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Development and Performance Evaluation of an Improved Waste Plastic Shredding Machine

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Abstract
An energy-efficient plastic shredder was developed to recycle waste plastic, focusing on energy conservation and environmental sustainability, thereby reducing pollution and landfill space exhaustion. This paper presents a 60 kg plastic shredding machine designed and fabricated to address the environmental impact of plastic waste. The machine uses a combination of belt and gear drives, enhancing energy utilization. A 5.0 hp electric motor-powered machine was used to shred 10kg of polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and polypropylene (PP) each at various sieve sizes of 10 mm, 7.5 mm, and 5.0 mm, determining its shredding time, specific mechanical energy, and recovery efficiency. The flakes of waste plastic were weighed and collected for testing. The percentage retention of PET, HDPE, PVP, and PP flakes was determined by analyzing the efficiency of shredding, recycling, machine efficiency, and fragments in reducing plastic waste of size 10 mm² x 10 mm². The shredder achieved an optimal performance of 53.6% in shredding PET and 52.3% in HDPE, with 95% and 83% recovery efficiency, and reduced specific mechanical energy by 1% within 2 minutes. PP, with 48% shredded, reduced PVC by 61% with a 10 mm sieve size, achieving 94% recovery efficiency and 100% increased throughput to 238.1 kJ/kg. The shredder demonstrated exceptional performance in shredding PET and HDPE, with an average particle size of 6.29 mm², achieving 95% recovery efficiency and reducing specific mechanical energy within 2 minutes. The low-cost, efficient, and user-friendly machine enhanced recycling activities, promoted technology transfer, and improved waste processing for local entrepreneurs.

Keywords: *Plastic shredder, pollution, recovery efficiency, recycling, waste processing.*

1.0 Introduction

Plastics release hazardous substances into the environment and cause pollution (Nagpurkar *et al.*, 2018). Recycling waste plastics can be used to create new products like containers, lumber, and particle boards. Recycling is crucial for removing non-biodegradable plastic waste, which poses environmental and health risks, especially in developing economies like Nigeria (Shiri *et al.*, 2017). This conservation of energy and clean environment is a focus for attention. The plastic shredding machine effectively addresses waste plastic recycling issues and generates energy for human use by optimizing drive mechanism design parameters (Okunola *et al.*, 2016; Siddiqui *et al.*, 2017).

Plastic is a widely used and essential material in daily life, according to Shulipi and Monika (2013). This includes polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polystyrene or Styrofoam (PS), and various polymers like polycarbonate, polylactide, acrylic, acrylonitrile butadiene, styrene, fiberglass, and nylon (Momodu *et al.*, 2015). Plastic packaging generates significant waste due to its non-biodegradability, short life cycle, and rapid depletion of natural resources (Aderogba and Afelumo, 2012). Plastic waste accumulation in waterways and oceans, categorized into polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), and low-density polyethylene (LDPE), poses significant pollution concerns (Jaff et al., 2016). Global plastic waste, accounting for over 60% of municipal solid waste, poses a significant global challenge in waste management, necessitating urgent attention to address resource and energy issues (UNE, 2018).

Research on solid waste challenges in Nigeria and Africa is limited, while efforts on plastic waste in Nigerian cities and towns are ongoing. The development of a low-cost waste plastic shredding machine using local materials was necessary to overcome the challenges of high-cost and bulky machinery in these countries. Informal sector plastic producers face high production costs, impacting product pricing. Recycling addresses society's growing waste disposal crisis, requiring expansion and cheaper machinery to address issues and produce new products (Jonescu *et al.*, 2013).

Recycling systems collect and divert waste from landfills and process it into recyclable materials. Sustainable plastic waste management requires cost-effective processes involving all sectors, including industries and local communities (Ikpe and Owunna, 2017; Ayo *et al.*, 2017). Plastic garbage alone makes up more than 20% of Nigeria's municipal solid waste stream (Emagbetere *et al.*, 2017), making it a problem that affects the whole world. Global warming and the scarcity of safe drinking water in Nigeria's growing population have led to a constant demand for bottled water. Nigeria's plastic

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waste is sourced from various sectors, including agriculture, electronics, automotive, construction, consumer goods, furniture, sports, health and safety, and packaging (UNE, 2018).

