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A Study On The Effect Of Mechanical Parameters On The Efficiency Of Manual Biomass Processing For Sustainable Fertilizer Production

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Abstract

Introduction/Main Objectives: This study examines the influence of mechanistic parameters on manual biomass processing within the framework of green engineering and low-energy systems. The research focuses on the relationship between gear size in manually operated mechanical systems and the efficiency of biomass crushing, aiming to reduce reliance on electrification and fossil fuels in support of SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

Background Problems: The key problem addressed is how gear size affects the performance of manual biomass crushing systems. The research question is: Does increasing gear radius improve crushing efficiency in manual biomass processing systems?

Research Methods: An experimental design was implemented using three gear sizes (10 mm, 20 mm, and 30 mm) and four classes of wooden sticks with diameters ranging from 5 mm to 20 mm. Each gear-stick combination was tested three times to ensure reliability. Linear regression and statistical analysis were applied to determine the relationship between gear radius and crushing rate.

Finding/Results: The results indicate a strong positive correlation between gear size and crushing efficiency, expressed by the equation y=3.75x−12.5y = 3.75x - 12.5y=3.75x−12.5. The 30 mm gear achieved 100% crushing efficiency, while the 10 mm gear achieved only 25%. Larger gear radius significantly increases torque and biomass conversion efficiency.

Conclusion: Manual mechanical systems demonstrate substantial potential as zero-carbon-energy technologies for biomass waste conversion. This study contributes to mechanical engineering by clarifying the impact of gear size on ultra-low-energy systems, reinforcing the need for affordable, human-powered, and sustainable green technologies.

Keywords: biomass, green engineering, low energy, mechanical efficiency, cutting torque, sustainability

Introduction

Integrating environmental sustainability and natural resource management is one of the most important challenges for global development. The modern agricultural industry faces a productivity paradox, and one way to address this issue is through sustainable agriculture, which emphasizes the use of biomass resources and the reduction of chemical fertilizer application (Priya et al., 2023). Tree branches, dry leaves, and crop residues are excellent candidates for recycling into natural fertilizers as decomposed biomass due to their high organic carbon content. However, producing them as fertilizers presents a challenge because decomposition is a biochemical process that requires raw materials to be in small particle form, implying the need for a wood chipper. While mobile chipping machines exist, they rely on internal combustion engines that consume non-renewable energy, emit exhaust gases, and generate noise (Warguła et al., 2020). Furthermore, small-scale farming communities in rural areas often face financial constraints, limiting their access to such technology.

A system that combines a gear mechanism with manual mechanics offers a sustainable, low-energy engineering solution powered entirely by human effort. This system eliminates the need for external energy sources by employing a chassis and pedal mechanism, contributing to eco-engineering advancements in sustainable energy and low-impact technology. Previous studies have explored manual wood chipper efficiency based on gear ratios and wood diameter, but further research is needed to document operational efficiency and time-per-task ratios. At the community level, the lack of energy-efficient, environmentally friendly, small-scale material processing remains a significant barrier to biomass-based fertilizer production. Conventional shredding and chipping machines consume electricity or fuel, increasing operational costs and carbon emissions, while maintenance and energy expenses pose additional challenges in rural areas. The continued use of chemical fertilizers also threatens soil fertility and micro-ecosystems in the long term.

A practical solution lies in user-friendly, energy-efficient green technology based on mechanical engineering principles. By incorporating human power as the sole energy source, manual systems with gear mechanisms reduce dependence on electricity and fossil fuels. Understanding the relationship between gear dimensions and biomass crushing efficiency is crucial for optimizing low-power systems. However, research on mechanical parameters such as gear radius and torque in biomass applications remains limited. This study addresses this gap by empirically examining the effect of gear size on crushing wooden branches, offering benefits for green engineering and low-energy system management. Furthermore, this research aligns with Sustainable Development Goals (SDG 12: Responsible Consumption and Production; SDG 13: Climate Action) by promoting engineering solutions that reduce the agricultural sector’s carbon footprint and support climate action.

