UNIVERSIDAD DISTRITAL
FRANCISCO JOSÉ DE CALDAS

Tecnura

https://revistas.udistrital.edu.co/index.php/Tecnura/issue/view/1328

DOI: https://doi.org/10.14483/22487638.24604

INVESTIGACIÓN

Design and scaled prototype implementation of an organic material shredder mill

Diseño de un triturador de material orgánico e implementación de un prototipo a escala

Richard Geovanni Morán Perafan[1], Carlos Andrés Bernal Carvajal[2], Manuel Felipe Bastidas Diaz[3], Steven Alexander Pérez Yela[4], Fabio Camilo Gómez Meneses[5], Jorge Andrés Chamorro Enríquez[6], Álvaro León Ibarra Ordoñez[7]

Fecha de Recepción: 18 de diciembre de 2025 **Fecha de Aceptación**: 24 de septiembre de 2026

Cómo citar: Moran-Perafan R.G, Bernal-Carvajal C.A., Bastidas-Diaz M.F., Pérez-Yela S.P., Gómez-Meneses F.C., Chamorro-Enriquez J.A., Ibarra A.L., «Design and scaled prototype implementation of an organic material shredder mill», *Tecnura*, vol. 30, n.° 90, oct. 2026. 4–23. https://doi.org/10.14483/22487638.24604

Abstract

Objective: This study presents the design and validation of a dual-shaft shredder for organic waste treatment, aiming to produce briquettes and compost for rural communities in developing countries.

Methodology: A mechanical and electronic design methodology was used to develop key components, including shafts, gears, blades, a frame, and control circuits. Shaft and blade strength were verified via static Finite Element Analysis (FEA). The process employed theoretical calculations, simulation tools, and CAD/CAE software. A functional scaled prototype was fabricated using 3D printing and commercial components.

Results: The dual-shaft system achieved the particle size required for briquetting and composting, providing necessary volume reduction and aeration. This directly enhances compaction for briquettes and temperature control for compost, a key factor in biological degradation. Analysis of the prototype identified critical construction and operational factors, ensuring efficiency and durability under real conditions.

Conclusions: The prototype confirms the shredding mechanism's functionality and effectiveness in reducing organic waste volume. Optimizing particle size significantly improves the composting process and briquette compaction, establishing a viable and replicable solution for organic waste treatment, primarily in rural areas of developing countries.

Keywords: Compost, Mechanical design, Organic waste, Prototyping.

1 Postdoctoral researcher, Prometeus, Pasto, Nariño, Colombia. Email: richardmoraning@gmail.com
2 Mechatronics Engineering Student, Universidad Mariana, Pasto, Nariño, Colombia. Email: carlosan.bernal@umariana.edu.co
3 Mechatronics Engineering Student, Universidad Mariana, Pasto, Nariño, Colombia. Email: manuelfe.bastidas@umariana.edu.co
4 Mechatronics Engineering Student, Universidad Mariana, Pasto, Nariño, Colombia. Email: stevenal.perez@umariana.edu.co
5 Mechatronic Engineering Professor, Universidad Mariana, Pasto, Nariño, Colombia. Email: fgomez@umariana.edu.co
6 Mechatronic Engineering Professor, Universidad Mariana, Pasto, Nariño, Colombia. Email: jchamorro@umariana.edu.co
7 Mechatronic Engineering Professor, Universidad Mariana, Pasto, Nariño, Colombia. Email. Email: aibarra@umariana.edu.co

Resumen

Objetivo: Este estudio presenta el diseño y la validación de una trituradora de doble eje para el tratamiento de residuos orgánicos, con el fin de producir briquetas y compost en comunidades rurales de países en desarrollo.
Metodología: Se utilizó una metodología de diseño mecánico y electrónico para desarrollar los componentes clave, incluyendo ejes, engranajes, cuchillas, la estructura y los circuitos de control. La resistencia de los ejes y las cuchillas se verificó mediante un análisis estático por elementos finitos (FEA). El proceso empleó cálculos teóricos, herramientas de simulación y software CAD/CAE. Se fabricó un prototipo funcional a escala utilizando impresión 3D y componentes comerciales.
Resultados: El sistema de doble eje logró el tamaño de partícula requerido para el briqueteado y el compostaje, proporcionando la reducción necesaria de volumen y aireación. Esto mejora directamente la compactación para las briquetas y el control de temperatura para el compost, un factor clave en la degradación biológica. El análisis del prototipo identificó factores críticos de construcción y operación, asegurando su eficiencia y durabilidad en condiciones reales.
Conclusiones: El prototipo confirma la funcionalidad y efectividad del mecanismo de trituración para reducir el volumen de residuos orgánicos. La optimización del tamaño de partícula mejora significativamente el proceso de compostaje y la compactación de briquetas, estableciendo una solución viable y replicable para el tratamiento de residuos orgánicos, principalmente en zonas rurales de países en desarrollo.
Palabras clave: molino, cuchillas, doble eje, compostaje, prototipo, residuos orgánicos, aireación, degradación biológica.

Introduction

Effective waste management is a pressing global challenge, crucial for safeguarding public health, protecting the environment, and conserving natural resources [1]. As urbanization and consumption intensify, municipal solid waste generation is rising; global production is currently estimated at 1.7 to 1.9 billion metric tons per year and is expected to reach 2.5 billion metric tons by 2025 [2]. A substantial share of this waste is household biodegradable material, which, when mismanaged, leads to environmental degradation, economic losses, and public health hazards [3].

Conventional disposal methods such as landfilling and incineration face sustainability issues, including greenhouse gas emissions and inefficient resource use [4]. In contrast, alternatives like composting and briquetting offer more sustainable pathways for managing organic residues [5, 6, 4]. Circular economy strategies promote reuse, recycling, and composting, reducing reliance on virgin materials and mitigating environmental impacts [7]. Composting, in particular, provides an effective means of converting organic waste into nutrient-rich fertilizer, improving soil quality and decreasing dependence on chemical fertilizers, which are both costly and environmentally harmful [3].

