Original Research Article

Development and Performance Analysis of a Mini Twin-Shaft Shredder for Efficient Polyethylene Terephthalate (PET) Bottle Recycling in the Philippines

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ABSTRACT

Polyethylene terephthalate (PET) stands out as the most widely recycled plastic globally. However, in the Philippines, the processes associated with PET recycling, particularly the transportation of PET bottles from collectors and consolidators to processing plants, demand significant time, monetary resources, and effort due to the lack of appropriately sized shredder machines in local junkshops to reduce bulkiness. As a response, this study aimed to design a mini twin-shaft ~~polyethylene terephthalate (~~PET~~)~~ bottle shredder. The design took into account the constraints and prerequisites of local junkshop proprietors, municipal and barangay local government units, and non-government organizations.

The machine was comprised of five essential components: the hopper, shredding chamber, power transmission, prime mover, and frame. Post-consumer PET bottles were employed as test materials for experimentation at different treatment speeds: 30, 40, and 50rpm. The experimental layout followed a completely randomized design (CRD). Performance metrics, including shredding capacity, shredding efficiency, and energy demand, were scrutinized based on shaft speed alterations through analysis of variance testing. Additionally, a comparison among means was executed using the least significant difference (LSD) method, with a significance level of 5%.

Results indicated that the highest shredding input capacity of 34.07 kg/hr was attained at a shaft speed of 50rpm, along with a shredding efficiency of 91.3%. The presence of unshredded materials was identified as the primary cause of device inefficiency, constituting 6.44% of the total test materials input. The energy demand was calculated at 0.132 kW-hr/kg. The resulting product dimensions primarily ranged between 25 and 50mm. A cost analysis demonstrated that the machine would need to shred a cumulative 6,889kg of PET bottles to reach the breakeven point, given a custom rate of Php7/kg. The initial investment cost of Php124,383 could be recuperated in a mere 1.91 years, yielding an added net income of Php210,000/yr for PET collectors and/or consolidators.

Keywords: PET (Polyethylene Terephthalate), Plastic Recycling, Plastic Shredder, Twin-shaft Shredder, Cost Analysis, Market Feasibility

1. INTRODUCTION

The Philippines annually imports a total of 24,000 metric tons of PET materials, encompassing resin, preforms, sheets, and finalized packaging products. These materials are subsequently converted into 22,592 metric tons of bottles and containers for both food and non-food applications, as well as packaging materials for electronic products. In 2001, the generated amount of industrial and post-consumer waste reached 5,040 metric tons, resulting in a 21% recovery rate of PET plastic waste. The primary participants involved in the collection and retrieval of PET industrial and post-consumer waste include junkshops, PET consolidators, and PET recyclers [1].

To date, only half of PET waste is globally recycled, while the remainder is incinerated or dumped in landfills, rivers, and oceans. To address the continuously escalating rate of waste generation, the government sector promotes the collection, retrieval, and recycling of waste such as PET bottles. One crucial step in the bottle recycling process involves size reduction, wherein the shredding process is employed. Shredding yields smaller pieces of coarse, irregularly shaped plastic flakes, which can subsequently undergo further processing. Based on conducted interviews at a local junkshop, manual volumetric reduction demands excessive time and labor. Furthermore, no machines have yet reached the junkshops to facilitate the reduction of their plastic collections.

Local junkshops lacking the capital to purchase trucks for hauling their products to plastic melting factories rely solely on truck rentals. The expenses for transportation range from Php9,000.00 to Php16,000.00 per load based on volume. A ten-wheeler truck can accommodate 2 to 2.7 tons of uncompressed PET bottles, depending on the loading strategy, and around 6 tons when the bottles are pressed, irrespective of the loading type. Pressing and shredding bottles enhance material density, thus increasing the volume the truck can carry in a single trip. Additionally, shredded PET bottles command a higher selling price than those that haven't undergone the shredding process. Consequently, reducing the size of PET bottles before transporting them to processing centers reduces expenses and processing time, ultimately boosting profits for local junkshop owners.

