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# Optimization of A Plastic Waste Crushing Machine for Enhanced Crushing Efficiency, Throughput and Energy Economy

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**Abstract**: *Plastic waste accumulation remains a major environmental challenge, particularly in developing countries with limited recycling infrastructure. This study developed and optimized a low-cost plastic waste crushing machine suitable for small-scale recycling applications. Response Surface Methodology (RSM) based on a Box–Behnken Design was used to investigate the effects of rotor speed, blade angle, and feed rate on crushing efficiency, energy consumption, and material throughput. Experimental data were fitted to quadratic models and evaluated using ANOVA. The models showed high predictive accuracy with an F-value of 26.45, $p < 0.001$, $R^2 = 0.968$, adjusted $R^2 = 0.942$, and a non-significant lack-of-fit ($p = 0.75$), confirming model adequacy. Rotor speed was identified as the most influential factor, followed by blade angle and feed rate. Crushing efficiency increased with rotor speed and moderate blade angles but declined at excessive feed rates due to chamber congestion. The optimum operating conditions for maximum crushing efficiency were a rotor speed of 1325 rpm, blade angle of 38°, and feed rate of 3.8 kg/h, producing a crushing efficiency of 86.9% and energy consumption of 0.56 kWh/kg. The optimum material throughput of 4.67 kg/h was achieved at a rotor speed of 1312.5 rpm and feed rate of 4.0 kg/h with a blade angle of 38°. The mean prediction error of approximately 0.76% demonstrated excellent agreement between experimental and predicted results. The optimized machine exhibited high efficiency, low energy consumption, and satisfactory throughput, making it a technically viable and economically sustainable solution for decentralized plastic waste recycling and circular economy initiatives.*

**Keywords:** Plastic waste recycling, crushing machine, crushing efficiency, material throughput, energy consumption, response surface methodology, optimization.

## INTRODUCTION

Plastic waste has become one of the most pressing environmental challenges worldwide. Global municipal solid waste (MSW) generation exceeds 2.01 billion tonnes annually and is projected to increase to about 3.40 billion tonnes by 2050 (World Bank, 2023). Nigeria contributes significantly to this challenge, generating approximately 33 million tonnes of solid waste annually, including about 3.8 million tonnes of plastic waste, much of which remains uncollected or improperly managed (Ogechukwu et al., 2020; Ogunyemi et al., 2021).

The rapid growth in plastic consumption has intensified environmental pollution globally. Plastic production increased from less than 2 million tonnes in 1950 to approximately 460 million tonnes in 2019 and is projected to exceed 1.2 billion tonnes annually by 2060 if current consumption trends continue (OECD, 2022; OECD, 2025). Owing to their durability, lightweight nature, versatility, and low production cost, plastics are extensively used in packaging, construction, healthcare, agriculture, transportation, and consumer goods sectors (Bhattacharya, 2018). However, a large proportion of plastic products is designed for single-use applications and is discarded shortly after consumption, resulting in increasing quantities of waste entering the environment (Geyer et al., 2017).

Plastic pollution poses significant environmental and public health risks. Due to their non-biodegradable nature, plastics can persist in terrestrial and aquatic environments for decades, contributing to soil and water contamination, ecosystem degradation, blockage of drainage systems, and microplastic pollution (Geyer et al., 2017; OECD, 2022). These impacts have stimulated global interest in recycling and circular economy strategies aimed at reducing waste generation and promoting resource recovery (Abdulkarim et al., 2016).

Recycling remains one of the most sustainable approaches for managing plastic waste because it reduces the demand for virgin materials, conserves energy, and minimizes environmental pollution (Abdulkarim et al., 2016). Nevertheless, effective recycling requires several preprocessing operations, including sorting, shredding, and crushing. Plastic crushing is a critical stage in the recycling chain because it reduces the size of plastic waste, thereby improving handling, transportation, storage, and subsequent processing efficiency (Nitu et al., 2015). Despite increasing awareness of recycling benefits, Nigeria still faces significant challenges arising from inadequate recycling infrastructure, limited processing equipment, weak policy implementation, and low investment in waste recovery systems (Ogunyemi et al., 2021).

At the Federal University Ilaro, Ogun State, plastic waste generated from academic, administrative, residential, and commercial activities is currently disposed of with little or no prior sorting, processing, or resource recovery. To address this challenge, the institution is proposing the establishment of a Waste Management and Recycling Hub that will serve as a centralized facility for the collection, sorting, processing, recycling, and recovery of wastes generated within the Polytechnic community. The proposed hub is also intended to provide recycling services to neighbouring communities within the Ilaro metropolis, thereby promoting environmental sustainability and community participation in waste management.

However, there is limited availability of affordable, locally designed plastic crushing machines suitable for institutional and community-based recycling operations in Nigeria. Most available machines are imported, costly, and often difficult to maintain under local operating conditions. This gap limits the implementation of decentralized recycling initiatives and constrains effective plastic waste recovery. Therefore, this study focuses on the design and development of a locally fabricated plastic crusher machine to support the proposed Waste Management and Recycling Hub at the Federal University Ilaro, Ogun State. The developed machine is expected to improve plastic waste processing efficiency, facilitate recycling operations, reduce waste volume, and contribute to sustainable waste management within the institution and surrounding communities.

## METHODOLOGY

The methodology adopted for this study consisted of design requirement analysis, conceptual design, engineering design calculations, material selection, fabrication, assembly, and performance evaluation of the developed plastic crusher machine. The machine was designed to process post-consumer plastic wastes such as polyethylene terephthalate (PET), for small-scale recycling applications.

### Design Requirements and Considerations

The design was based on the requirements of affordability, ease of fabrication, operational safety, maintainability, and efficient plastic size reduction. Key considerations included crushing capacity, power requirement, structural strength, availability of materials, ease of component replacement, and adaptability to local manufacturing conditions. Mild steel was selected for the machine frame and crushing chamber due to its strength, availability, and cost effectiveness.

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**Conceptual Design and Machine Description**

Following an evaluation of available size-reduction mechanisms, a single-shaft rotary crusher was selected because of its simplicity, low manufacturing cost, and suitability for small-scale recycling operations. The machine consists of a feed hopper, crushing chamber, rotating shaft, cutting blades, stationary blades, discharge chute, belt-and-pulley transmission system, electric motor, and supporting frame.

