Turkish Journal of Agricultural Engineering Research

https://dergipark.org.tr/en/pub/turkager
https://doi.org/10.46592/turkager.1260521

Turk J Agr Eng Res
(TURKAGER)

ISSN: 2717-8420
2023, 4(2), 151-177

Research Article

Development and Performance Evaluation of Double Shaft Plastic Bottle Crusher for Small Scale Industrial Application

Muyiwa Abiodun OKUSANYA[a], **Christopher Bamidele OGUNLADE**[a*], **Samuel Dare OLUWAGBAYIDE**[a]

[a] *Department of Agricultural and Bio-Environmental Engineering, Federal Polytechnic Ilaro, Ogun State, NIGERIA*

(*): Corresponding Author: christopher.ogunlade@federalpolyilaro.edu.ng

Article Info

Received: 09.03.2023 **Accepted:** 01.08.2023 **Published:** 31.12.2023

ABSTRACT

Plastic pollution is a problem that is affecting many aspects of human endeavour. Searches are being made for ecofriendly alternatives and waste management practices that can lessen the impact of plastic pollution. On the list are waste plastic reuse, use of bioplastics, reduction of reliance on plastic usage, and plastic waste recycling. In this technical brief, a plastic shredder was developed to recycle plastic waste in the value chain. Plastic shredder is a machine that turns used plastic bottles to smaller particle sizes to enhance portability, easiness and readiness for use into new products. While in operation, the prime mover drives the transmission shafts with low speed in the range of 25 to 65 rpm to give shredding torque that masticates materials fed in, into desired granular size. Bivariate Linear regression was the statistical model used to understand the relationship between the two variables of evaluation, the predictor x (speed) and the response variable y (shredding capacity). Since significance F (0.0216) is less than 0.05, there is 95% confidence that there is linear relationship between speed of rotation and shredding capacity of the machine. Model equation is therefore given as $Y = \mathbf{0.952\ X_1 - 11.725 \pm 2.53}$. *The machine respectively gave highest shredding capacity for PET bottles, Tin can and wastepaper as 56.52 kg* h^{-1}*, 29.60 kg* h^{-1} *and 42.09 kg* h^{-1} *at optimum speed of 65 rpm. If operated for 8 hours in a day, it can favorably shred almost half a ton of plastic bottles (452.16 kg* day^{-1}*). The machine was developed at an affordable cost of $817.72. The paper shredded with the machine can be pulped and made into poultry egg crates and paper print used in building industry. The machine is less stressful to operate and economical to run and maintain. If the machine is widely adopted, the menace caused by nonbiodegradable materials like plastic will be ended.*

Keywords: *Shredder, Mastication, PET bottles, Shredding capacity*

To cite: Okusanya MA, Ogunlade CB and Oluwagbayide SD (2023). Development and Performance Evaluation of Double Shaft Plastic Bottle Crusher for Small Scale Industrial Application. *Turkish Journal of Agricultural Engineering Research (TURKAGER), 4(2): 151-177.* *https://doi.org/10.46592/turkager.1260521*

INTRODUCTION

Nigeria has the highest Gross Domestic Product (GDP) and is the most populous country on the African continent. The sporadic rise in the country's population has made its citizens' consumption of plastics to surge from 578,000 tonnes in 2007 to approximately 1,250,000 tonnes in the recent time. As a result, the per capita usage of plastic has increased from 4.0 kg to 6.5 kg, or roughly 5% annually. Each resident is reportedly consuming 7.5 kilogram of plastic annually (Okorafor, 2022). Also, report by World Bank reveals that plastic trash makes about 12% of all municipal solid waste created globally. Out of the plastic waste generated, only 14% of that waste is collected for recycling and only 9% of the waste collected is eventually recycled (World Bank, 2018).

The overuse of plastic and improper management of the country's wastes represents a threat to human health and the environment because they leach harmful chemical contents into foods, drinks, and the environment, including endocrine disrupting chemicals that have been linked to infertility, diabetes, and prostate/breast cancer. In order to solve the problem of plastic menace that has put the nation's ecology and public health in peril, the government of Nigeria embraced a circular economy model in collaboration with United Nations Industrial Development Organization, UNIDO (Okorafor, 2022).

The ongoing circular economy initiatives in Nigeria include: National Plastic Waste Recycling Programme under which at least one plastic recycling plant is to be established in each of the 774 Local Government Areas in the country; Community Based Waste Management Programme that encourages the involvement of local communities in modern waste management practices such as waste sorting, segregation, composting and recycling as well as ownership of projects; The World Bank Assisted Pro-Blue Project for Lagos aimed at reducing marine plastic pollution and creating plastic recycling markets; Waste to wealth entrepreneurship programme for the empowerment of the most vulnerable group especially youth and women; Putting in place, legal and regulatory framework - National Policies on Solid waste, Plastic waste and Battery waste Management; Studies on the Alternative Packaging Material to Plastics in collaboration with UNIDO; Establishment of the Nigeria Circular Economy Working Group; etc. (Ikeah, 2018). The initiatives are hoped to address plastic waste menace constituting nuisance to our environment.

Plastic waste has become a global menace that threatens the environment and human health. The widespread use of single-use plastics, such as water bottles, bags and food packaging, has led to a massive accumulation of plastics waste in landfills and oceans. Plastic waste has also taken a toll on terrestrial ecosystems. It clogs drains and contributes to flooding in urban areas (see Figures 1a, 1b and 1c for more details on how plastic waste pollution impacts some urban areas of Lagos, Nigeria). The poorest members of society are frequently negatively impacted by poor waste management practices. Our resources need to be used and then reused continuously so that they do not end up in landfills or clog drains.

Efforts to tackling plastic waste menace have been implemented globally so as to promote sustainable development goal of 2030 (SDG 12, 14 and 15) through an absolute reduction in plastics. If efficient waste collection systems are implemented globally while also reducing the usage of plastics, there will be enormous positive effects. Removing plastic from beaches and collecting it at sea are vital initiatives; they will not make much of a difference if the flow of plastic is not also decreased. Moreover, plastics and chemical additives pose a threat to ecosystems in the ocean and on land; they can suffocate animals, make them unable to consume enough food, making them easier prey for other animals, sicken coral reefs, and do much more; their significant reduction will hasten the restoration of ecosystems and biodiversity. (Plastic Soup Foundation, 2016).

Utilizing biodegradable plastic as a substitute for traditional plastic is another workable method of reducing plastic waste pollution. Regulations and financial incentives can be used to encourage firms to use biodegradable packaging materials this will lower the demand for traditional plastics and reduce plastic pollution. Other common methods of managing plastic garbage include landfilling and cremation. However, according to a paper by Okusanya and Ibrahim (2020), burning plastic produces toxic dioxin emissions, and if incinerators are inefficient, the chemicals seep into the environment, causing air pollution and creating photochemical haze that is dangerous to human health. Additionally, it was discovered that landfilling should be avoided at all costs because it has negative effects on people and puts plant and animal life in jeopardy.

Collaborative effort from people, industry, and government at all levels of governance is needed to find a sustainable solution to plastic pollution problem. Individuals can help reduce plastic trash by adopting proper disposal and consumption practices. This can involve recycling properly, utilizing reusable water bottles and shopping bags, avoiding single-use plastics whenever possible. Government should implement laws and regulations governing efficient methods of managing plastic waste and form alliances with groups dedicated to sustainable development.

Everything we consume becomes waste including plastic bottles. The process of treating waste materials to produce new products is termed recycling. Recycling significantly will reduce the amount of plastic waste generated annually. Energy consumption and air pollution coming from plastic waste combustion will also reduce significantly where plastic waste recycling is in practice (Degli and Marzetti, 2019). Recycling is therefore a good waste management practice of choice one can explore. Shredding PET (Polyethylene terephthalate) plastic is an essential step in the recycling process. Once the bottles are shredded, they can be cleaned, washed, and separated from other materials such as caps, labels and residues. The PET flakes can then be melted and reprocessed to create new plastic products, including fibers for textiles, plastic strapping, and the production of new bottles. By reducing PET plastic to smaller pieces, they take up less space in recycling facilities, making transportation and storage more efficient. Shredded PET plastic can be used for various applications beyond recycling. It can be used in the manufacturing of construction materials, like carpets, insulation, or even as a raw material for the production of polyester fabrics.