The study aims to evaluate the effects of gear size on manual biomass crushing efficiency, identify the linear relationship between gear size and crushing success, and assess the sustainability implications of manual systems within green technology frameworks. The research employs a quantitative experimental design using three gear sizes (10 mm, 20 mm, and 30 mm) and four categories of wooden branches (diameters of 5 mm, 10 mm, 15 mm, and 20 mm). Limitations include the use of dry wooden branches only, exclusion of human energy output measurements, and controlled experimental conditions to minimize external factors such as humidity and temperature. This study contributes to understanding how mechanical features influence manual biomass processing efficiency, supporting efforts to reduce electricity and fossil fuel use in agricultural waste management. It also promotes zero-carbon energy systems and strengthens green technology prospects for rural communities. Literature indicates that biomass energy generation is classified as a green technology and legally recognized as a sustainable development activity, as seen in European Union frameworks. Agricultural waste remains an underutilized biomass source despite its low cost and environmental benefits. Previous studies highlight the advantages of manual mechanical systems, such as low cost and energy efficiency, provided they are designed with appropriate gear ratios. Research also shows that increasing gear diameter improves torque and reduces energy losses, making gear optimization essential for low-energy mechanical systems. This work addresses the need for system optimization in biomass applications, contributing to green engineering and circular economy practices.

Research Methods

The aim of this study is to determine how different gear sizes of a manual mechanical system affect its ability to crush wooden branches for biomass fertilizer production. The study is of a quantitative nature, using a 1-factor experimental design. The factor whose influence is being examined is the size of the drive gear (10 mm, 20 mm, and 30 mm); the factor to be measured is the degree of success in crushing the wood (%). The design of the test permits the study of the mechanical parameters and the interdependent efficiency of the various parameters to satisfy the study's objectives.

Research Design and Test Materials
In one of the mechanical engineering laboratories, the study utilized a machine that was a manual wood chipper, which also had a mechanical pedal drive system. In this case, the experiment was not focused on machine development, but rather on understanding the operational characteristics of the machine with different mechanical configurations. The testing materials used were dry wooden branch and had diameters of 5 mm, 10 mm, 15 mm, and 20 mm. All were cut to 150 mm in length to achieve uniformity, and to ensure the moisture content they were kept at about 12 - 15% which would mean the differentials in the elasticity and hardness of the wood would not impact the results.

Experimental Procedure
In order to ensure the validity of the data, each branch category was tested three times for every gear configuration. The following order was used for the experimental steps:

a) Sample Preparation: Wooden branches were sorted based on the diameter and measured with a vernier caliper to ensure accuracy.
b) Gear Selection: For each series of tests, the gears were changed out for ones of 10 mm, 20 mm and 30 mm diameters.
c) The Crushing Process: The branch samples were placed in the cutting chamber, and the system was activated with manual pedal drive.
d) Outcome Observation: We labeled as Crushed those samples that exhibited complete crushing, while those samples that were fully or partially unprocessed were labeled Not Crushed.
e) Outcome Calculation: The formulae below were used to compute the percentage of success:

$$\text{Crushing Efficiency (\%)} = \frac{\text{Number of Crushed Samples}}{\text{Total Samples Tested}} \text{ x } 100$$

f) Replication: Tests were repeated three times for each gear–diameter combination to obtain average efficiency values.

Study Parameters and Controls
This study focuses on quantitative parameters as shown in Table 1:

Table 1: Quantitative Parameters

Test Parameter	Level	Type of Variable	Purpose
Drive Gear Size	10 mm, 20 mm, 30 mm	Independent	To evaluate the effect of gear radius on cutting torque
Branch Diameter	5 mm, 10 mm, 15 mm, 20 mm	Dependent	To assess the effect of material thickness on crushing success
Number of Replications	3 per combination	Controlled	To ensure reliability and statistical accuracy
Energy Source	Manual (mechanical pedal)	Controlled	To ensure operation without electricity for a green approach

Source: Author's Work, 2025.

