BSP Advances in Science, Engineering and Technology
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Design, Fabrication, and Performance Evaluation of an Optimized Thermoplastic Waste-Crushing Machine for Sustainable Recycling Applications

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Abstract

The management of thermoplastic waste presents a significant environmental and operational challenge, especially in developing countries where recycling infrastructure is limited. This study presents the design, fabrication, and performance evaluation of a modified thermoplastic waste-crushing machine developed to enhance crushing efficiency, reduce energy consumption, and promote localized plastic recycling. Key innovations in the machine include a redesigned rotor with three sharp-edged blades, optimized blade geometry, improved hopper configuration, and enhanced pulley alignment. The machine was constructed using locally sourced materials and standard workshop tools. Experimental testing was conducted using polyethylene (PE) and polypropylene (PP) at varying feed rates and rotor speeds (1000–1200 RPM). Results showed a maximum crushing efficiency of 88% and a significant reduction in crushing time, up to 194 seconds faster than a conventional design. Crushed particles exhibited consistent size and morphology, and the machine demonstrated high operational repeatability with minimal variance across multiple trials. The modified machine offers a viable and scalable solution for decentralized plastic waste management, particularly in resource-constrained environments. It contributes toward sustainable recycling practices by enabling effective on-site plastic size reduction, reducing logistics costs, and facilitating material reuse in a circular economy.

Keywords: Thermoplastic Waste, Plastic Crushing Machine, Recycling Technology, Design Optimization, Crushing Efficiency, Sustainable Waste Management.

1.0 Introduction

Plastic waste management remains one of the most pressing environmental challenges globally, particularly in developing countries like Nigeria, where population growth, urbanization, and industrialization have intensified waste generation rates. Plastic materials, due to their widespread use, low cost, and desirable physicochemical properties such as durability, water resistance, and lightweight nature, are omnipresent in packaging, consumer goods, and industrial applications. However, their non-biodegradable nature poses a significant threat to the environment when improperly disposed of, clogging drainage systems, polluting ecosystems, and reducing land productivity by inhibiting natural biological processes [1]–[3].

Thermoplastics, which constitute a large fraction of plastic waste, are particularly suitable for recycling due to their ability to soften and reshape upon heating without undergoing chemical degradation [5]–[6]. Examples include polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). In contrast to thermosets, thermoplastics retain their polymeric structure upon reheating, making them ideal candidates for mechanical recycling and reuse in new applications [6]. Despite these advantages, efficient processing of thermoplastics remains a technical bottleneck, particularly in low-resource settings where local recycling infrastructure is often inadequate [7]-[12].

Recycling efforts in Nigeria are further hindered by logistical constraints associated with the irregular shape, bulkiness, and volume of unprocessed plastic waste [13]-[15]. The transport of such materials to centralized recycling facilities incurs high cost and energy penalties. To address this issue, on-site crushing and size reduction of plastic waste is necessary to enhance handling, storage, and transportation efficiency [2], [3], [7].

Plastic crushing machines have been identified as essential tools in this context, offering the potential to transform large, heterogeneous plastic materials into uniform flakes suitable for downstream processing [16]. Prior studies have explored various machine configurations, such as vertical crushers, manually operated units, and machines utilizing slider-crank or Scotch yoke mechanisms [17]–[20]. However, many of these designs exhibit limitations, including inefficient cutting mechanisms, alignment issues, or high-power consumption [16], [18].

In response to these challenges, this study presents the design, construction, and performance evaluation of a modified thermoplastic waste-crushing machine, aimed at improving efficiency, structural integrity, and energy performance. The core modifications include reducing the number of rotor blades from six to three, introducing sharper rotor blade geometries, redesigning the hopper to minimize spillage during operation, and enhancing pulley alignment to reduce mechanical losses. These innovations draw upon recommendations from previous works and are tailored for fabrication using locally available materials and artisanal methods, thus promoting technological self-reliance and economic feasibility [3], [4].