Junkshops could avail themselves of a plastic shredding machine offered for free by a plastic melting factory, provided the quota for plastic volume delivery within a specific timeframe is met. However, for local junkshop owners, the terms set by the melting factory are challenging to meet due to limited time and capital. Consequently, no junkshop in the vicinity has yet accepted this demanding offer. The general objective of the study was to develop a mini twin-shaft polyethylene terephthalate (PET) bottle shredder. Specifically, the study aimed to design this machine using locally available materials, fabricate it using local manufacturing technology, evaluate the device's performance in terms of shredding capacity and efficiency, determine its energy demand, and analyze the associated cost of its usage.

2. MATERIAL AND METHODS

2.1 Conceptualization of the study

The conceptualization of the study took into consideration the input of local junkshop owners, municipal and barangay local government units, as well as non-government organizations during interviews. Feedback revealed that certain junkshop owners tend to compress PET bottles using vehicles before delivering them to processing plants in order to reduce bulkiness. Others refrain from doing so due to a lack of available pressing areas, vehicles, and the labor-intensive nature of the process. Municipal and barangay local government units emphasized waste disposal as a major concern, with some spending 30 to 50 million pesos per month solely on waste transportation. Non-government organizations reported difficulties in advancing their recycling initiatives due to the absence of machinery in the locality and the local market capable of facilitating further plastic processing to create more products from PET bottles. Consequently, to address these challenges and enhance the economic and environmentally friendly aspects of recycling, a mini twin-shaft PET bottle shredder was developed using locally available materials and machine technology essential for recycling purposes.

Figure 1 illustrates the study's conceptual framework, following the input-process-outcome approach. The framework is primarily built upon the study's overarching objective, which is the development.