Successful composting, however, requires adequate preprocessing, especially shredding, to optimize particle size and aeration, both of which are critical for accelerating biological decomposition [8]. Although industrial shredders are available, they are often inaccessible to rural communities in developing regions due to high costs and technical complexity. This study addresses that gap by designing and

validating a dual-shaft shredder mill for organic waste treatment, tailored specifically for rural communities in developing countries such as Colombia.

The proposed shredder supports circular economy initiatives by enabling the transformation of organic waste into compost, fostering local sustainability, reducing environmental impact, and creating socioeconomic opportunities. The design emphasizes affordability by using locally available materials, ease of maintenance via a straightforward mechanical structure, and operational reliability for processing various organic waste streams commonly found in rural settings. By optimizing particle size for efficient composting, the shredder empowers communities to turn waste into agricultural value, advancing circular economy practices at the grassroots level.

The novel contribution of this work lies in the integrated design and validation of a low-cost, locally manufacturable dual-shaft shredder specifically tailored to the operational constraints of rural communities in developing countries. Unlike existing industrial solutions that are either prohibitively expensive or too technically complex for such contexts, this study provides a comprehensive, replicable framework—from kinematic and kinetic analysis through FEA-based component verification to a functional scaled prototype—that demonstrates the feasibility of decentralized organic waste preprocessing. This work thereby addresses a documented gap in the literature concerning affordable, maintainable, and context-appropriate shredding technologies for rural waste management.

Methodology

The present study was implemented using the mechanical design methodology proposed by [9], which consists of ten stages: identification of need, background research, goal statement, performance specifications, ideation and invention, analysis, selection, detailed design, prototyping and testing, and production. All stages are briefly described below, except for the last, which was excluded due to the limited scope of the study.

The methodology begins with the identification of a need, where the problem is clearly defined. This is followed by background research, which involves reviewing existing knowledge about similar solutions, materials, and technologies to establish a foundation for the project. A goal statement then outlines the design objectives. Next, performance specifications define the functional requirements that the final design must meet.

During the ideation and invention phase, potential designs are brainstormed and sketched, exploring different mechanisms for the shredder. The analysis stage evaluates these alternatives from technical, economic, and practical perspectives to determine their viability, eliminating impractical solutions

early on. In the evaluation and selection phase, design options are compared based on criteria such as cost, efficiency, and feasibility to identify the best solution.

Once a design is selected, the detailed design phase refines it with precise dimensions, material selections, and manufacturing methods. This stage employs extensive engineering tools, including free-body diagrams, theoretical analysis, sketches, CAE/CAD modeling, dynamic simulations, and component selection methodologies. Finally, prototyping involves building a physical or digital model to validate real-world performance before full-scale production.

Results

Identification of need

The study addresses the need for a simple, affordable, and effective way to shred organic waste in rural areas of developing countries like Colombia. Many of these places lack proper organic waste management, so people often burn trash or let it rot, causing pollution and health problems. Existing shredders are usually too expensive, too complicated, or not robust enough for tough farm waste like wood logs, corn stalks, or banana leaves.

Background research

Composting has proven to be an effective waste management solution, reducing landfill contributions and associated methane emissions while producing valuable soil amendments [10]. The mechanical pretreatment of organic waste through shredding significantly enhances composting efficiency by increasing the surface area available for microbial decomposition [11]. Studies indicate that optimal particle sizes between 1.5–3 cm accelerate biodegradation while maintaining adequate pile porosity for oxygen diffusion [12]. Excessive size reduction below this range risks compaction, which can impede airflow and promote anaerobic conditions that slow decomposition rates.

Various shredding technologies have been developed to process organic waste, each with distinct advantages and limitations. Hammer mills use high-speed rotating the hammers (typically 1,500–3,000 rpm) to fracture materials through impact, generating particle sizes as small as 1–5 mm in industrial applications [13]. However, their performance declines with moist or fibrous feedstocks due to clogging and accelerated wear on hammer bearings. Jaw crushers, operating at slower speeds (100–300 rpm), apply compressive forces in a V-shaped chamber but struggle with soft, wet organic matter, making them better suited for rigid materials like wood or bone [14]. Ball mills, employing hardened steel balls or rubber grinding media, achieve fine particle sizes (<0.1 mm) but require precise speed control (60–80% of critical speed) to balance centrifugal force and grinding efficiency, resulting in high energy consumption and noise [15]. Roller mills, with adjustable gaps (0.1–20 mm) and textured the rollers, provide

gradual size reduction but exhibit limited effectiveness for fibrous or high-moisture biomass due to material slippage between rollers [16].

Among these systems, blade mills have demonstrated superior suitability for organic waste processing, particularly due to their ability to handle wet, fibrous materials through shearing rather than pure impact or compression. Recent designs incorporate counter-rotating shafts (20–100 rpm) with staggered blades (thickness: 8–25 mm, diameter: 100–200 mm) fabricated from tough materials like S45C carbon steel to resist impact and wear [17, 18, 19, 20]. The absence of output screens in many blade mills prevents clogging, while low-speed, high-torque operation improves energy efficiency compared to high-speed impact mills.

Recent implementations highlight technology's adaptability across different scales. [18] developed a portable dual-shaft shredder powered by a 3.5 hp, 3600 rpm petrol engine with a speed ratio of 1:40, achieving a throughput of 360 kg/h of vegetable waste in a compact format (2m × 1 m × 1.6 m). [17] optimized blade geometry in a double hexagonal shaft configuration with 26 blades (100–200 mm diameter, 8–15 mm thickness), demonstrating durability in a 338.5 mm × 285 mm × 195 mm shredding chamber. Smaller-scale designs, such as the single-shaft system by [19], used a 0.5 hp motor (1380 rpm) with a 3:1 speed reduction through a belt-pulley transmission. Agricultural applications, like the double-shaft coconut leaf shredder by [20], employed 150 mm diameter blades (25 mm thickness) driven by a 2 hp motor (1440 rpm, 3:1 reduction), yielding 80–90 kg/h of processed material.

Goal statement

By considering the required functional vision of the shredder, we arrive at the following statement:

"Design a means to reduce organic waste into uniformly small particles to accelerate decomposition, suitable for rural communities with limited resources."

Performance specifications

Based on previous research, the specifications are provided in Table 1.