The environmental urgency driving this research cannot be overstated. Since the 1950s, global plastic production has escalated from 5 million tons annually to nearly 100 million tons, with substantial contributions from developing regions due to shifts in consumption patterns and packaging technologies [8], [10]. In urban centers, plastic waste is now a major component of municipal solid waste streams, following food and paper waste in volume [9]. While developed countries have adopted commercial-scale recovery and recycling systems [11], developing nations like Nigeria must adopt context-appropriate solutions to leverage the so-called "latecomer advantage" by adapting proven technologies for local use [10].

This study, therefore, contributes to the field by bridging the gap between advanced recycling technologies and localized engineering solutions. Through rigorous design, empirical testing, and comparative performance analysis, the modified crushing machine is positioned as a viable intervention for sustainable waste management, environmental preservation, and circular economy development in Nigeria and similar regions.

2.0 Literature Review

The global proliferation of plastic waste, particularly from packaging applications, has heightened the need for sustainable management solutions and efficient recycling technologies. Packaging, defined as the science and art of enclosing or protecting products for distribution, storage, sale, and end-use, plays a central role in virtually all sectors—from food and pharmaceuticals to industrial logistics [12]. Its primary functions include containment, preservation, transportation, information dissemination, and consumer appeal. Over the decades, packaging materials have evolved from rudimentary natural options like leaves and pottery to advanced synthetic polymers that offer high versatility, barrier properties, and durability.

Plastics have become the dominant packaging material due to their lightweight nature, moldability, and cost-effectiveness. Attributes such as resistance to corrosion, low permeability, and ability to be engineered into various sizes, colors, and strengths make them particularly valuable in modern economies. In Nigeria, for instance, plastic packaging is extensively used for food items such as bread and biscuits, bottled water, and industrial chemicals, contributing significantly to municipal waste volumes [7]. While these plastics serve vital protective and logistical roles, their post-consumer management remains a critical environmental concern.

The recycling of plastic waste has emerged as a vital response to the environmental and public health implications of uncontrolled plastic disposal. Recycling conserves petroleum resources, reduces land and marine pollution, and mitigates greenhouse gas emissions associated with virgin plastic production [9]. Mechanically, the recycling process typically involves a sequence of stages: collection, sorting, crushing, cleaning, and reprocessing into new products. Of these stages, crushing or size reduction is pivotal, as it facilitates material handling, enhances processing efficiency, and ensures compatibility with downstream equipment.

However, only a subset of plastics, primarily thermoplastics such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyethylene terephthalate (PET), are widely recycled due to their capacity to be re-melted and reshaped without significant degradation [6]. In contrast, thermosetting polymers are excluded from traditional recycling streams, as their cross-linked molecular structures prevent reprocessing once cured.

Over the past few decades, global plastic consumption has surged dramatically, escalating from approximately 5 million tons annually in the 1950s to nearly 100 million tons by the early 21st century [8], [10]. This growth is particularly pronounced in rapidly developing regions where economic expansion and urbanization have fueled demand for consumer products and their associated packaging materials. Consequently, plastic waste now constitutes a significant portion of municipal solid waste, often ranking just behind food and paper in volume [9].

Despite this escalating crisis, recycling infrastructure in many developing countries, including Nigeria, remains underdeveloped. This gap presents both a challenge and an opportunity. Countries that lag in recycling technology adoption can leverage the "latecomer's advantage" by deploying already proven, cost-effective systems and adapting them to local contexts [10]. Furthermore, simple yet robust innovations such as modified plastic crushing machines can enhance local recycling capacity, reduce transportation burdens, and promote circular economy models.

The current study draws on this body of knowledge and seeks to improve upon existing crushing technologies by introducing design modifications informed by field observations and previous research. Through locally fabricated, energy-efficient, and structurally optimized solutions, the work aligns with global efforts to scale sustainable plastic waste management technologies and reduce the environmental burden of non-biodegradable waste.

3.0 Materials and Methods

3.1 Conceptual Design

The conceptual design for the "Design, Construction, and Testing of a Modified Thermoplastic Waste-Crushing Machine" focuses on developing an efficient, durable, and cost-effective machine capable of reducing thermoplastic waste into manageable and reusable granules. The machine integrates a robust crushing mechanism, typically involving rotary blades, to break down thermoplastic materials into small particles suitable for recycling. A hopper directs the waste into the crushing chamber, while adjustable blades and sieves enable control over particle size. The design also incorporates safety features, such as an automatic shutoff and overload protection, to prevent equipment damage and ensure user safety. To test its effectiveness, the machine's performance is evaluated in terms of throughput, particle size distribution, and energy efficiency. This modified crusher aims to provide an accessible and sustainable solution to manage thermoplastic waste, encouraging recycling efforts and reducing environmental impact.