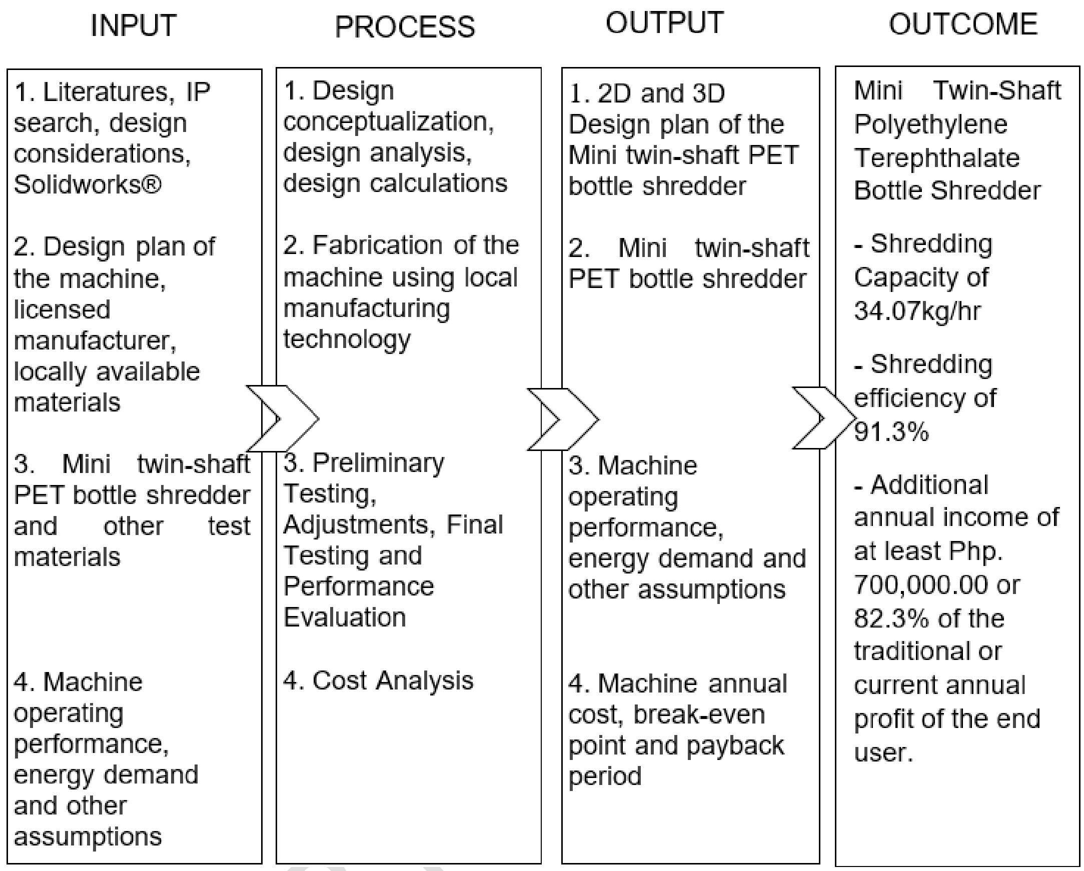

Fig. 1. Conceptual framework of the study

2.2 Design concept of the machine

The design of the PET bottle shredder was guided by the daily quantity of PET bottles amassed by PET bottle collectors and consolidators. The shredder consists of five main components (Figure 2): the hopper, shredding chamber, power transmission system, prime mover, and frame. The construction materials employed for the machine encompassed an electric motor, v-belts, v-pulleys, spur gears, angular bars, screws, ball bearings, high tensile bolts and nuts, G.I sheet, MS plate, high carbon steels, and shafts.

1	Hopper	4	Electric motor
2	Shredding Chamber	5	Frame
3	Transmission System		

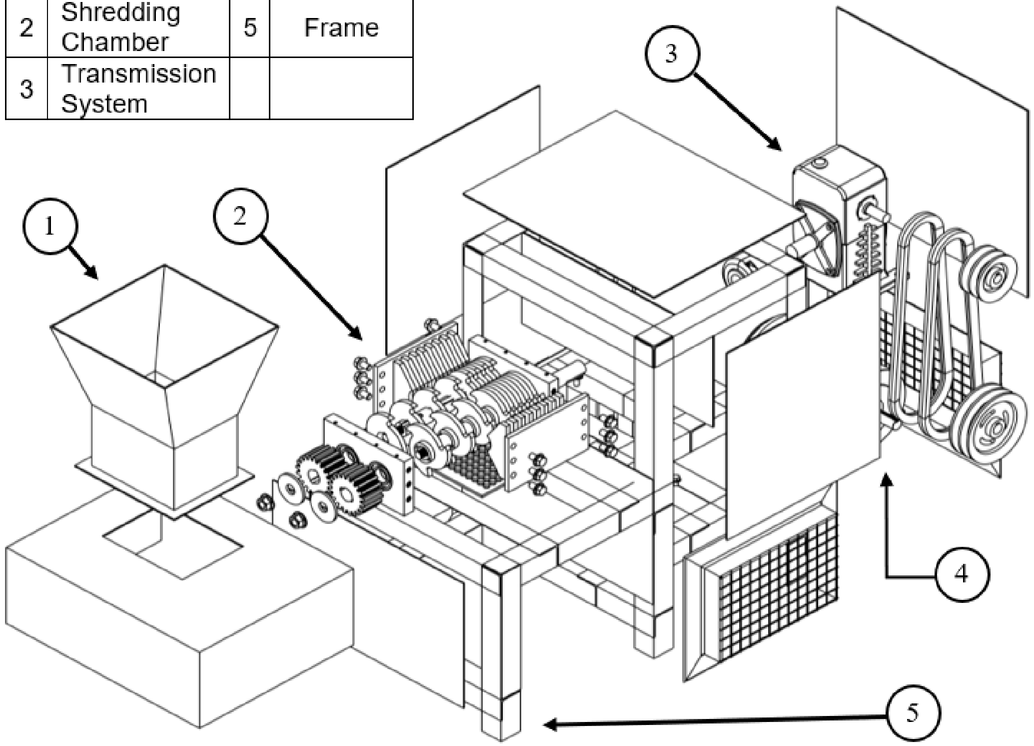

Fig. 2. Mini twin-shaft PET bottle shredder exploded view

2.3 Design of Major Components

2.3.1 Hopper

The material chosen for the hopper was a G.I steel sheet, specifically designed to accommodate the materials being fed into the shredder. It also functions as a guard to prevent shredded materials from exiting the shredding chamber and scattering. The dimensions of the hopper were calculated utilizing the formula for the volume of a truncated pyramid, as presented in the equation 1.