The process of shredding PET bottles involves feeding the bottles into a shredder or granulator machine that contains sharp blades or rotating cutters. These blades or cutters tear the bottles into smaller pieces, typically ranging from a few millimeters to a few centimeters in size. The resulting PET flakes can then be further processed for recycling or used for other purposes. This technical brief is therefore geared towards developing PET bottles shredder of 500 kg capacity in one hour for managing plastic waste at small scale level.

Figure 1a. *Plastic waste clogging drains in urban area of Lagos, Nigeria.*

Figure 1b. *Plastic waste dump at Idimu Area, Lagos, Nigeria (Okusanya and İbrahim, 2020).*

Figure 1c. *Plastic Waste Dump at Egbeda Area, Lagos, Nigeria (Okusanya and Ibrahim, 2020).*

MATERIALS and METHODS

Design Consideration

Some relevant factors were considered in the design and development of the plastic shredder; such factors include power requirement, ease of replacement of various components, ease of mobility, possibility of machine duplication, safety of operation of parts, cost of construction, types of load and stresses, machine kinematics, machine kinematics and cost of maintenance. A 12 mm thick mild steel plate was used for the construction to prevent shearing of part and ultimate machine failure.

Design Philosophy

The transmission shafts of the shredder work in an interwoven manner through the help of gear drive to deliver a strong abrasive force on the materials in the shredding chamber so as to achieve mastication into desired granular size.

Component Parts of the Machine

The designed shredder thus reduces the particle size of used plastic for easy movement and ease of conversion into another new product. The shredder is made up of the following parts:

i. Hopper: a section that takes in waste PET into the shredding chamber.

ii. Shredding chamber: where the waste pet bottle is reduced into smaller size. This chamber is made up of mild steel. The shredding chamber has two counter rotating shafts that are 500 mm long and 35 mm in diameter. On the shaft are 12mm mild steel plates attachment which are machined on the lathe.

iii. Transmission shafts: The shafts are two in number. One acts as driving shaft while the other acts as driven shaft. The counter rotation of the shafts is aided by set of gears at the peripheral of the transmission line.

iv. Cutter blade: This cuts the pet bottle into smaller grains with its sharp edge.

v. Bearing: it is a mechanical device that supports another part (like transmission shaft) set in motion to reduce friction.

vi. Chain drive: It is used to transfer power or motion from the shaft of the prime mover to the driving shaft of the shredder.

vii. Counterweight: This is a heavy mass of iron mechanically linked in opposition to a load. It supports the machine and maintains balancing.

viii. Member frame: it is a support on which other component parts rest to make the entire assembly stable. It is made from mild steel and has a dimension of 480 mm x 480 mm x 400 mm.

ix. Discharge outlet: The shredded plastic passes through an outlet provided at the peripheral of the machine. It is made from mild steel and has a dimension 279 mm × 131 mm x 102 mm.

x. Prime mover: is a machine that receives and modifies energy as supplied by some natural sources or fuel and transforms it into mechanical work. The machine fabricated is powered by a petrol engine with a reducer gear assembly.

xi. Channel: It is the platform that maintains the stability of the machine. It carries the load and weight of the machine. It is made up of angle iron.

Material Selection

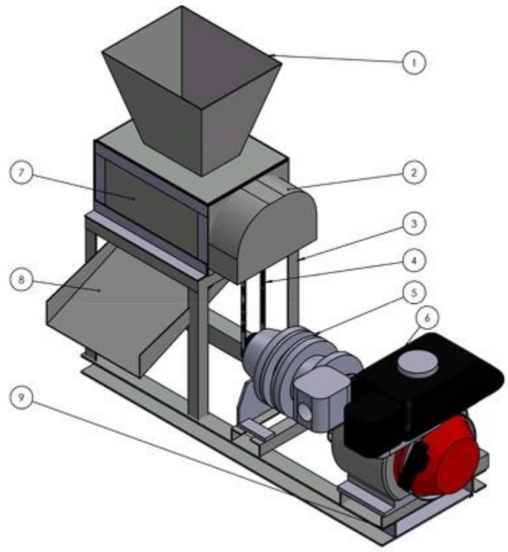
Table 1 below shows the materials used for construction of various subcomponents of the shredder assembly. The dimensions, remarks and the criteria for selection of those components were also presented in the table.

Table 1. *Material selection.*

Machine component	Criteria for material selection	Machine selected	Dimension	Remark
Hopper	Must be strong and able to acquire more material	Galvanized mild steel of 6 mm thickness	493 mm x 320.94 mm x 450.00 mm	It does not twist and has ability to occupy more material (fabricated)
Shredding chamber	Ability to withstand cutter blade vibration and impact force and torque	Galvanized mild steel of 6 mm thickness	611.61 mm x 450.00 mm	Durable (fabricated)
Transmission Shaft	Must be strong	Stainless steel	492.40 mm long and ϕ 35 mm	It was machined
Cutter blade	Must be strong and have sharp cutting edges	Mild steel of 12 mm thickness	120 mm x 150 mm x 40 mm	It has strong and sharp edges for crushing (machined)
Gear reducer	Ability to increase and decrease the speed of the engine	Mild steel of 8 mm thickness	275 mm x 392 mm x 320 mm	Available (bought readymade)
Chain	Must be strong and not flexible	Chain	Size: 50, pitch: 15.88 mm , roller diameter: 10.16 mm	Stable (bought readymade)
Sprocket	Ability to have a good wear property	Mild steel	150 mm x 75 mm	Bought readymade
Bearing	Must be durable and strong	Mild steel	Flange bearing of 35 mm diameter	Bought readymade
Counter weight	Ability to withstand load of the shaft for balancing	Cast Iron block	200 mm x 75 mm	Available and durable
Channel	Must be able to withstand dead load imposed by the self-weight of the shredder	Angle iron of 6 mm thickness	1047 mm x 365 mm x 80 mm	Constructed
Bolts and nuts	Must be hard and durable	Alloy steel	Various sizes ranging from 13 mm to 24 mm	Bought readymade
Prime mover	Must be a medium or high speed engine	Petrol engine	13 HP Petrol Engine (GX 390)	Bought readymade

Machine Description

The shredder uses mastication principle to reduce the size of pet bottle fed into the crushing chamber through the hopper. The machine assembly is powered by a prime mover (13 HP petrol engine). The power from the prime mover is harnessed by direct coupling, reduction gear and chain drive. The reducer is linked to the prime mover through direct coupling. The reducer assists in bringing down the speed from the prime mover (2400 rpm) to 120 rpm. The speed is further reduced to 65 rpm and below through chain drive between reducer shaft and transmission shaft of the shredder assembly. Once materials are fed into the shredding chamber through the hopper, cutter blades on the shaft then grab the materials to masticate it into desired granular sizes. Masticated Pet bottles are afterwards discharged through discharge unit. Figures 2, 3 and 4 are respectively the pictorial view, autographic projection and exploded view of the machine assembly.