3.2 Design

This project consists of the design, construction, and testing of a modified thermoplastic crushing machine considering various important parameters. It involves the process of designing different parts of this crushing machine, considering forces and ergonomic factors for people to use. A concentration was given to the parts whose design is critical. Their design is important in the sense that the performance of the machine will not be accurate if they are misdesigned.

3.2.1 Design Considerations

i. Minimum force required to crush the thermoplastics
ii. Standard size and type of plastics
iii. Material selection is based on economic, service requirements (functionality), and fabrication requirements.

3.2.2 Design procedure

The study aims to give complete design information on the fabricated thermoplastic crushing machine. This consists of the explanations and some other parameters related to the project. The thermoplastic crushing machine consists of three main units. The crushing zone comprises the hopper, shaft, cutter, and screen. The power transmission zone includes the electric motor, pulley, belt, and bearing, while the third is the collection zone, which is responsible for the discharge of plastic crushed pieces to the container on the ground level.

3.2.3 Modification of the existing crushing machine design

The modification of the machine design involves redesigning the major parts of the machine for possible improvement of its performance. Four under-listed parts are very important to the function of the crushing machine:

i. The Rotor
ii. The cutting knives or blades
iii. Plastic flakes screen
iv. Basic frame

A sketch of the modified thermoplastic crushing machine is shown in Figure 1a. The design and construction of all the above parts are very important, and if not done properly, will not achieve the desired result envisaged. Theoretical details for the design and construction of the above-mentioned component were followed as stated below:

3.2.4 The Rotor

The rotor is that part of the machine that carries the blades, and as it rotates, it cuts the plastic material into small pieces. The rotor is mounted using two or more bearings whose sizes and capacities are to be appropriately determined to withstand static and dynamic forces/torque acting on it.

3.2.5 Cutting Knives or Blades

The knives or blades are primarily used for shearing the plastics. The rotor and blades could either be designed separately and fitted by any of the appropriate fastening methods or designed as an integral unit. They will have improved cutting angles, which may vary according to the material being crushed. However, the special design of the blade can facilitate cutting two or three materials with one cutting angle. The shearing efficiency of the blade is greatly dependent on the cutting angle geometry, metallurgical composition (carbon content and alloying elements) of the cutting blades, type of heat treatment, and blade arrangement on the rotor. The existing crushing machine consists of six cutting blades.

Rotor blades are as critical as the rotor itself, and they are to be designed in such a way that they last for at least up to the end of their useful life (up to the last possible re-sharpening without failure). Their failure in service could cause serious damage to machine parts, especially the screen. In other words, they must be designed with an appropriate fatigue life.

3.2.6 Plastic Flakes Screen

The screen is a high tensile sheet of steel (HTS) that has holes on it so that it only allows pieces of plastic of average size to pass through it. The biggest plastic pellet is usually slightly smaller than the screen holes. Pellets may be 2 to 3mm longer than the screen holes, while the smallest could be as tiny as 1mm. The shape of the flakes is rectangular, triangular, or square, but rarely circular screen design has to ensure that it does not stretch plastically in service, thereby increasing the size of the holes on it. If this happens, the size of the granules will be much larger than required, and as such, the granulated material may cause processing problems. Moreover, a very secure way of filling it into the frame is necessary.

3.2.7 Basic frame

The frame is part of the skeletal structure of the machine on which the rotor is mounted on two or more bearings, and the screen is also fitted on it. Below the screen is the space where crushed material is discharged for delivery to a large container for storage. The frame has to be rigid enough to support the rotor, blades, hopper, flywheel, screen, etc, without excessive lateral deflection.