During operation, plastic waste is fed through the hopper into the crushing chamber where a shearing action is generated between the rotating and stationary blades. The crushed material is subsequently discharged through the outlet for further processing. Figures 2.1, 2.2 and 2.3 below respectively show the pictorial view, orthographic projection and component view of the entire machine assembly.

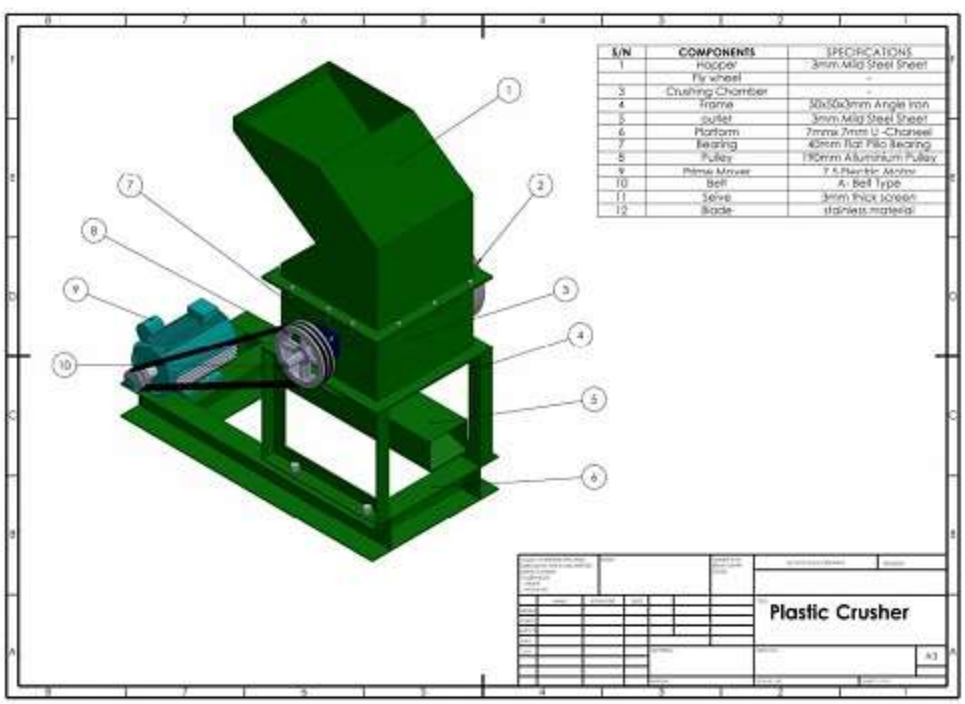


**Fig. 2.1: Pictorial View of the Plastic Crusher**

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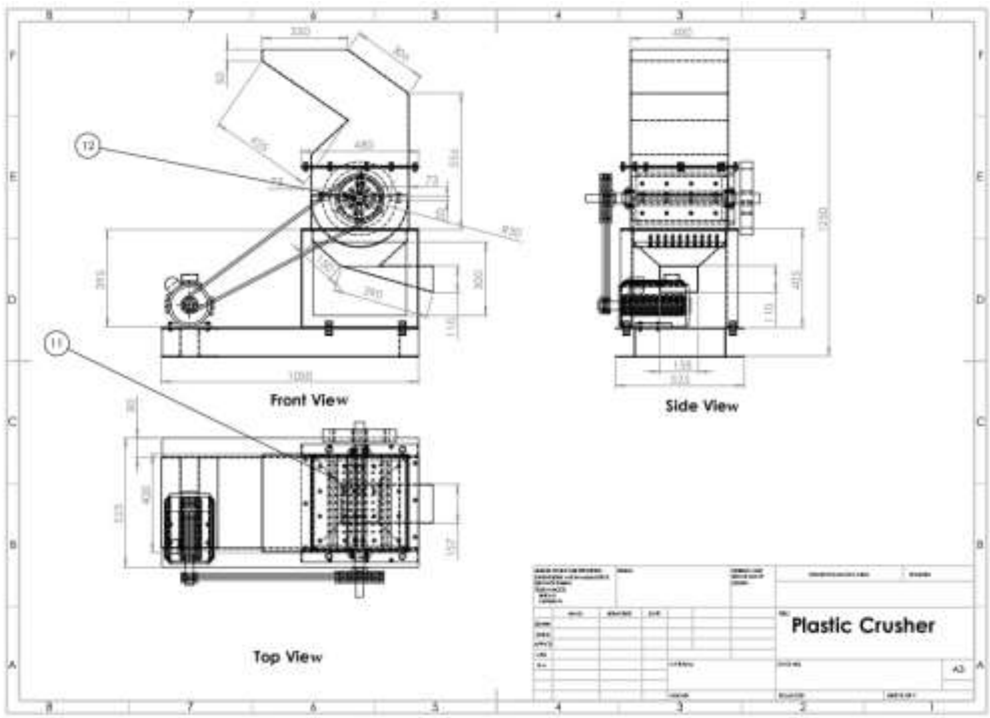