S/N	COMPONENT	SPECIFICATIONS
1	Hopper	2mm Mild Steel Plate
2	Guide	2mm Mild Steel Plate
3	Frame	50x50x5mm i Mild SteelAngle iron
4	Chain	-
5	SpeedReduction Gear	Ratio 30 to1
6	Prime Mover	10hp Petrol Engine
7	Shredding Unit	-
8	Outlet	2mm Mild Steel Plate
9	Engine Seat	70x 70x7mm channel

Figure 2. *Pictorial view of the pet bottle shredder.*

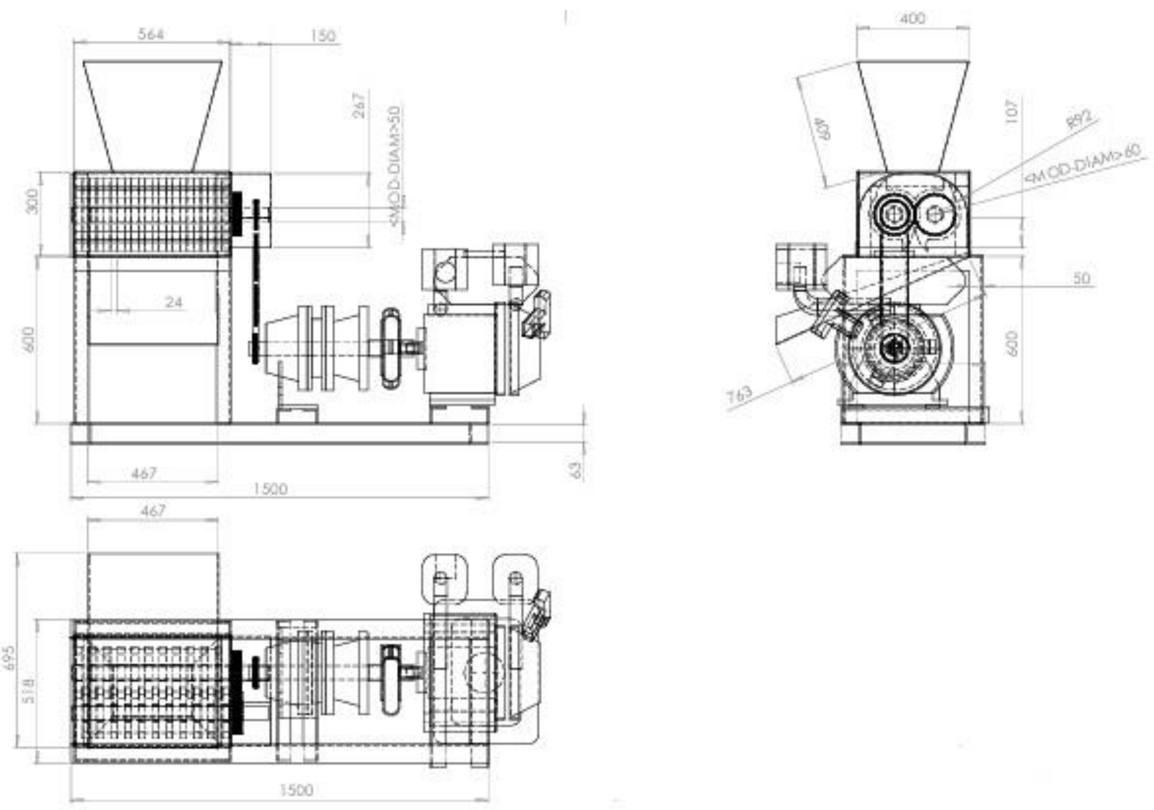
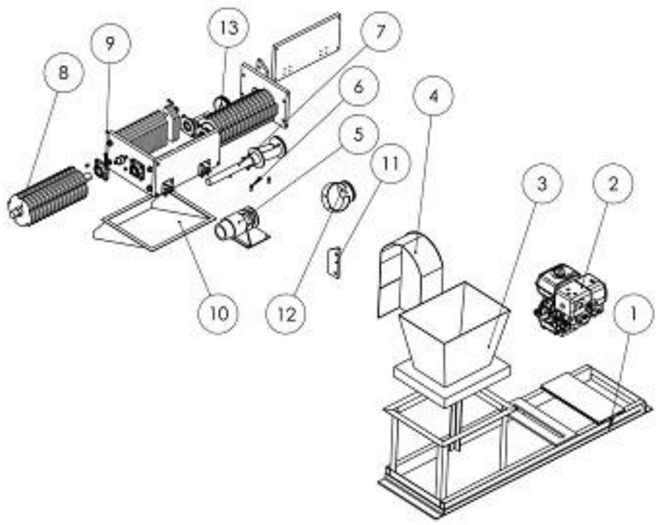


Figure 3. *Orthographic projection of pet bottle shredder.*



S/N	COMPONENTS
1	Support Stand Frame
2	Petrol Engine
3	Hopper
4	Gears Cover
5	Reducer Gear
6	Bolt and Nuts
7	Shaft
8	Cutters
9	Bearings
10	Outlet
11	Cutter Spacer
12	Coupling (rubber)
13	Spockets

Figure 4. *Exploded view of the machine assembly.*

Design Calculation of the Shredder

Hopper design

The hopper is trapezoidal in shape. It was designed to aid easy of material flow into the shredding chamber. Angle of repose, cross section area, mass flow rate and volume of plastic to be accommodated are the parameters considered in the design of the hopper.

Volume of hopper

Volume of the Hopper, $Vh = \frac{1}{3}\ x\ h\{A1 + A2\sqrt{A1 + A2}\ \}$ (1)

Where, A_1 = Area of top base in m^2

A_2 = Area of bottom base in m^2

h = Height of hopper in m = 251 mm = 0.251 m

V_h = Volume of hopper in m^3

$A_1 = 0.494\ x\ 0.45 = 0.223\ m^3$

$A_2 = 0.37\ x\ 0.35 = 0.1295\ m^2$

$Vh = \frac{1}{3} x\ 0.251\{0.223 + 0.129$

$5\sqrt{0.223 + 0.1295)}\ \}$

$Vh = 0.0251 m^3$ (See Figures 2 and 5 for details)

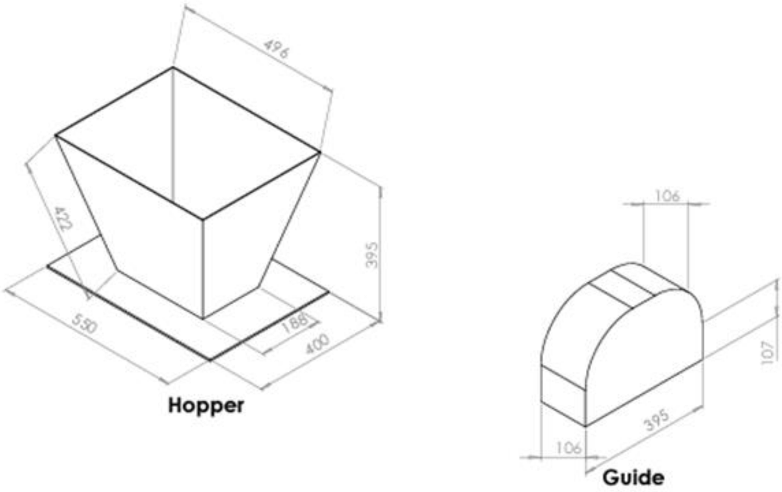


Figure 5. *Hopper design.*

Angle of repose

Angle of repose, ∅ is otherwise known as angle of pour. It is a function of coefficient of both sliding friction(μs) and rolling friction (μr) (Khurmi and Gupta, 2004).

$$\emptyset = \tan^{-1}(\mu s) \quad (2)$$

μ_s is 0.54 (Engineering Toolbox, 2004) for recyclable plastic like PET bottles.

By using Equation 2, the angle of repose can then be found.

$\emptyset = \tan^{-1}(0.54) = 28.4^0$.
Angle of repose is therefore 28.4^0

Number of PET bottle in the hopper

Volume of PET bottles in the shredding chamber, V_{pet} $\pi r^2 h$

Where r is the radius of the PET bottle (cm) = 3.5 cm = 0.035 m
h is the height of the PET bottle (cm) = 26 cm = 0.26 m
$V_{pet} = \pi\ x\ 0.035^2\ x\ 0.26 = 0.001001\ m^3$
$Number\ of\ PET\ Bottles = \frac{Volume\ of\ Hopper}{Volume\ of\ PET\ Bottles} = \frac{0.0251}{0.001001}$
$Number\ of\ PET\ Bottles\ the\ hopper\ can\ take\ at\ a\ time = 25.07 \approx 25\ bottles$
The hopper can therefore take 25 pieces of PET bottles at once.

