products into smaller shapes and particles which eases transportation and enhances other recycling steps. Crushing is important due to the limited presence of recycling facilities, which are primarily located in major cities such as Osogbo, Ota and Lagos in Southwestern Nigeria. As a result, plastic waste necessitates transportation to these locations or the use of alternative disposal methods.

Various machines have been fabricated to crush plastics into smaller pieces. However, most machines are expensive and bulky and therefore difficult to transport from one location to another. The crusher made by Ogechukwu et al. (2020) required manual cutting of the tip of plastic bottles before feeding while the shredding machine developed by Edke et al. (2020) was designed and customized for a particular type of plastic. The crusher developed by Olukanni et al. (2020) was big and heavy, about 200 kg, requiring two electric motors to function efficiently. Consequent upon these limitations, a portable and cheaper crusher was designed and reported here.

2. Design Concept

The design aimed to meet specific criteria: a high grinding rate, portability, cost-effectiveness, and satisfactory efficiency. The plastic crusher comprises four integral components: the feeding unit, the grinding unit, the power unit, and the frame, all meticulously designed to fulfill the specified criteria.

2.1. The Feeding Unit

The feeding unit, composed of the hopper and the domed head, receives the plastic waste before directing it to the cutters where cutting occurs. The cuboid-shaped hopper, with a volume of 837480 mm^3, was crafted from a 3 mm-thick mild steel plate and measures 120 × 99.7 × 70 mm^3. The domed head functions as the hinged top cover of the grinding chamber, facilitating ease of operation. Additionally, it acts as a protective shield for the operational cutter, with the stationary cutter securely welded to the inner extremities of the cover. The cover boasts a radius of curvature of 170 mm, a length of 390 mm, and a breadth of 263 mm.

2.2. The Grinding Unit

The grinding unit or chamber consists of the shaft, cutter assembly, net, bearing, bearing support, pulley, lower part, and outlet. The shaft, belt, and pulleys constitute the power transmission system. The shaft is supported by radial ball bearings (external diameter of 65 mm and internal diameter of 20 mm) to enable smooth rotation without wobbling. The radial ball bearings were chosen due to their exceptional level of performance and equal distribution of axial and radial loads. The solid shaft, made from mild steel, has a diameter of 25 mm and a length of 418 mm. The rotary cutter assembly, which consists of four blades, is connected to the shaft and cuts the plastic against a stationary cutter welded to the inner edge of the domed head. Each blade is 7 mm thick and 176 mm long and positioned at 121.8 mm from the axis of the shaft.

2.3. The Power Unit

There are two pulleys, the 20 mm-diameter small pulley, which is connected to the electric motor, transmits power through the belt to the 100 mm-diameter large pulley connected to the driven shaft. The lower part of the machine is a shelled cuboidal shape that supports the net and the outlet. The lower part also formed the half of the grinding chamber which shielded the half portion of the cutter assembly. It is welded to the frame and measures 248 mm in length, 191.97 mm in breadth, and 230 mm in height. This outlet or discharge collects the ground plastics and creates a path through which the ground plastics exit the machine.

2.4. The Frame

The frame, made from mild steel and with a dimension of 445.36 mm high, 388 mm in length and 300 mm in breadth, gives the machine support and stability.

2.5. Detailed Design Calculations

2.5.1. Design of the Large Pulley

The design of the large pulley is based on the power and speed needed to be transmitted to the shaft. Given the thickness of the pulley to be 25 mm and the inner and outer diameter of the pulley as 20 and 100 mm, respectively, then:

Volume of the pulley = area of the pulley x thickness

Area of the pulley= $\left\{\frac{\pi}{4} \times (100^2 - 20^2)\right\} = 7539.82\ \text{mm}^2 = 7.54\ \times 10^{-3}\ m^2$