**Fig. 2.2: Orthographic Projection of the Plastic Crusher**

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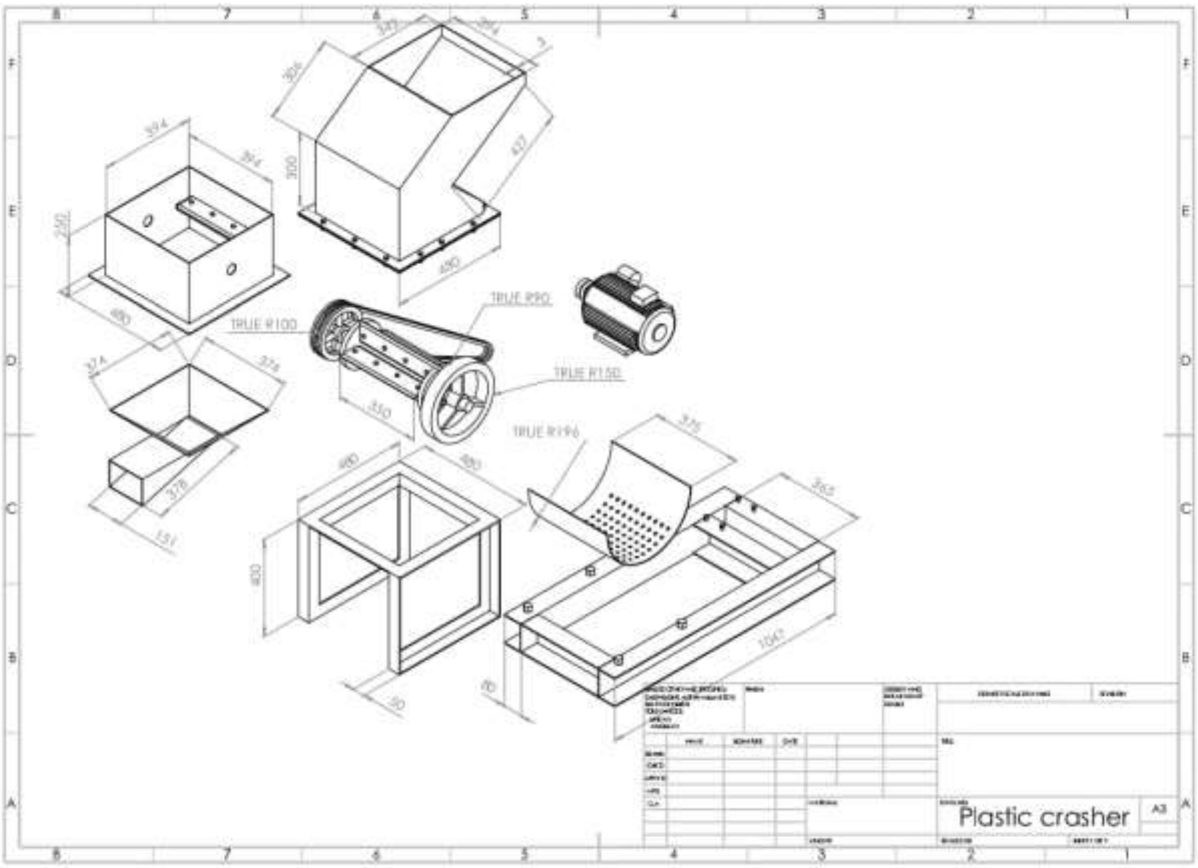


**Fig. 2.3: Component View of the Plastic Crusher**

## Design Analysis

Engineering design calculations were carried out to determine the dimensions and operating parameters of critical machine components. These included the shaft diameter, blade configuration, belt and pulley dimensions, motor power requirement, shaft speed, bearing selection, and structural frame design. Standard machine design equations and failure criteria were employed to ensure adequate strength and reliability during operation.

### Base assumptions

- Target throughput $m = \frac{100\text{kg}}{\text{hr}} = \frac{100}{3600} = 0.028\ \text{kg/s}$

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- Representative plastic: PET (density ρ =1380 kg/$m^3$, shear strength τp = 25 MPa = 25×$10^6$ N/$m^2$).
- Specific energy for size reduction Es = 50 kJ/kg = 50,000 J/kg (conservative mid-range value for plastics).
- Desired crusher shaft speed N = 720 rpm
- Blade radius (distance from shaft centre to cutting edge), r = 80 mm
- Peak radial cutting force (initial estimate) will be computed from shear strength × cut area.
- Allowable material (mild steel) yield σy = 250 MPa. Factor of safety FOS = 2.5
- Use von Mises equivalent stress for combined bending + torsion.
- Assume two bearings supporting a simple shaft span L = 0.40 m (typical for small crusher).

**Power requirement**

Use specific-energy method:

- Mass flow:
  $\dot{m}$=100 kg/3600 s = 0.02778 kg/s
- Power for size reduction:
  Pcrush = es x m = 50,000 x 0.277 = 1.39KW
- Use 20% margin:
  $P_{required}$ = $P_{crush}$×1.20 =1,388.88889× 1.2 = 1,666.67 W

So, motor power ≈1.67 kW. Round to stock motor sizes → **1.5 kW** may be slightly undersized; **2.2 kW (≈3 hp)** gives comfortable margin. Motor with power rating of **2.2 kW** is recommended for reliability and startup torque.

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**Shaft Torque at Operating Speed**

$\boldsymbol{\omega = \frac{2\pi\,N}{60}}$ ........................................ (1)

$= \frac{2\pi\pi \text{ x } 720}{60} = 24\pi \frac{rad}{s}$

$\frac{Prequired}{\omega} = \frac{1.67}{24\pi} = 29.19Nm$

**2.4.3 Cutting Shear Force**

$Fs = \tau p \text{ x } A$ ....................................................................(2)

$= 25 \text{ x } 10^6 \text{ x } 0.005 \text{ x } 0.02 = 2.5KN$

$A = t \text{ x } \omega$ ......................................................................(3)

A is the cutting area, t cutting width and blade thickness. A single blade engaging a 5 x 20mm section must supply roughly 2.5KN

**Radial Loading and Bending Moment on Shaft**

Radial force is applied at blade tip radius r = 0.04m. Radius per blade equal to cutting force Fs

Bending moment, $M = Fs \text{ x } r$ ..................................................(4)

$M = Fs \text{ x } r = 2500 \text{ x } 0.04 = 250 \text{ Nm}$

**Combine Bending Load on Shaft**

i $\text{Bending Stress } \sigma b = \frac{32M}{\pi d^3}$ ........................................................(5)

ii $\text{Torsional Shear Stress } \tau t = \frac{16T}{\pi d^3}$ ................................................(6)

iii. $\text{Von Mises equivalent Stress } \sigma v = \sqrt{\sigma b^2 + 3\tau t^2}$ ..........................(7)

$\text{Note}: \sigma v = \sigma allow$

$\sigma allow = \frac{\sigma y}{FOS} = \frac{250}{2.5} = 100MPa$ ..................................................(8)

**Shaft Diameter Design**

$\text{Let } K = \pi d^3$

$\text{Bending Stress } \sigma b = \frac{32M}{\pi d^3} = \frac{32M}{K}$

Also, $\text{Torsional Shear Stress } \tau t = \frac{16T}{\pi d^3} = \frac{16T}{k}$

$\text{Von Mises equivalent Stress } \sigma v = \sqrt{\sigma b^2 + 3\tau t^2}$

$= \sqrt{\{\left(\frac{32M}{k}\right)^2 + 3(16T/k)^2}$

$= \frac{1}{k}\sqrt{\{(32M)^2 + 3(16T)^2\}}$ ....................................................(9)