$$V = \frac{1}{3}\left(A_1 + A_2 + \sqrt{A_1 + A_2}\right) x\, h \qquad (1)$$

where: $A_1 = S_1{}^2$

$$A_2 = S_2{}^2$$

$$\text{Tan}\ \theta = \frac{h}{\frac{S_1 - S_2}{2}} \qquad (2)$$

where: V= Volume of the truncated pyramid

A_1 = Area of the upper base, mm^2

A_2 = Area of the lower base, mm^2

h = height of the truncated pyramid, mm

S_1 = Width of the upper base, mm

S_2 = Width of the lower base, mm~~2~~[no squared numbers]

θ = angle of inclination of the hopper side, The G.I. steel sheet possesses a yield strength of 470MPa. Using this value along with the estimated load that the hopper will bear, the thickness of the G.I. steel sheet was determined utilizing the fundamental equation:

$$\sigma = \frac{P}{A} \tag{3}$$

Where: σ = Allowable stress, MPa
P = load, N
A = Area, mm^2

2.3.2 Shredding Chamber and Blade Assembly
This component serves as a holder, protector, and enclosure for the blade assembly, which comprises the blades and shafts. Designs and calculations were performed on a per-part and/or component basis.

2.3.2.1 Shredder blade with spacer
The plastic bottles are shredded through the action of the blade assembly. According to the research conducted by Villafañe et al. [7], the stress at the average breaking point of PET falls within the range of 140MPa to 210MPa. The analysis of blade force is determined by the shearing force required to fracture the bottle and can be computed using the following formula.

$$\frac{F_{sh}}{A} = \frac{Sut}{F.O.S.} \tag{4}$$

Where: F_{sh} = shearing force, N
A = Area of contact of blade to the material to be cut, mm^2
Sut = Yield strength of PET bottles, MPa
F.O.S. = Factor of Safety

The blade assembly consists of eight pairs of three-toothed blades. Because of the intermeshing action of these blades, a gap between them is necessary. Therefore, distance rings, with the same thickness as the blades, function as spacers to maintain the required spacing.

2.3.2.2 Shredder Shafts
The design of the shredder's shafts aimed to prevent bending. AISI 4340 steel was chosen as the fabrication material. The shaft diameter was determined using the following equation:

$$d_o{}^3 = \frac{16}{\tau_d \pi}\left[\sqrt{(C_m \text{ x } M_B)^2 + (C_t \text{ x } T)^2}\right] \tag{5}$$

Where: d_o = diameter of the shaft, mm
τ_d = design shear stress, MPa
C_m = bending factor
M_B = bending moment, N.mm
C_t = torsion factor
T = torque, N.mm

2.3.2.3 Spur Gears
Gears were linked on the same side of the shaft to generate counter-rotation of the shafts. The design and calculations of the spur gears were guided by PAES 306:2000. [5] (Table 1).

Table 1. Spur gear calculations.

To obtain	Given	Formula
Module	Circular pitch	$\frac{\text{Circular pitch}}{\pi}$
	Number of teeth and pitch diameter	$\frac{\text{Pitch diameter}}{\text{Number of teeth}}$
Pitch diameter	Number of teeth and module	Number of teeth x Module
Number of teeth	Pitch diameter and module	$\frac{\text{Pitch diameter}}{\text{Module}}$
Tooth thickness of the pitch line	Module	1.5078 x Module
Outside diameter	Pitch diameter and addendum	Add 2 addendums to the pitch diameter
Minimum whole depth	Module	Coarser than 1.0583 module, 2.35 x module
Addendum	Module	addendum = module
Dedendum	Module	dedendum = 1.25xmodule
Clearance	Whole depth and addendum	Subtract two addendums from the whole depth
Center distance	Number of teeth of driver and driven gear, t_1 and t_1 Module	$\frac{\text{module}(t_1 \text{ and } t_1)}{2}$

2.3.2.4 Transmission System

This component was devised to fulfill the requisite low speed and enhance the necessary torque during shredding.