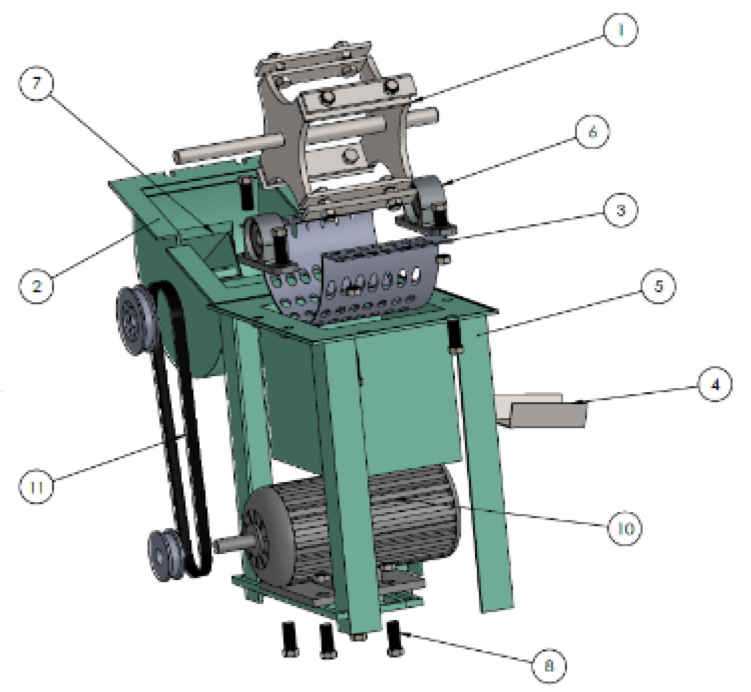
Thickness of the pulley as designed = 25 mm

The volume of the pulley $= 7539.82 \times 25 = 188495.56\ \text{mm}^3$ or $1.88 \times 10^{-4}\ \text{m}^3$

Weight of the pulley $= \rho_{\text{steel}} \times$ volume of the pulley $\times$ g (Khurmi & Gupta 2005)

where; ρ_{steel} = density of mild steel $= 7850\ \text{kg/m}^3$ and $g = 9.81\ \text{m/s}^2$

Therefore, the weight of the pulley $= 7850 \times 1.88 \times 10^{-4} \times 9.81 = 14.52$ N



11	BELT DRIVE 2	1
10	MOTOR	1
9	NUT	10
8	BOLT	10
7	The inlet	1
6	Ball Bearing Support	2
5	Frame and the lower part	1
4	Outlet	1
3	net	1
2	Domed cover	1
1	Shaft and cutter assembly	1
ITEM NO.	DESCRIPTION	QTY.

Figure 1 Exploded view of the plastic slicer

2.5.2. Design of the cutter assembly and shaft

The cutter assembly was mounted on the shaft. The weight added to the shaft due to the cutters mounted on the shaft is also considered while designing.

Area of the circle from which the frame that supports the blade of the cutter assembly is designed $= \frac{\pi}{4} \times (D_2^2 - D_1^2) - (4 \times \text{Area of the segment of the circle cut out})$ (1)

where D_1 and D_2 are the outer and inner diameters, respectively.

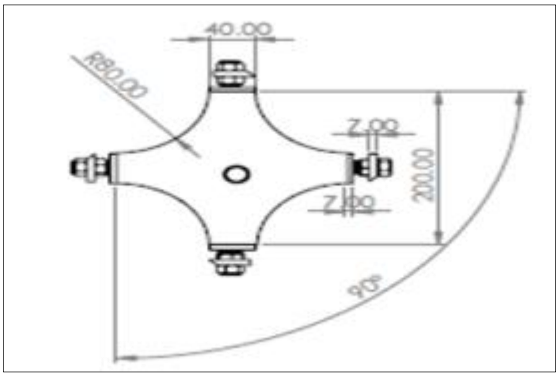


Figure 2 Cutter assembly

The cutter assembly is shown in Figure 2.

Area of the segment of the circle cut out (Bird, 2002) $= r^2 \left[\frac{\theta\pi}{360} - 0.5 sin\theta\right]$ (2)

$$= 80^2 \left[\frac{90\pi}{360} - 0.5\sin(90)\right] = 1826.55\ mm^2$$

Area of the circle from which the frame that supports the blade of the cutter assembly is drawn or designed $= \frac{\pi}{4} \times (D_2^2 - D_1^2) - (4 \times 1826.55)$

$$= \frac{\pi}{4} \times (200^2 - 25^2) - (4 \times 1826.55) = 30925.05 - 7306.19 = 23618.86\ mm^2$$