Plastic recycling reduces energy consumption, costs, and imports of virgin resin, creating jobs and sourcing foreign exchange, making it more affordable for people. Recycling saves funds on drainage, landfill management, and ocean cleanups while benefiting the economy by generating revenue and creating new jobs, addressing unemployment in Nigeria (Hoornweg *et al.*, 2013; Dutta and Choudhung, 2018). Ugoamadi and Ihesiulor (2011) designed a plastic recycling machine using locally available materials for waste polythene bags, film sheets, and PET bottles. It was suggested a belt and pulley system for improved efficiency. Okiy *et al.* (2018) developed a pneumatic injection plastic molding machine and simulated die assembly using ANSYS software. Atadius and Oyejide (2018) improved the machine design with belt and pulley transmission for thin plastic filament production for efficiency.

A plastic shredder is being developed to conserve energy, maintain cleanliness, and produce new products by recycling waste plastic into small pieces for transportation and processing. The study aims to improve the efficiency of a plastic shredder, transforming plastic waste into reusable products, sustainable energy, and community employment.

2.0 Materials and Methods

The material selection was based on factors such as availability, ease of fabrication, maintenance, noise reduction, low production cost, aesthetics, durability, and resistance to wear and corrosion.

The machines constructed from mild steel, cast iron, and chemical paint are designed considering safety, power, compactness, ease of operation, and overall production cost. The v-belt drive is chosen for its optimal combination of fraction, rotation speed, bearing load, and belt service life. The belt drive's operation depends on frictional force and belt elasticity, requiring a short inter-pulley distance. The shaft design follows Tables 1 and 2 specifications.

Table 1: Operating condition (Raji *et al*. 2020)

Design specification	Value
Hours per day duty	10
Power rating of prime mover, P_n	5 hp
Rotational speed of prime mover	1400 rev/min
Rotational speed of drive shaft	980 rev/min
Service factor, Ks	1.3
Sheave center distance, C	1400 mm

Table 2: Design specification (Raji *et al*. 2020)

Parameters	Value
Design load	60 kg
Rotational speed of shaft	980 rev/min
Power transmitted, P_d	2.91 kW
Bending factor for shock, k_m	2
Torsion factor for fatigue, k_t	1.5
Allowance Stress, τ_{all}	40 Mpa

2.1 Design Criteria and Calculations

The plastic shredding machine design prioritizes affordability, ease of operation, material availability, strength, durability, and small size, featuring an electric motor, local materials, and high tensile strength. The velocity ratio for a belt drive is the mathematical expression of the difference between the velocity of the driver and the follower as contained in equation 1 (Baishya *et al.*, 2015). The belt is pre-loaded with tension (T_o) to prevent slippage on the pulleys, as contained in equation 2. The belt friction forces, belt wrap angle, and center distance between the driving and driven pulleys are determined using equations 3 to 5 (Daniyan *et al.*, 2017).

$$\frac{N_2}{N_1} = \frac{D_1}{D_2} \quad (1)$$

$$2T_o = T_p + T_n \quad (2)$$

$$\frac{T_p}{T_h} = \exp\left(\frac{\mu\theta}{\mathrm{Sin}\frac{\beta}{2}}\right) \quad (3)$$

$$\theta = \pi \pm 2\mathrm{Sin}^{-1}\frac{D-d}{2C} \quad (4)$$

$$C = 2D_1 + D_2 \quad (5)$$

The required torque for operation is determined by pull and hold forces, belt length, and shaft design dimensions, considering bearing supports, mounted components, and dynamic as contained in 6 and 7 (Atadiou and Oyejide (2018). The angle iron support beam and frame stand are designed to resist bending and buckling, ensuring the lengths of each stand do not exceed Lc as expressed in equations 8 to 10 (Ayo *et al.*, 2017).