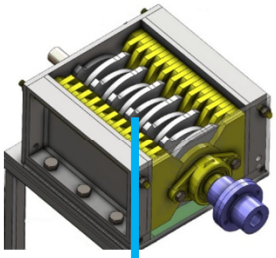
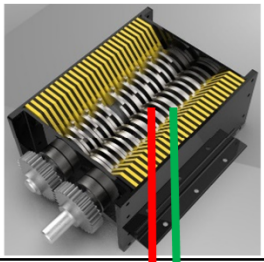
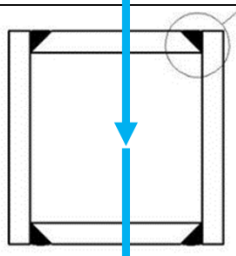
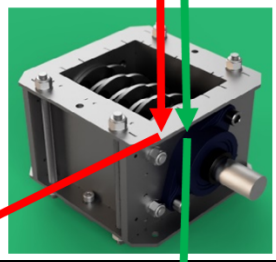
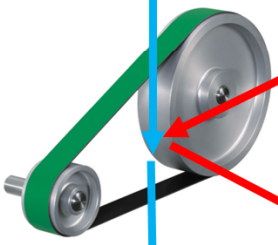
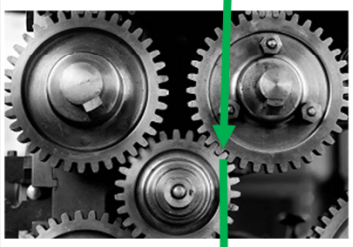
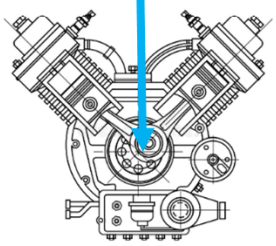
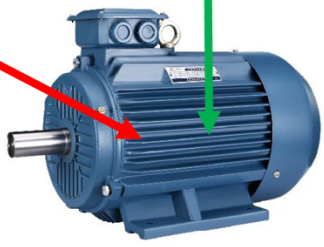
Table 1. *Performance specifications.*

Criteria	Acceptable range
Raw material	Wet or dry organic waste, such as peels, shells or logs
Processed material size	Less than 2 cm
Cost	Less than 7300 USD
Energy Supply	Electric energy, 110 V AC @ 60 Hz

Ideation and invention

Design proposals were based on blade shredders and different technologies used to construct them, such as speed reduction systems, structural element joining, the number of shafts, and the type of engines. To consider the various possible combinations, a morphologic matrix was used, which is presented in Table 2.

Table 2. *Morphological matrix considering the different design proposals.*

Design proposals	Design options			
Number of shafts	Single		Double	
Shredder chamber joining method	Welding		Bolts	
Speed reduction system	Pulleys and belts		Gear Reductor	
Type of motor	Internal combustion		Electric motor	

Analysis

The morphological matrix produced 16 potential design variations, with only three selected for in-depth analysis, as shown in Table 2. The blue route (Proposal 1) offers the simplest and most cost-effective solution but makes compromises in performance and maintenance requirements. This single-shaft design typically incorporates screening systems at the bottom of the cutting chamber, which can present operational challenges. Soft, wet materials tend to adhere to these screens, necessitating frequent inspections and cleaning. While single-shaft shredders are often recommended for processing soft materials, their effectiveness becomes questionable when harder contaminants, such as bones or wood logs, are present in the waste stream [21].

In comparison, the green route (Proposal 2) features higher-performance components and provides intermediate maintenance convenience. This design eliminates belt and pulley transmissions but introduces greater mechanical complexity through its dual-shaft configuration. Although this solution comes at a premium cost, it offers distinct advantages: the twin-shaft system effectively handles both soft and hard materials, while the interlocking blade design provides self-cleaning properties that reduce long-term maintenance needs [21].

The red route (Proposal 3) closely follows the green route's design philosophy but incorporates a pulley-belt transmission system, a more conventional approach frequently referenced in technical literature [17]. This modification results in slightly lower costs but increases maintenance demands due to the inherent wear characteristics of belt-driven systems. The trade-off between initial investment and ongoing maintenance requirements becomes a key consideration when evaluating this option against the other proposals.

Evaluation and selection

The design proposals were evaluated using a performance-based assessment matrix. Table 3 shows the comparative results of the three alternatives, each rated according to their compliance with the established evaluation criteria. The rating system assigned 5 points for complete fulfillment of requirements, 3 points for partial fulfillment, and 1 point for minimal or unsatisfactory performance. After careful analysis, Proposal 2 was selected as the preferred solution, having achieved one of the highest overall scores. This alternative not only demonstrated strong initial performance but also showed superior long-term operational characteristics, making it the most suitable option to align with all design specifications and project requirements.

Table 3. *Proposal evaluation results.*

Design proposal	Cost	Mixed materials	Size material control	Maintenance need	Autocleaning	Additional mechanism	Total
1	5	1	5	3	1	1	16
2	1	5	1	3	5	5	20
3	3	5	1	1	5	5	20

Detailed design

Camber size

A review of several commercial shredder designs [17, 22] shows that the smallest models have chamber dimensions ranging from 400 to 660 mm in length by 270-500 mm in width. A chamber size of 790 mm long, 550 mm wide, and 410 mm high was heuristically determined (Figure 1).

