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Development of Appropriate Technology: Redesign and Performance Analysis of a Leaf Shredder Machine

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Abstract
The implementation of appropriate technology for organic waste management in local communities is often hindered by high production costs. This study aims to redesign a reference leaf shredder machine to produce a cost-effective prototype accessible to rural areas. While an initial prototype was developed through strategic component substitution, performance evaluations revealed critical operational flaws, including excessive vibration, outlet chute clogging and leakage, and insufficient motor starting torque. In response, an iterative design process was conducted to modify the structure, functional components, and Standard Operating Procedures (SOP).The results demonstrate comprehensive improvements, such as structural reinforcement theoretically shifted the frame's natural frequency from 91.98 Hz to 106.15 Hz, successfully distancing it from the motor's harmonic excitation frequency of 93.2 Hz to avoid resonance. Clogging and leakage were resolved by replacing the perforated plate with a wire mesh and applying sealant, while motor torque limitations were mitigated through an SOP supported by a safety cover design. The final prototype effectively resolves all technical issues, offering a stable, functional, safe, and affordable solution with a capacity of 3 kg per 10 minutes operating cycle, making it ready for community-level implementation.

Keywords: Appropriate technology, iterative design, leaf shredder machine, modal analysis.

Introduction

Organic waste management in Indonesia faces significant challenges following the government policy that prohibits organic waste disposal to landfills starting from 2025 [1]. This regulation addresses severe environmental impacts, as organic waste accumulation generates leachate that contaminates soil and groundwater [2–4]. Furthermore, anaerobic decomposition releases large volumes of methane gas, contributing to global warming and posing fire and explosion risks [5–8]. Consequently, this policy acts as a crucial driver for developing sustainable waste management initiatives, specifically focusing on solutions at the community or village level.

Active public participation is essential for processing organic waste into valuable products within the community [9–15]. For instance, data from the Sarimukti Landfill in 2015 indicated that organic waste constituted the largest portion of solid waste (50.86%), dominated by leaf waste, which accounted for 40.50% of the total organic fraction [16]. Leaf waste holds significant potential for conversion into compost, mulch, or biochar, processes that reduce volume while providing economic and ecological benefits [9–11, 14, 17–19].

Shredding is a critical initial step in the leaf waste processing chain. This process reduces particle size to increase surface area, which significantly accelerates decomposition for composting [20, 21], facilitates fermentation for animal feed [22, 23], and optimizes biochar production [24]. Without effective shredding, community-level organic waste processing becomes slow and inefficient. Therefore, the availability of reliable, affordable, and scalable shredding technology is a prerequisite for successful sustainable organic waste management.

To address this prerequisite, a low-cost leaf shredder prototype was developed using substituted components. However, initial performance evaluations revealed several critical operational flaws that rendered the machine impractical. These included excessive vibration compromising stability, partial clogging and leakage at the outlet chute, and the inability of the motor to maintain blade rotation, causing the machine to stall. Addressing these issues, this study aims to perform a comprehensive redesign of the machine. The improvement efforts focus on modifying the frame structure, replacing the screen design, and establishing Standard Operating Procedures (SOP) supported by design modifications to overcome motor torque limitations.

Methods

This study employs an iterative design engineering and prototype development approach. The research workflow is divided into several main stages: measurement and digital documentation, design modification, prototype fabrication, performance analysis, and final documentation, as shown in **Fig. 1**.