$$F_R = (T_p^2 + T_h^2 - 2T_pT_h\text{Cos}\theta)^{1/2} \quad 6$$

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \frac{D_1+D_2}{4C} \quad 7$$

$$T_D = \frac{60PK_L}{2\pi N} \quad 8$$

$$L_c = \pi\sqrt{\frac{EI_{xx}}{F}} \quad 9$$

The mild steel feed hopper feeds shredded polyvinyl chloride to the extruder, with a feeding chute capacity of 2.1 x $10^{-2}m^3$ considering the hopper's cross-section area and width. The calculation of shredding force, power, and angular velocity for converting plastic bottle waste into desired sizes is based on equations 10, 11, and 12. Each of the components was designed and fabricated (John et al., 2019).

$$T = Fr \quad 10$$

$$P = \frac{P\omega}{60} \quad 11$$

$$\omega = \frac{2\pi N}{60} \quad 12$$

The shaft design considers dimensions for strength and load integrity, considering bearing supports, mounted components, and dynamic, as illustrated in Figure 1

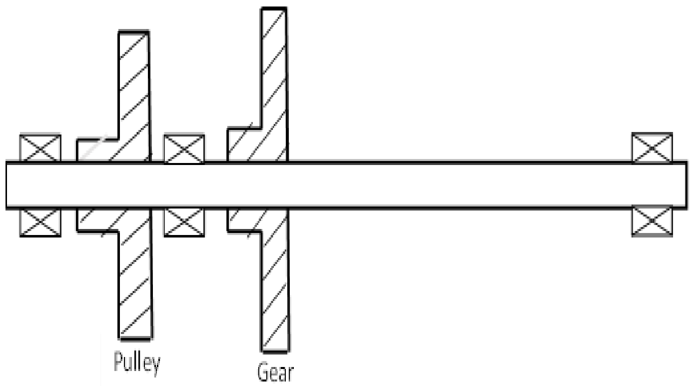

Figure 1: Shaft design

Equations 13 to 19 are used to determine the percentage retention of bottles, which shows how well shredding, recycling, machine efficiency, and fragment reduce plastic waste of size 10 mm² x 10 mm² (Ikpe *et al.*, 2017; Ayo *et al.*, 2018).

$$M_{sr} = M_1 - M_s \quad 13$$

$$R_t = \frac{M_{sr}}{M_1} \times 100 \quad 14$$

$$S_\eta = \frac{M_{s1}}{M_s} \times 100 \quad 15$$

$$R_\eta = \frac{M_0}{M_1} \times 100 \quad 16$$

$$S_{ME} = \frac{P_t}{Q} \quad 17$$

$$\varepsilon = \frac{W_R}{W_F} \quad 18$$

$$\eta = \frac{W_P}{W_R} \quad 19$$

Figure 2 presents a stepwise design layout flow chart for the shredding machine, from material selection to assembly stage.