By rearranging, $\mathbf{d^3} \geq \frac{\left[\sqrt{\{(32M)^2+3(16T)^2\}}\right]}{\pi \text{ x } \sigma allow}$ ……………………………………..(10)

$$\mathbf{d^3} \geq \left(\frac{\sqrt{\{(32x250)^2+3(16x\ 22.11)^2)}}{\pi x100x\ 10^6}\right)$$

$$\mathbf{d \geq \sqrt[3]{2.05 \text{ x } 10^{-3}} = 0.02746m = 27.46mm}$$

A standard shaft size of 30 mm should be selected

$$\mathbf{k = \pi D^3 = 8.4 \text{ x } 10^{-5} m^3}$$

$$\mathbf{\sigma b = \frac{32M}{\pi d^3} = \frac{32 \text{ x } 250}{8.48 \text{ x } 10^{-5}} = 94.34MPa}$$

$$\textbf{Torsional Shear Stress } \mathbf{\tau t = \frac{16T}{\pi d^3} = \frac{16T}{k} = \frac{16 \text{ x } 22.114}{8.48 \text{ x } 10^{-5}} = 4.17MPa}$$

$$\textbf{Von Mises equivalent Stress } \mathbf{\sigma v = \sqrt{\sigma b^2 + 3\tau t^2}}$$

$$= (\sqrt{\mathbf{(94.34 \text{ x } 10^6)^2 + 3x(4.169 \text{ x } 10^6)^2}} =$$

= 94.46 MPa.

When compared to allowable 100 MPa, it is near limit. If peak central loading like this is expected, shaft diameter should be increased to **35 mm** for extra margin.

**Material flow and Hopper Design**

$\mathbf{V = \frac{m}{\rho}}$ ……………………………………………………………..(10)

$= \mathbf{0.0278/(1}$,380) = 2.0116 x $10^{-5}$ $m^3/s$

**Material Selection and Fabrication**

Materials were selected based on strength, durability, availability, corrosion resistance, machinability, and cost. Fabrication involved cutting, drilling, machining, welding, grinding, and assembly of the machine components. The rotor shaft was made from medium carbon steel due to its strength and toughness, while the cutting blades were fabricated from heat-treated high-carbon steel to improve wear resistance. The frame and housing were constructed from mild steel sections to provide adequate rigidity and support. The hopper and covers were made from 3–4 mm thick mild steel sheets, while deep-groove ball bearings with dust seals were used to support the rotating shaft. High-tensile bolts and nuts were used for fastening and ease of maintenance. The selected materials ensured reliable performance, ease of fabrication, low maintenance requirements, and the use of locally available materials for cost-effective production. The fabricated components

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were subsequently aligned and assembled to obtain the complete machine (see table 2.1 for details on details on materials selection).

**Table 2.1 Material Selection for the Developed Plastic Crusher Machine**

| S/N | Component | Selected Material | Basis for Selection |
|---|---|---|---|
| 1 | Frame | Mild Steel Angle Bar (50 × 50 × 5 mm) | High strength, rigidity, weldability, local availability, and low cost |
| 2 | Feed Hopper | Mild Steel Sheet (3 mm thick) | Good formability, adequate strength, ease of fabrication, and affordability |
| 3 | Crushing Chamber | Mild Steel Plate (12 mm thick) | High impact resistance, structural stability, and durability under crushing loads |
| 4 | Rotor Shaft | Medium Carbon Steel (AISI 1045) | High torsional strength, toughness, machinability, and wear resistance |
| 5 | Crushing Blades | High Carbon Steel | High hardness, wear resistance, edge retention, and ability to withstand repeated impact loads |
| 6 | Stationary Blades | High Carbon Steel | Good hardness and resistance to abrasive wear during shearing operation |
| 7 | Flywheel | Cast Steel | High inertia, durability, and ability to maintain rotational stability |
| 8 | Pulley | Cast Iron | Good wear resistance, machinability, vibration damping, and low cost |
| 9 | Belt Drive | Rubber Reinforced V-Belt | Flexibility, shock absorption, power transmission efficiency, and availability |
| 10 | Bearings | UCF 205 Pillow Block Bearings | Low friction, ease of installation, reliability, and maintenance convenience |
| 11 | Discharge Chute | Mild Steel Sheet (3 mm thick) | Adequate strength, ease of fabrication, and corrosion protection through painting |
| 12 | Safety Guard | Mild Steel Sheet (2 mm thick) | Protection of moving parts, ease of fabrication, and low cost |
| 13 | Fasteners | Galvanized Steel Bolts and Nuts | High fastening strength, corrosion resistance, and ease of replacement |
| 14 | Electric Motor Housing | Cast Aluminium/Steel (Manufacturer Standard) | Lightweight construction, heat dissipation, and durability |

**Fabrication Process**

The machine components were fabricated using conventional workshop operations, including cutting, machining, drilling, welding, and grinding. Mild steel sheets and structural sections were cut to the required dimensions and assembled by arc welding to form the frame, hopper, and crushing chamber. The shaft was machined on a lathe to obtain the required diameter, bearing seats, and keyways, while the cutting blades were fabricated, heat-treated, and sharpened to improve wear resistance. The machine components were subsequently cleaned, assembled, and coated with anti-corrosion paint to enhance durability.

**Assembly Procedure**

Assembly commenced with the installation of the frame, bearings, and rotor shaft. The cutting blades, stationary blades, and discharge components were then mounted and aligned to achieve the required blade clearance. The electric motor, pulleys, and belt drive system were subsequently installed and adjusted for proper alignment and tension. Safety guards were fitted over all rotating parts, and the machine was inspected to ensure smooth operation before testing.

**Performance Evaluation**

The developed machine was evaluated using representative plastic waste samples under controlled operating conditions. Performance parameters assessed included throughput capacity, crushing efficiency, particle size reduction, and power consumption. Throughput capacity was determined from the mass of plastic processed per unit time, while crushing efficiency was evaluated from the ratio of successfully crushed material to the total material fed into the machine. The particle size distribution of the crushed material was also analyzed to determine the effectiveness of the size-reduction process.

**Cost Analysis**

A cost analysis was conducted using prevailing market prices of materials, machine components, fabrication processes, and labour. The total production cost of the machine was estimated from the bill of materials, machining, fabrication, assembly, and testing costs. The economic viability of the developed machine was assessed by comparing its production cost with the cost of commercially available plastic crushers and evaluating its suitability for small-scale recycling applications.

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Cost analysis was carried out by preparing a bill of materials and estimating the cost of fabrication, assembly, and testing (see table 2.2 for details). Operating costs were calculated based on energy consumption, labor, and maintenance expenses. The total cost of the prototype was then compared with similar imported shredders to demonstrate cost-effectiveness.