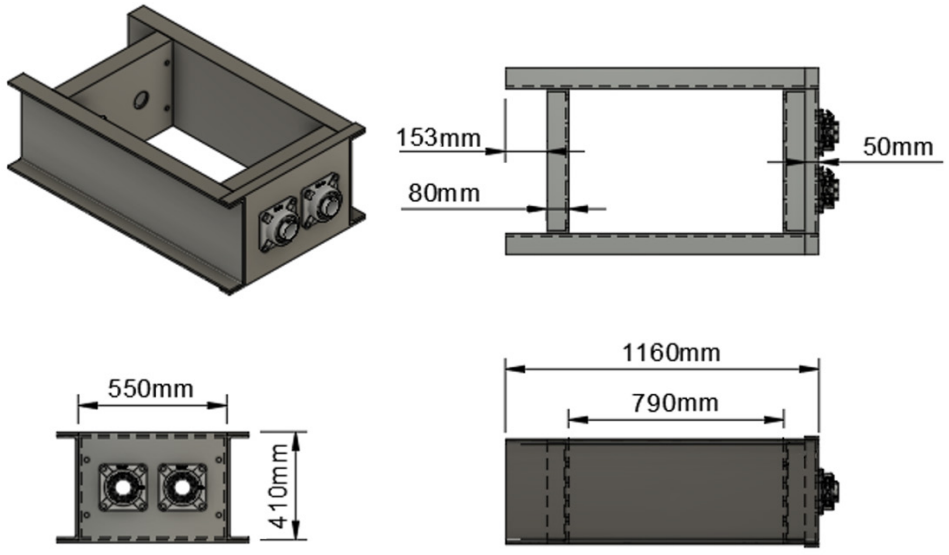


Figure 1. *The proposed dimensions of the shredder mill's crushing chamber.*

Source: Authors.

Kinematic and kinetic analysis

The calculation of the required cutting force and driving shaft torque must account for the configuration and dimensions of the blade assembly. Figure 2 illustrates the overall design concept and the primary components of the shredder, including the motor, speed reducer, shafts, bearings, cutting blades, hopper, and structure. A dual-shaft configuration was adopted, using 36 blades distributed equally

with 18 blades per shaft. To facilitate assembly and disassembly while ensuring a secure grip on each blade, hexagonal shafts with an across-flats dimension of 100 mm were selected. If a shaft of another shape were used, it would be necessary to implement an adjustment method such as welding or using keyways, which would complicate the construction process and could cause the mechanism to fail due to wear caused by corrosion from waste.

A pair of gears is incorporated to synchronize the shafts and provide the counter-rotating action necessary for effective cutting. As the system operates with high torque and low speed, a speed reducer is included to achieve the target rotational speed of 20 rpm for each shaft.

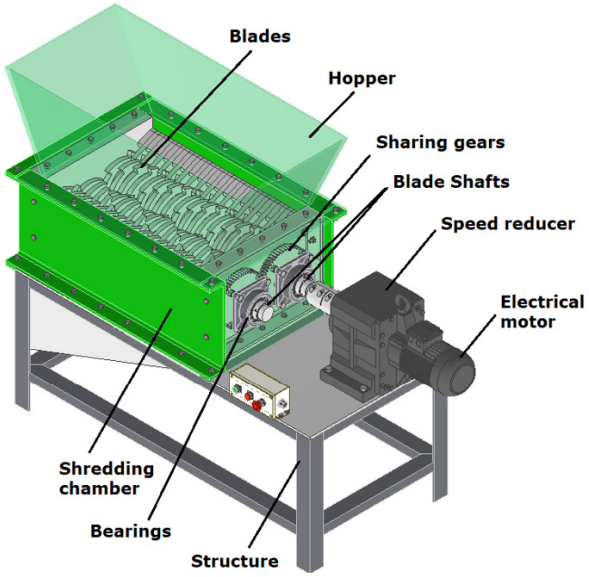
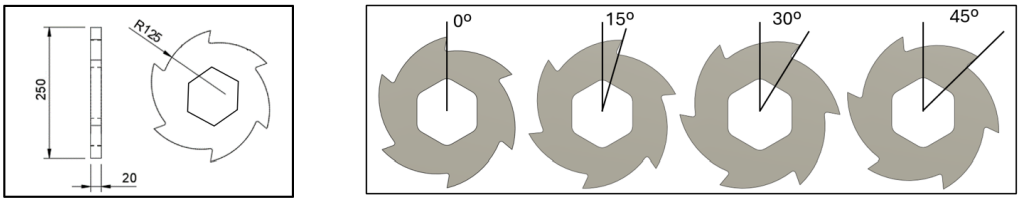


Figure 2. *Design concept and main components.*

Source: Authors.

Commercial blades were implemented to simplify maintenance and the replacement of worn components. A search of industrial manufacturer catalogs [23] was conducted to reference designs with standardized, manufacturable dimensions. The selected blade geometry is shown in Figure 3a. Commercial blades are manufactured from tool steel, with the final user selecting from available grades such as 65Mn, 9CrSi, Cr12MoV, SKD-11, and HSS. For this analysis, the material is assumed to be HSS (High-Speed Steel, Sy = 1148 MPa [24]). To promote an efficient and uniform shredding process, a set of blades was designed following a principle of progressive inclination. In this design, each consecutive blade features a cutting edge angled 15 degrees greater than the previous one, creating a helical cutting pattern along the shaft (Figure 3b).



a. b.

Figure 3. *Blade dimensions (mm) and assembly order in the shaft.*

Source: Authors.

Power Calculations

The assessment of shaft torque begins with the calculation of the cutting force on each blade. This force is determined as the product of the shear strength of the organic material and its transverse cross-sectional area. Given the significant variability in the mechanical and geometric properties of organic material [25], a limit condition was analyzed using a conservative value for the shear strength of hardwood [26], taken as 8.2 MPa. The transverse shearing area was calculated based on a material width of 20 mm and a blade thickness of 20 mm. Thus, the maximum shear force in each blade was 3280 N.

Each blade contributes a torque of approximately 410 N·m, calculated as the product of the shear force and a 125 mm moment arm, as shown in Figure 3. This calculation assumes the force and arm are orthogonal. For a conservative design, it was determined that a maximum of five blades per shaft would be engaged simultaneously (Figure 4). Consequently, the total required torque per shaft is 2050 N·m. The power for each shaft was then calculated as the product of torque and rotational speed, resulting in 4,293 W per shaft and a total system power requirement of 8,587 W.