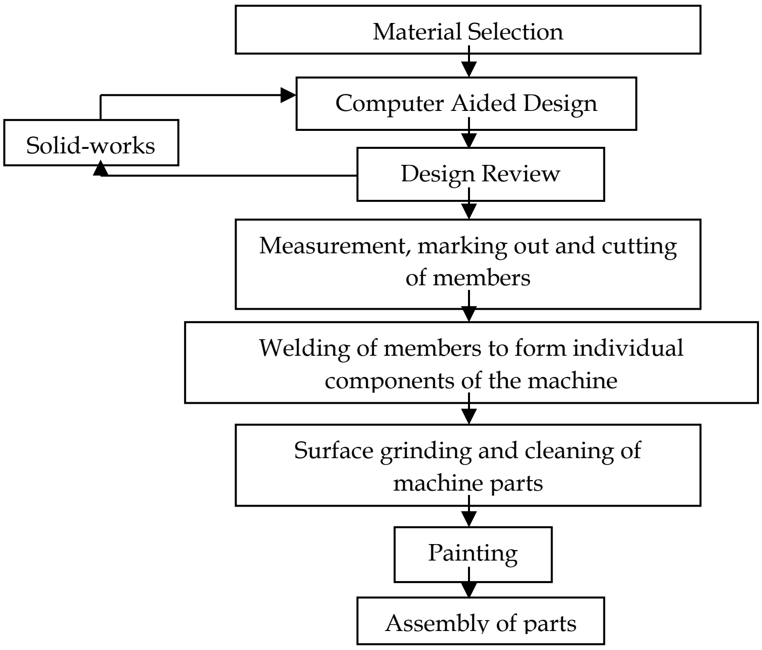

Figure 2: Flow chart of design steps

2.2 System Description

The waste plastic shredder comprises a feeding, shredding, cutting, power, and machine frame made of a 16-gauge galvanized mild steel sheet. The machine is powered by a prime mover that moves through the belt to the driven pulley shaft and the machine frame. The shredding unit is designed to reduce waste plastic into smaller pieces, consisting of a 50mm-long shaft and a 55mm-long, 200mm-diameter cylinder. The feeding unit facilitated the transfer of waste plastics into the shredding unit, which was equipped with a 50mm shaft and a 30mm diameter cylinder. The shredding unit is equipped with 12mm mild steel cutters, serrated teeth, and galvanized mild steel outlet for efficient plastic shredding. The process involved marking, cutting, welding, and finishing components to achieve the desired shape and dimension, then assembling them to create the desired machine, as shown in Figures 3 and 4 (Tolulope, 2016). The machine design concept is presented in Figure 5.

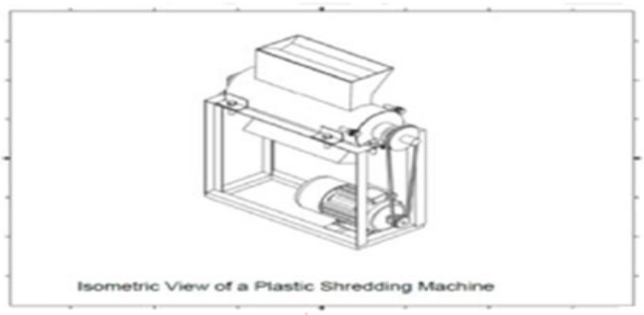

Figure 3: *CAD of Shredding Machine*

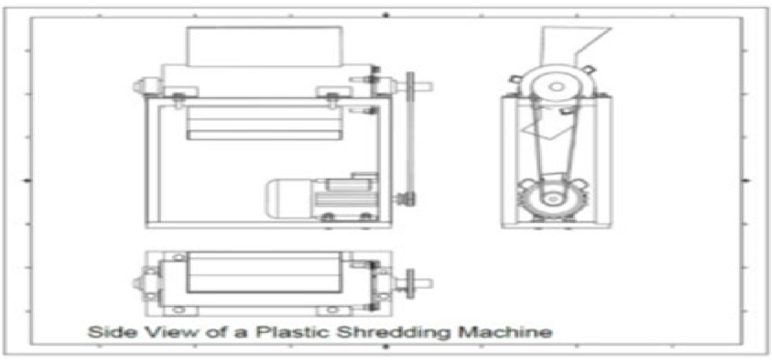

Figure 4: Orthographic drawing of shredding machine

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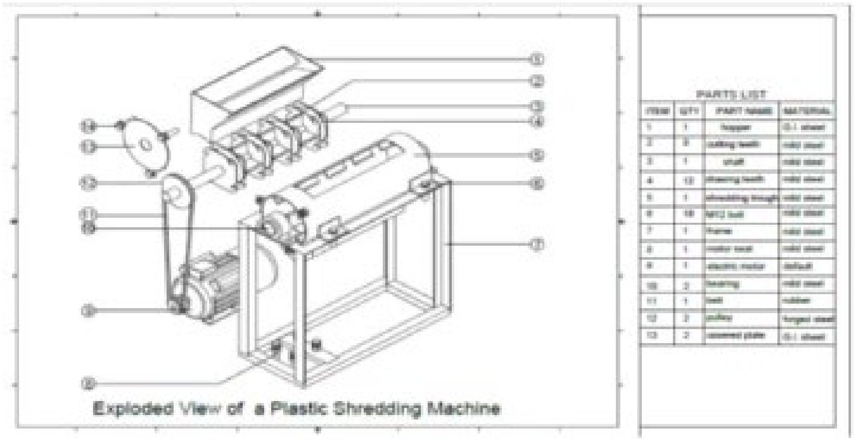