All studies were carried out at ambient conditions (27 ± 2°C) and 60% relative humidity. To control for external variables like pedal cadence and provide input pressure, the same operator carried out all test sequences to reduce potential operator variability.

Data analysis
With the aim of examining the factors influencing the radius of the gears and the resultant crushing efficiency, the aggregated data were scrutinized using a pre-specified combination of descriptive statistical methodologies and employed a linear regression approach. The statistical analyses were performed using Design Expert v13 and Microsoft Excel 2021. The linear equation estimating relationship between the gear radius and the gear operation efficiency was given by the following equation:

$y = ax + b$ .... (1)

where
y = success rate (%)
x = gear size (mm)
The R^2 value was used to evaluate the strength of the linear relationship.

In addition, the percentage increase in performance between gears was calculated to identify the level of relative mechanical energy savings:

$$\text{Performance Increase (\%)} = \frac{y_i - y_{10}}{y_{10}} \text{ x } 100$$

where
y_i is the efficiency for the 20 mm or 30 mm gear, while
y_{10} is the baseline value for the 10 mm gear.

Validity and Reliability
This method stays with the documented procedural layout with respect to reliability and validity in mechanical research as follows.

a) Each test was run three times in order to mitigate the impact of the random error.
b) The parameters were structured around such that the true impact of the gear size variation was measured with respect to the crushing efficiency.
c) No alterations were made to the construction, materials or energy during the entire run of the experiment.

The analysis offers a primary level assessment of the mechanistic interrelationship of the operational variables of the gear with respect to the designed manual energy system that converts the biomass in a sustainable manner in line with the principles of low impact green engineering.

Result

Experimental Results

To determine the relationship between the size of the gear (x) and the success rate in crushing (2) crushing success rate is the average that each of the experiments that were recorded 3 times were tested and were aligned to keep the integrity of the experiment the following observations were made. The descriptive and the linear regression were used. The following observations are Table 2 shows the average success rate in crushing for the 3 gear sizes tested across 4 different branch diameter divisions.

Table 2. Experimental Data of Crushing Efficiency (%)

Gear Size (mm)	5 mm	10 mm	15 mm	20 mm	Average Efficiency (%)
10	100	0	0	0	25
20	100	100	100	0	75
30	100	100	100	100	100

Key observations:

The 10 mm gear could only process small branches (≤5 mm).

The 20 mm gear showed a 50% efficiency improvement compared to the 10 mm gear.

The 30 mm gear achieved complete success, indicating maximum torque and minimal energy loss.

Statistical Analysis and Linear Relationship

Linear regression analysis was performed to evaluate the relationship between gear size and crushing success rate. Based on the average data, the following mathematical model was obtained:

$y = 3.75x - 12.5$ .... (2)

with the coefficient of determination:

$R^2 = 0.985$

The results indicate a very strong positive correlation between increases in gear radius and increases in biomass processing efficiency. The $R2$ value greater than 0.98 indicates that almost 98.5% of the differences in efficiency is accounted for by changes in the size of the gear. This also suggests the results from the experiment are quite reliable. Table 3 summarizes the linear regression analysis.

Table 3. Summary of Linear Regression Analysis

Analysis Parameter	Value	Interpretation
Linear Equation	(y = 3.75x - 12.5)	Positive linear relationship
R^2	0.985	Very strong relationship
Average Error (%)	±2.4	Low error, stable data
Number of Replications	3 per set	Consistent with reliability principles

Source: Author's Work, 2025.