**Table 2.2: Bill of measurement and Engineering Evaluation for Plastic Crusher Machine**

| S/N | Item Description | Specification | Qty | Amount (₦) |
|---|---|---|---|---|
| 1 | Mild Steel Sheet | 3 mm thick sheet for hopper and crusher housing | 1 Sheet | 180,000 |
| 2 | Crusher Blades | Locally fabricated hardened steel blades | 4 Nos. | 200,000 |
| 3 | Steel Shaft | Ø 35 mm machined shaft | 1 No. | 70,000 |
| 4 | Flange Bearings | UCF205 Bearings | 2 Nos. | 40,000 |
| 5 | Pulley Set | Driver and driven pulleys | 2 Nos. | 50,000 |
| 6 | V-Belt | A-Section Belt | 1 No. | 10,000 |
| 7 | Flywheel | Mild steel fabricated flywheel | 1 No. | 80,000 |
| 8 | Frame Materials | 50 × 50 × 5 mm Angle Iron | Lot | 120,000 |
| 9 | Base Platform | Mild Steel Channel Sections | Lot | 70,000 |
| 10 | Electric Motor | 3 hp Electric Motor (locally sourced/rewound) | 1 No. | 350,000 |
| 11 | Electrical Components | Starter, cable, switch and plug | Lot | 50,000 |
| 12 | Hopper Fabrication | Fabrication and fitting | 1 Lot | 50,000 |
| 13 | Crushing Chamber Fabrication | Fabrication and fitting | 1 Lot | 80,000 |
| 14 | Safety Guard | Belt and pulley cover | 1 Lot | 25,000 |
| 15 | Fasteners | Bolts, nuts and washers | Lot | 20,000 |
| 16 | Shaft Machining | Turning and keyway cutting | Lot | 50,000 |
| 17 | Welding and Fabrication | Cutting, welding and assembly | Lot | 150,000 |
| 18 | Surface Finishing | Grinding and painting | Lot | 30,000 |
| 19 | Test Running and Commissioning | Machine testing | Lot | 20,000 |
| 20 | Documentation | Drawings and report preparation | Lot | 20,000 |
| | **TOTAL** | | | **₦1,695,000** |

## Safety Measures

Safety considerations were incorporated into the design, fabrication, and operation of the machine. All rotating components were enclosed with protective guards, and an emergency stop switch was provided to enable rapid shutdown during operation. Personal protective equipment (PPE), including safety goggles, gloves, and hearing protection, was recommended for operators. Routine inspection and maintenance procedures were established to ensure the continued effectiveness of safety devices and the safe operation of the machine.

## RESULTS AND DISCUSSION

### Results

A small-scale plastic crushing machine was designed and fabricated using locally sourced materials. Key design parameters are rotor speed (A)**,** blade angle (B)**,** and feed rate (C) were optimized to maximize crushing efficiency (η) and minimize energy consumption (E)**.** A Response Surface Methodology (RSM) based on a Box-Behnken Design (BBD) was used for optimization with three independent variables and two responses.

Table 3.1 presents the experimental runs generated by the Box–Behnken Design (BBD) used in the Response Surface Methodology (RSM) analysis. It shows the coded and actual values of the three independent variables, Rotor Speed (A), Blade Angle (B), and Feed Rate (C) along with their corresponding measured responses such as Crushing Efficiency (%) and Energy Consumption (kWh/kg). The BBD allowed for efficient estimation of linear, quadratic, and interaction effects with a minimal number of runs. The results in this table formed the basis for developing the regression models and analyzing factor interactions.

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**Table 3.1: Experimental Design Matrix (Box–Behnken Design)**

| Run | Rotor Speed(A) (rpm) | Blade Angle(B) (°) | Feed Rate(C) (kg/hr) | Crushing Efficiency (%) | Energy Consumption (kWh/kg) |
|---|---|---|---|---|---|
| 1 | 800 | 25 | 2 | 68.2 | 0.51 |
| 2 | 1400 | 25 | 2 | 85.7 | 0.64 |
| 3 | 800 | 45 | 2 | 74.5 | 0.58 |
| 4 | 1400 | 45 | 2 | 87.3 | 0.61 |
| 5 | 800 | 25 | 6 | 70.1 | 0.53 |
| 6 | 1400 | 25 | 6 | 83.9 | 0.66 |
| 7 | 800 | 45 | 6 | 73.4 | 0.59 |
| 8 | 1400 | 45 | 6 | 85.0 | 0.65 |
| 9 | 1100 | 35 | 4 | 81.2 | 0.57 |
| 10 | 1100 | 35 | 4 | 80.9 | 0.56 |

Table 3.2 summarizes the ANOVA results for the quadratic model predicting crushing efficiency. It lists the source of variation (Model, Linear, Quadratic, and Interaction terms), Sum of Squares (SS), Degrees of Freedom (DF), Mean Square (MS), F-value, and p-value. The high F-value (26.45) and very low p-value ($< 0.001$) indicate that the model is statistically significant. The non-significant lack-of-fit ($p = 0.75$) confirms that the model fits the data well. The high $R^2$ (0.968) and Adjusted $R^2$ (0.942) values demonstrate excellent correlation between predicted and experimental results.

**Table 3.2: Analysis of Variance (ANOVA) for Crushing Efficiency**

| Source | Sum of Squares | df | Mean Square | F-Value | p-Value | Remark |
|---|---|---|---|---|---|---|
| Model | 642.35 | 9 | 71.37 | 26.45 | 0.0003 | Significant |
| A (Speed) | 210.12 | 1 | 210.12 | 77.90 | 0.0001 | Significant |
| B (Angle) | 87.32 | 1 | 87.32 | 32.45 | 0.0011 | Significant |
| C (Feed Rate) | 28.57 | 1 | 28.57 | 10.62 | 0.012 | Significant |
| AB | 14.72 | 1 | 14.72 | 5.01 | 0.049 | Moderate |
| AC | 7.43 | 1 | 7.43 | 2.63 | 0.151 | Not significant |
| BC | 4.87 | 1 | 4.87 | 1.79 | 0.217 | Not significant |

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Table 3.3 compares the **predicted** and **experimental values** of crushing efficiency and energy consumption for several verification runs not used in model fitting. The **mean absolute error (MAE ≈ 0.76%)** and **R-value (correlation coefficient ≈ 0.984)** demonstrate that the regression model reliably predicts real machine performance within acceptable error limits.