3.2.8 Other Parts of the Crushing Machine

Apart from those four parts, there are other parts like the base, hopper, granulate evacuating system, guards, and covers, which are to be fabricated from steel. Of all these parts, only the hopper requires designing in detail, while others do not. The design of the hopper entails selecting the material from which it should be made, specifying the sizes of its boundary, and specifying the geometry that could best suit the performance of the crushing machine. The design of the granulate evacuating system entails choosing the size of the outlet that would allow the crushed pieces to flow to the container directly below it. Guards and covers are to be constructed from ordinary sheet metal.

3.2.9 Modification of the Crusher Design

The important aspects that are to be modified are:

i. Pulley alignment
ii. Changing the rotor configuration by reducing the number of blades mounted on it (from six blades in the existing machine to three blades)
iii. Redesigning the geometry of the blades to have a sharper edge on the rotor blades and a flat edge on the two-stator blades
iv. Redesigning the hopper

The modification of the above components could bring about an increase in output and a reduction of unidirectional axial force on the rotor. The modification will be a unique rearrangement of knives/blades on the rotor and its cutting geometry changes.

3.2.10 Material Selection

The materials used in this work were appropriately selected based on economic considerations, appearance, and durability. Table 1 presents the dimensions and the material from which various parts of this machine are made.

Table 1: List of Machine Parts and Their Material Type

S/N	Name of Part	Quantity	Dimensions	Revised Material	Justification
1	Hopper	1	600×300×260 mm	**Stainless Steel (AISI 304)**	Corrosion-resistant, food-grade, easy to clean
2	Ball Bearing	2	Internal Ø 32 mm	Bearing Steel (AISI 52100)	High hardness, fatigue resistance, and wear resistance
3	V-belt	1	1000×13×8 mm	Reinforced Neoprene Rubber	High flexibility, abrasion, and heat resistance
4	Driven Pulley	1	Ø 150×16.25 mm	Grey Cast Iron (Grade FG 260)	Good damping, machinability, and wear resistance

5	Driver Pulley	1	Ø 75×16.25 mm	Grey Cast Iron (Grade FG 260)	Similar to the driven pulley for compatibility and performance
6	Base Frame	1	760×600×380 mm	Mild Steel (Low Carbon Steel A36)	Good weldability, cost-effective for structural frames
7	Hopper Opening	1	340×260 mm	Stainless Steel (AISI 304)	Matches hopper material for uniform corrosion resistance
8	Crusher Outlet	1	340×300 mm	Stainless Steel (AISI 304)	Same reason as the hopper; improves wear and corrosion resistance
9	Adjustable Motor Base	2	290×45 mm	Mild Steel (A36)	Structurally adequate and easy to machine
10	Rotor Blades	3	240×80×20 mm	Tool Steel (AISI D2)	Excellent hardness, wear resistance, and retains edge sharpness
11	Stator Blades	2	240×80×20 mm	Tool Steel (AISI D2)	Same as rotor blades to ensure compatibility and cutting efficiency
12	Rotor	1	Ø 250×300 mm	Alloy Steel (AISI 4140)	High strength and toughness for rotating components
13	Screen	1	340×260 mm	Abrasion-Resistant Steel (AR400)	Resists wear from repeated plastic impacts
14	Bolts and Nuts	22	—	Medium Carbon Steel (Grade 8.8)	Provides sufficient tensile strength and torque resistance for machine assembly

3.3.0 Construction Procedure and Operational Sequence

The construction procedure of the "Design, Construction, and Testing of a Modified Thermoplastic Waste-Crushing Machine" involves several key steps, starting with the design phase, where critical machine components, such as the crushing chamber, blades, and motor assembly, are specified and modeled to achieve efficient waste reduction. Next, in the construction phase, materials like stainless steel for durability and thermoplastic-compatible metals are selected, and components are fabricated through machining, welding, and assembly. Blades are sharpened or shaped to suit different thermoplastic types, enabling effective crushing. The motor is mounted with secure connections to drive the blades with appropriate torque and speed. Once assembled, the machine undergoes rigorous testing to assess its crushing efficiency, throughput, and safety features. Adjustments are made based on test results to optimize performance and ensure the machine effectively reduces thermoplastic waste into smaller, manageable particles for recycling applications.