Chain drive design

Chain drive is one of the drive mechanisms used in harnessing power produced by the prime mover. The power harnessed is then directed to the transmission shaft through the drive chosen to set the entire assembly in motion. Chain drive was the drive of choice used to transmit power from the reduction gear linked to the prime mover (petrol engine) to the transmission shafts responsible for mastication of materials under consideration.

Pitch diameter of sprocket

The pitch diameter is a function of the chain pitch and the number of teeth in the sprocket. The pitch diameter of sprocket is therefore given by Equation 3 (Srivastava *et al.*, 2012).

$$PD = \frac{P}{Sin(\frac{180}{N})} \tag{3}$$

Where P = the chain pitch,
N = Number of teeth in the sprocket
PD = Pitch diameter.

For small sprocket of 19 teeth and 12.7 mm pitch, the pitch diameter is given as

$$PD = \frac{12.7}{Sin(\frac{180}{19})} = \frac{12.7}{sin9.47} = \frac{12.7}{0.1645} = 77.20\ mm$$

For big sprocket of 29 teeth and 18.45 mm pitch, the pitch diameter is given as

$$PD = \frac{19.2}{Sin(\frac{180}{29})} = \frac{19.2}{sin6.21} = \frac{19.2}{0.1081} = 177.61\ mm \approx 178\ mm$$

Length of chain

The length of chain can be determined using Equation 4 (Srivastava *et al.*, 2012).

$$\frac{L}{P} = \frac{2C}{P} + \frac{N1+N2}{2P} + \frac{(N2-N1)^2}{\left\{4\pi^2\left(\frac{C}{P}\right)\right\}} \tag{4}$$

Where C is the center distance between the sprockets; N_1 and N_2 are number of teeth on the two sprockets.
If the center distance between the two sprockets is taken as 800 mm and chain pitch for standard roller chain according to ANSI standard is 3.2 mm, the length of chain is then given as:

$$\frac{L}{3.2} = \frac{2x800}{3.2} + \frac{19+29}{2x3.2} + \frac{(29-19)^2}{\left\{4\pi^2\left(\frac{800}{3.2}\right)\right\}} = 500 + 7.5 + 0.0101 = 507.51$$

$$\frac{L}{3.2} = 507.51$$

Therefore, L = 3.2 x 507.51 = 1624.03 mm
Hence, chain length L = 1.624 m

Chordal speed variation of sprocket

$$\frac{\Delta v}{v} = \frac{\pi}{N}\left\{\frac{1}{sin\left(\frac{180}{N}\right)} - \frac{1}{tan\left(\frac{180}{N}\right)}\right\} \tag{5}$$

Where the chain velocity is v = NPn; P = pitch and n = angular speed in rev s^{-1} (Srivastava *et al.*, 2012).

Chain velocity estimation

$$V = N1P1n1 = N2P2n2 \tag{6}$$

Where the chain velocity is v = NPn in the driving sprocket or driven sprocket; P = pitch and n = angular speed in rev/s (Srivastava et al, 2012).

If angular speed, n is 65 rpm = 65/60 = 1.08 rev. s^{-1}; N_1 = 19, and P_1 = 12.7 mm, then:

$$V = 1.08\ x\ 19\ x \frac{12.7}{1000} = 0.261\ ms^{-1}$$

For angular speed of 25 rpm, sprocket of 29 teeth and pitch of 18.45 mm, then:

$$V = 25\ x\ 29\ x \frac{18.45}{1000} = 13.38\ ms^{-1}$$

In calculating chordal speed variation at speed n1 of 25 rpm, sprocket teeth of 29 teeth and pitch of 18.45 mm,

$$\frac{\Delta v}{v} = \frac{\pi}{N}\left\{\frac{1}{sin\left(\frac{180}{N}\right)} - \frac{1}{tan\left(\frac{180}{N}\right)}\right\} = \frac{\pi}{29}\left\{\frac{1}{sin\left(\frac{180}{29}\right)} - \frac{1}{tan\left(\frac{180}{29}\right)}\right\}$$

$$= \frac{\pi}{29}\{\ 9.25 - 9.195)$$

$$= \frac{\pi}{29} x\ 0.55 = 0.00596$$

Therefore, chordal speed variation, $\frac{\Delta v}{v} = 0.596\ \%$

Reduction gear assembly

The reduction gear has speed ratio of 1:30 for the 13 Hp petrol engine. The net output speed of rotation of the prime mover is 3,600 rpm; net torque is 26.4 N m at 2,500 rpm. Net output Power, P= 13 Hp = 0.746 x 13 = 9.7 kW.

Since the reduction gear has speed ratio of 1:30, the speed is brought down to: n $= \frac{3600}{30} = 120\ rpm$. The speed is further stepped down by chain drive linking the reducer shaft to driving shaft of the shredder. The reduced speed is after wards transmitted to the driving and driven shafts run by spur gears on them. The speed is further stepped down by chain drive.

Input power requirement

The input power measurement can be determined from the name plate information of the prime mover used to power the machine. It can also be determined from the drive for the transmission shaft of the machine. In this endeavor, the input power for the shredder was calculated based on torque requirement of the transmission shafts. Power requirement of the driving and the driven shaft is calculated using the formula in Equation 7 (Belonio, 2004).

$$P = \frac{2\pi NT}{60,000}\ (KW) \tag{7}$$

Where N= final speed of rotation of transmission shaft in rpm = 65 rpm
T = torque requirement of the transmission shaft = 25.725 Nm.

$$P = \frac{2\pi\ x\ 65\ x\ 25.725}{60,000} = 0.1752\ KW = 175.2\ W$$

Torque requirement

$$T = F \times r \quad (8)$$

Where F is the total load on the shafts and r is the radius of the shaft (Ossian, 2023).

F = 1470 N (see Equation 7 for details).

$r = \frac{35}{2 \ x \ 1000} = 0.0175 \ m$

$T = 1470 \ x \ 0.0175 = 25.725 \ Nm$

Transmission shaft design

Shaft design consists primarily of the determination of the correct shaft diameter to ensure satisfactory strength and rigidity when the shaft is transmitting power under various operating and loading conditions. Shafts are usually in cross-section and may be either hollow or solid. The shaft considered for design in this research brief is solid cylindrical shaft (See Figure 6 for details).

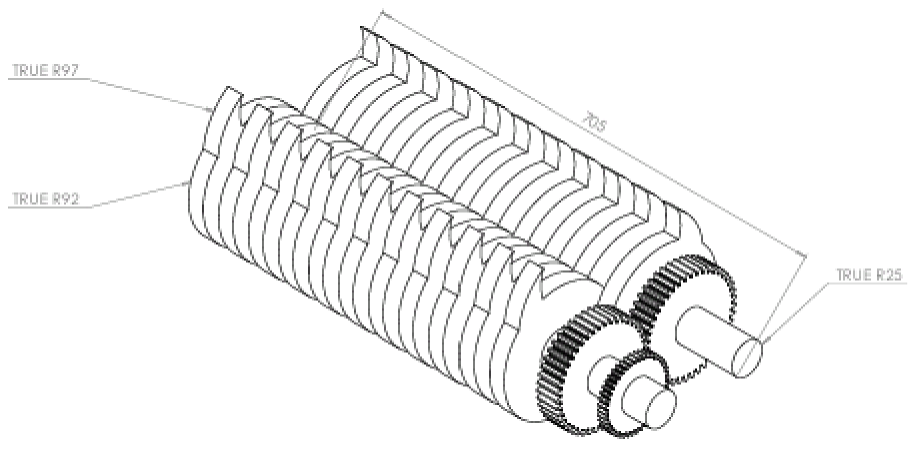


Figure 6. *Shafts design.*

The ASME code equation for solid shaft diameter is as given in equation in Equation 9 (Hall *et al.*, 2017).

$$d^3 = \frac{16}{\pi \ Ss} \sqrt{\{(KbMb)^2 + (KtMt)^2\}} \quad (9)$$

To determine the shaft diameter, the following parameters are given:
K_b = 2, K_t = 1.5 (fatigue factors for solid shaft), G = 10 x 10^9 Nm^{-2} (stainless steel shaft parameter), Ss = 55 MNm^{-2} (Maximum allowable stress for solid shaft), MB = 172 Nm (from bending moment calculation), M_T = 26.4 Nm (torsional moment is from name plate of prime mover).

