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Research Article

Design and simulation of ash fertilizer making machine using three-dimensional computer aided design

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Abstract

The ash fertilizer making machine is responsible for processing oil palm empty fruit bunches (OPEFB) or waste and converting them into ash fertilizer. The current study was carried out to achieve to achieve an appropriate design and simulation for obtaining an optimal machine design. The design process consists of two processes, including the chopping and the combustion. The simulation process is implemented on the frame design and blade shaft. It applied specifically to the blade using variations in the OPEFB load during the chopping process. The frame design has dimensions of 1000 mm length x 1190 mm width x 800 mm height. The frame is made of European standard (UNP) 65 iron and 50 mm x 50 mm angle iron with a thickness of 3 mm using mild steel material. The calculation results indicate that the designed machine uses a 23-horsepower diesel engine to drive the blade at a rotation of 2200 revolutions per minute where the blade is rectangular with an angle 45° of inclination. The combustion process uses liquefied petroleum gas to burn OPEFB and is assisted by a blower to accelerate OPEFB into ash. This study conducted simulations on the machine frame and machine blades using SolidWorks Simulation. The simulations were performed as static tests to obtain the distribution of displacement and yield strength. The results for the frame show a maximum displacement (9.565e-02) mm and yield strength (4.189e+07) N/m^2, while the results for the machine blade indicate a displacement (9.455e+00) mm and a yield strength (5.300e+08) N/m^2.

1. Introduction

Indonesia leads global palm oil production, with 49.5 million tons of crude palm oil produced in 2024 [1,2]. This dominance not only strengthens the national economy but also results in the massive generation of agricultural residues that require sustainable management. This productivity generates significant biomass waste, notably oil palm empty fruit bunches (OPEFB), which constitute 23 % of the weight of fresh fruit bunches [3]. The continuous and centralized supply of OPEFB from palm oil mills ensures its availability as a low-cost renewable raw material. OPEFB is a lignocellulosic material containing cellulose (40–50 %), hemicellulose (15–30 %), and lignin (15–25 %), with a relatively high cellulose content compared to many other agricultural residues, making it a promising source of value-added products [2,4,5]

It is estimated that one ton of fresh fruit bunch produces 21 % of crude palm oil, 23 % of empty fruit bunch (EFB), 14–15 % of palm pressed fiber, and about (6–7) % of palm kernel shell [6,7]. The most abundant waste in the palm oil industry is OPEFB, producing about 50 million tons per year

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worldwide [8]. The EFB waste from the palm oil industry is a lignocellulosic residue rich in coarse fibre and still containing residual lipids/oil after the oil extraction process [9].

The EFB waste from oil palm production constitutes a major solid waste stream that, if unmanaged, contributes to environmental degradation [10]. Therefore, an environmentally friendly, efficient, and economically valuable waste processing solution is needed [11]. One potential effort to utilize OPEFB waste is to convert it into ash fertilizer through a controlled shredding and burning process, which has been shown to improve soil nutrients and plant growth when applied appropriately [12,13]. OPEFB biomass can be thermally converted into value-added products such as fertilizer and biochar using controlled pyrolysis or combustion processes, resulting in soil ameliorants that improve nutrient status and plant growth [14,15]. Biochar derived from OPEFB have been shown to improve the quality of organic fertilizer and enhance soil fertility, providing a value-added use of agricultural waste [16-18].

Several studies have been conducted on OPEFB shredding or processing tools. The design and performance evaluation of palm oil empty fruit bunch shredding machines have been reported, however designs with gasoline engine drives and AutoCAD application still show limitations in capacity and operational efficiency [19,20]. A rotary chopper type shredding machine with SolidWorks simulation shows increased shredding efficiency in the design and cutting process, although previous designs have not integrated a combustion system for further processing [21,22]. A palm frond shredding machine with a rotary system and a 7 HP diesel drive demonstrated a considerable shredding capacity of approximately 244 kg/h at 1300 rpm in performance tests, though this design focuses solely on chopping performance without integration of downstream processing systems [23].

The redesign of coconut fiber shredding machines has focused on optimizing blade geometry and screening systems to improve shredding performance and consistency of shredded particle sizes, although most designs do not explicitly integrate a circular saw blade system capable of producing uniform pieces in the range of (2-18) mm [24]. Several studies have investigated the utilization of OPEFB ash as a component of fertilizer production, including characterization of the ash for Nitrogen, Phosphorus, and Potassium (NPK) synthesis and its agronomic effects when applied as nanoparticles. However, research focusing specifically on the design and structural mechanical analysis of an ash fertilizer making machine from OPEFB as a complete system remains scarce, with most literature concentrating on material characterization or small-scale processing [25,26,27]. Studies on the importance of structural strength analysis in shredding machine design to ensure optimal performance have also been conducted, with research focusing on finite element analysis and mechanical performance evaluation of shredder components [28]. Simulation of frame strength in agricultural machine design also strengthens the need for in-depth analysis in design, as demonstrated by finite element simulations of power weeder frames and structural analyses of rotary drum machines and agricultural tricycle frames [29].