Given a 7 mm-thick cutter, its volume = $23618.86 \times 7 = 165332.02\ mm^3$ or $1.65 \times 10^{-4}\ m^3$ The weight of the cutter = $7850 \times 1.65 \times 10^{-4} \mathrm{m}^3 \times 9.81 = 12.73$ N

Total weight of the frame that supports the blade of the cutter assembly $=$ n $\times$ 12.73

Where n = number of the frame that supports the blades $= 2$

Total weight of the frame that supports the blades $= 2 \times 12.73 = 25.46$ N

Also, the weight of the blades = number of blades (n) x volume of each blade x $\rho_{\mathrm{steel}} \times 9.81$ (3)

Weight of the blades = $8 \times 4.928 \times 10^{-5} \times 7850 \times 9.81 = 30.36\ N$

Where 8 is the number of blades which is 4 blades + 4 flat bars that the blades were bolted with.

Total weight of the cutter assembly acting on the shaft = weight of the frame that supports the blade of the cutter assembly + weight of the blades = $25.46 + 30.36 = 55.82\ N$

2.6. Design of the Shaft

The shaft design is dependent on the forces or weights acting on it due to the cutter assembly, the reactions of the bearings supporting the shaft, and the torsional strength of the shaft due to the rotary motion of the shaft. Since the two shafts are carrying the same load except for the additional load of the pulley carried by the first shaft, only the shaft carrying the pulley shall be considered (Fig. 3a). The shear force and bending moment of the shaft are analyzed based on the free-body diagram of the shaft (Fig. 3b).

The reactions at the bearing support along the length of the shaft, Ray and Rdy, can be obtained by using force and moment equations:

From the force equilibrium: $\text{Ray} + \text{Rdy} = (317.16 \times 0.176) + 14.52 = 70.34$

For the moment equilibrium at A, $\Sigma M_A = 0$;

$$317.16 \times 0.176(0.088 + 0.074) - Rdy \times (0.074 + 0.176 + 0.07) + 14.52 \times 0.42 = 0$$

$Rdy = \frac{9.04+6.098}{0.32} = 47.32\ N, Rcy = 70.34 - 47.32 = 23.02\ N$

Diameter of the Shaft

The diameter of the shaft was calculated using Equation. (4) (Khurmi & Gupta 2005)

$$\frac{\tau}{r} = \frac{T}{I_p} \tag{4}$$

Where T is the torque to be transmitted by the shaft which is 30.65 Nm, the polar moment of inertia for the shaft section $I_p = \frac{\pi}{32} d^4$ and the torsional shear stress $\tau = 42$ MPa

Accordingly, the diameter of the shaft can be obtained as follows:

$$d = \sqrt[3]{\frac{16T}{\pi \times \tau}} = \sqrt[3]{\frac{16 \times 30.65}{\pi \times 42 \times 10^6}} = 0.0155 m\ or\ 15.5 mm \tag{5}$$

Therefore a shaft of 20 mm diameter is selected

From Figure. 3 (a), the shear force analysis and bending moment were obtained as follows:

Shear force analysis:

Let S = shear force and taking each section,

Between A and B; $S_{AB} = 23.02\ N$

Between B and C; $S_{BC} = 23.02 - (317.16 \times 0.088) = -4.89\ N$

Between C and D; $S_{CD} = 23.02 - (317.16 \times 0.176) + 47.32 = 14.52\ N$

Between D and E, $S_{DE} = 23.02 - 317.16 \times 0.176 + 47.32 - 14.52 = 0\ N$

The shear force diagram and the bending moment diagram are shown in Fig. 2b

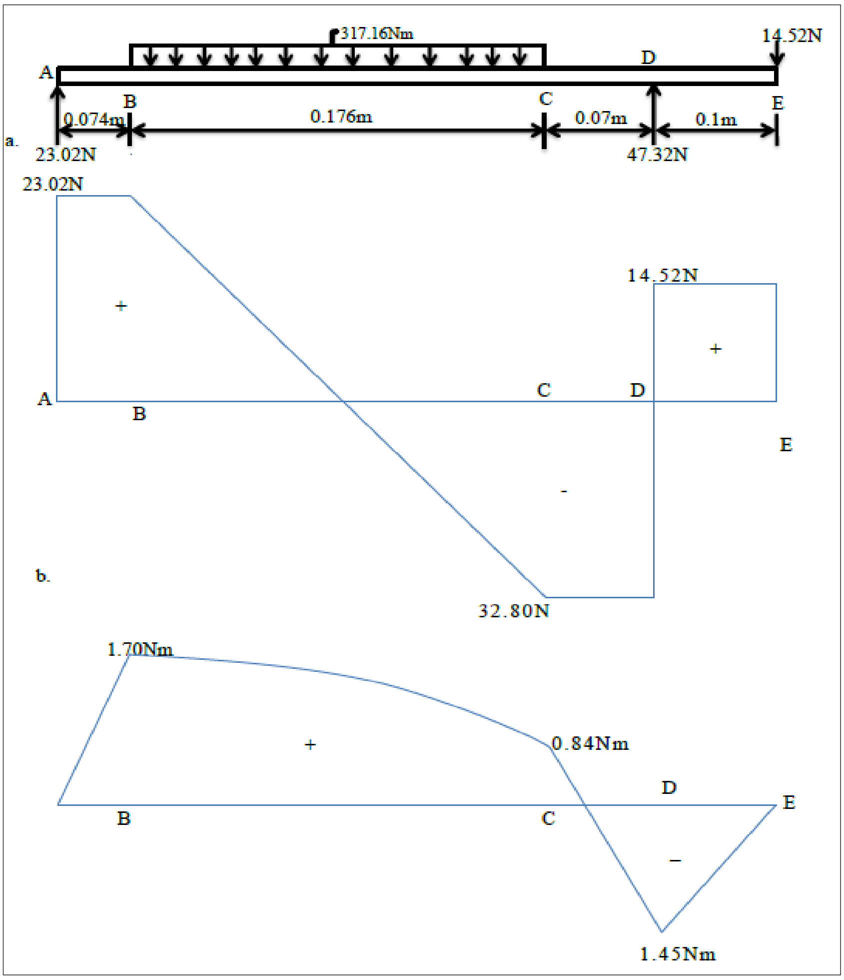


Figure. 3 (a) Free body diagram of the shaft and forces acting on it (b) The shear force and bending moment diagrams of the shaft

2.6.1. Bending moment analysis

Let M = bending moment

Between points A and B; $M_{AB} = 23.02x$ (Where x is the distance between A to B); at A; $M_A = 0$; at B; $M_B = 23.02 \times 0.074 = 1.70Nm$

Between B and C; $M_{BC} = 1.70 + 46.50x - 158.58x^2$ (Where x is the distance from B to C)

At point C; $M_C = 23.02 \times 0.25 - 317.16 \times 0.176 \times 0.088 = 0.84\ Nm$

Between C and D; $M_{CD} = 0.84 - 32.80x$ (Where x is the distance from C to D)

At point D; $M_D = (23.02 \times 0.32) - (317.16 \times 0.176 \times 0.158) = -1.45\ Nm$

Between points D and E; $M_{DE} = -1.45 + 14.5x$ (Where x is the distance from D to E)

At point E; $M_E = (23.02 \times 0.42) - (317.16 \times 0.176 \times 0.088) + (47.32 \times 0.10) = 0.00\ Nm$

2.7. Design Analysis of the Belt and the Pulleys

Belt and pulleys were chosen based on the transmitting torque or power from the electric motor to the cutter shaft and this also depends on the center distance between the driver and driven shaft. The center distance, the type of belt (V-belt), and the diameter of the driver and driven pulleys are chosen due to the power needed to be transmitted to the driven shaft. The speed of the motor N_m chosen was 1440 rpm, center distance x was 352 mm, and the diameter of the crankshaft pulley D_s is 100 mm and the diameter of the motor pulley D_m is 50 mm.