The operational sequence is the step-by-step procedure followed during the construction of the machine. The individual parts of the machine were constructed as follows:

3.3.1 Hopper

The hopper was fabricated by folding a 4 mm-thick mild steel sheet to the required shape. The required sheet to be used was then measured and marked out using a tape rule, a steel rule, a scriber, and a marking out table. This was followed by cutting the marked-out sheet using a shearing and cutting machine.

3.3.2 The Base Plate

The base plate is a 4mm mild steel sheet on which all other parts were mounted. It was cut with a guillotine to the specified dimensions and reinforced with a rectangular-angle iron frame. Four slots were machined for bolting and adjusting the electric motor to alter the tension of the V-belt. Other holes for bolting the basic frame were also drilled.

3.3.3 The Screen

The screen was fabricated from steel sheet metal of 4mm thickness, which was measured and marked out to the size of the screen using a tape rule and steel rule. The marked-out sheet metal was cut out as required using a hacksaw and a cutting machine. The sheet metal was center punched after measuring and marking the bore (diameter of 4mm) to be drilled. The centre-punched sheet metal was then drilled using a drilling machine.

Other parts of the machine not stated above were purchased and, in some cases, modified to suit the machine's requirements. For instance, the driver and driven pulleys were purchased and suitable holes were bored on them to accommodate the rotor shaft size. The keyway was also machined appropriately and four damping supports were purchased for fitting under the base plate in order to dampen vibration.

3.3.4 Assembly Process

The assembly process commenced once the key components of the thermoplastic crushing machine were fabricated and available in the workshop. The procedure began with the mounting of the electric motor onto its base, where it was initially fixed loosely to allow alignment adjustments. Subsequently, the base frame was mounted and carefully aligned with the motor pulley to ensure optimal belt drive efficiency. The bearing supports were then installed, followed by the placement of the rotor shaft with the mounted blades or knives.

Once the rotating system was properly secured, the hopper and the screen were installed. These components were strategically designed such that the hopper and the base jointly form the machine's head. The entire assembly process was guided by a previously developed 3D CAD model, and the final product was cross-verified with this digital reference, as shown in Figure 1.

Figure 1 provides a visual comparison between the (a) CAD model of the thermoplastic crusher and (b) the fully constructed machine. Both views confirm the accuracy of physical fabrication relative to the design intent.

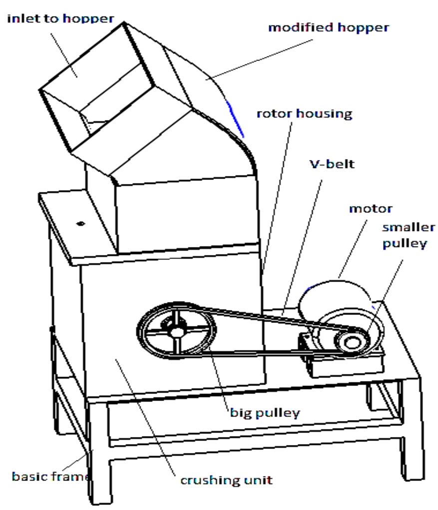
3.3.5 Finishing and Painting

Finishing operations are critical for ensuring the functional, protective, and aesthetic quality of mechanical systems [21]. This process included edge smoothing, surface deburring, and the application of anti-corrosive paint. A grinding disc mounted on a cutting machine was used to smoothen the welded joints and remove burrs or sharp edges that could impair handling or structural integrity.

The objectives of the finishing process were:

i. To prevent corrosion on the exposed metal surfaces
ii. To reduce wear on contact areas
iii. To enhance the overall aesthetics and professionalism of the final machine

After mechanical finishing, the entire machine was painted with a protective enamel coating, improving durability and ensuring alignment with industrial-grade manufacturing practices [22].



(a)

(b)

Figure 1: Thermoplastic Crushing Machine (a) CAD model (b) after construction

Finishing operation is said to be an operational method of completing product machining. It is a process of retouching the parts for accuracy and neatness. Finishing was carried out to achieve the following objectives:

i. To prevent corrosion of the sheet metal surface
ii. To prevent wear
iii. Aesthetic

The finishing was carried out first using a cutting machine with a grinding disc to file off the corners and edges produced during the welding operation to attain a smooth surface. The entire machine was then painted.