Given that the machine is anticipated to operate primarily in locations with available electricity and doesn't require mobility for its functioning, an electric motor is the most appropriate choice as the prime mover. The capacity of the electric motor utilized in the machine was determined based on the computed torque applied to the blade assembly. This calculation was performed using equations 6, 7, and 8.

$$T = Fsh \times D \tag{6}$$

Where: Fsh = shearing force, N
D = distance from the center to the tip of blade, mm

$$P = 2\pi TN \tag{7}$$

Where: P = Power, Hp
T = Torque, N.mm
N = Speed, rpm

$$N_1D_1 = N_2D_2 \tag{8}$$

Where: N_1 = Speed of the driver pulley, RPM
D_2 = Diameter of the driver pulley, mm
N_2 = Speed of the driven pulley

D_2 = Diameter of the driven pulley

2.3.2.5 Frame Assembly

The shredding chamber, motor, and speed reducer were affixed to the frame constructed from angular bars, secured in place using bolts and nuts. The maximum bending moment was computed through the shear and moment diagram. Subsequent calculations for determining the dimensions of the angle bar employed in fabricating the machine were achieved using the following formula:

For the calculation of allowable stress used equation 9.

$$\sigma_{Allow} = \frac{YS}{FOS} \tag{9}$$

Where: σ_{Allow} = Allowable Stress, MPa
YS = Yield Strength or Ultimate strength, MPa
FOS = Factor of Safety

After the calculation of the allowable stress, compute for the section modulus using the formula:

$$Z = \frac{M_{max}}{\sigma_{Allow}} \tag{10}$$

Where: σ_{Allow} = ultimate strength of the material, MPa
M_{max} = Maximum bending moment, N.mm
Z = Section modulus of angle bar, mm^3

For solving the outer side and inner side of angle bar, the following formula was utilized:

$$Y = \frac{I}{Z} \tag{11}$$

Where: I = Moment of Inertia, N.mm
Y = Distance from Neutral Axis, mm

The thickness of the angle bar was calculated using equation 25.

$$t = \frac{a - a_1}{2} \tag{12}$$

Where: t = Thickness of angle bar, mm
a = Outer side of angle bar, mm
a_1 = Inner side of angle bar, mm

Table 2. Summary table of the properties of materials and factor of safety used in different component

Component	Material Used	Yield Strength, MPa	Factor of Safety	Allowable Stress, MPa
Hopper	G.I sheet	470	3	156.67
Shredder Blades with Spacers	AISI4340	710	1.5	473.33
Shredder Shafts	AISI 4340	710	3	236.67
Spur Gear	AISI 1045	530	3	265

Frame	ASTM A36	250	2.5	100

3. RESULTS AND DISCUSSION

3.1 Description of the machine

The manufactured machine (Figure 3) operated in a continuous feeding manner, allowing materials to be consistently fed into the machine until all materials were shredded. In the event of machine clogging, a reversal in the rotational speed direction of the electric motor shaft was necessary to clear the shredding chamber.

Fig. 3. Fabricated PET bottle shredding machine

3.2 Machine Performance Evaluation

The machine underwent evaluation in terms of capacity, efficiency, and energy demand, influenced by various shaft speeds (30rpm, 40rpm, and 50rpm). The obtained results were subjected to statistical analysis using the Statistical Tool for Agricultural Research (STAR).

3.2.1 Machine Shredding Capacity

It is the ratio of the weight of the input plastic materials minus the weight of unshredded plastic materials, divided by the total weight of the input plastic materials to the shredder, expressed in kg/hr, as determined by the following equation:

$$Ci = \frac{Wi}{T} \quad (13)$$

Where: Ci = Input Capacity, ~~K~~g/hr.[should kg/hr]
Wi = Weight of Input Materials, ~~K~~g[should kg]
T = Operating Time, hr.

The highest shredding capacity was achieved at the fastest shaft speed of 50rpm, with an average value of 34.07kg/hr. This was followed by 40rpm with a mean value of 21.69kg/hr, and the lowest capacity was recorded at the slowest speed of the main shaft, with an average value of 15.67kg/hr. Analysis of variance indicated that shaft speed had a significant impact on the machine's shredding capacity at a 5% level of significance.