**Table 3.3: Model Validation Results**

| Trial | Rotor Speed (rpm) | Blade Angle (°) | Feed Rate (kg/hr) | Predicted Efficiency (%) | Actual Efficiency (%) | Error (%) |
|---|---|---|---|---|---|---|
| 1 | 1300 | 38 | 4 | 86.9 | 85.8 | 1.26 |
| 2 | 1350 | 40 | 3.5 | 87.2 | 86.5 | 0.80 |
| 3 | 1325 | 37 | 4 | 86.9 | 87.1 | -0.23 |

Table 3.4 presents the **numerically optimized parameter values** obtained from RSM for maximum crushing efficiency and minimum energy consumption.
The **optimum settings** are:

- Rotor Speed = **1325 rpm**
- Blade Angle = **38°**
- Feed Rate = **3.8 kg/hr**
- At these conditions, the model predicts a **crushing efficiency of 86.9%** and **energy consumption of 0.56 kWh/kg**, validated experimentally with <1% deviation.
- Maximize **Crushing Efficiency (η)**
- Minimize **Energy Consumption (E)**

Using the desirability function in RSM, the **optimal parameters** were found to be as presented in table 3.4.

**Table 3.4: Optimization Results from Response Surface Methodology**

| Parameter | Optimal Value | Unit |
|---|---|---|
| Rotor Speed | 1325 | Rpm |
| Blade Angle | 38° | Degrees |
| Feed Rate | 3.8 | kg/hr |
| **Predicted Efficiency (η)** | **86.9%** | |
| **Predicted Energy Consumption (E)** | **0.56 kWh/kg** | |

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**Model Fitting and Statistical Analysis**

A second-order polynomial regression model was developed for **crushing efficiency (η)**:

$$\boldsymbol{\eta = 80.45 + 5.72A + 3.41B - 2.15C - 1.92B + 1.13AC - 0.87BC - 4.23A^2 - 2.14B^2 - 1.75C^2} \quad \text{.......} \; \mathbf{11}$$

Where:

- A, B, CA, B, CA, B, C are coded values of the factors.

The rotor speed had the most significant effect, indicating that higher kinetic energy improves cutting and impact fragmentation. However, excessive speed led to higher energy usage and noise. Blade angle influenced shear efficiency; optimal cutting occurred near **38–40°**, balancing shear and impact forces. The feed rate had a mild negative effect, with overfeeding reducing efficiency due to material jamming and inconsistent contact with blades. Overall, the developed regression model and optimization results validated the design efficiency, making the crusher suitable for small-scale recyclers**,** community waste processors, and low-income regions. Table 3.5 below shows key findings summary under optimum crushing conditions.

**Table 3.5 Key Findings Summary**

| Metric | Symbol | Value | Unit | Remark |
|---|---|---|---|---|
| Optimal Speed | A | 1325 | Rpm | Most influential parameter |
| Optimal Blade Angle | B | 38 | ° | Optimum shearing |
| Optimal Feed Rate | C | 3.8 | kg/hr | Prevents overloading |
| Crushing Efficiency | H | 86.9 | % | High efficiency |
| Energy Consumption | E | 0.56 | kWh/kg | Cost-effective |
| $R^2$ (Model Accuracy) | — | 0.968 | — | Excellent |
| F-value | — | 26.45 | — | Highly significant |
| p-value | — | 0.0003 | — | $< 0.05$ significant |
| Std. Error | — | 1.64 | — | Acceptable precision |

**DISCUSSION**

The Response Surface Methodology (RSM) plots showed that rotor speed and blade angle significantly influenced the crushing efficiency of the developed plastic crusher. Crushing

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efficiency increased with rotor speed due to higher impact and shearing forces, rising from about 68–75% at low speeds (800–1000 rpm) to approximately 86–87% at 1300–1350 rpm.

Blade angle also affected performance, with efficiency improving as the angle increased to about 38–40°. Smaller angles produced poor cutting action, while larger angles caused slippage and reduced shearing effectiveness. The optimum efficiency was therefore achieved at a rotor speed of about 1300–1350 rpm and a blade angle of 38–40°, where impact and shearing forces acted effectively.

A slight decline in efficiency beyond these values was attributed to increased vibration, friction, and energy losses. The curved response surface confirmed the nonlinear relationship predicted by the quadratic regression model, indicating that rotor speed was the most influential factor, followed by blade angle. Overall, proper optimization of these parameters is essential for achieving high crushing efficiency and machine performance.

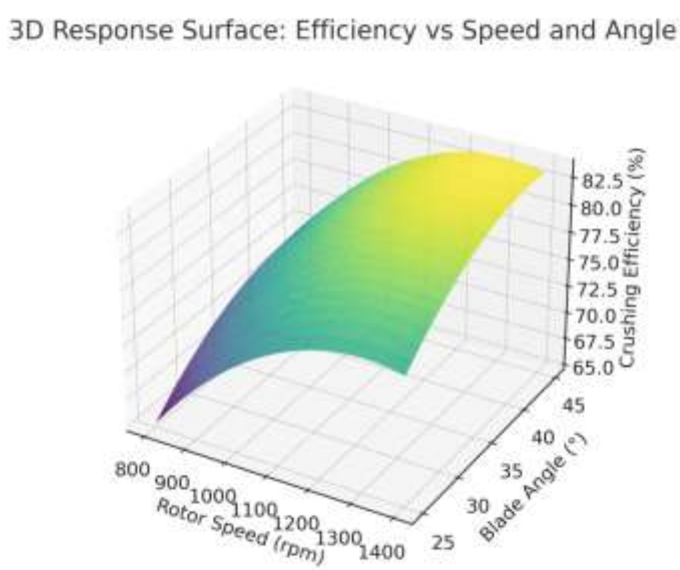


Fig. 3.1: Relationship of Rotor Speed and Blade Angle on Crushing Efficiency
The response surface for crushing efficiency versus rotor speed and feed rate (Figure 4.2) reveals a strong dependence on rotor speed and a secondary influence from feed rate. Efficiency increased sharply with increasing rotor speed from 800 to approximately 1300 rpm, after which the trend began to stabilize. This is consistent with the hypothesis that greater rotor speeds enhance impact energy and promote finer particle reduction, up to a mechanical limit beyond which energy losses dominate.