In supporting the efficient utilization of EFB, three-dimensional modelling technology and structural simulation are very important, as evidenced by studies utilizing computer aided design and finite element analysis in agricultural machinery design to evaluate structural integrity and optimize component performance before physical prototyping [30,31]. SolidWorks software allows detailed design visualization and structural analysis, enabling designers to model components digitally and carry out stress and deformation assessments through built-in simulation tools [32,33]. Numerical simulation using SolidWorks is important to improve the durability and efficiency of agricultural machinery design, as demonstrated through finite element analyses that evaluate stress distribution and structural performance of agricultural machine components [32-35].

Design and simulation were performed using SolidWorks to create a three-dimensional model of the machine and analyze the strength of the frame and blade shaft against static loading, with finite element and static simulation techniques providing stress, displacement, and safety factor data for design evaluation [29,36,37]. This simulation ensures that the design meets safety standards and can perform optimally in the field by evaluating stress distribution, deformation, and safety factors under operational loads through finite element and structural analysis [32]. Evaluation of the distribution of forces, stresses, strains, and displacements in the machine structure can also be done through this simulation, as demonstrated by finite element analyses that assess stress, deformation, and displacement responses under loading conditions [32]. With this development, a machine for making ash fertilizer from OPEFB is expected to be an appropriate technological solution that supports sustainable palm oil waste processing, as sustainable EFB waste management technologies aim to convert biomass residues into useful soil amendments and organic fertilizers while reducing environmental impacts [11,38]. This study presents a novel contribution by developing an integrated machine for OPEFB ash fertilizer production that simultaneously combines shredding and combustion processes within a single system. Unlike previous studies that focus on individual processing stages or material characterization, this research emphasizes a system-level design approach supported by three-dimensional modelling and comprehensive finite element analysis to evaluate structural strength, stress distribution, deformation, and safety factors under operational conditions. This integrated design not only improves process efficiency and mechanical reliability but also offers a practical and sustainable solution for large-scale utilization of palm oil biomass waste into value-added agricultural inputs.

2. Design

The design of this machine to produce ash fertilizer from oil palm empty fruit bunches (OPEFB) was undertaken to create a tool capable of processing waste practically and efficiently in two main stages: shredding and combustion. The machine (Fig. 1) was designed using a mechanical design approach based on computer aided design software, which generates a three-dimensional model and simultaneously analyzes the structural strength under working loads.