The mean shredding capacities at various shaft speeds were found to be significantly distinct from one another, as demonstrated by the comparison among treatment means (Table 3). Notably, higher shredding capacity was observed at higher shaft speeds. This result aligns with Ekman R.'s study [2], which suggests that as the shaft speed of a twin-shaft shredder increases, the blade tooth's cutting rate accelerates when interacting with the fed materials.

As a consequence, PET bottles are fed to the shredder at a faster rate, yielding a larger capacity. However, this also elevates the likelihood of clogging. This observation is further supported by Fitzgerald G.'s findings [3], indicating that low-speed shredders are constrained in capacity by their rotor speed and tolerances, with maximum throughput defined by the volumetric displacement between the cutting surface and the shaft's RPM. Consequently, increasing the capacity of shear shredders could potentially involve constructing larger machines based on the same size reduction principle. Moreover, Glass R. [4] also noted that shredder shaft speed can serve as an indicator of a shredder's capacity with respect to the material being processed. Materials with lower material properties may lead to a higher shredder capacity compared to materials with higher material properties, assuming the same knife tip force for the shredder.

Table 3. Mean shredding capacity at various main shaft speed, kg/hr

Treatment RPM	Means
30	15.67 a
40	21.69 a
50	34.07 b

*Means with the same letter are not significantly different.

3.2.2 Machine Shredding Efficiency

It is the ratio of the weight of the input plastic materials minus the weight of unshredded plastic materials, divided by the total weight of the input plastic materials to the shredder, expressed as a percentage, as determined by the following equation:

$$\text{Es} = \frac{\text{Ws}}{\text{Wi}} \text{ x } 100 \qquad (14)$$

Where: Es = Shredding Efficiency, ~~K~~g[should kg]
Ws = Weight of Shredded Materials, ~~K~~g[should kg]
Wi = Weight of Input Material, ~~K~~g[should kg]

The shredding efficiency of the machine, as detailed in Table 4, decreases with the rise in shaft speed. At a shaft speed of 30rpm, the shredding efficiency was observed to be 94.64%, declining to 92.17% and 91.26% respectively, at 40 and 50rpm. Analysis of variance indicated that shredding efficiency was significantly influenced by the shaft speed. A comparison among means in Table 4 revealed that the shredding efficiency at the lowest shaft speed of 30rpm was notably higher than at 40 and 50rpm. No significant differences were observed when comparing 40 and 50rpm.

From the conducted sampling, it was found that at 30rpm, the least amount of unshredded material (>50mm) was recorded, which had a considerable impact on the device's shredding efficiency. It was noted that a screen placed below the shredding chamber served as the medium for flake sizing, preventing flakes larger than 50mm from passing through the screen holes. Nevertheless, a higher rpm of the shafts equated to a faster blade cutting rate and feeding rate of PET bottles into the machine. Consequently, new materials being fed forced some larger-than-50mm flakes to pass through the screen holes, leading to an increased amount of unshredded materials at higher rpm. Conversely, a slower rpm of the shredder shafts resulted in a more gradual feeding and cutting rate, allowing the blades more time to lift materials longer than 50mm for another round of shredding instead of forcing them through the screen holes.

Additionally, higher rpm of the shafts also led to a greater quantity of powder-like sized flakes, which constituted the scattering loss and further impacted the shredder's efficiency.

Table 4. Mean shredding efficiency at various main shaft speed, %

Treatment RPM	Means
30	94.64 a
40	92.17 b
50	91.26 b

*Means with the same letter are not significantly different.