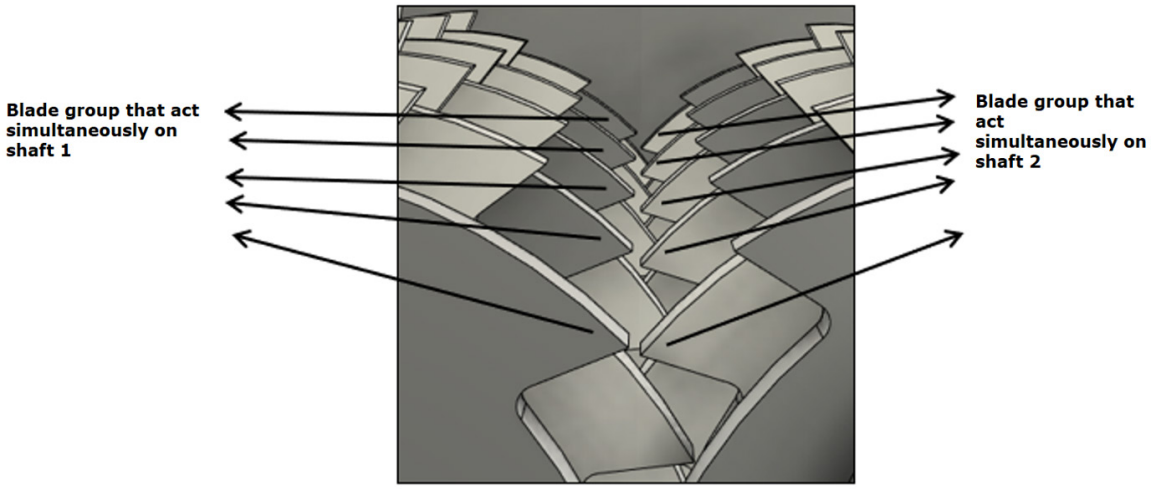


Figure 4. *Simultaneous action of the blades during shredder operation.*

Source: Authors.

Shaft design

A finite element model was developed to assess the structural integrity of the main shaft. The model applied the boundary conditions and loads detailed in the free body diagram in Figure 5 and tabulated in Table 4. These include the five cutting forces and their associated torques at blade locations B through F, as well as the force and torque from the gear at point G. The shaft is supported at points A and H. The material was specified as normalized AISI 1050 steel (Sy = 425 MPa, Sut = 752 MPa, Se' = 376 MPa [27]), selected for its mechanical properties and local availability. Blade weights were omitted due to their negligible impact, and the analysis was confined to the critical points of the shaft.

Table 4. *Boundary conditions, locations and load magnitudes to shaft static simulation.*

Point	Distance X from origin	Reaction Y (N)	Reaction Z (N)	Force Y (N)	Force Z (N)	T (N.m)
A	0	-9244.2	2915.6			
B	198			3136,7	-959,0	410,0
C	374			3136,7	-959,0	410,0
D	550			3136,7	-959,0	410,0
E	726			3136,7	-959,0	410,0
F	902			3136,7	-959,0	410,0
G	993			18636,4	-6783,1	2050
H	1082	-25075,6	8662,5			-4100

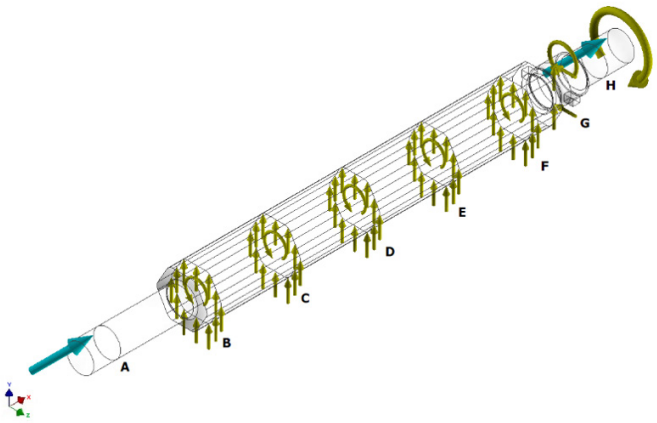


Figure 5. *Free-body diagram of the main shaft.*

Source: Authors.

The finite element model used six-node triangular elements. The mesh size was determined through a convergence analysis based on von Mises stress, using a criterion of less than 10% difference between successive mesh refinements.

The results of the static stress analysis are presented in Figure 6. The maximum von Mises stress was 110.6 MPa, located at the circular transition between the hexagonal and circular sections. At this critical location, the shaft diameter is 60 mm, subject to a combined bending moment of 2359.7 N·m and a torque of 2050 N·m. Stresses in the hexagonal section were significantly lower, at approximately 9.7 MPa. The minimum static safety factor, calculated in the circular section, was 2.9. A subsequent fatigue analysis was performed on the critical circular section following the methodology presented by [28, 29], yielding a fatigue safety factor of 2.0.

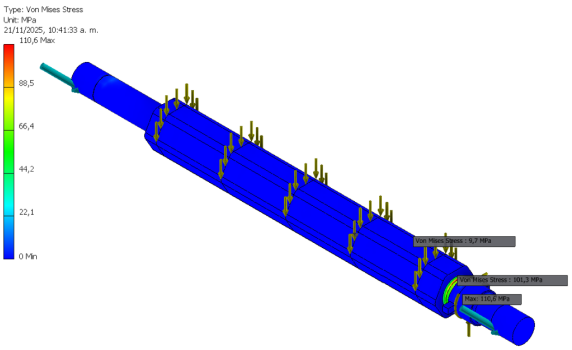


Figure 6. *Results of the shaft static stress analysis.*

Source: Authors.

Blade strength verification

The blade geometry is shown in Figure 7. A finite element model was developed to perform a static analysis. The model's boundary conditions are illustrated in Figure 7A: the shaft hole was fully constrained, and a force of 3280 N was applied to one face of the cutting tooth. The analysis yielded a maximum von Mises stress of 45.3 MPa at the tooth root, resulting in a safety factor of 51.8. Actual operating conditions are more aggressive than anticipated due to wear. Tool steel is therefore recommended for the blades, as its properties are suited to withstand this heightened level of abrasion.