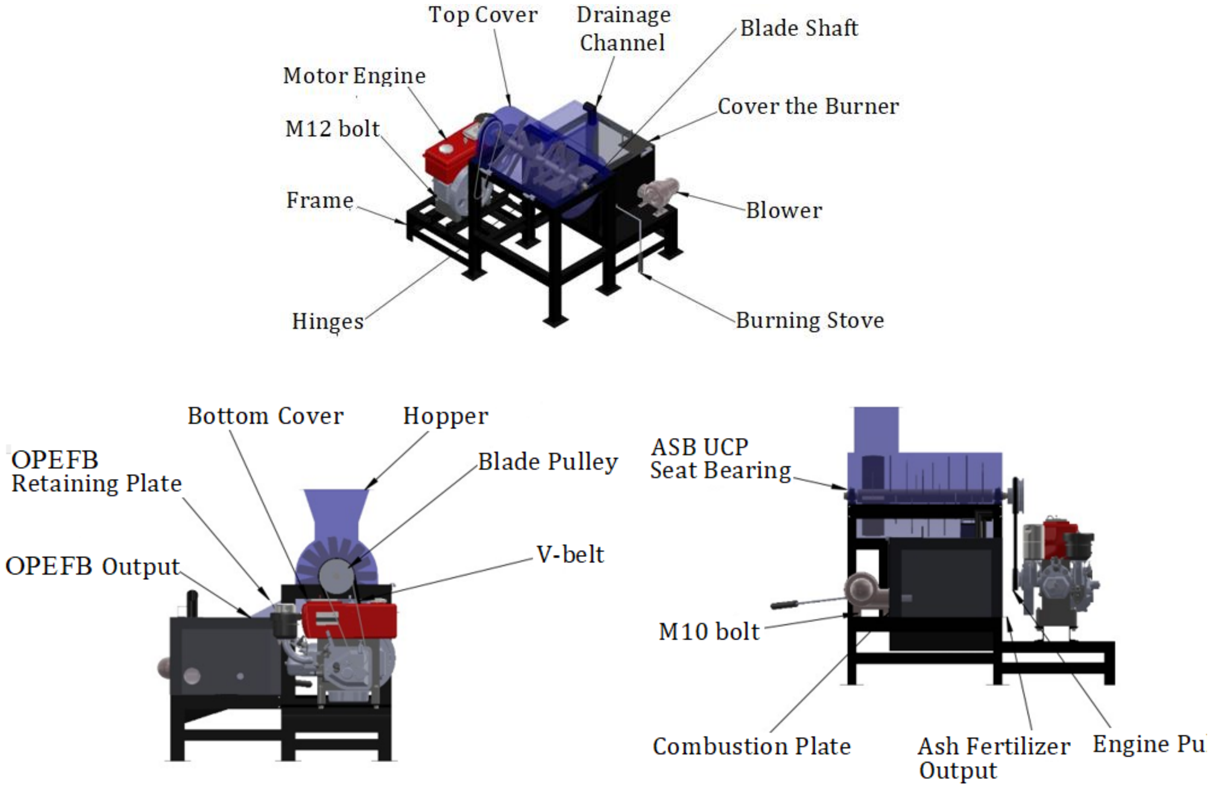


Fig. 1. Designed model of ash fertilizer making machine

3. Modeling and Simulation

The modeling and simulation stages are performed as part of design validation to ensure that the designed machine structure can perform safely and efficiently under operational conditions. The primary objective of the modeling and simulation using SolidWorks software is to virtually test, validate, and optimize, validate, and optimize product designs under real-world conditions to improve product quality, reduce costs, and accelerate time-to-market.

The main goals of the ash fertilizer making machine model include:

- Speeding up the process of converting an oil palm empty fruit bunches (OPEFB) into ash.
- Providing a sturdy and safe structure.
- Easy to operate by users on a small or medium industrial scale.
- Offering relatively economical and affordable production costs.

The main specifications of the ash fertilizer making machine model include:

- Machine dimensions are 1000 mm length × 1190 mm width × 800 mm height.
- Frame material is European standard (UNP) 65 mm width × 42 mm height for the main structure, and angle iron 50 mm width × 50 mm height as reinforcement.
- Chopper shaft is made of solid steel (round bar) and it has dimensions including 60.3 mm in diameter and 770 mm in length.
- Crushing knife is made of a steel strip (hammer mill type) that measures 160 mm length × 40 mm width × 5 mm thickness.
- Powertrain has a 23-horsepower diesel engine that rotates at 2200 revolutions per minute (rpm).
- Transmission type is a B V-belt with a final speed of 550 rpm and 4:1 reduction ratio.,
- Combustion system is a closed liquefied petroleum gas stove and a 3-inch centrifugal blower with 370 watts of power to assist the combustion process.
- The entire design is modular for easy assembly and maintenance.
- The shredding process aims to reduce the size of the OPEFB for faster and more even combustion.
- The blower is used to accelerate combustion and produce dry ash.

Table 1. Parameter of simulation

No	FEA Parameter Category	Component / Feature	Specification Details & Values
1	Material Properties	Analysis Type	Overall System
		Machine Frame (Mild Steel)	Density: 7850 kg/m^3, Elastic Modulus: 2.1 x 10^{11} N/m^2 Poisson's Ratio: 0.28 yield Strength: 5.30 x 10^8 N/m^2
		Shaft & Blades (AISI 1045 Steel)	Density: 7850 kg/m^3, Elastic Modulus: 2.05 x 10^{11} N/m^2 Poisson's Ratio: 0.29 yield Strength: 5.30 x 10^8 N/m^2
2	Element Types	Machine Frame Weldments	3D 2 node structural beam element (6 DOFs per node)
		Chopper Shaft & Blades	High quality 10 node parabolic tetrahedral solid elements
3	Mesh Quality Validation	Aspect Ratio	<3.0 (for $> 99.5\%$ of solid elements)
		Jacobian Ratio	1.0 (at integration points: 0% distorted elements)
		Skewness/Deviation	Optimized for high convergence (<0.1 average)
4	Boundary Conditions	Frame Bottom Foundation	Rigid Fixed Fixtures (restricting 3 translations and 3 rotations)
		Blade Shaft Journals	Bearing Fixtures (allowing axial rotation, zero radial/axial translation)
5	Applied Loads & Location	Engine Mount (Frame)	Linear Static Force: 2,060.1 N (Downward direction)
		Shaft Mount & Cover (Frame)	Linear Static Force: 264.87 N (Downward direction)
		Blower Mount (Frame)	Linear Static Force: 41.20 N (Downward direction)

Chopper Shaft (Dynamic)	Mass Load: 2.0 kg OPEFB (19.62 N) + Cutting Torque: 56.37 Nm.