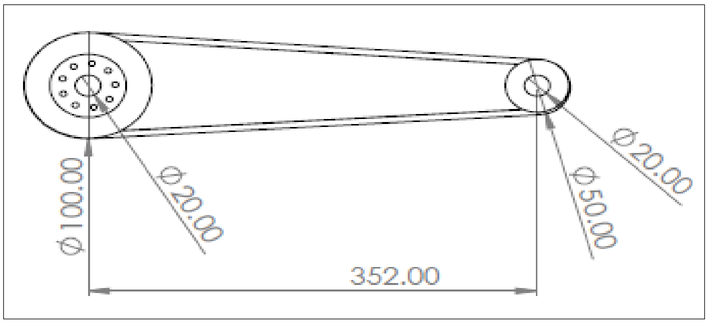


Figure 4 Diagram of the pulley system

The speed transmitted to the crankshaft N_s is calculated as 720 rpm based on the equation below:

$$\frac{N_s}{N_m} = \frac{D_m}{D_s} = \frac{N_S}{1440} = \frac{50}{100} = N_S = \frac{1440 \times 50}{100} = 720 \text{ rpm} \quad (6)$$

The torque transmitted by the shaft $T = \frac{power\ of\ the\ motor}{\omega}$ (Khurmi & Gupta 2005) (7)

$$where, \omega = \frac{2\pi}{60} N_s = \frac{2\pi}{60} \times 720 = 75.4\ rev/s \quad (8)$$

And the power of the electric motor is 2 hp ≅ 1491.4 $Watt$

Therefore, $T = \frac{1491.4}{73} = 20.43\ Nm$

The length of the belt is calculated as 0.94 m using Eq. (9):

$$L = \frac{\pi}{2}(D_m + D_s) + 2x + \frac{(D_s - D_m)^2}{4x} \quad (9)$$

$$L = \frac{\pi}{2}(50 + 100) + 2 \times 352 + \frac{(100-50)^2}{4 \times 352} = 75\pi + 704 + 1.78 = 941.4\ mm$$

The electrical energy consumed by the machines is 1.5 kWh using

$E = IVt$ (Bird, 2002), (10)

where $V = source\ voltage = 240\ V$ and $I = source$ current $= 10\ A$.

2.7.1. Working Principle of the Plastic Grinding Machine

Plastic bottles occupy more space than most other wastes. Therefore, crushing them enhances their ease of transportation from the point of collection to the point of recycling. The plastic crushing machine in Figure 1 operates based on a lever system attached to a crankshaft. The crankshaft bears the cutters, which crush the plastic bottles by forcing them against stationary cutters. The lever mechanism (V-belt) is powered by an electric motor which was determined by the number of plastic bottles that were crushed per second. The pulleys and the belt constitute the power transmission unit. The crank plate was attached to the shaft, which was also made of mild steel. Ball bearings are present to reduce friction on the shaft while it rotates and avoid bending stresses from acting on the torsional rods. It was ensured that the diameter of the crank plate is small to enhance the high working speed of the machine. The rotary motion of the pulley rotates the crank plate. The frame, upon which most other components rest, was made of mild steel. Figures 5 (a) and (b) show the 3D model of the plastic grinder and the actual machine developed.