3.2.3 Energy Demand

The amount of electricity consumed by the machine to process a kilogram of PET bottle expressed in kilowatt-hour per kilogram.

$$\text{Ed} = \frac{\text{Pi x T}}{\text{Wi}} \tag{15}$$

Where: Ed = Energy Demand[it must be : not =, because it is as a description or not as an equation]

Pi : Power Input, (~~K~~w)[should kW]
T : operating Time, (hr)
Wi : Weight of Input Material, ~~K~~g[should kg]

Table 5 reveals that at 30rpm, the highest energy demand is observed, amounting to 0.205 kW-hr/kg, followed by 40 rpm with 0.181 kW-hr/kg, and 50 rpm necessitating the lowest energy demand of 0.132 kW-hr/kg. The analysis of variance indicates that shaft speed significantly impacts the energy demand of the machine at a 5% level of significance. A comparison among treatment means reveals that the energy demand at 30rpm does not exhibit any significant difference compared to the energy demand at 40 rpm.
These findings align with Fitzgerald G.'s study [3], suggesting that the rotor speed of low-speed high-torque (LSHT) shredders notably influences power consumption and device capacity. As rotor speed decreases, the specific energy required for waste processing tends to increase.

Table 5. Mean energy demand at various main shaft speed, kW-hr/kg

Treatment RPM	Means
30	0.2047 a
40	0.1810 a
50	0.1317 b

*Means with the same letter are not significantly different.

3.2.4 Cost Analysis on the use of the device

The result of the cost analysis in Table 5 resulted to the cost of shredding equation as

$$\text{CS} = \frac{27{,}364.26}{\text{V}} + 3.03 \tag{16}$$

Where: CS = cost of Shredding, Php/kg
V = Volume of PET to be shredded, ~~K~~g/yr[should kg/yr]

With equation 16, the cost curve was drawn and shown in Figure 4. Generally, it was observed that the cost of shredding (Php/kg) decreased as the annual volume of PET bottles to be shredded increased. Information obtained from local junkshop owners in La Trinidad, Benguet revealed that an average of 60,000kg of PET bottles were collected in one year. With this volume, and at a rated capacity of the machine of 34.07kg/hr, it needed to operate about 1,765 hrs per year, equivalent to 220-250 days when it works 7-8hrs per day. At this volume (60,000kg/yr), the cost of operation, as computed using equation 16, would be Php3.49/kg. Hence, using the machine for custom service operation, the custom rate of about Php7/kg could safely be assumed. At Php7/kg rate, operating the machine would break-even at 6,889kg/yr. Using the machine for custom operation (Php7/kg) for a volume of 60,000kg/yr, will yield a net income of Php210,600/yr, resulting to a payback period of 1.9yrs.

Table 6. Cost analysis of using the machine

Particulars	**Value**	**Unit**
1. ANNUAL FIXED COST	27,364.26	Php/yr
Depreciation	11,194.47	Php/yr
Interest on Investment	13,682.13	Php/yr
Tax and Insurance	2,487.66	Php/yr
2. VARIABLE COST	103.16	Php/hr
Operator's Wage	43.75	Php/hr
Repair and Maintenance	37.31	Php/hr
Power Cost	22.1	Php/hr
3. BREAKEVEN POINT	6,889	Kg/yr