To validate the structural integrity of the ash fertilizer making machine under maximum operational condition, a rigorous 3D Finite Element Analysis (FEA) was executed utilizing SolidWorks Simulation. The simulation was performed as a linear static structural analysis to evaluate the stress distribution, resultant displacements, and structural safety factors. The machine frame structural weldments were discretized using 3-dimensional 2 node linear structural beam elements, whereas the chopper shaft and cutting blade assembly were modeled using high quality second order (parabolic) 10 node tetrahedral solid elements to accurately capture localized stress concentrations. Detailed physical and mechanical properties of the materials used including Mild Steel for the frame and AISI 1045 Carbon Steel for the blade shaft assembly are structured in Table 1. Mesh quality validation criteria were strictly enforced to ensure numerical convergence, maintaining an average aspect ratio below 3.0 for over 99% of the solid elements and a Jacobian ratio of 1.0 at all integration points. Boundary condition were established by applying rigid fixed supports at the bottom feet of the frame to replicate ground anchoring, while bearing fixtures were applied to the shaft journals to permit rotation along the longitudinal axis while restriction radial and axial translations. The applied loads were configured as linear static forces and torques positioned at their exact physical locations, simulating the weight of the motor engine, blower, blade assembly, and the dynamic resistance torque during the OPEFB chopping process.

4. Results and Discussion

4.1 Simulation Results of Machine Frame

The displacement simulation results of the machine frame section (Fig. 2) are obtained using computer aided design (CAD) software. The components to be tested on the frame consist of angle iron measuring 50 mm wide x 50 mm high, UNP iron measuring 50 mm width x 50 mm height, European standard (UNP) iron measuring 65 mm width x 42 mm height, and an iron plate with a thickness of 5.5 mm. The simulation results provide different values of force including (2060.1, 264.87, and 41.2) N on the motor mount, on the blade shaft mount and cover, and on the blower and mount respectively.

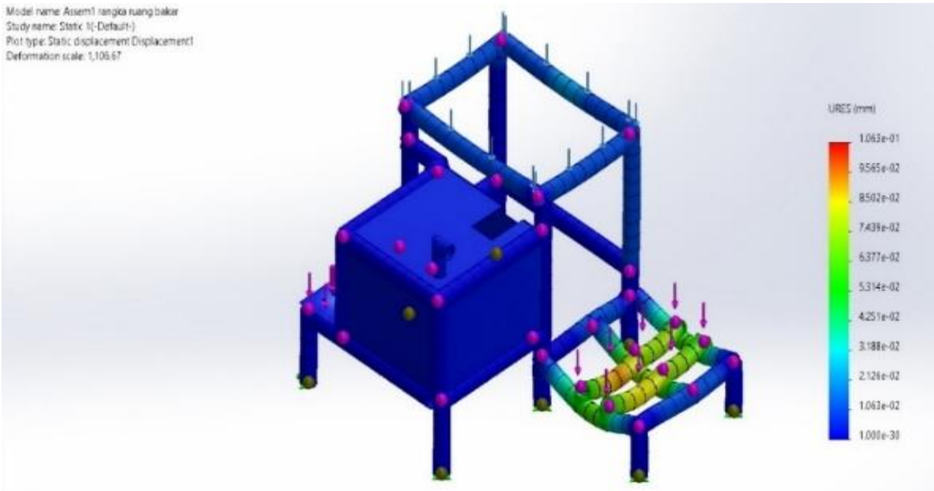


Fig. 2. Displacement simulation results of machine frame

The displacement simulation results show that the light blue, green, yellow, and orange engine mounting frames are areas that experience displacement at values of (3.188e-02– 9.565e-02) mm. This behavior occurs because the engine mounting directly supports the motor's weight, whereas the dark blue areas represent the rigid segments of the frame experiencing minimal displacement ranging from (1.000e-30 – 2.126e-02) mm. This can be further confirmed by the shear stress simulation results presented in Table 1, which indicate that the ash fertilizer making machine frame is structurally safe, as all calculated shear stresses (τ_1 to τ_{11}) remain within the allowable shear stress limits. The strain simulation results of the machine frame section (Fig. 3) show that the blue area experiences very little strain (almost no change in shape) at values of 0.000e+00 – 3.348e+06. This finding is further validated by the shear stress simulation results shown in Table 1, which demonstrate that the frame operates safely, since the shear stress values (τ_1 to $\tau 4$) do not exceed the permissible shear stress.