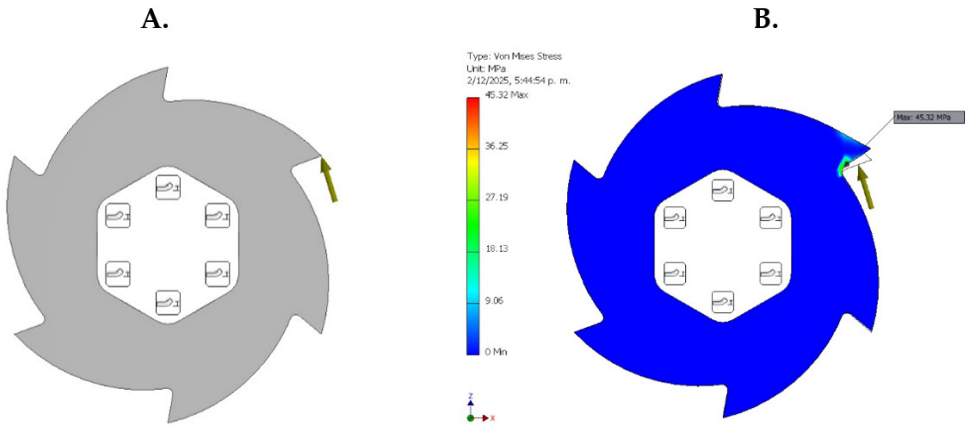


Figure 7. *Blade finite element model, A. Boundary conditions, B. Von Mises static stress analysis results.*

Source: Authors.

Sharing Gear Design

Spur gears were designed using the Component Generator within Autodesk Inventor Professional 2025 (Figure 3). The input parameters, defined by the operational conditions of the shredder, were set as follows: 210 mm center distance, 20° pressure angle, unity speed ratio (for direction inversion only), 5 mm module, 4293 W nominal power, 20 rpm angular speed, and 14NiCr18 steel material (Sac = 1550 MPa and Sat =483 MPa). According to the AGMA 2001-D04:2005 standard, the calculation results provided a face width of 40 mm, 40 teeth, and respective safety factors of 1.28 against bending stress and 1.41 against contact stress.

Gearmotor Selection

A coaxial shaft gearmotor was selected to meet the required nominal power of 8587 W at 20 rpm. The chosen unit was a SIEMENS motor, model D.168-LA160MB4 [30], with a rated power of 13.2 kW and an output speed of 22 rpm, resulting in a service factor of approximately 1.5. The slight discrepancy in angular speed falls within acceptable operating limits and does not adversely affect performance.

CAD Design

The final design is shown in Figure 8, which includes the overall dimensions. The solid waste falls directly into the upper hopper, passes through the crushing chamber to be shredded and exit through the discharge hopper.

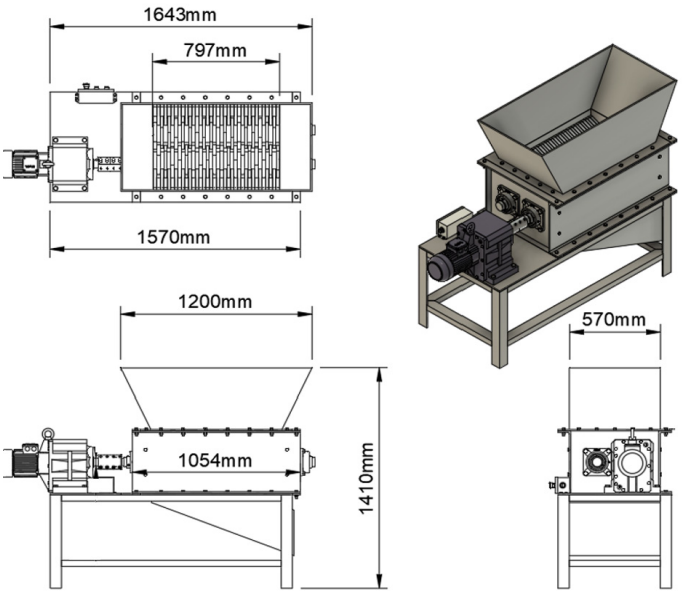


Figure 8. *Actual Shredder Plan.*

Source: Authors.

Prototyping

To validate the proper functioning of the shredder mechanism, a scaled prototype was designed and constructed. The prototype was built primarily using 3D printing technology and laser-cut wood panels. It incorporates a 6 rpm geared motor with a nominal torque of 91 kg*cm and a direct gear drive power transmission system. The prototype is built to a 1:4 scale relative to the original design, as illustrated in Figure 9.

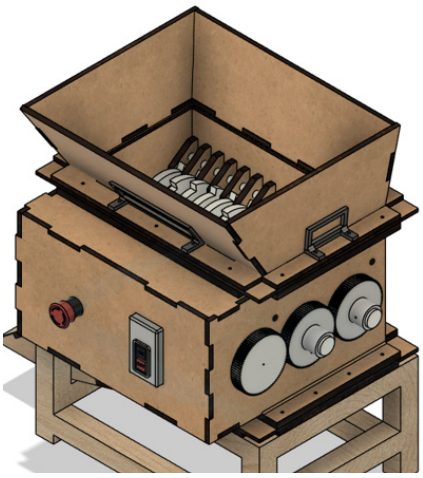


Figure 9. *Design of the shredder prototype.*

Source: Authors.

For the construction of the prototype, low-cost and easy-to-handle materials were selected to replicate the functional conditions of the full-scale system. The primary structural materials included 4 mm MDF, plywood, wooden slats, and custom PLA parts produced via 3D printing. Key mechanical elements consisted of shafts, bearings, chains, printed gears, PVC rollers, and tarpaulin. The electronic system was built using a DC motor, a power supply, a speed controller, a solid-state relay, push buttons, a potentiometer, and an emergency stop. Fabrication relied on a 3D printer for PLA components and a CO_2 laser cutter, with assembly carried out using common tools such as a drill, screwdrivers, a soldering iron, a multimeter, and clamps. The design and preparation process used software including Inventor Professional 2025 for modeling and simulations, Cura and Creality Print for slicing, and Cade Simu for electronic circuit simulation.

Before fully sealing the crushing chamber, the blades were assembled onto their respective shafts and spacers. The blades must be placed in a specific, offset sequence to function correctly. To align the blade spacers during this process, threaded alignment rods were installed at each of the four ends of the shaft assembly (Figure 10).



Figure 10. *Installation of blades and spacers.*

Source: Authors.