$d^3 = \frac{16}{\pi \ Ss} \sqrt{\{(KbMb)^2 + (KtMt)^2\}}$

$d^3 = \frac{16}{\pi \ x \ 55 \ x \ 10^6} \sqrt{\{(2 \ x \ 172)^2 + (1.5 \ x \ 26.4)^2\}}$

d = $\sqrt[3]{\{\frac{16}{\pi \, x \, 55 \, x \, 10^6}}\sqrt{\{(2 \, x \, 172)^2 + (1.5 \, x \, 26.4)^2\}}\}$

d = $\sqrt[3]{\{9.26 \, x \, 10^{-8} \, x \sqrt{\{344^2 + 39.6^2}}$

d = $\sqrt[3]{\{9.26 \, x \, 10^{-8} \, x \sqrt{\{119904.31\}}}$

d = $\sqrt[3]{3.2065 \, x \, 10^{-5}}$

d = 0.0318 m

d ≈ 32 mm

Diameter of shaft section for each shaft can be taken as 35 mm

Shear Force and Bending Moment Calculation

Force analysis

Finding reactions R_A and R_B at the bearing section:

Weight of spur gears, W_1 = 350 N;

Weight of blades on the main shaft in the shredding chamber, W_2 = 700 N;

Weigh t of the counterbalance W_5 = 200 N;

Weight of the main Shafts W_3 = 200 N;

Weight of materials (plastic) to be processed per operation, W_4 = 20 N.

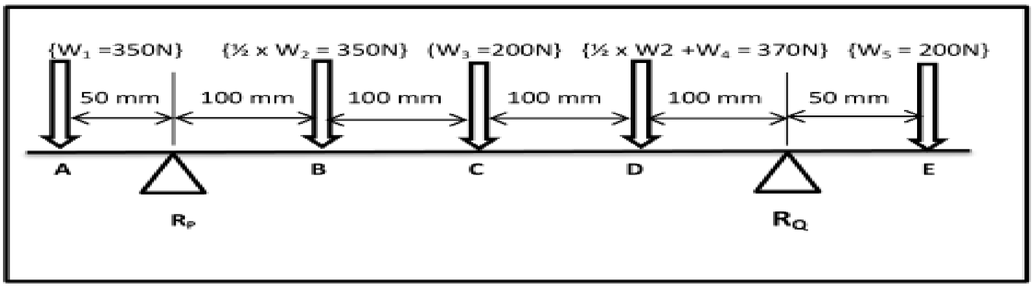


Figure 7. *Force analysis on the transmission shafts.*

The reactions R_P and R_Q are at the supports (the bearing sections)

ΣM about R_B = 0,

$$\Sigma M \, (CCW) = \Sigma M \, (CW) \quad (10)$$

Where CW is clockwise moment and CCW is anticlockwise moment (Anyakoha, 2016).

$$R_P + R_Q = W_1 + W_2 + W_3 + W_4 + W_5 \quad (11)$$

Where R_P and R_Q are respectively reactions at the two supports (Anyakoha, 2016).

$R_P + R_Q$ = 350 + 700 + 200 + 20 + 200 = 1470N

$\Sigma M \, (CCW)$ = (W_1 x 0.45) + {(½ x W_2) x 0.3} + (W_3 x 0.2) + {(½ x $W_2 + W_4$) x 0.1)}

= 350 x 0.45 + 350 x 0.3 +200 x 0.2 + 370 x 0.1

= 157.5 + 105 + 40 + 37

$\Sigma M \, (CCW)$ = 339.5 Nm

$\Sigma M \, (CW)$ = R_P x 0.4 + W_5 x 0.05

= 0.4R_P + 200 x 0.05

= 0.4R_P + 10

From analysis above:
$0.4R_P + 10 = 339.5$
$0.4R_P = 339.5 – 10 = 329.5$
$R_P = 823.75$ N
From Equation 2, $R_Q = W_1 + W_2 + W_3 + W_4 + W_5 – R_P$
$R_Q = 1470 – 823.75 = 646.25$ N
$R_Q = 646.25$ N
See Figures 7 and 8 for details of shear force and bending moment diagram.

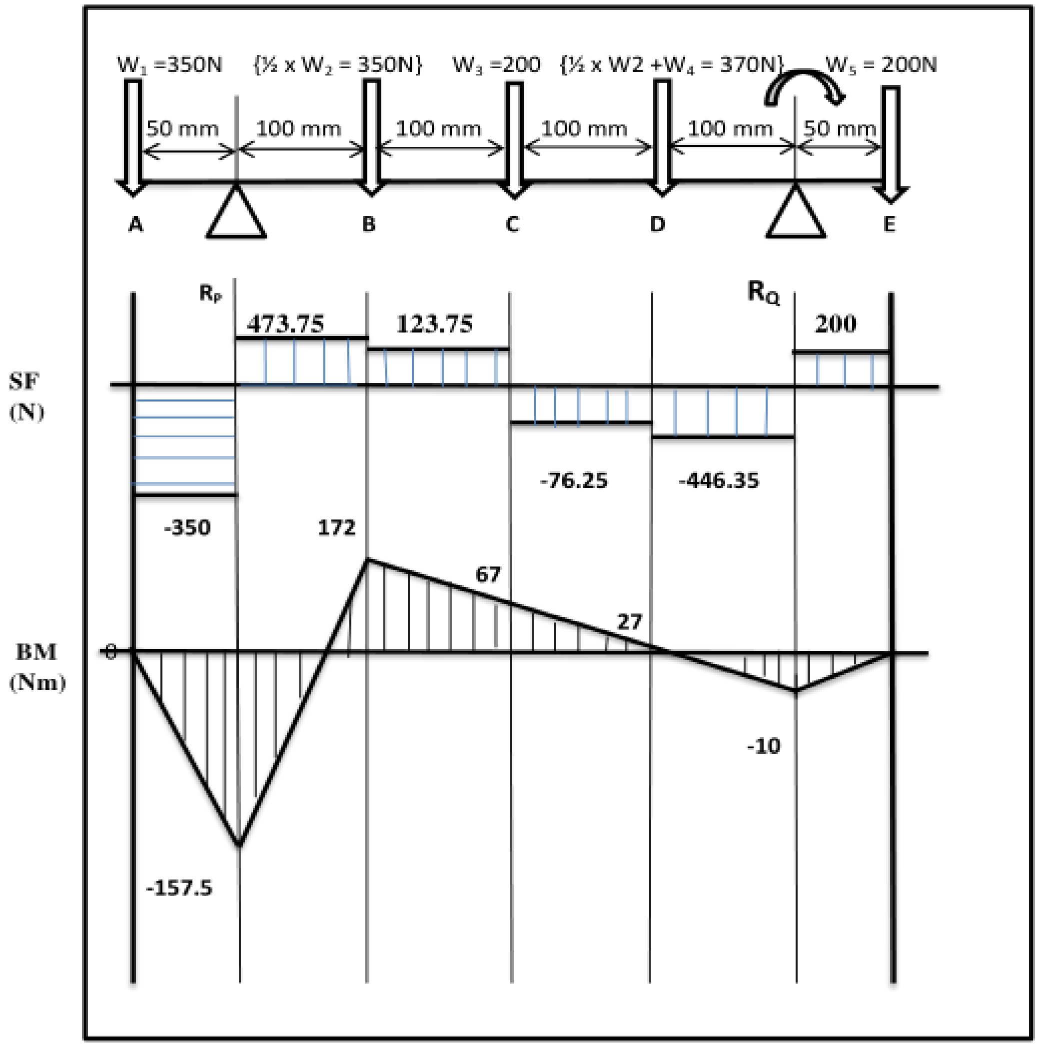


Figure 8. The shear force and bending moment diagram.