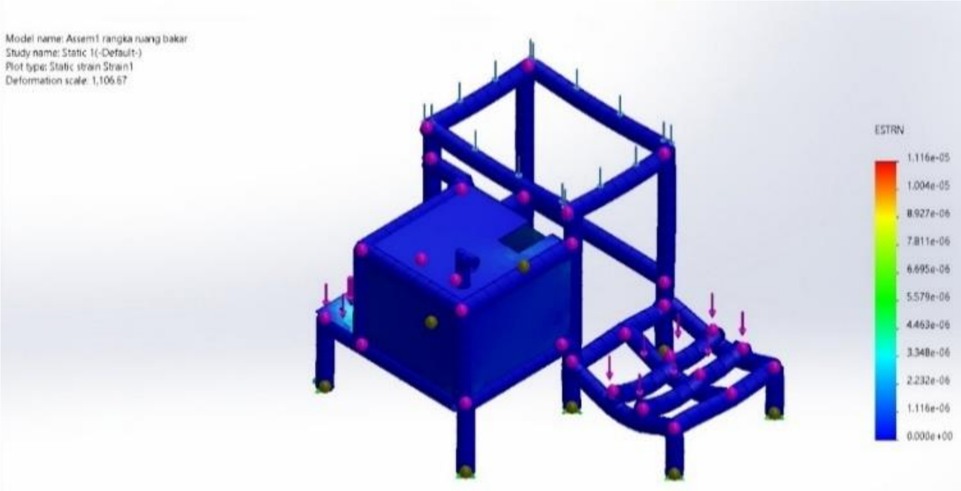


Fig. 3. Strain simulation results of machine frame

The stress simulation results of the machine frame section (Fig. 4) show that the light blue, green, yellow, and orange engine mounting frames are areas that experience deformation at values of (9.313e+06 – 4.189e+07) N/m^2. This is because the iron supports the engine and the dark blue frame does not experience deformation at values of (6.336e-03 – 4.660e 06) N/m^2. The shear stress simulation results in Table 1 confirm that the ash fertilizer making machine frame is safe, as the shear stresses (τ_1 to τ_{10}) are within allowable limits and does not exceed yield strength of 5.300e+08 N/m^2.

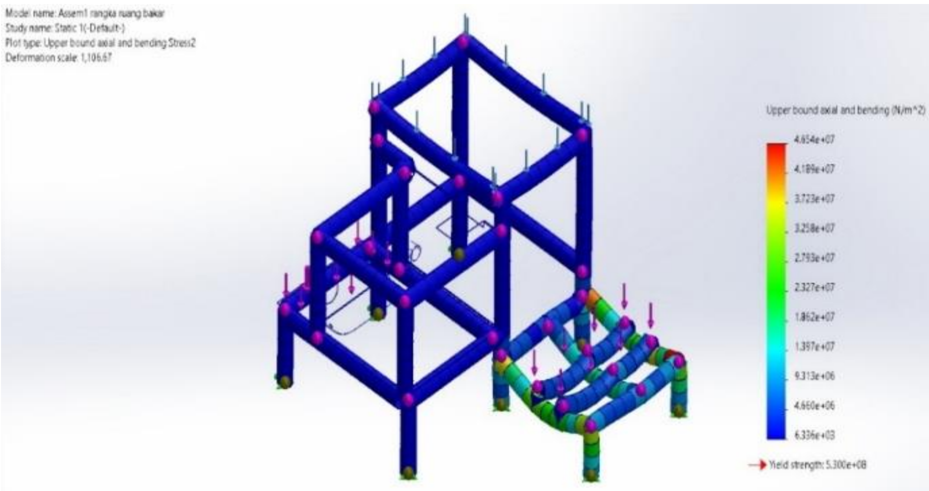


Fig. 4. Stress simulation results (yield strength) of machine frame

4.2 Simulation Results of Machine Blade Axis

The displacement simulation results of the machine blade axis (Fig. 5) are obtained using computer aided design (CAD) software. The components to be tested were blade shaft, blade, and bolts and nuts as locks. This simulation will be given a mass of 2 kg of OPEFB and a force of 19.62 N on the shaft, a torque of 56.36865 N.m to cut the OPEFB, and a blade shaft speed of 57.59 rad/s.

The displacement simulation results of the machine blade axis (Fig. 5) show that the dark blue blade shaft did not experience any deformation at values of (9.455e+00 – 9.810e+07) mm. These results indicate that the blade shaft is safe because it is still within the specified range of yield strength (τ1 to τ2).