Figure 5: Exploded view of the shredding machine

2.3 System Fabrication and Assembly

The components were designed and fabricated following the proper fabrication process, as illustrated in Figure 6. The shredding unit is a machine used to cut waste plastic into smaller pieces, consisting of a 50mm-long shaft and a 55mm-long, 200mm-diameter cylinder. The machine utilizes a 5 hp electric motor, a 110 mm diameter driven pulley, and a 60 mm diameter driver pulley to shred waste plastic and discharge it freely.

Figure. 6: Modified shredding machine

2.4 System Performance Evaluation

The shredding machine successfully shredded 10 kg of PET, HDPE, PVC, and PP each at different sieve sizes. The machine's shredding time, specific mechanical energy, and recovery efficiency were assessed by measuring the initial plastic mass and sieving it using a 10mm screen for different sizes. Four plastic types (PET, HDPE, PVC, and PP) were shredded at 1400 rpm motor speeds but at varying times. The system performance evaluation involved analyzing results from four different sizes of shredded plastic for eight minutes each. The test assessed the efficiency of shredding, recycling, machine efficiency, and fragments in reducing plastic waste by weighing and collecting flakes and determining waste fragment retention percentages.

3.0 Results and Discussion

Tables 3 to 5 present machine performance results, while Figure 12 summarizes average size and percentage of plastic shredded at four different sieve sizes. The shredder achieved an optimal performance of 53.6% in shredding PET at a sieve size of 10 mm, with an average shredded size of 5.07 mm². The machine shreds a bottle in 3 minutes with a recovery efficiency of 95% and minimal specific mechanical energy at 392 KJ/kg, with a throughput of 19 kg/hr.

HDPE, with 48% shredded, has an average particle size of 13 mm² compared to 12.23 mm² for PVC. The shredder performed optimally at a 7.5 mm sieve size for PET shredding, achieving 52.8% output within 2 minutes and an average particle size of 6.29 mm². PVC SME reduced by 61% with a 10 mm sieve size, 94% recovery efficiency, and 100% increased throughput to 238.1 KJ/kg, followed by HDPE and PP with minimal variance. The machine shredded 53.3% of PET plastic into 7.51 mm² particles in 2 minutes, reducing specific mechanical energy by 1% and achieving 95% recovery efficiency with a 31.67 kg/hr throughput. The machine efficiently shredded 52.3% of HDPE with an average particle size of 4.58 mm² within 4 minutes, achieving an 83% recovery efficiency. The summary of the system performance is as stated in Figure 7.

Table 3: Shredded plastic at 10 mm

	PET		HDPE		PVC		PP	
S/N	Ave. size (mm²)	% shredded	Ave. size (mm²)	% shredded	Ave. size (mm²)	% shredded	Ave. size (mm²)	% shredded
1	0.66	13.4	1.01	12.5	3.71	28.1	4.48	13.8
2	1.89	27.8	4.53	28.5	8.04	24.6	11.70	27.7
3	5.07	53.6	13.60	48.0	12.23	37.3	18.05	37.0

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Table 4: Shredded plastic at 7.5 mm

	PET		HDPE		PVC		PP	
S/N	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded
1	0.79	14.8	0.64	12.6	1.07	24.1	2.12	15.7
2	1.73	26.7	3.25	23.2	5.32	27.6	6.44	30.0
3	6.29	52.8	8.27	48.8	10.21	39.4	14.25	40.0

Table 5: Shredded plastic at 5 mm

	PET		HDPE		PVC		PP	
S/N	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded	Ave. size (mm^2)	% shredded
1	0.93	16.2	0.53	13.5	0.36	20.1	0.67	15.1
2	1.62	25.6	2.12	17.4	1.89	30.5	1.18	29.8
3	7.51	53.3	4.58	52.3	7.32	41.5	2.86	40.5