3.4 Experimental Testing

Following the design and fabrication phases, experimental testing was carried out to evaluate the performance of the modified thermoplastic waste-crushing machine. The testing aimed to verify the operational efficiency, reliability, and functionality of the machine under different load conditions using representative samples of thermoplastic waste. The parameters assessed included crushing efficiency, energy consumption, particle size uniformity, and throughput.

To ensure the machine's design objectives were met, the testing also examined the interaction between the blade configuration, motor performance, and frame integrity under applied operational stresses. The experiments were conducted in accordance with established engineering testing protocols and safety practices.

3.4.1 Experimental Testing Approach

The testing procedure involved the following key stages:

i **Preparation**: A range of thermoplastic waste types, primarily polyethylene (PE) and polypropylene (PP), were collected, cleaned, and cut into pre-defined sizes to simulate actual post-consumer plastic waste.
ii **Calibration**: The machine was inspected for alignment, lubrication, and operational readiness. The motor speed, blade clearance, and belt tension were verified against the design specifications.
iii **Execution**: Known quantities of plastic material (e.g., 0.2 kg, 0.4 kg, 0.8 kg) were fed into the hopper. The machine was operated at set rotational speeds (typically 1000–1200 RPM), and the time taken to fully crush the material was recorded using a stopwatch.
iv **Measurement and Analysis**: The output was collected, weighed, and passed through a standard set of sieves to determine particle size distribution. Energy consumption was monitored using a digital power meter. All data were recorded for each trial, and the process was repeated thrice per condition to ensure repeatability and reliability.
v

The efficiency of the machine was computed using the formula:

$$\eta = \left(\frac{W_{\text{output}}}{W_{\text{input}}}\right) \times 100\%$$

Where W_{output} = Mass of crushed material collected, and W_{input} = Initial mass of thermoplastic material fed into the machine.

3.4.2 Test Design Parameters

The following variables and metrics were incorporated into the experimental design:

Input Parameters:

i Material Type: Various thermoplastics (e.g., polyethylene, polypropylene).
ii Initial Particle Size: Pre-cut plastic pieces of 15 mm and 20 mm.
iii Feed Quantity: Controlled input weights of 0.2 kg, 0.4 kg, and 0.8 kg.
iv Machine Settings: Rotor speed variations of 1000 RPM and 1200 RPM.

Output and Performance Metrics:

i Crushing Time (s): Measured duration from feed to complete crushing.
ii Final Particle Size (mm): Evaluated using standardized sieve analysis.
iii Power Consumption (kWh): Measured using a calibrated power meter.
iv Crushing Efficiency (%): As calculated above.

Instrumentation and Equipment Used:

i Modified thermoplastic waste-crushing machine.
ii Digital power meter for real-time energy consumption monitoring.
iii Stopwatch for accurate timing.
iv Digital scale for input/output weight measurements.
v Sieve shaker with mesh sizes ranging from 1 mm to 6 mm for particle size analysis.

3.4.3 Experimental Protocols

Two major experiments were conducted:

a. **Load Condition Test**: The machine was operated with increasing quantities of thermoplastic waste. For each input quantity, the time to fully crush the material was measured, and the particle size distribution was assessed. This experiment was intended to simulate different real-world waste input scenarios and measure the machine's throughput under varying loads.
b. **Performance Evaluation Test**: The machine's efficiency was analyzed by comparing input and output mass, energy consumption, and particle uniformity. Each test was repeated three times to ensure reproducibility, and the average values with standard deviations were computed to evaluate performance consistency.

All test results were documented and used to validate the machine's ability to perform its intended function effectively. These findings were later used to benchmark the modified machine against a previously existing design.

4.0 Results and Discussion

This section presents and interprets the results obtained from experimental evaluations of the modified thermoplastic waste-crushing machine. Data collected include crushing time, particle size, power consumption, and crushing efficiency under different loading and machine speed conditions. All tests were performed in three replicates to ensure statistical validity and repeatability.