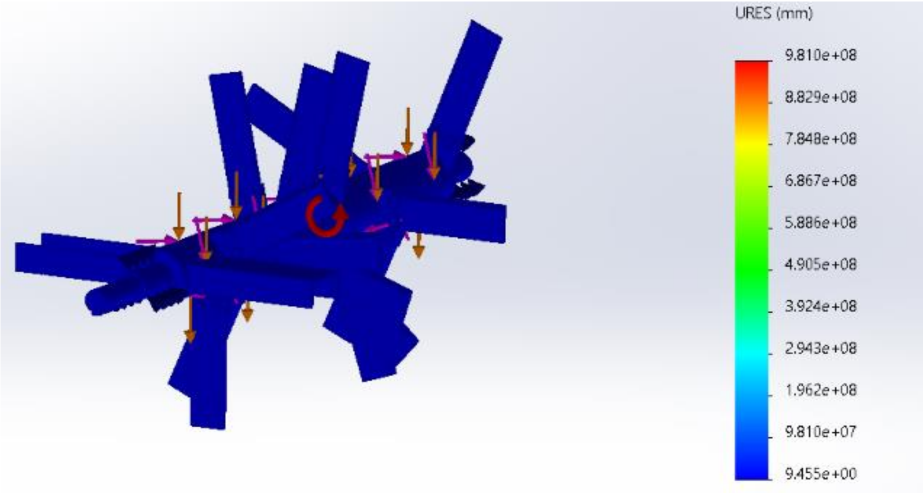


Fig. 5. Displacement simulation results of machine blade axis

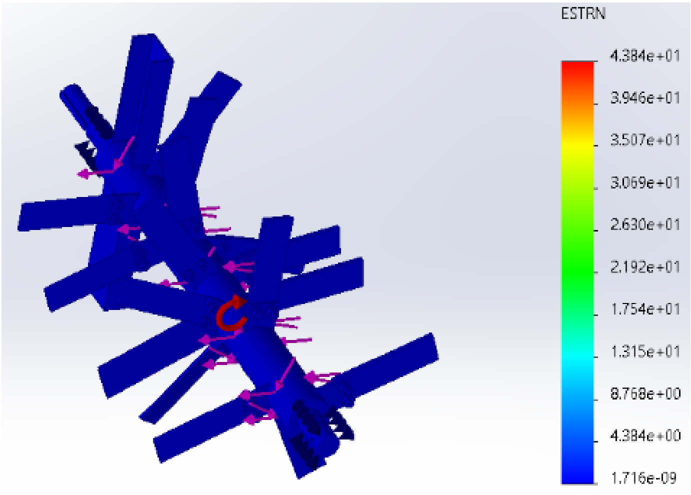


Fig. 6. Strain simulation results of machine blade axis

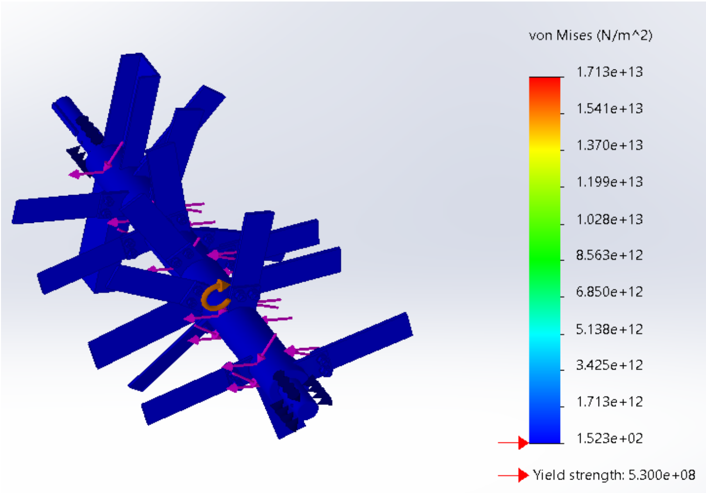


Fig. 7. Stress simulation results of machine blade axis

The strain simulation results of machine blade axis (Fig. 6) show that the dark blue blade shaft has an area that experiences very little strain (almost no change in shape) at values 1.716e+09 – 4.384e+00. These results indicate that the blade shaft is safe because it is still within the range of yield strength (τ_1 to τ_2).

The stress simulation results of the machine blade axis (Fig. 7) show that the dark blue blade shaft is an area that experiences very little stress at values of (1.523e+02 – 1.713e+12) N/m^2. This is due to the strong blade structure along with the material used AISI 1045 (carbon steel) and the amount of OPEFB chopped of 3 kg. These results state that the blade shaft is safe because it is still within the yield strength (τ_1 to τ_2) and does not exceed yield strength of 5.300e+08 N/m^2

4.3 Load Distribution Analysis of Machine Frame

The simulation results of the machine frame provided a yield strength of 5.300e+08 N/m^2. This data proves that the machine frame is safe because the data of yield strength (τ_1 to τ_{11}) does not exceed the yield strength data as shown in Table 1 and (Fig. 8).

Table 2. Yield strength data of machine frame

No	Input load (Action load)	Yield strength (N/m^2)										
		τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}
1	F total received by machine frame = F cutting + F blade + F OPEFB + F (machine engine) F total = 175 kg + 13.07 kg + 3 kg + 210 kg + 4.2 kg = 405.27 kg	6.34e +03	4.66e +06	9.31e +06	1.40e +10	1.86e +07	2.33e +07	2.79e +07	3.26e +07	3.72e +07	4.19e +07	4.65e +07

The shear stress graph results of the machine frame show that (τ_1 to τ_3) has no spike, but at τ_4 there is an increase at 1.4e+10, and at (τ_5 to τ_{11}) it goes back to stable. The yield strength of 5.300e+08 N/m^2 indicates that the ash fertilizer making machine frame is safe.