ΣM about a turning point is zero. IF R_A is taken as reference point, the resultant moment at each point is as given below:
W_A: $M_A = W_1 \times 0.45 = 350 \times 0.45 = - 157.5$ Nm
W_{RP}: $M_{RP} = M_A + R_P \times 0.4 = -157.5 + 823.75 \times 0.4$
$= -157.5 + 329.5$
$M_{RP} = 172$ Nm
W_B: $M_B = M_{Rp} - W_2 \times 0.3 = 172 – 350 \times 0.3$
$M_B = 172 – 105$
$M_B = 67$ Nm

$M_C = M_B - W_3 \times .2 = M_B - 200 \times 0.2$
W_C: $M_C = 67 – 40 = 27$ Nm
$M_D = M_C – \{½ \times W_2 + W_4 = 370N\} \times 0.1$
W_D: $M_D = 27 – 370 \times 0.1 = - 10$ Nm
R_Q: $M_{Rq} = M_D + 0 = - 10$ Nm
W_5: $M_E = M_{RB} + W_5 \times 0.05$
$M_E = - 10 + 200 \times 0.05 = -10 + 10$
$M_E = 0$
M_{bmax} = maximum bending moment on the transmission shaft
M_{bmax} = **172 Nm**

Stress Analysis of Transmission Shafts

Using the bending moment value (calculated) in Figure 9 to determine the following type of stresses experienced by the transmission shafts:

Bending stress

$$\sigma b = \frac{\{Mb\ x\ Ymax\}}{I} \tag{12}$$

y = c (shaft radius in meter) = $\frac{0.035}{2} = 0.0175\ m$

I = second moment of inertia (m^4)
$Mb = Bending\ moment\ of\ the\ shaft\ in\ Nm = 172\ Nm$

$$I = \frac{\pi d^4}{32} = \frac{\pi\ x\ 0.035^4}{32} = 1.47 \text{ x } 10^{-7} \text{ m}^4 \tag{13}$$

(Gopal, 2010).

$$\sigma b = \frac{\{172\ x\ 0.0175\}}{I}$$

$$= \frac{\{172\ x\ 0.0175\}}{1.47\ x\ 10^{-7}} = 2.04\ x\ 10^7 Nm^{-2} = 20.4\ MPa$$

Bending stress, σb is therefore 20.4 MPa

Normal stress

$$\sigma n = P/A \tag{14}$$

Where P is total load on the shaft in N and A is cross sectional area of shaft in m^2 (Gopal, 2010).

P = 1470 N, $A = \frac{\pi d^2}{4} = \pi\ x \frac{0.035^2}{4} = 0.000962\ m^2$

σn = 1470/ 0.000962 = 1,528,066.53 Pa
Normal stress, σn on the shafts is 1.53 $M\ Pa$

Torsional stress

$$\sigma t = \frac{Mt\ x\ r}{J} \tag{15}$$

Where Mt is torsional moment of shaft, r the radius and J the polar moment of inertia (Gopal, 2010).

$$J = \frac{\pi d^4}{64} = \pi\ x \frac{0.035^4}{64} = 7.37\ x\ 10^{-8}\ m^4$$

$$\sigma t \quad = \frac{21.79\ x\ 0.0175}{7.37\ x\ 10^{-8}} = 4.93 \text{ MPa}$$

Torsional Stress, σt on the shaft assembly is therefore 4.93 MPa

Shear stress

$$\tau = \frac{16}{\pi d^3}\sqrt{Mb^2 + Mt^2} \quad \text{(allowable)} \tag{16}$$

d = shaft diameter, Mb = bending moment, Mt = torque or torsional moment and τ = shear stress (Gopal, 2010).

$$\tau = \frac{16}{\pi\ x\ 0.035^3}\sqrt{(172^2 + 26.4^2} = \frac{16}{\pi x 0.035^3}\ x\ \sqrt{(30280.96)}$$

τ = 20.67 M Pa (below 55 M Pa which is maximum allowable value for solid shaft)

Principal stress

$$\sigma max = \frac{\sigma x + \sigma y}{2} \pm \sqrt{\left\{\frac{(\sigma x - \sigma y)^2}{2} + \sigma xy^2\right\}} \tag{17}$$

σx = Normal stress in axial axis, $\sigma x = normal\ stress\ in\ radial\ axis,\ \sigma xy$ = shear stress (Gopal, 2010).

$$\sigma max = \frac{\sigma x + 0}{2} \pm \sqrt{\left\{\frac{(\sigma x - 0)^2}{2} + \sigma xy^2\right\}}$$

$$\sigma max = \frac{1.53 + 0}{2} \pm \sqrt{\left\{\frac{(1.53 - 0)^2}{2} + 20.67^2\right\}}$$

$\sigma max = 21.46\ MPa$

Principal Stress, σmax is therefore 21.46 M Pa

Critical design stress

Critical Stress is the minimum amount of the stress that is exerted by the external force acting over the shaft assembly, which is required for initiating the motion towards causing shaft failure.

$$\sigma cr = \frac{\pi E}{(L/r)} \tag{18}$$

$\sigma cr = critical\ stress$ (N m^{-2})

L/r = slenderness ration (Gopal, 2010).
E = young modulus of stainless steel shaft used (Nm^{-2}) = $210 \ x \ 10^9$ Nm^{-2}
L = length of shaft (m) = $0.5m$
r = radius of shaft (m) = $0.0175m$

$$\sigma cr = \frac{\pi \ x \ 210 \ x \ 10^9}{\left(\frac{0.5}{0.0175}\right)^2}$$

$$\sigma cr = 6.6 \ x \frac{10^{11}}{816.33} = 8.1 \text{ x } 10^8 \text{ Pa}$$

$$\sigma cr = 0.81 \text{ GPa}$$

Shaft Design for Torsional Rigidity

Rigidity is based on the permissible angle of twist. The amount of twist permissible depends on the particular application and varies about 0.3° per meter for machine tool shafts to about 3° per meter for line shafting.

According to SAME on solid circular shaft,

$$\theta = \frac{584MtL}{Gd^4} \tag{19}$$

$\theta = angle \ of \ twist \ (degree)$
L = length of shaft (m) = 500 mm - designed
Mt =torsional moment (Nm) = $4.93 \text{ x } 10^6$ Nm (name plate)
G = torsional modulus of elasticity (Nm^{-2}) = $80 \text{ x } 10^{12}$ Nm^{-2} - standard
d = shaft diameter = 35 mm - Calculated
R = *D/2* = 35/2 = 17.5 mm = 0.0175 m

$$\theta = \frac{584 \ x \ 24.6 \ x \ 0.5}{80 \ x \ 10^{12} x \ 0.0175^4} = 0.0168^{\circ}$$

$\theta = 0.0168^{\circ}$. Since the value is less than 3° per meter (3° / m >>> 0.0168°/m), angle of twist of the 0.5 m long transmission shaft is within permissible range.

Principle of operation

The description of a typical experiment was used to explain the experimental procedure. The PET bottle shredder uses mastication principle to shred materials fed into it. During working process, its prime mover drives the transmission shafts of the machine with a low speed and strong shredding torque to masticate materials to be processed. These speed and torque are then transmitted to revolving cutter blades on the driving and driven shafts moving in an interwoven manner. However, utilizing the gap between counter rotating blades gives rise to cutting edges of plastic shredder, thereby masticating the large pieces of PET bottles, tin can, or paper processed into desired granular sizes (see Figures 12, 13 and 14 for more details).

Materials for Evaluation and Variables Considered

Materials used for evaluation of the plastic shredder are Paper Catton, Tin Can and PET Bottles, Sensitive measuring scale, stopwatch and recording materials. Variables considered during evaluation are speed of rotation and shredding capacity.