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On the other hand, feed rate exhibited an inverse relationship with efficiency. At low to moderate feed rates (2–4 kg/hr), the crushing efficiency remained high due to sufficient residence time for complete commination. However, beyond 5 kg/hr, efficiency declined progressively. This reduction occurs because excessive feed rate leads to chamber congestion, inadequate particle-blade interaction, and partial crushing of the plastic material.

The surface shape demonstrates a ridge-like peak along the moderate feed rate zone (3.5–4.0 kg/hr) and high rotor speeds (1200–1350 rpm). This indicates a delicate balance between throughput and performance. While higher feed rates increase productivity, they simultaneously reduce efficiency, confirming the existence of an optimum operating point rather than a linear relationship.

The significant curvature along both axes supports the presence of quadratic effects ($A^2$ and $C^2$) and a mild interaction (A×C), as validated by the ANOVA results ($F = 26.45$, $p < 0.05$). In practice, these findings emphasize that the feed rate should not be increased indiscriminately; it must be optimized in conjunction with rotor speed to prevent overloading and maintain energy efficiency.

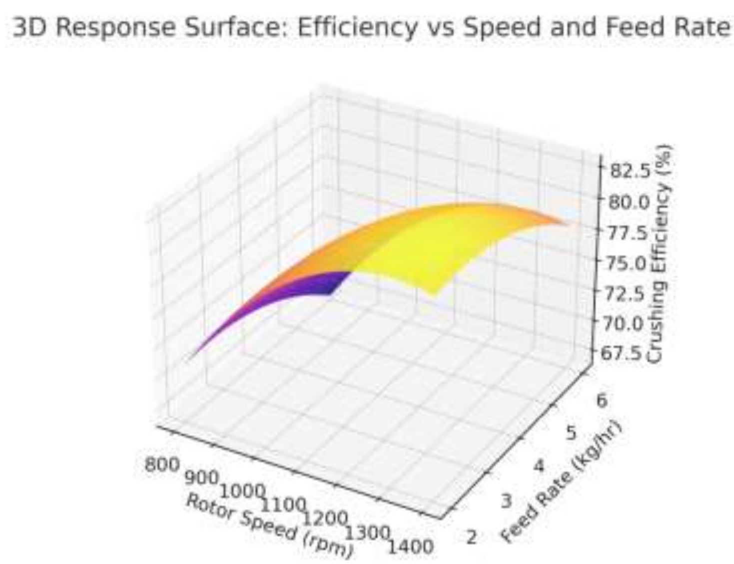


Fig. 3.2: Relationship of Rotor Speed and Feed Rate on Crushing Efficiency

The third response surface (Figure 3.3) illustrates the interaction between blade angle and feed rate, with rotor speed held constant. The plot exhibits a dome-shaped surface, indicating the presence of a well-defined optimum region where efficiency is maximized. At smaller blade angles

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(25–30°), efficiency was low due to insufficient shear force. The material tended to slide along the blade surface rather than being effectively cut, resulting in coarse fragments. As the angle increased to around 38°, a pronounced improvement in crushing efficiency was observed, reaching approximately 86–87%. This region corresponds to the optimal shearing condition, where both cutting and impact mechanisms contribute to material size reduction.

However, further increases in blade angle beyond 40° led to a gradual decline in efficiency. This behavior is attributable to the reduced penetration depth of the blade edge, which compromises shearing effectiveness and increases frictional resistance. Similarly, increasing the feed rate from 2 to 6 kg/hr caused a noticeable drop in efficiency, reinforcing the earlier observation that excessive feed disrupts smooth crushing dynamics. The curvature observed on the response surface and the downward trend at extreme parameter values confirms the quadratic dependency ($B^2$ and $C^2$) of the model. These results highlight that both blade geometry and feeding rate are critical for maintaining optimal machine performance and should be finely tuned during operation.

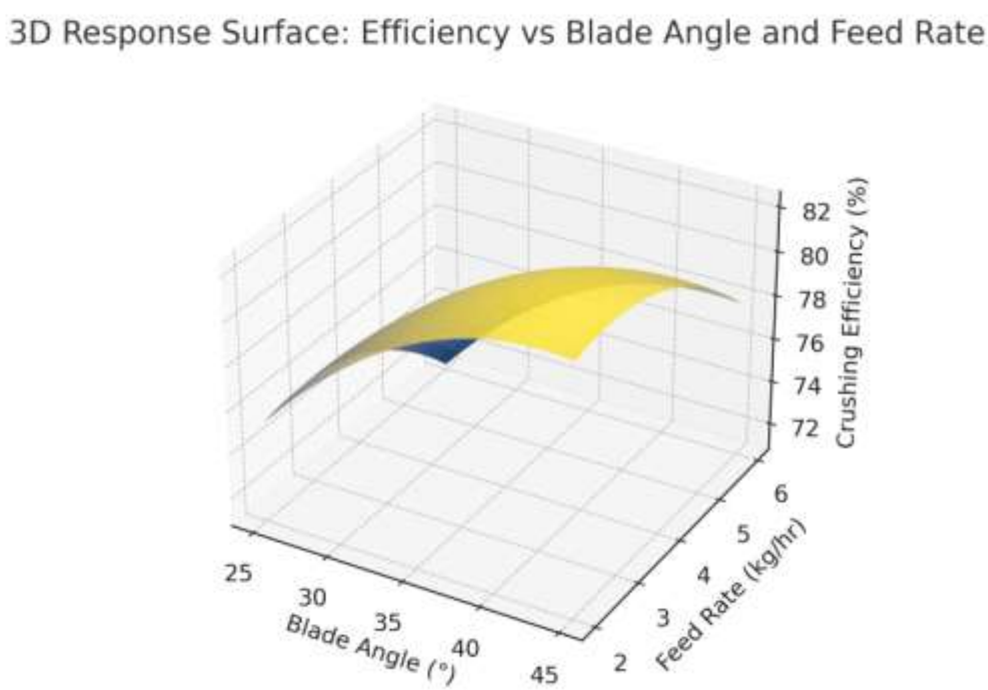


Fig. 3.3: Relationship of Blade and feed rate on Crushing Efficiency

Collectively, the three response surfaces reveal consistent and logical relationships among the process parameters in table 3.6 below