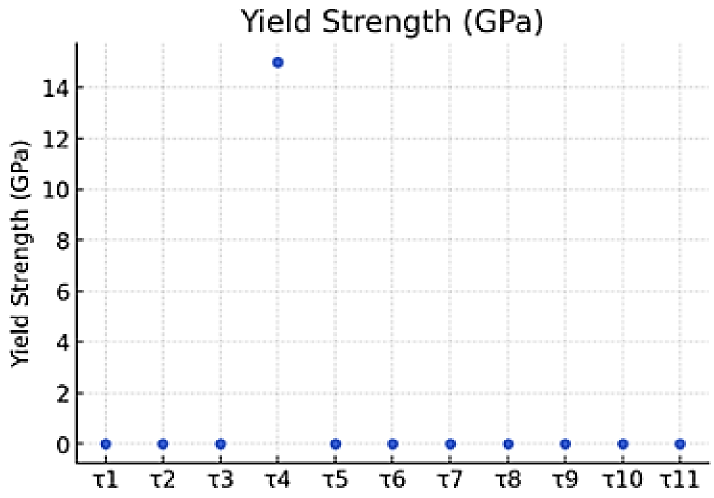


Fig. 8. Shear stress graph of machine frame

4.4 Load Distribution Analysis of Machine Blade Shaft

The simulation results of the machine blade shaft provided a yield strength of 5.300e+08 N/m^2. This data proves that the machine blade shaft is safe because the data (τ_1 to τ_{11}) does not exceed the yield strength data as shown in Table 2 and (Fig. 9).

Table 3. Yield strength data of machine blade shaft

No	Input load (Action load)	Yield strength (N/m^2)										
1		τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}	τ_{11}

F total received by knife shaft = F OPEFB + F blade F total = 3 kg + 13.07 kg = 16.07 kg with torque 56.36865 N.m to cut OPEFB, and speed 57.59 rad/s of knife shaft	1.91e+02	2.01e+11	4.03e+11	6.04e+11	8.05e+11	1.01e+11	1.21e+12	1.41e+12	1.61e+12	1.81e+12	2.01e+12

The shear stress graph results of the machine blade axis show that the smaller load is to be chopped OPEFB and received by the blade axis. The obtained value on the graph indicates that the minimum value of the load is received by the machine blade shaft and the maximum value of the machine blade shaft is obtained at (τ_1 to τ_{11}). The simulation data, simulation result data of 3 kg EFB, and design and actual data are presented in Tables 3, 4, and 5.

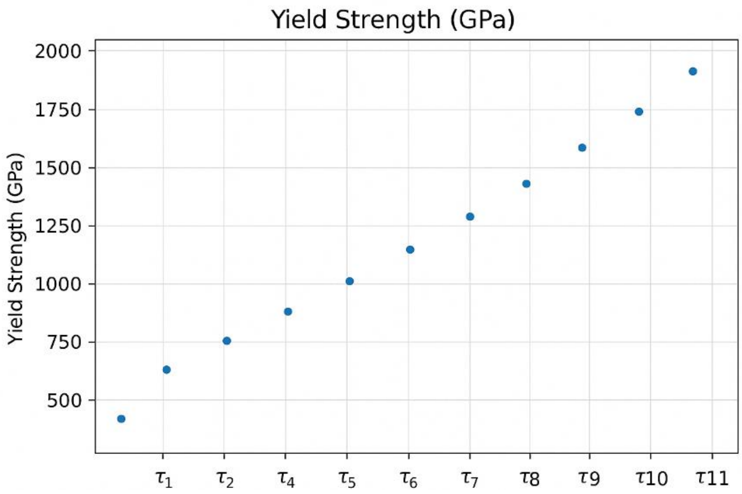


Fig. 9. Shear stress graph of machine blade axis

Table 4. Simulation data

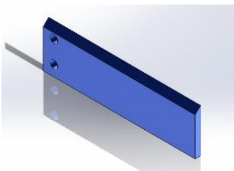
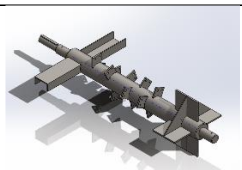
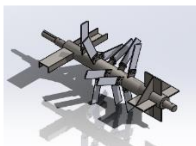
No	Blade material	Shaft material	Blade dimensions (mm)	Shaft dimensions (mm)	Assembly dimensions (mm)	Blade speed (rpm)
1	AISI 1045 Steel	AISI 1045 Steel	 Length = 140 mm, Width = 40 mm, Thickness = 5 mm	 Length = 770 mm, Pulley shaft diameter = 4 mm, Knife shaft diameter = 31 mm	 Length 770, width 337	550