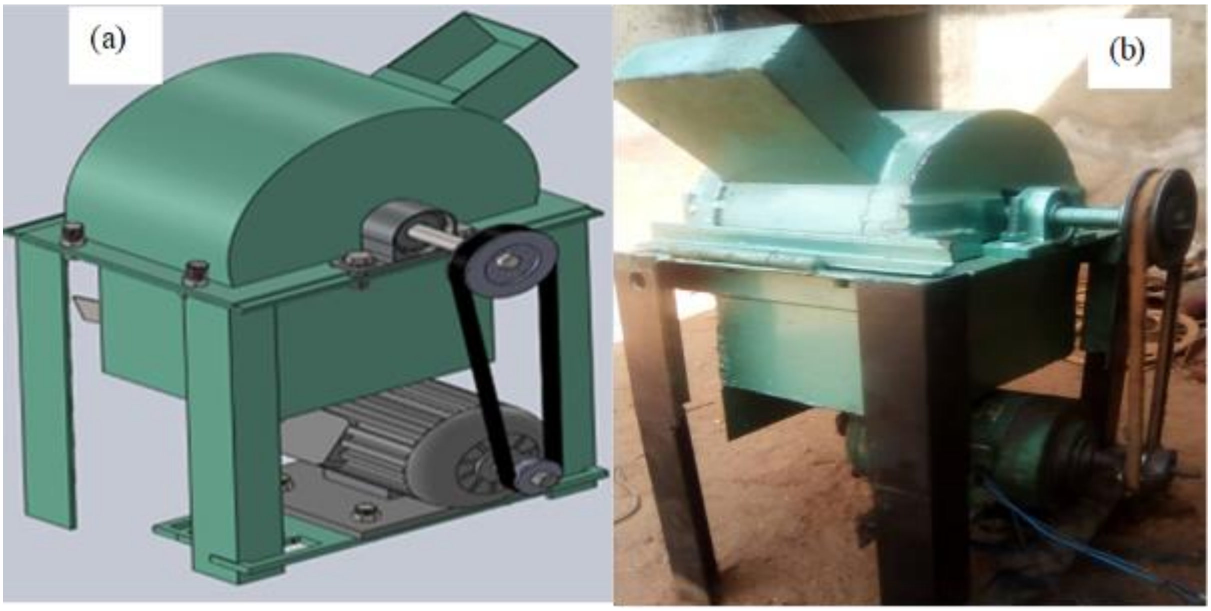


Figure 5 (a) 3D model of the plastic grinder and (b) the actual grinder

3. Results and Discussions

3.1. Performance Evaluation

The performance evaluation of the machine was carried out with four categories of plastics namely; high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinylchloride PVC, and Polyethylene terephthalate (PET). The samples were gathered from a local community in Ogbomoso, Oyo State, Southwest Nigeria. The crushing was done in two batches for each type of polymer at the machine speed of 1440 rpm. The average weights of the original and crushed plastics were measured and recorded. The Machine Throughput Capacity (MTC) is calculated in terms of the grinding rate.

$$Average\ Grinding\ Rate\ (AGR) = \frac{Average\ weight\ of\ plastics\ fed\ into\ the\ machine\ (M_f)}{average\ time\ (t)} \quad (11)$$

The efficiency of the machine (η) is the ratio of the average mass of plastics ground by the machine to the desired size (M_g) to the average mass of plastics fed into the machine (M_f) i.e.

$$\eta = \frac{M_g}{M_f} \times 100 \quad (12)$$

The MTCs and crushing efficiency for all the plastic samples are presented in Table 1 and Figure. 6. Accordingly, both the MTC and crushing efficiency differ for different plastic types. The MTC for HDPE, LDPE, PVC, and PET are 2.83, 2.71, 6.00, and 1.60 kg/h, respectively. This implies the machine has the highest throughput capacity when crushing PVC while the lowest value was obtained for PET. Similarly, the crushing efficiency was 72.30, 53.03, 60.00, and 50.00% for HDPE, LDPE, PVC, and PET, respectively. These results indicate that it is easier to crush HDPE, LDPE, and PVC than PET. The pictorial views of the plastics before and after crushing are shown in Table 2 which indicates efficient crushing of the plastic wastes. This study, therefore, depicts that plastic wastes of different sizes can be reduced to smaller sizes, about 4 mm in diameter, using the fabricated plastic crushing machine.

In comparison with the existing literature by OECD (2018), the developed machine is portable, unlike the previous machines which are bulky or complex (Table 3). It was also observed that one of the earlier machines made from cast iron grinds faster with less noise compared to the fabricated machine. Also, the current machine is unable to crush PET as efficiently as other types of plastics. Consequently, a bailer or a pelletizing machine will be more effective.

Table 1 Performance evaluation of the crusher based on different polymer types

Polymer	**M_f (kg)**			**M_g (kg)**			**Time t (s)**			**MTC**		**Efficiency (%)**
	M_{f1}	M_{f2}	Average	M_{g1}	M_{g2}	Average	t_1	t_1	average	(kg/s)	(kg/h)	
HDPE	0.40	0.35	0.38	0.30	0.25	0.275	489	464	476.5	0.00079	2.83	72.30
LDPE	0.30	0.35	0.33	0.15	0.20	0.175	424	441	432.5	0.00075	2.71	53.03
PVC	0.40	0.40	0.40	0.25	0.23	0.240	254	226	240.0	0.00167	6.00	60.00
PET	0.20	0.30	0.25	0.10	0.15	0.125	512	614	563.0	0.00044	1.60	50.00

M_f = Mass fed into the machine (kg), M_g = Mass of plastics crushed (kg), t = crushing time (s), MTC - Machine Throughput Capacity