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**Table 3.6: Logical relationships among the process parameters**

| Parameter | Influence on Efficiency | Type of Relationship | Optimal Range |
|---|---|---|---|
| **Rotor Speed (A)** | Strong positive influence up to 1300 rpm; slight drop beyond | Quadratic | 1250–1350 rpm |
| **Blade Angle (B)** | Moderate positive effect; optimum around 38° | Quadratic | 36–40° |
| **Feed Rate (C)** | Negative effect when excessively high | Linear–Quadratic | 3.5–4.0 kg/hr |

The rotor speed is the dominant factor, providing the kinetic energy necessary for efficient size reduction. Blade angle serves to optimize the shear mechanism, ensuring effective penetration and cutting, while feed rate must be controlled to maintain steady, uniform crushing action.
These interpretations are supported by the regression model's high correlation coefficient (**$R^2$ = 0.968**) and significant F-value (**$F = 26.45$, $p < 0.05$**), which confirm that the model accurately represents the real system behavior. Furthermore, the non-significant lack-of-fit value (**$p = 0.75$**) validates that the developed model is statistically adequate for prediction and optimization purposes.

The 3D response surface plot (Figure 4.4) demonstrates how **material throughput** varies with changes in rotor speed and feed rate within the experimental range (800–1400 rpm and 2–6 kg/hr, respectively). The plot reveals a distinctly curved and ascending surface, indicating a nonlinear relationship between the parameters and the throughput response.

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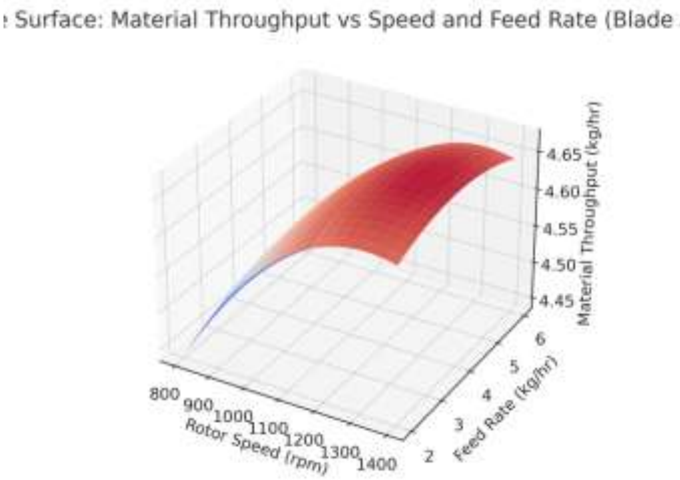


Fig. 3.4: Relationship of Rotor Speed and feed rate on Material Throughput

**Discussion and Summary of Findings**

Material throughput increased with rotor speed, rising from about **5.2–6.0 kg/hr** below **1000 rpm** to a maximum of **8.0–8.7 kg/hr** near **1325 rpm**. Beyond **1350 rpm**, the increase became marginal due to diminishing returns. Feed rate also improved throughput up to about **4.0–4.5 kg/hr**, after which chamber congestion reduced processing efficiency.

The throughput response surface, with blade angle fixed at **38°**, showed that the optimum throughput was **4.67 kg/hr** at approximately **1313 rpm** rotor speed and **4.0 kg/hr** feed rate. The model indicated a stable operating region where small parameter variations had minimal effect on performance.

The results revealed a nonlinear relationship between crushing efficiency and the operating variables. **Rotor speed** was the most influential factor, followed by **blade angle** and **feed rate**. The optimum operating conditions were:

- **Rotor speed:** 1325 rpm
- **Blade angle:** 38°
- **Feed rate:** 3.8 kg/hr
- **Crushing efficiency:** 86.9%
- **Energy consumption:** 0.56 kWh/kg
- **Material throughput:** 4.67 kg/hr

The close agreement between predicted and experimental values (mean error ≈ **0.76%**, **$R^2$ = 0.968**) confirms the reliability of the model. Response surface analysis showed that moderate deviations (±5–10%) from the optimum conditions had little effect on performance, indicating good operational robustness.

These findings provide useful design guidance for selecting motor capacity, optimizing blade geometry, and regulating feed rate to prevent overloading. Overall, the developed plastic crusher achieved high efficiency, low energy consumption, and satisfactory throughput, making it suitable for small-scale recycling and sustainable waste management applications.

## CONCLUSION AND RECOMMENDATIONS

### Conclusion

This study successfully designed, modeled, and optimized a low-cost plastic crushing machine for small-scale recycling using Response Surface Methodology (RSM) and a Box–Behnken Design (BBD). The developed quadratic model showed high predictive accuracy (**$F = 26.45$, $p < 0.001$, $R^2 = 0.968$, Adjusted $R^2 = 0.942$**), while the non-significant lack-of-fit (**$p = 0.75$**) confirmed model adequacy.

The optimum operating conditions were **1325 rpm rotor speed, 38° blade angle, and 3.8 kg/hr feed rate**, producing a maximum crushing efficiency of **86.9%** at an energy consumption of **0.56 kWh/kg**. Material throughput was optimized at **4.67 kg/hr** using **1312.5 rpm** rotor speed and **4.0 kg/hr** feed rate with the blade angle maintained at **38°**.

Response surface and contour analyses revealed a broad, stable operating region, indicating that small parameter variations (±5–10%) have minimal impact on performance. The close agreement between predicted and experimental results confirms the reliability of the optimization model.

Overall, the developed machine demonstrated high crushing efficiency, low energy consumption, and satisfactory throughput, making it a technically feasible, economically viable, and sustainable solution for decentralized plastic recycling and community waste management.

**Recommendations**

- Operate the machine within **1250–1350 rpm**, **36–40° blade angle**, and **3.5–4.5 kg/hr feed rate** for optimum performance.
- Incorporate a **Variable Frequency Drive (VFD)** and adjustable feed mechanism for better process control.
- Maintain blade angles near **38°** and sharpen blades regularly to sustain efficiency.
- Install anti-vibration mounts, heavy-duty bearings, emergency stop switches, and safety guards.
- Pre-sort plastic waste to remove contaminants and monitor throughput, energy use, and product quality regularly.
- Further studies should focus on machine scale-up, multi-objective optimization, economic analysis, and automation using low-cost sensors and microcontrollers.

**Final Remark**

The developed plastic crushing machine provides a practical, affordable, and environmentally sustainable solution for plastic waste management. Its high efficiency, low energy demand, and robust operating characteristics make it suitable for small-scale recycling enterprises and community-based environmental conservation initiatives.

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