Table 5. Simulation result data of 3 kg EFB

Construction load					Simulation results	
OPEFB capacity (kg)	Shaft and blade construction load (kg)	Construction torque (N·mm)	Cutting torque (N·mm)	Total construction torque, OPEFB, and cutting load (N.m) simulation results	Yield strength (N/m²)	Statement analysis
3	13.07	286128. 76	24034.50	56368.65	5.30e+11	From the simulation results on the knife shaft using a 3D CAD application, the yield strength obtained was 5.300e+08 N/m². These results

	prove that the knife shaft is considered safe because the data (τ_1 to τ_{11}) do not exceed the yield strength value.

Table 6. Design and actual data

No	Design results	Design	Current
1	Frame	1. UNP iron 65 mm x 42 mm 2. Angle iron 50 mm x 50 mm 3. Dimensions: L = 1000 mm, W = 1190 mm, H = 800 mm 4. Assembly process by welding.	1. UNP iron 65 mm x 42 mm 2. Angle iron 50 mm x 50 mm 3. Dimensions: L = 1000 mm, W = 1190 mm, H = 800 mm 4. Assembly process by welding.
2	Blade shaft	1. Round bar iron Ø = 76. 2 mm 2. Dimensions: L = 770 mm D1 = 4 mm, D2 = 31 mm	1. Round bar iron Ø = 76. 2 mm 2. Dimensions: L = 770 mm D1 = 4 mm, D2 = 31 mm
3	Knife	1. Iron strip 2. Dimensions: L = 140 mm, W = 40 mm, H = 5 mm	1. Iron strip 2. Dimensions: L =140 mm, W = 40mm, H = 5 mm
4	Engine motor	1. 18 HP power 2. 2200 rpm rotation	1. 23 HP power 2. 2200 rpm rotation
5	Transmission	Type B V-belt, No. 57	V-belt type B, No. 60
6	Pulley	1. Pulley 1 Dp 3 inches 2. Pulley 2 Dp 12 inch	1. Pulley 1 Dp 3 inches 2. Pulley 2 Dp 12 inch
7	Blower	1. 3-inch centrifugal blower 2. Power = 370 watts 3. Rotation = 3000/3600 4. 1 phase 5. AMP = 2 A	1. 3-inch centrifugal blower 2. Power = 370 watts 3. Rotation = 3000/3600 4. 1 phase 5. AMP = 2 A
8	Incinerator	LPG gas stove	LPG gas stove

5. Conclusions

This research was motivated by the challenge of managing the oil palm empty fruit bunches (OPEFB) in Indonesia, which reached a volume of 46.7 to 58.4 million tons in 2023. Without proper management, this waste has the potential to become a source of environmental pollution. Although various Empty Agricultural Fiber Waste processing tools have been developed previously, such as an AutoCAD-based shredder by Nasirly [20], which still has capacity limitations, or a rotary chopper machine by Rivalga [39], which does not yet integrate a combustion system, there is still a gap in the development of machines that combine the shredding and combustion processes in a single structurally validated unit. This study addresses these challenges by designing and simulating an integrated ash fertilizer production machine using the 3D computer aided design (CAD) software. This approach offers novelty in terms of dual process integration (shredding and combustion) and in-depth structural strength validation prior to fabrication, ensuring operational safety and efficiency. There are a number of conclusions that can be mentioned as follows:

- The designed machine has the capability to process OPEFB into ash fertilizer with overall dimensions of 1000 mm length × 1190 mm width × 800 mm height using a 23-horsepower diesel engine.
- Based on computer aided design software for simulation, the two parts including (frame structure and blade shaft) of the designed machine are considered safe because the

maximum stress that occurs in these parts is below the elastic value of the material that is used to manufacture the two parts.

- The designed machine demonstrates good performance in facing workloads, ensuring reliability and durability during the operation process.
- The integrated OPEFB processing process in one machine unit increases the efficiency and effectiveness of ash fertilizer production.
- The results for the frame show a maximum displacement (9.565e-02) mm and yield strength (4.189e+07) N/m^2.
- The yield strength of the machine blade shaft is 5.300e+08 N/m^2 based on the simulation results. This value proves that the blade shaft is declared safe because the (τ_1 to τ_{11}) data does not exceed the yield strength data.
- The machine blade shaft testing with a load (2, 4, 6, 8, and 10) kg of OPEFB provides a yield strength of 5.300e+08 N/m^2. This proves that the blade shaft is safe for use with up to 10 kg of OPEFB.

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