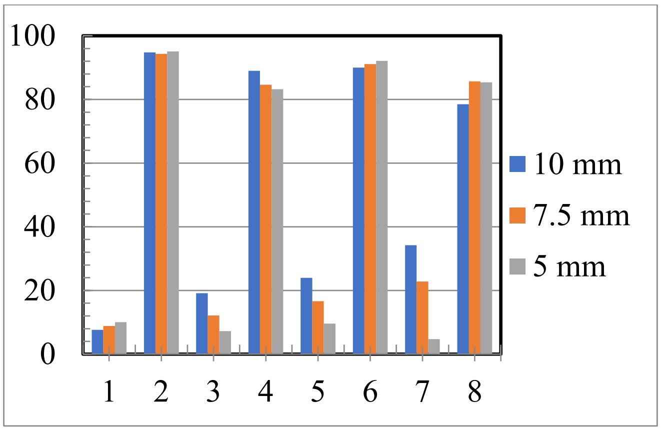

Figure 7: Machine performance with three sieve size

The research evaluates the efficiency and suitability of a plastic shredding machine designed for domestic and commercial use in various Nigerian cities. The plastic shredding machine can effectively decrease plastic bottle waste, thereby promoting a healthier environment for the average citizen. The processing of waste plastic materials will improve the production of high-quality products for domestic and industrial use (Pavankumar et al., 2018). This will boost the national economy by reducing imports, maximizing local materials, saving costs, and promoting technology transfer. The machine is recommended for local entrepreneurs due to its cost-effectiveness and environmental benefits.

4.0 Conclusion

A low-cost, efficient plastic shredder is being developed for the informal sector to conserve energy, maintain cleanliness, produce new products, promote sustainable energy, and create community employment. The study evaluates the efficacy of a plastic shredding machine, highlighting its potential to reduce waste, enhance product quality, boost the economy, and benefit local entrepreneurs. It can process 50 kg of waste plastic and is effective for HDPE, PVC, and PET waste, making it affordable for small and medium-scale processing plants. The machine's simplicity and affordability make it ideal for small-scale plastic recycling businesses, contributing to environmental and economic benefits while enhancing waste plastic processing for high-quality products. Promoting technology transfer for small- to medium-scale recycling machine production, reducing labor, fatigue, and costs in environmentally friendly conditions for local entrepreneurs. The design for a shredded paper machine should be automated with a belt conveyor, replaced with a reverse-driven prime mover, and incorporated into future designs. Proper blade spacing and hardware programming technology should be incorporated for improved operation. Brush spacers can be used to automatically clean blades, and inter-shaft spacing should be shortened to increase shredding efficiency.

Nomenclature

Symbol	Description	Unit
T	Torque	Ns
F_r	Crushing force	N
R	radius or length of the crank	Mm
P	Power required	W
Ω	angular velocity	rad/s
N	Speed	Rpm
W_P	Weight of the pelletized sample	Kg
W_F	Weight of plastic fed into the machine	Kg

Symbol	Description	Unit
W_R	Recovered weight after pelletizing	Kg
T	time taken for complete pelletizing	S
T_D	Design torque	Ns
K_L	Load factor	
D_1	Diameter of the driver	Mm
D_2	Diameter of the driving	Mm
C	Centre distance between driving pulley and driven pulley	Mm
θ_1	Angle of lap for driving pulley	Rad
θ_2	Angle of lap for driving pulley	Rad
N_1	Speed of the driver	m/s
N_2	Speed of the driving	m/s
Θ	Belt wrap angle on the driving pulley	Rad
μ	Coefficient of friction between the belt and the pulleys	
B	Pulley groove angle	rad
D	Pitch diameters of the driving	mm
D	Driven sheaves	mm
F	Force exerted by the machine elements	N
L_c	Length of the beam frame	mm
E	Young's modulus for mild steel	N/m^2
I_{xx}	second moment of area for the beam	Ns
I_{yy}	second moment of area for the beam column stand	Ns
T_p	Pull force on the belt (tight) side belt tension	N
T_n	Hold force on the belt (slack) side belt tension	N

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