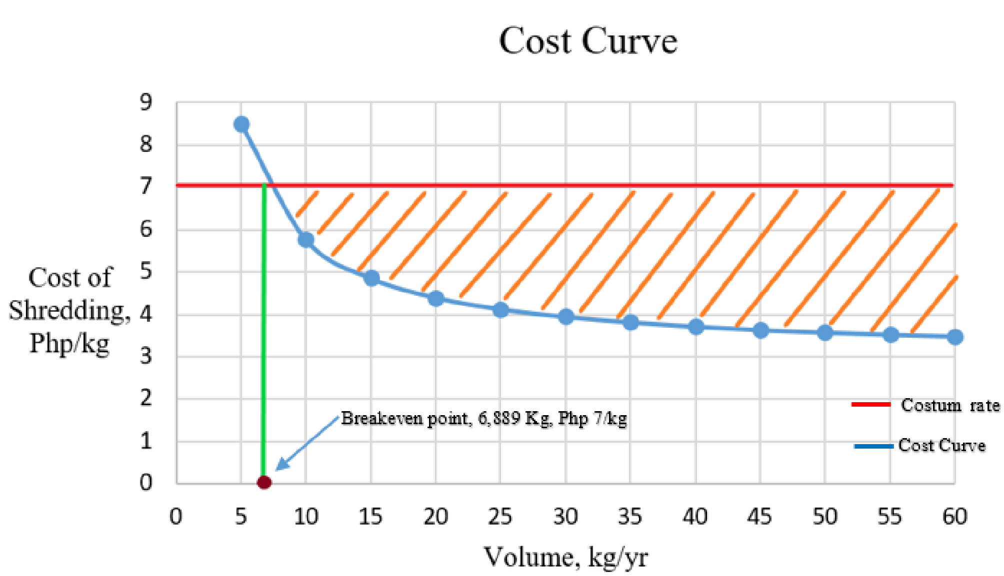

Fig. 4.Cost curve of using the machine

3.2.5 Market Feasibility

Table 7 outlines the market feasibility of the machine. Based on the gathered data regarding the annual volume of collected PET bottles (60,000kg/yr), a comparative projection of income for local junkshops, with and without a shredding machine, was calculated. The assumption was made that the plastic shredder is individually owned by the local junkshop. The results revealed that utilizing the PET bottle shredder would yield an annual net income difference of Php757,174.00/yr in comparison to local junkshops operating without a shredding machine. The payback period would be as short as 0.15 years of operation or 38 working days. However, since it takes 48 days to shred a truckload of plastic products, the realistic payback period for the machine would be after the first delivery of shredded plastics, amounting to a 270% rate of return.

Table 7.Market feasibility of using the machine

Particulars	Without Shredding Machine	With Shredding Machine
a. Initial cost		124,383
b. Amount of PET to be processed, kg/yr	60,000	60,000
c. Ten-wheeler van Capacity, kg/truckload	2,450	11,359
d. Number of deliveries per year	28	6
e. Average transportation cost per trip, Php	10,000	10,000
f. Annual Transportation cost, Php/yr (from table 13)	280,000	60,000
g. Annual Fixed cost, Php/yr (from table 13)		27,364.26
h. Annual Variable cost, Php/yr (from table 13)		253,058.65
i. Annual Operating cost, Php/yr (g+h)	280,000	280,422.91
j. Unshredded PET bottle plastic melting factory price, Php/kg	18	
k. Shredded PET bottle plastic melting factory price, Php/kg		49.5
l. PET bottle junkshop price, Php/kg	18	18
m. Profit, Php/kg (k-l)	20	31.4
n. Annual Revenue, Php/yr (axm)	1,200,000	1,884,000
o. Annual Net Income, Php/yr (n-i)	920,000[1]	1,603,577[2]
p. Additional Income (Bonus) if plant quota (4 tons) is met, Php/yr		73,597
q. Difference in Annual Net Income, Php/yr (2-1)	**683,577**	
r. Payback Period, yrs.	**0.15**	
s. Rate of Return, %	**270**	

4. CONCLUSION

Based on the study's objectives and findings, the following conclusions can be drawn. The concept and mechanism of the developed PET bottle shredder machine have been proven effective in reducing labor, time, and expenses involved in processing PET bottles, while also generating additional income for collectors and consolidators. The machine can be

constructed using locally available materials and local manufacturing technologies. The machine's performance was satisfactory across its key parameters, including shredding capacity and shredding efficiency. Shredding efficiency decreased as shaft speed increased; however, higher shaft speeds resulted in greater shredding capacity for the machine.
The energy demand of the shredder was observed to be 0.132 kW-hr/kg at a shaft speed of 50rpm and 0.205 kW-hr/kg at 30rpm. The power consumption of the machine was deemed economical, with an annual power consumption cost of Php 39,005. The cost analysis of utilizing the machine demonstrated its financial viability. Local junkshop owners could reduce their transportation costs by 21.4 percent and potentially increase profits by Php 757,174 per year by implementing the machine for shredding PET bottle products. The fabrication cost of the machine was Php 124,383. The projected annual operating cost amounted to Php 280,423, with a calculated breakeven weight of Php 6,889kg and a payback period of 38 working days.

DISCLAIMER

Some part of this manuscript was previously presented and published in the following conference.

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tsae.en.kku.ac.th/wp-content/uploads/2021/07/TSAE2021-PRECEEDINGS_ed.pdf

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