Performance evaluation

To evaluate the machine's performance at different transmission shaft rotation speeds, PET bottles, Tin cans, and paper were employed. The rotational speed was in the range of 25 rpm to 65 rpm. An electronic weighing balance was used to measure the weight of the evaluation materials. The goal of doing this was to help calculate how many kg of materials will pass through the machine in an hour. The duration of the shredding exercise was also calculated using a stop watch. The results from each material evaluated were tabulated and analyzed to determine the shredding capacity in 1 hour or one day of 8 hours operation.

Method of Analysis of Results

Null hypothesis for variables considered is Ho: $0.5 \leq r \leq 1$; while alternative hypothesis is H_1: $r < 0.5$. Bivariate Linear regression was the statistical model used to understand the relationship between the predictor and the response variable. Y is response variable, βo is intercept on y axis, X_1 / Xn is the predictor, β_1 / β_n is the regression coefficient and ε is the model error. Variable X, being the predictor is the speed of rotation of the shredder in revolution per minutes (rpm); and variable **y** being the response variable is the shredding capacity in kilogram per hour (kg h^{-1}). Analysis toolPak of Microsoft excel was used to analyze the relationship between the predictor and the response variable. The general model for both bivariate and multivariate data for linear regression analysis is as presented in Equation 20 below (Zach, 2020).

$$y = \beta o + \beta 1X1 + \beta nXn + \varepsilon \quad (20)$$

Cost Estimation of PET Bottle Shredder

Cost of engineering products like newly developed PET bottle Shredder can broadly be grouped under direct or indirect cost (Hasiehurst, 1981). Direct cost is the cost of factors which are directly attributed to the manufacture of a specific product (i.e. materials and labour costs). Indirect cost on the other hand is that indirectly attributed to the manufacture of a specific product, such as overhead cost (usually expressed in percentage of direct labour cost) (Ajav *et al.,* 2018). The costing of the newly designed and fabricated shredder was based on the detailed factorial estimate method (Sinnot, 1993). This is because fabrication of the machine is complete and detailed breakdown and estimation of component parts is possible. The cost analysis of the machine is shown in Table 2 below.

Table 2. *Bill of Engineering Quantity and Measurement (BEME).*

S/N	Materials	Specification	Quantity	Unit Price (N)	Total Amount (N)
1	Petrol engine	13.0 hp petrol engine	1	95,000	95,000
2	Plate (mild steel)	12 mm	1	45,000	45,000
3	Shaft	30 mm	2	20,000	15,000
4	Plate	5 mm	1	35,000	35,000
5	Sprocket	130/75	1	5,000	5,000
6	Sprocket	200/75	1	10,000	10,000
7	Bearing	-	2	3,250	7,500
8	Counter Balance Weight	5 kg	1	10,000	10,000
9	Welding and Turning	-	-	45000	45,000
10	Bolt & Nut	-	-	3,000	3,000
11	Blade	269/74 mm	6	1,670	10,000
12	Transport	-	-	7,000	7,000
13	Miscellaneous	-			12,500
	TOTAL				**300,000**

i. Materials Cost = ₦ 300,000

ii. Direct Labour Cost: (Machining of Main Shaft , Bending, painting) = ₦ 15,000

iii. Indirect/Overhead Cost: = 20% of ₦ 300,000 = ₦ 60,000

Grand-total = Material cost + Labour cost + Overhead cost **= ₦ 300,000 + ₦ 15,000+ ₦ 60,000 = ₦** 375,000

At $ 1.00 = ₦ 458.59

₦ 375,000 = $ 817.72

RESULTS AND DISCUSSION

The shredder developed was evaluated with PET bottles at various speed of rotation ranging from 25 rpm to 65 rpm. The speed was varied for each batch processed to establish the speed at which the shredding capacity is optimum. The result is as shown in Table 3 below. The weight of materials processed was kept constants for all the speed level tested. Highest shredding capacity was observed at 65 rpm. Beyond this speed, machine uneven vibration was observed. It was also observed that the time it took to shred each batch reduces as the speed of rotation increases.

Table 3. *Shredder evaluation using PET bottles.*

	Weight (g)	Time (s)	Speed (rpm)	Shredding capacity (kg h^{-1})
1	157	32	25	17.66
2	157	28	35	20.19
3	157	24	45	23.55
4	157	15	55	37.68
5	157	10	65	56.52

Versatility of the machine for other materials like empty tin can and paper was also tested. The impact of various speed of rotation of the prime mover on materials evaluated was observed and reported in Tables 4 and 5 below. The weight was also kept constant throughout the process. In Table 4, shredding capacity was lowest (13.32 kg h^{-1}) at 25 rpm and highest (29.60 kg h^{-1}) at 65 rpm. The shredding capacity of the machine was observed to be higher when PET bottle (52.52 kg h^{-1}) was processed as compared to Tin can (29.6 kg h^{-1}). This could be due to the fact that ultimate tensile strength of PET bottle (220 MPa) was higher than that of Tin can (150 MPa). For the shredding process, Figures 8, 9 and 10 are respectively the charts of the shredding capacity of PET bottles, paper and empty Tin can.

Table 4. *Shredder evaluation using empty tin can.*

S/N	Weight (g)0/	Time (s)	Speed (RPM)	Shredding capacity (kg h^{-1})
1	148	40	25	13.32
2	148	34	35	15.67
3	148	28	45	19.02
4	148	24	55	22.20
5	148	18	65	29.60

In Table 5, the lowest and highest shredding capacity obtained are respectively 14.8 kg h^{-1} and 42.09 kg h^{-1}. It was observed that the machine is also versatile for shredding paper which can later be made into pulp to form egg crates used at poultry farm. It was more convenient for the machine to shred paper than other materials used for evaluation. The only thing observed with it is that it is not as compact as other materials are. This could be responsible for delay in picking before shredding.

Table 5. *Shredder evaluation using paper.*

S/N	Weight (g)	Time (s)	Speed (RPM)	Shredding capacity (kg h^{-1})
1	152	37	25	14.80
2	152	30	35	18.24
3	152	27	45	20.27
4	152	19	55	28.80
5	152	13	65	42.09

Bivariate linear regression was the statistical model used to understand the relationship between the ***explanatory variable*** (speed of rotation) and the ***response variable*** (shredding capacity). The results of the analysis are as shown in Tables 6 and 7 below. The pictures of the machine assembly during evaluation exercise and product of evaluation are as shown in Figures 10, 11 and 12. The formula in Equation 21 was used to determine the shredding capacity of each material processed (Abdulkadir *et al.*, 2020).

$$Shredding\ Capacity = \frac{m}{t}\ (kgh^{-1}) \tag{21}$$

m is the mass of material processed by the shredder or weight of shredded materials fed in in kilogram - the material is either PET bottle, Tin can or Paper.
t is the time it took to process the material – it is measured in hour.

The charts of shredding analysis presented in Figure 8 shows the relationship between shredding capacity and speed of rotation of the transmission shaft. PET bottle was picked for the analysis since the design favors PET bottles shredding more perfectly as it is the highest on the list (56.52 kg h^{-1}). From the graph, it can be deduced that increase in speed of rotation of transmission shaft leads to corresponding increase in quantity of plastic shredded per time. At 25 rpm, the quantity shredded in 1 hour is 17.66 kg. When the speed is considerably increased, the quantity shredded also increased. At 65 rpm, 56.52 kg was shredded in 1 hour. Beyond this speed, machine uneven vibration was observed. If the machine is operated for 8 hours in a day at the limit of the observable speed, it can favorably shred up to half a ton (452.16 kg day^{-1}).

The results also show the machine is versatile for shredding other waste packaging materials generated around farm on daily basis. The paper shredded can be pulped and made into poultry egg crates and paper print used in building industry.