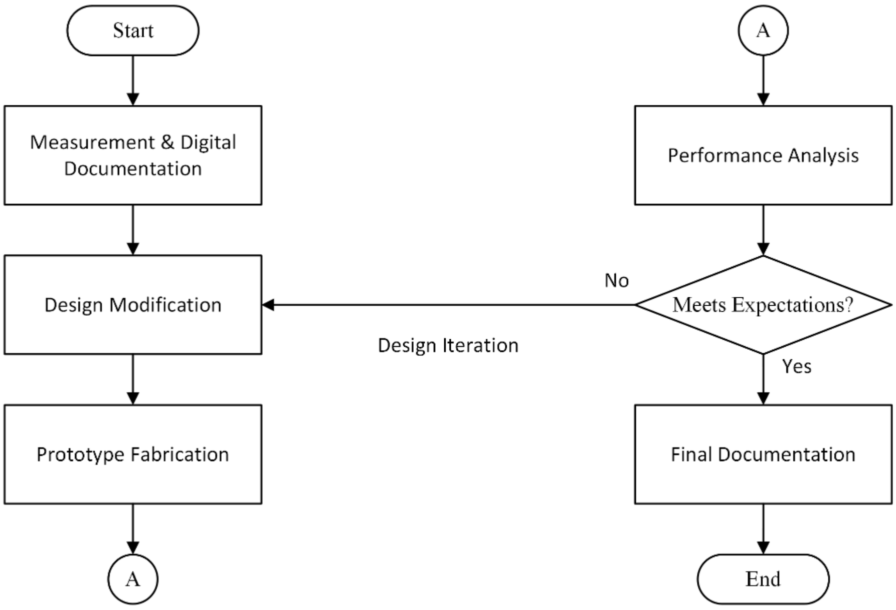


Fig. 1 Flowchart of the Redesign Process

The process begins with the measurement and digital documentation of the reference prototype, which is transformed into a 3D CAD model to establish an accurate technical database as the foundation for modification. Based on this digital data, an initial design modification is conducted with a primary focus on reducing production costs through the substitution of the drive motor and the hopper material.

The modified design is subsequently realized into a physical prototype through fabrication, assembly, and finishing processes. The completed prototype then enters the performance analysis stage. Initial testing results indicated performance below expectations, identifying three main issues: excessive vibration, clogging and leakage in the outlet chute, and suboptimal blade rotation leading to motor stall.

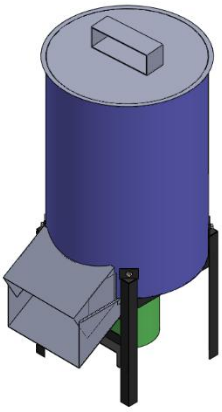
These failures necessitated a design iteration. Technical solutions were implemented by redesigning the frame structure, changing the screen type, applying sealant, and establishing a new SOP. Following these improvements, the prototype was re-tested until its performance proved stable and efficient. The final stage involves documenting the final prototype, including working drawings, bill of materials, and complete technical specifications.

Results and Discussion

The iterative design process, as outlined in the flowchart in **Fig. 1**, was successfully executed. Several constraints were identified in the initial prototype, which subsequently drove the redesign process to produce a final prototype with rectified performance. Performance analysis before and after modification demonstrates the effectiveness of the applied design solutions.

Existing Leaf Shredder and Initial Digital Model

The process began with an analysis of an existing leaf shredder, as shown in **Fig. 2**a. This machine served as the basis for further development. Through detailed measurement, dimensional references for each component were obtained and transformed into a 3D model using CAD software, as seen in **Fig. 2**b. This digital model served as the baseline for functional analysis and design modification planning.



(a) (b)

Fig. 2 Existing Shredder (a) Prototype (b) 3D model

To address production cost constraints, modifications were made to the baseline model by substituting the shredder motor from a water pump motor to a lower-cost washing machine motor. Additionally, the stainless steel hopper was replaced with a repurposed paint bucket, a substitution that significantly reduced production costs. The modified baseline model is presented in **Fig. 3**.

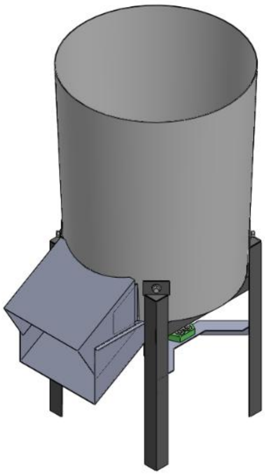


Fig. 3 3D model of the initial prototype

Manufacturing Process of the initial Prototype

The initial prototype was manufactured according to the modification results, utilizing a washing machine spin motor and a plastic bucket as the hopper. **Fig. 4**a shows the fabrication process, while the final result of the initial prototype is shown in **Fig. 4**b.