4.1 Results

The experimental results for four test conditions using polyethylene and polypropylene are presented in Table 2. Each test was conducted with different feed rates, initial particle sizes, and machine speeds.

Table 2: Experimental Results of the Modified Plastic Crushing Machine

Test No.	Material Type	Initial Particle Size (mm)	RPM	Feed Rate (kg/h)	Crushing Time (s)	Final Particle Size (mm)	Power Consumed (kWh)	Crushing Efficiency (%)
1	Polyethylene	20	1000	50	30	5	0.15	85
2	Polypropylene	20	1200	50	28	4	0.18	88
3	Polyethylene	15	1000	60	35	5	0.16	82
4	Polypropylene	15	1200	60	32	4	0.20	87

To assess repeatability, each test condition was conducted three times. The mean crushing times and standard deviations are presented in Table 3.

Table 3: Average Crushing Time and Statistical Consistency (n = 3 Trials)

Weight of Plastic (kg)	Average Crushing Time (s)	Standard Deviation (s)	Nature of Crushed Pieces
0.2	64	±1.5	Triangular, rectangular, and irregular shapes
0.4	246	±2.8	Triangular, rectangular, and irregular shapes
0.8	416	±3.2	Triangular, rectangular, and irregular shapes

For benchmarking, the crushing time of the modified machine was compared against the previous design under similar conditions, as shown in Table 4.

Table 4: Comparative Crushing Time: Previous vs. Modified Crusher Design

Weight of Plastic (kg)	Previous Crushing Time t_1 (s)	Modified Crushing Time t_2 (s)	Time Saved (t_1 - t_2) (s)
0.2	118	64	54
0.4	362	246	116
0.8	610	416	194

In addition to the tabulated results, performance trends were visualized using two key plots shown in **Figure 2**.

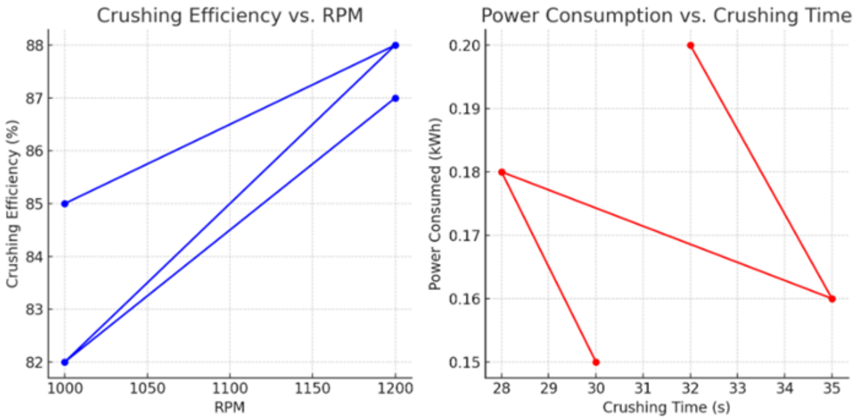


Figure 2. (a) Variation of crushing efficiency with rotor speed (RPM), showing improved performance at higher rotational speeds; (b) Relationship between power consumption and crushing time, indicating increased energy demand with longer operational durations.

4.2 Discussion

The results demonstrate the effectiveness of the design improvements made to the thermoplastic waste-crushing machine.

4.2.1 Influence of RPM on Crushing Efficiency

As depicted in Figure 2(a) and supported by data in Table 2, crushing efficiency increased with rotor speed. The highest efficiency (88%) was achieved at 1200 RPM for polypropylene, indicating that higher RPMs enhance shearing action, reduce crushing time, and improve material breakdown. However, this must be balanced against increased energy use, as highlighted in the next subsection.

4.2.2 Relationship Between Crushing Time and Power Consumption

Figure 2(b) illustrates a direct correlation between longer crushing durations and higher power consumption. For instance, Test 4 (PP at 1200 RPM and 60 kg/h) recorded a higher power usage (0.20 kWh) due to prolonged operation. These findings, aligned with Table 2, suggest that operational parameters such as feed rate, RPM, and blade geometry must be jointly optimized to minimize energy consumption while maintaining efficiency.