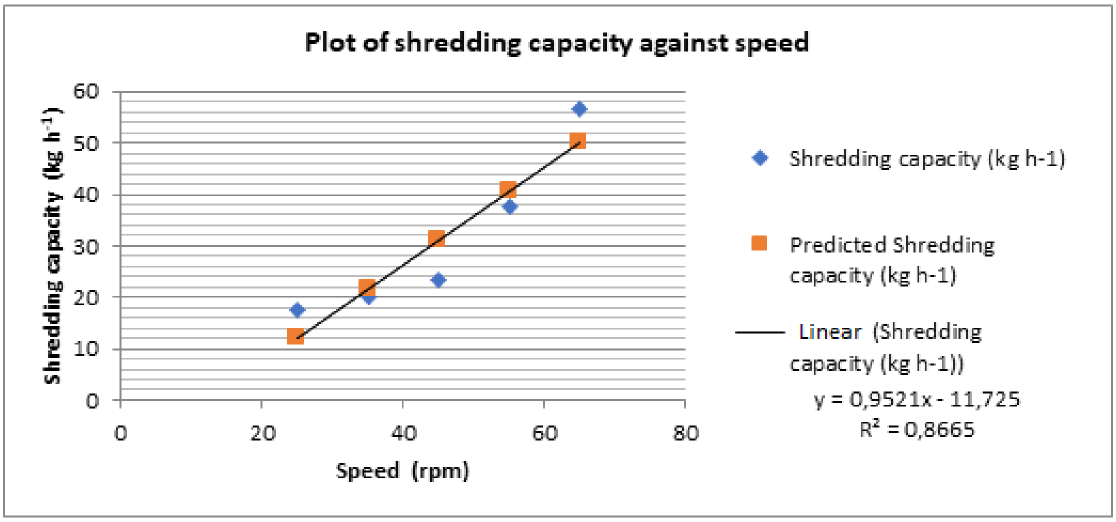


Figure 9. *Shredding capacity at various speed using PET bottles.*

The results presented in Tables 6 and 7 show that 5 observations were used for the model of the predictor and response variable. The coefficient of determination, R square in Table 6 (0.867) implies 86.7 % of the variation in the shredding capacity can be explained by the speed of rotation experienced (PET bottles). The multiple R value, 0.9308 reveals there is strong level of correlation or linear relationship between the explanatory variable (speed) and response variable (shredding capacity). It also implies that null hypothesis defined is within acceptable limit. The standard error, 2.53 is larger than the coefficient of the predictor (speed) which is 0.95 rpm. On the average, the observed value of predictor falls 2.53 rpm from the regression line (see Tables 6 and 7 for details).

Table 6. *Regression statistics for PET bottles.*

Regression Statistics	
Multiple R	0.93086928
R Square	0.86651762
Adjusted R Square	0.82202349
Standard Error	2.52617
Observations	5

Table 7 shows the analysis of variance (ANOVA) of the regression statistics. From the table, it can also be inferred that the number of independent variables in the model is 1 as regression degree of freedom (df) is 1 while total df is 4. F value in Table 7 is 19.48 and the Significance F is 0.0216. The F value assists in testing the hypothesis that the slope of the independent variable is zero. The Significance F is otherwise called the p value for the null hypothesis. It assists in confirming that the coefficient of the independent variable is zero. Since the p-value is below 0.05, it implies there is 95% confidence that the slope of the regression line is not zero. Hence, there is significant linear relationship between speed of rotation and shredding capacity of the machine. For individual p-value in Table 7, it can be inferred that the predictor (speed) is statistically significant – meaning the predictor is applicable for the model.

Table 7. *Analysis of variance for PET bottles evaluation.*

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	1	906.49441	906.4944	19.47488	0.02159
Residual	3	139.64059	46.54686		
Total	4	1046.135			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-11.7245	10.17678	-1.15208	0.332765	-44.11154
Speed (rpm)	0.9521	0.21575	4.413035	0.021592	0.26550

Coefficients and intercept presented in Table 7 can be used to express linear regression model stated in Equation “20”. The response variable, y can be established from the parameters in Table 6. (Intercept on y axis) is -11.7245 kg h^{-1} while ε, being the model error has value of 0.9521. Therefore, response variable y in Equation “20” is expressed as: Y= $\mathbf{0.952X_1 - 11.725 \pm 2.53}$

Figure 10. *Front view of the developed shredder assembly.*

Figure 11. *Machine evaluation exercise with tin can and paper.*

Figure 12. *Products of machine evaluation exercise.*

Variable $\mathbf{X}_1$ in the model is the speed of rotation of the shredding process; βo is intercept on y axis, ε is the model error and variable **Y** is the shredding capacity in kg h^{-1} ($y = \beta o + \beta 1X1 + \varepsilon$). For example, for every unit increase in speed of rotation of the machine, shredding capacity increases commensurately. The machine reached highest shredding capacity for PET, paper and can respectively as 56.52 kg h^{-1}, 42.09 kg h^{-1} and 29.60 Kg h^{-1} at 65 rpm. Beyond this optimal speed, uneven vibration of the machine assembly is experienced. Also, when the machine is operated below 25 rpm, it results in machine eventual seizure and stoppage. Similar things were observed for the model of predictor and response variable of ***paper*** and ***empty tin can***. The machine has comparative advantage over diesel or electric motor-powered engine as it is less stressful to operate and economical to run and maintain. It has shredding capacity that can manage daily waste generated from soft drink, can or paper in a farm, academic institution, shopping mall, market, school and training institute. If the machine is given wide publicity, the menace caused by nonbiodegradable materials like plastic will be ended.

CONCLUSION

The world's inability to keep up with the management of exponentially rising output of plastic wastes has made plastic pollution emerged as one of the most urgent environmental threats. In addressing the menace of plastic pollution in developing economy like Nigeria, PET bottle shredder was developed and evaluated in this study. Plastic shredder is a machine used to cut recyclable plastic materials into smaller pieces of granules. Plastic shredder was developed in this study for small scale shredding of PET bottles. The machine developed was made of mild steel of 12 mm thickness to avoid seizure of parts and eventual machine failure while in use for extended period of time. Machine performance was evaluated using empty PET bottles. The shredder gave the highest shredding capacity of 56.52 kg h^{-1} at 65 rpm. Versatility of the machine was tested for other materials like empty Tin can and paper waste. At 65 rpm, the machine gave shredding capacity of 42.09 kg h^{-1} for paper and 29.60 kg h^{-1} for Tin can. The cost of production of the machine is $817.71. The speed of rotation for process optimization is 65 rpm. Machine design of shredder used in industries was scaled down in this research brief to make the machine attractive and affordable for small scale processors. If the machine is widely adopted, the menace caused by nonbiodegradable materials like plastic will be ended. More also, it will help all stake holders involved to embrace habit of value addition as they turn their daily waste generated to wealth. PET plastic shredding therefore plays a crucial role in combating plastic waste nuisance and promoting a circular economy.

The following recommendations are given about the machine while in operation:

i. To use the machine above 65 rpm, the machine must be installed and damped.

ii. The machine will give better shredding capacity results if bailer is first used to compress the materials to be shredded.

iii. The provision in the machine assembly for direct coupling of the petrol engine to the reducer should be housed.

iv. The machine can be adopted for home use to encourage culture of value addition.

v. More evaluation exercises should be carried out on the machine for process optimization.

vi. More research works should be done to develop other machines involved in effective waste management. The machines include among others the crusher, extruder, granulator, washing machine, bale breaker, plastic melting and molding machine, etc.

DECLARATION OF COMPETING INTEREST

The authors (M.A. Okusanya, C.B. Ogunlade and S.D. Oluwagbayide) hereby declares that there is no conflict of interest what so ever on this work.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Muyiwa Abiodun Okusanya: Conceptualization, investigation, methodology, writing – original draft.
Christopher Bamidele Ogunlade: Formal analysis, data curation, validation, fabrication.
Samuel Dare Oluwagbayide: Conceptualization, visualization, fabrication, review, and editing.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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