(a) (b)

Fig. 4 Initial prototype (a) manufacturing process (b) finished product

Performance Evaluation of the Initial Prototype

The initial prototype underwent functional testing to validate its performance under operational conditions. Testing was conducted by feeding dry leaf material into the machine. Performance analysis was carried out qualitatively through direct observation of the machine's response during operation. The testing revealed the following constraints:

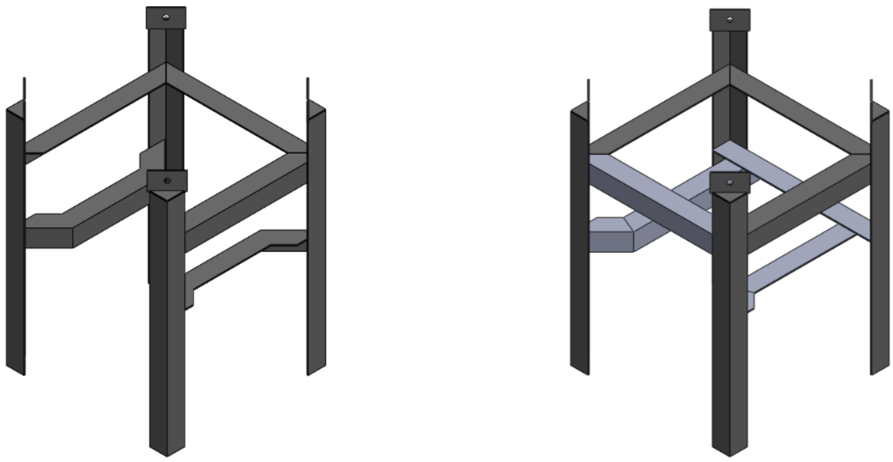
- **Excessive Vibration**: Significant vibration occurred in the frame structure during operation. This vibration caused operational instability, characterized by a rattling noise and the machine shifting from its original position caused by its own vibration. This condition not only reduced user comfort but also posed a potential safety risk.
- **Outlet Chute Clogging**: Periodic clogging occurred in the material outlet. Analysis indicated that this was caused by leaf veins that were not perfectly shredded and became stuck in the screen. These veins obstructed the flow of shredded material, eventually forcing a manual shutdown for cleaning.
- **Leakage at the Outlet Chute**: In addition to clogging, sealing issues were identified at the connection between the outlet chute and the shredding chamber. Gaps in this connection caused leakage, where a portion of the shredded material spilled out of the designated path. While this did not directly reduce shredding performance, it significantly reduced operational practicality by creating additional cleanup work for the user.
- **Insufficient Motor Performance**: As a safety procedure, testing was conducted by feeding material into the chamber while the motor was off. A significant issue was identified where the blades failed to rotate when the machine was activated if the chamber was already filled with a large volume of material. This phenomenon indicates that the starting torque was insufficient to overcome the load caused by the leaf waste.

These identified operational constraints, such as structural instability due to vibration, functional issues due to clogging and leakage, and motor failure, collectively demonstrated that the initial prototype was not operating as expected. Consequently, a redesigning process was necessary to achieve a reliable and practical design.

Prototype Development and Redesign Process

Following the identification of operational constraints, a systematic redesign process was conducted to address each issue fundamentally. Technical decisions were made not only to rectify problems but also to address their root causes, while maintaining low-cost design principles.

To address the excessive vibration found in the initial prototype, engineering intervention focused on increasing the stiffness of the frame structure. This modification was implemented by adding reinforcement structures, particularly in areas adjacent to the motor, which serves as the primary source of dynamic excitation. **Fig. 5** presents a visual comparison between the frame configurations before and after modification.



(a) (b)

Fig. 5 Frame structure (a) initial prototype (b) final prototype

Quantitative validation of the design's effectiveness was conducted through modal analysis using the finite element method. This analysis aimed to characterize the dynamic response of the structure by determining its natural frequencies. If the excitation frequency from an external source, such as the motor, coincides with the structure's natural frequencies, resonance will occur, leading to significant vibration amplification. The comparative results of the modal analysis for both designs are presented in **Table 1**.