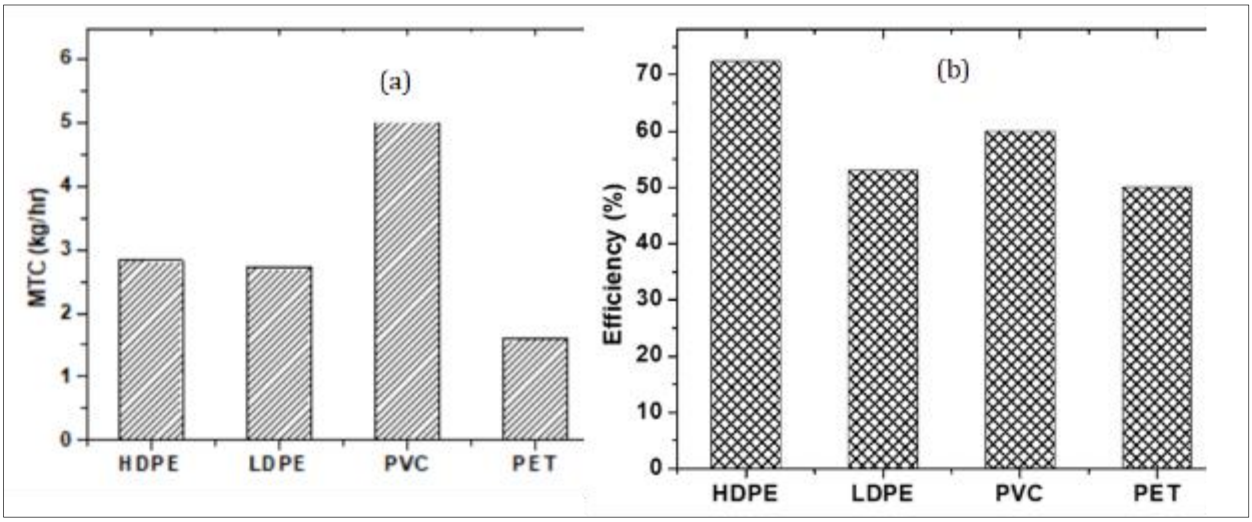


Figure 6 (a) Machine Throughput Capacity (MTC) and (b) efficiency of the crushing machine

Table 2 Table showing pre and post-crushed states of the different plastic types

S/N	Polymer	Before Grinding	After Grinding
1	High-Density Polyethylene (HDPE)		

2	Low-Density Polyethylene (LDPE)		
3	Polyvinylchlo ride (PVC)		
4	Polyethylene Terephthalat e (PET)		

Table 1 shows a comparative study of the existing crushing machines based on parameters such as size, the system of operation, Efficiency, Technical- know-how and cost.

Table 3 Comparison of the previous literatures and the present work

	Jadhav et al. 2018	**Vijayananth et al. 2018**	**Owunna 2018**	**Shiri et al. 2017**	**Present work**
Size	Bulky (150 kg)	Portable (50 kg)	The machine is bulky (120 kg)	Very bulky (1880 kg)	Portable (40kg)
System of operation	Requires a series of processes	Very complex system of operation	Imperfections in the shredder in blade design	Design system is complex	Simple system of operation
Efficiency	35 %	63.45 %	53.6 %	80%	72.30 %
Technical Know-how	Requires expertise in its operation	Made use of a prime mover at three different speed levels	Complex requires automation	Requires high technical know-how in its operation	No technical know-how is required (can be operated by a layman)
Cost	Cheap,13,000 rupees (# 73478)	Expensive, 40,000 rupees (# 226,087)	Expensive (# 453,000)	Very expensive (# 531,000)	Less expensive (# 102,600)

4. Conclusions

A portable, low-cost, and highly efficient plastic crushing machine has been developed for small-scale applications. The machine is effective for grinding plastics such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinylchloride PVC, and Polyethylene terephthalate (PET) at a mean throughput capacity of 2.83, 2.71, 6.00, and 1.60 kg/h, respectively. When appropriately deployed, the machine can help promote plastic recycling process which is a significant way of controlling pollution. The machine is safe to use with a compact housing, requires non – professionalism, and is user-friendly. The machine throughput can be enhanced by increasing the size for commercial purposes.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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