The geared DC motor was coupled to the shredder shafts through a gear system. Once the gears were mounted, movement tests were conducted on the blades by manually moving the shafts to identify any potential blockages (Figure 11). The shredder was fixed onto a sturdy base with wooden slat reinforcements. Additionally, two protective hoppers were added—one at the top and the other at the bottom—to prevent accidents during use (Figure 12).



Figure 11. *Motor-shaft coupling.*

Source: Authors.



Figure 12. *Photo of the complete system with cover.*

Source: Authors.

Preliminary Shredding Tests

Initial tests were conducted to verify the overall operation of the prototype under controlled, operator-supervised conditions. First, the startup and continuous operation of the motors were verified. When voltage was applied through the control system, both motors started correctly and ran without seizing or interruption. Subsequently, shredding tests were performed using soft organic waste like peel, leaves and paper. These tests evaluated the system's cutting behavior, noise levels, vibration, and material output. A preliminary analysis of the shredded material confirmed its suitability for composting, with a resulting average particle size of 14 mm, as shown in Figure 13. While these results validate the prototype's functionality, the final shredder—constructed with metal components for greater stiffness—is expected to deliver significantly higher performance. However, it will be part of future work.

A. B.



Figure 13. *Shredding tests, A. Waste shredding process, B. Shredding results.*

Source: Authors.

Discussion

The results obtained in this study demonstrate the technical feasibility of the proposed dual-shaft shredder for organic waste processing. The particle size achieved (14 mm average) falls within the optimal range of 1.5–3 cm reported by [12] for accelerating biodegradation while maintaining adequate pile porosity for oxygen diffusion. This confirms the system's suitability for composting applications.

When compared with existing designs, the proposed shredder offers distinct advantages in terms of accessibility and context-appropriateness. The portable dual-shaft shredder developed by [18], while achieving a higher throughput of 360 kg/h, relies on a petrol engine and a complex 1:40 speed reduction system that may be impractical for rural communities with limited technical support. Similarly, the single-shaft system by [19] requires a 3:1 belt-pulley transmission, which introduces maintenance demands that may not be sustainable in resource-constrained settings. In contrast, the direct gear transmission adopted in Proposal 2 eliminates belt wear and reduces long-term maintenance requirements, albeit at a higher initial cost. This trade-off was deemed acceptable given the project's emphasis on operational reliability.

The design exhibits high safety factors. This conservatism is intentional, as actual operating conditions—particularly with harder or more abrasive feedstocks—may exceed the assumed shear strength of 8.2 MPa. The recommendation to use tool steel for the blades further mitigates this risk.

This study has several limitations that must be acknowledged. First, the validation was performed using a scaled prototype fabricated primarily from PLA and MDF, which do not replicate the mechanical properties, wear resistance, or durability of the metallic components intended for the full-scale design. Consequently, the prototype's performance under continuous operation or with harder feedstocks (e.g., wood logs, bones) was not assessed. Second, the long-term durability of the prototype—particularly the wear of 3D-printed gears and PLA blades—was not evaluated over multiple operational cycles. Third, the prototype was tested exclusively with soft organic waste (peels, leaves, paper); its performance with fibrous or high-moisture materials remains to be determined. Fourth, the corrosion resistance of the selected materials under prolonged exposure to organic waste was not investigated. These limitations should be addressed in future work through the construction and testing of a full-scale metal prototype under real operating conditions.

Based on the particle size measurements obtained, the proposed shredder is most immediately suited for composting applications, where a particle size of 1.5–3 cm is optimal. For briquetting, additional size reduction or compaction equipment may be required to achieve the finer particle sizes necessary for dense, durable briquettes [31].

Conclusions

This study confirms that the integrated design of a low-cost, locally manufacturable dual-shaft shredder constitutes a technically and contextually viable solution for the pretreatment of organic waste in rural communities of developing countries. The combination of hexagonal shafts, staggered blades, and direct gear transmission proved effective in reducing waste volume and producing a particle size suitable for composting, thereby validating the central hypothesis that accessible and maintainable shredding technologies can be developed without sacrificing functional performance.

Incorporating interchangeable metal inserts in the cutting area facilitates maintenance and reduce costs, along with conducting field tests in rural communities to evaluate adoption, usability, and sustainability under real-world conditions.

Finally, exploring the integration of this technology with other stages of organic waste valorization—such as briquetting and larger-scale composting—is encouraged, thereby consolidating a technology transfer pathway that contributes to the circular economy and the sustainable development of rural areas. Furthermore, although a full-scale prototype using metallic materials was not constructed, this study demonstrates that rapid prototyping and functional evaluation of a design can be achieved without substantial financial investment. This approach is particularly valuable for rural communities and low-resource settings, where such investments are often prohibitive.

References

[1] S. Schmidt and D. Laner, "Reducing the climate impact of residual waste treatment: A German case study on carbon management strategies," *Waste Management*, pp. 137–150, 2025, doi: https://doi.org/10.1016/j.wasman.2025.02.048

[2] Y. Teshome, N. Habtu, and M. Molla, "Global journal of environmental science and management municipal solid wastes quantification and model forecasting," *Global Journal of Environmental Science and Management*, pp. 227–240, 2023

[3] J. Narasimha and T. Parsai, "A comprehensive review on the decentralized composting systems for household biodegradable waste management," *Journal of Environmental Management*, pp. 1–20, 2023

[4] B. Assamoi and Y. Lawryshyn, "The environmental comparison of landfilling vs. incineration of MSW accounting for waste diversion," *Waste Management*, pp. 1019–1030, 2012, doi: https://doi.org/10.1016/j.wasman.2011.10.023

[5] N. Ferronato, I. Calle, M. Gorritty, F. Conti, and V. Torretta, "Are waste-based briquettes alternative fuels in developing countries? A critical review," *Energy for Sustainable Development*, pp. 220–241, 2022, doi: https://doi.org/10.1016/j.esd.2022.03.013

[6] T. Sarker, S. Nanda, V. Meda, and A. Dalai, "A Review of Technical and Economic Aspects of Biomass Briquetting," *Environmental Chemistry Letters*, pp. 4–35, 2022