Table 1. Modal Analysis Results

Mode	Natural Frequency [Hz]	
	initial prototype	final prototype
1	91,981	106,15
2	108,18	118,8
3	212,24	141,82
4	217,15	197,19
5	275,2	292,89
6	282,03	323,39

The structure's natural frequency values were compared with the forced vibration frequency induced by the shredder motor. An analytical approach was used to estimate the excitation frequency based on a motor rotational speed of 1400 rpm (equivalent to 23.3 Hz). Since the shredding machine uses two blades, the fundamental excitation frequency, or Blade Pass Frequency (BPF), is 46.6 Hz.

Although the fundamental excitation frequency was significantly distant from the natural frequency of the initial prototype, observations revealed a rattling sound indicating resonance. Further analysis led to the hypothesis that this phenomenon was caused by the second harmonic of the excitation frequency (46.6 Hz × 2 = 93.2 Hz), which was critically close to the first mode natural frequency of the initial prototype structure. Based on this hypothesis, the frame redesign aimed to increase structural stiffness to shift the natural frequency away from this second harmonic.

Modal analysis results for the final prototype show an increase in the first mode natural frequency to 106.15 Hz. This value provides a significant margin from the 93.2 Hz harmonic frequency, successfully mitigating the risk of resonance. Empirical validation through testing of the final prototype confirmed the success of this modification, as the previously observed rattling sound was eliminated.

To address the clogging issue identified in the outlet chute, a crucial modification was implemented on the screen component. The initial perforated metal plate screen was replaced with a wire mesh. This selection was based on technical considerations to maximize the flow of shredded material. Fundamentally, wire mesh offers two advantages over perforated plates. First, the woven structure of the wire mesh has a significantly smaller total solid surface area, minimizing contact areas that could potentially trap leaf fragments. Second, the selected wire mesh openings are relatively larger than the holes in the previous plate, increasing the probability of material discharge. The synergy of these two characteristics significantly reduces the likelihood of clogging.

(a) (b)

Fig. 6 Leaf screen (a) before modification (b) after modification

Regarding the material leakage at the connection between the outlet chute and shredding chamber, an improvement was implemented to ensure sealing integrity. Although this issue did not affect shredding performance, it directly impacted operational comfort and practicality. The solution involved applying sealant along the gap between the shredding drum and the outlet chute. This implementation effectively resolved the leakage issue, ensuring all shredded material is directed to the outlet as designed, thereby improving operator effectiveness and maintaining cleanliness.

Fig. 7 Application of sealant on the joint gap between the shredding drum and outlet chute

The limitation of starting torque in the shredder motor was addressed through an operational solution involving the development of a SOP based on empirical test data. The SOP formulation process began with a series of experiments to determine the maximum initial load the motor could handle. Testing was conducted using dry avocado leaves with the machine initially off, varying the leaf mass as listed in **Table 2**.

Table 2. Leaf Shredding Test Results

Trial Number	Total Leaf Mass Input [g]	Shredding Time	Results / Remarks
1	500	-	Blade failed to rotate (or Blade stalled)
2	315	-	Blade failed to rotate (or Blade stalled)
3	230	-	Blade failed to rotate (or Blade stalled)
4	200	1 minute	Leaves shredded well; humming sound detected at initial operation indicating excessive load
5	100	20 seconds	Leaves shredded well; no humming sound during initial operation

Based on the data in Table 2, the maximum leaf mass that can be shredded is 200 grams, although a humming sound at startup indicated excessive load. Meanwhile, at a mass of 100 grams, the absence of humming indicated that the initial rotational resistance was not significant.

Analysis of these findings presented an operational dilemma. To preserve motor life and avoid overload, batch feeding should not exceed 100 grams. However, starting the process from a standstill with such small volumes would be inefficient. Conversely, feeding material while the machine is already running at full speed poses significant safety risks to the operator.

A combined procedural and design solution was implemented to accommodate both needs. A safety cover equipped with a relatively small feeding hole was added to the shredding drum. This modification physically limits the volume of leaf input per batch to below the 100-gram threshold while simultaneously protecting the user from potential accidents. This solution enables safe feeding while the machine is running, passively enforcing the SOP to maintain optimal motor performance.