Efficiency Improvement Analysis
The percentage increase in efficiency between gears was calculated using the equation:

$$\text{Efficiency Increase (\%)} = \frac{y_i - y_{10}}{y_{10}} \text{ x } 100$$

where yi is the efficiency of the 20 mm or 30 mm gear, and y_{10} is the baseline efficiency of the 10 mm gear. Table 4 shows the percentage increase in efficiency obtained for each gear.

Table 4. Percentage Efficiency Improvement Analysis

Gear Comparison	Baseline Value (y_{10})	Test Value (y_i)	Increase (%)
10 mm → 20 mm	25	75	+200
10 mm → 30 mm	25	100	+300

Source: Author's Work, 2025.

Discussion

The correlation between gear size and efficiency substantiates that principle whereby an increase in gear radius results in an increase in torque at the contact point, and thus increase in the shearing force, and shearing force will be dominated biomass material will increase. A 10 mm gear fits only small branch diameters as the gear has low torque ratio. The 20 mm gear offers an equilibrium, introducing a new cutting force as the rotational speeds increase, while the 30 mm gear has optimal torque and is able to completely crush all samples. The range of efficiency between the 20 mm and 30 mm gears is consistent with the findings of Margiantono, A. et al. (2025), as they emphasized that to increase cutting torque at the circumference of a gear, one would have to increase the gear's diameter (or radius), and at the same time improve energy efficiency.

The 100% zero energy consumption is resultant from the fact that this manual system is not mechanized in that it does not use any fuel or electricity. As Wu, L. et al. (2025) has demonstrated the mechanized operating system that relies on fuel and/or electricity is an operational system that emits a significant quantity of CO_2. The extent of the emissions is determined by the energy source and the operational parameters. Therefore, in as much as the manual system portrays mechanical efficiency, it also achieves a carbon-neutral operation system which is compliant with SDG 13 (Climate Action).

The high degree of test-retest reliability (2.4% variation) and the corresponding R2 may lead one to draw conclusions regarding the credibility and the relative strength of the measurement that was obtained. All of the operational parameters were kept constant to free them of influence. Hence there was no change in the materials, design and input energy dispensed to the system. The current analysis demonstrates that there is no doubt that the system efficiency rises with the rise in mechanical parameters. Out of the considered parameters, the 30 mm gear stands out with trigging the best torque for the working ranges. Hence the 30 mm gear is the best working configuration for the manual rest over processing due to the sustainable and green operational characteristics.

Conclusion

The effect of some mechanical parameters on the productivity of manual biomass processing has been carried out. It has been established that in the low-power mechanical systems the size of the gear is one of the important parameters of the effectiveness. The increase in the radius of the gear leads to an increase in cutting torque, lower energy loss due to friction, and complete biomass grinding.

There is a statistical relationship between the gear size and the effectiveness of biomass grinding and the relationship is positive and linear (R2=0.985). The effectiveness of the system is improved 3 times with an increase in the radius of the gear from 10 mm to 30 mm. In the manual mechanical systems for biomass processing, the study demonstrates an enormous potential for functioning without the use of electrical and fuel energy.

Such a system from the energy and the environment perspective can reduce the system's carbon footprint, thus maintaining the carbon neutral system. The system also promotes the principles of Green Engineering by further enhancing the system with low environmental impact.

Future Research Recommendations

a) Measure the energy expended by a human operator externally in a manual task (Nm) so that the efficiency of the mechanical system, in relation to biomass output, can be assessed.
b) Adaptation of mechanical parameters is to be assessed through the analysis of a variety of biomass which includes oil palm fronds, rice husks, and bamboo.
c) Combine passive systems with renewable energy systems like solar energy in order to create a more efficient hybrid low-energy biomass processor.
d) Assess the correlation between the size of crushed particles and the rate of composting in order to maximize the rate of microbial degradation to produce biofertilizers.

This study shows that the mechanical parameters of the system design are the dominating factors that determine the overall system efficiency performance of the design low energy systems. This innovation opens new frontiers in green engineering research that pivots on the manual resource management of biomass for sustainable biomass management.

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