[7] D. Hariyani, P. Hariyani, S. Mishra, and M. Kumar, "A literature review on waste management treatment and control techniques," *Sustainable Futures*, pp. 1–26, 2025, doi: https://doi.org/10.1016/j.sftr.2025.100728

[8] S. Modupe, S. Oluwaseyi, O. Olubukola, and O. Olu, "Waste Management through Composting: Challenges and Potentials," MDPI, pp. 1–23, 2020

[9] R. Norton, *Design of Machinery*, 4th ed. New York: McGraw Hill, 2007.google

[10] E. Manea, C. Busbac, L. Razvan, M. Bumbac, and C. Nicolescu, "Composting as a Sustainable Solution for Organic Solid Waste Management: Current Practices and Potential Improvements," *Sustainability*, pp. 1–25, 2024, doi: https://doi.org/10.3390/su16156329

[11] P. Xu, Y. Li, S. Zhou, G. Zhang, Y. Wu, and Z. Yang, "Pretreatment and composting technology of agricultural organic waste for sustainable agricultural development," *Heliyon*, pp. 1–20, 2023, doi: https://doi.org/10.1016/j.heliyon.2023.e16311.24849-24849-correccion-estilo-EN.docx

[12] S. Mishra and K. Yadav, "Assessment of the effect of particle size and selected physico-chemical and biological parameters on the efficiency and quality of composting of garden waste," *Journal of Environmental Chemical Engineering*, pp. 1–19, 2022, doi: https://doi.org/10.1016/j.jece.2022.107925

[13] H. Aragon, C. Aragon, B. Miranda, and F. Sanabria, "Characterization and construction of a compact hammer mill for laboratory use to homogenize natural fibers of *Elaeis guineensis* and *Acrocomia* sp.," *Ingenieria*, pp. 134–152, 2023, doi: https://doi.org/10.15517/ri.v33i2.54419

[14] M. Zidek, F. Nikles, V. Sikorova, and F. Vanek, "Effect of changing jaw crusher parameters on granulometry and static angle of repose of crushed aggregate," *Geo Science Engineering*, pp. 179–185, 2023, doi: https://doi.org/10.35180/gse-2023-0098

[15] R. Jihad and I. Rodriguez, "Finite Element and Multibody Dynamics Analysis of a Ball Mill Glass Crusher," *Modelling and Simulation in Engineering*, pp. 1–17, 2023, doi: https://doi.org/10.1155/2023/1905702

[16] D. Ephraim, "Roller mills: Precisely reducing particle size with greater efficiency," June 2006. [Online]. Available: https://www.mpechicago.com/wp-content/uploads/2019/12/powder_and_bulk_engineering_6-06.pdf

[17] M. Andrianto and Fahriansyah, "3-D designing of an organic waste crusher," *IOP Conf. Series: Earth and Environmental Science*, pp. 1–11, 2019, doi: https://doi.org/10.1088/1755-1315/277/1/012009

[18] G. Resmi and V. Vinod, "Development and Fabrication of a Portable Shredding Machine for Rapid Composting of Organic Waste," *Nature Environment and Pollution Technology An International Quarterly Scientific Journal*, pp. 275–281, 2022, doi: https://doi.org/10.46488/NEPT.2022.v21i01.032

[19] B. Mahadev, A. Mohammed, Y. Abhishek, K. Manish, and A. Amith, "Design and Fabrication of Agricultural Waste Shredder Machine," *Advancement in Mechanical Engineering and Technology*, pp. 1–8, 2020

[20] I. Sanjay and T. Hemanth, "Design and Development of Agricultural Waste Shredder Machine," *International Journal of Innovative Science, Engineering & Technology*, pp. 164–172, 2015.

[21] SHENAOZG, "Differences Between Single-Shaft, Double-Shaft, and Quad-Shaft Shredder Blades," 2025. [Online]. Available: https://www.shenaozg.com/differences-between-single-shaft-double-shaft-and-quad-shaft-shredder-blades/

[22] R. Padmakar and P. Jaypal, "Design Review and Optimization of Twin Shaft Shredder Blades for Shredding of Paddy Straw," *International Journal of Advanced Research in Science, Communication and Technology*, pp. 603–615, 2022

[23] Metal, "Shredder Blades," Jan. 2025. [Online]. Available: https://maxtormetal.com/product/shredder-blades-shredding-knife/

[24] R. Talemi, J. Zhang, S. Hertelé, and W. De Waele, "Finite Element Analysis of Fretting Fatigue Fracture in Lug Joints Made of High Strength Steel," *MATEC Web of Conferences*, pp. 1–7, 2018.

[25] M. R. V. H. Carlos Andrés Ordóñez Ante, "Resistencia al corte de residuos sólidos urbanos: estado del arte," *Resistencia al corte de residuos sólidos*, pp. 6–9, 2007

[26] D. Kretschmann, "Mechanical Properties of Wood," in *Wood Handbook, Wood as an Engineering Material*. USDA, 2010

[27] Matweb, "Steel 1050 Normalized," Sep. 1, 2025. [Online]. Available: https://www.matweb.com/search/DataSheet.aspx?MatGUID=4ec109f9a85648669e7896223dbf3411&ckck=1

[28] S. D., M. Rivera, and R. Moran, "Development of a Safe Feeding Agave Leaf Decortication Machine," *Ingeniería*, vol. 30, no. 2, pp. 1–20, 2025, doi: https://doi.org/10.14483/23448393.23173

[29] Shigley, *Shigley's Mechanical Engineering Design*, 10th ed., vol. Torsion of Circular Shafts, J. K. N. Richard G. Budynas, Ed. New York: McGraw-Hill Education, 2015, pp. 90–95.

[30] SIEMENS, "Motorreductores MOTOX. Catálogo D 87.1 · 2008," 2009. [Online]. Available: https://rodesprex.com/catalogos/moto/sie01es.pdf

[31] S. Kpalo, M. Zainuddin, L. Manaf, and A. Roslan, "A Review of Technical and Economic Aspects of Biomass Briquetting," *Sustainability*, pp. 2–30, 2020, doi: https://doi.org/10.3390/su12114609