4.2.3 Statistical Repeatability and Output Uniformity

The standard deviation values in Table 3 were minimal (±1.5 to ±3.2 seconds), confirming the reliability of machine performance across multiple test runs. Furthermore, the consistent shape of the crushed particles, triangular, rectangular, and irregular, indicates uniform cutting dynamics and effective mechanical shearing across all trials.

4.2.4 Comparative Performance Analysis

The comparative data in Table 4 clearly indicate significant improvements in operational efficiency. The modified crusher reduced crushing time by up to 194 seconds for 0.8 kg of plastic, demonstrating a marked improvement in throughput compared to the previous design. These reductions are attributed to the modified rotor configuration, optimized blade geometry, and improved pulley alignment.

4.2.5 Fulfillment of Research Objectives

The combined results validate the aim of the project: to develop a more efficient, faster, and reliable plastic crushing machine. The time-saving improvements shown in Table 4, combined with high crushing efficiency in Table 2 and consistent performance in Table 3, indicate that the modified machine meets all design and performance expectations. These improvements suggest the machine is suitable for real-world application in decentralized plastic recycling systems, especially in resource-constrained environments.

5.0 Conclusion and Recommendation

5.1 Conclusion

This study successfully designed, constructed, and experimentally validated a modified thermoplastic waste-crushing machine, tailored to address the limitations of existing systems in terms of operational efficiency, structural reliability, and energy consumption. The machine incorporates a reconfigured rotor with three sharp-edged blades, redesigned stator blades, an improved hopper geometry, and optimized pulley alignment. These modifications collectively enhanced crushing efficiency, reduced energy losses, and improved overall machine performance.

Experimental evaluations demonstrated that the modified machine achieved crushing efficiencies as high as 88%, with significant reductions in crushing time, up to 194 seconds faster than the previous design for larger loads. Furthermore, the output particle size remained consistent, with crushed flakes exhibiting a uniform morphology suitable for downstream recycling processes. Statistical analysis of repeated trials confirmed the machine's reliability and repeatability, with low standard deviations (±1.5 to ±3.2 s) in crushing times across different tests.

The results of this research confirm the effectiveness of the proposed design in achieving faster throughput, improved energy use, and enhanced mechanical performance. The machine, fabricated using locally sourced materials and conventional workshop tools, presents a viable and scalable solution for decentralized plastic waste processing, particularly in developing countries where waste management systems are underdeveloped.

5.2 Recommendation

In light of the successful outcomes of this research, the following recommendations are proposed:

i **Industrial Upscaling**: The current prototype should be scaled for commercial use, with enhancements to the motor system and structural reinforcements to accommodate continuous, high-volume operations.

ii **Material Expansion**: Future designs should explore the machine's ability to crush a broader range of plastic types, including multi-layered or contaminated waste, to improve applicability in real-world recycling environments.

iii **Automation Integration**: Automation of material feeding, monitoring, and blade adjustment mechanisms should be incorporated to improve user safety, operational control, and productivity.

iv **Field Deployment and Long-Term Testing**: Field tests in actual waste processing centers should be conducted to evaluate durability, maintenance requirements, and adaptability under real operational conditions.

v **Environmental and Economic Assessment**: A comprehensive life cycle assessment (LCA) and cost–benefit analysis should be conducted to quantify the environmental and economic advantages of the machine in comparison to conventional plastic handling methods.

Through continued refinement and adoption, the proposed machine can play a vital role in promoting sustainable plastic waste management and supporting circular economy initiatives in low-resource settings.

Declarations

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. All expenses incurred during the design, fabrication, and testing of the modified thermoplastic waste-crushing machine were self-sponsored by the authors.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval

Not applicable. This study did not involve human participants or animals, and therefore ethical approval was not required.

Consent to Participate

Not applicable.

Consent to Publish

All authors have read and approved the final manuscript and consent to its publication.

Author Contributions

Aliyu N. H.: Conceptualization, Design Methodology, Fabrication, and Experimental Testing.

Abubakar R. A.: Data Analysis, Results Interpretation, Manuscript Writing, Editing, and Corresponding Author Responsibilities.

Both authors have read and approved the final version of the manuscript.

Data Availability
The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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