Fig. 8 Modified feeding chute

Based on the test results and performance analysis, a Standard Operating Procedure (SOP) was formulated to ensure safe, efficient, and durable operation of the leaf shredder. The core operating procedures include the following steps:

1. **Initial Activation**: Turn on the machine while empty and wait until the motor reaches maximum rotational speed, indicated by a stable operating sound.
2. **Gradual Feeding**: Insert dry leaf material gradually through the provided safety hole. The design of this hole automatically limits the input volume to maintain blade rotation stability and avoid motor overload.
3. **Feeding Cycle**: Continue feeding only after the previous material has been fully shredded.
4. **Performance Monitoring**: The operator must continuously monitor the motor sound. If a significant sound change is detected, indicating a drop in RPM, stop the feeding temporarily until the sound returns to normal.

Performance Comparison: Reference Machine vs. Final Prototype

As a final evaluation stage, a direct comparative analysis was conducted between the reference shredder machine and the final developed prototype. This analysis covers four fundamental parameters: production cost efficiency, operational safety, shredder motor capability, and manufacturing/assembly complexity.

The first parameter, which served as the primary driver for this redesign process, is production cost efficiency. The strategic decision was to substitute components, specifically replacing the conventional motor with a used washing machine motor and the metal drum with a plastic bucket was the key factor in reducing production costs. Based on component cost estimation analysis, the final prototype is projected to be significantly cheaper than the reference machine, with potential cost savings of approximately 30%.

This cost efficiency was achieved without compromising operational safety, while in fact enhancing it. The reference machine was equipped with a simple lid that remained wide open during feeding, creating a relatively high risk of direct contact. In contrast, the final prototype adopts an integrated cover design with a small feeding hole. This design implementation is safer and serves a dual function as a material flow limiter and a physical guard.

Regarding shredder motor capability, a performance difference exists as a direct consequence of the design compromises made. The reference machine, equipped with a higher-power motor, demonstrated the capability to handle bulk feeding. The final prototype, utilizing a lower-power motor to reduce costs, has lower torque and thus limits the bulk shredding capacity. However, this limitation is mitigated through the development of the Standard Operating Procedure (SOP), which guides users to perform gradual feeding, ensuring the machine operates within its optimal performance range without overloading.

In terms of manufacturing and assembly complexity, the final prototype demonstrates significant engineering advantages. The shredder motor comes with a built-in flange designed for vertical installation. This drastically simplifies the assembly process, as the motor can be mounted directly onto the main frame mount with easier and faster axial alignment relative to the shredding drum. Conversely, the motor on the reference machine was a standard type designed for horizontal mounting, requiring the fabrication of a more complex motor mount on the frame for vertical installation, which directly adds to manufacturing time and costs.

Conclusion

This study has successfully executed the iterative design of a low-cost leaf shredder prototype. Based on the operational constraints identified in the initial prototype, namely excessive vibration, outlet clogging, leakage, and motor torque limitations, a series of design and procedural improvements were effectively implemented.

Structural modification successfully eliminated the tendency for resonance. This was supported by modal analysis, which predicted a shift in the structure's natural frequency from 91.98 Hz to 106.15 Hz, moving it away from the motor's second harmonic excitation frequency of 93.2 Hz. Functional issues such as clogging and outlet leakage were resolved by replacing the screen with wire mesh and applying sealant. Furthermore, motor starting torque limitations were mitigated through the development of a Standard Operating Procedure (SOP) supported by a safety cover design with a restricted feeding hole.

The final result of this research is a functional, stable, safe, and affordable leaf shredder prototype with an operational capacity of 3 kg per 10-minute cycle. It is ready for implementation as an appropriate technology solution to support independent organic waste management at the community level.

Based on the research findings, several further developments are proposed. The primary recommendation for future research is to conduct direct vibration measurements to verify the actual vibration frequencies generated. This would provide more precise data under actual conditions to validate the modal analysis simulation results and accurately quantify the level of vibration reduction achieved.

Additionally, it is recommended to conduct long-term durability testing to evaluate component endurance under continuous use, particularly regarding the substituted motor. Finally, future research could focus on optimizing the blade design to increase shredding capacity without significantly increasing motor power requirements.

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