UNIVERSITY OF CAPE COAST

DEVELOPMENT AND EVALUATION OF CROP RESIDUE SHREDDER

SETH OSEI

2024

UNIVERSITY OF CAPE COAST

DEVELOPMENT AND EVALUATION OF CROP RESIDUE SHREDDER

BY

SETH OSEI

Thesis submitted to the Department of Agricultural Engineering of the School of Agriculture, University of Cape Coast, in partial fulfilment of the requirements for the award of Master of Philosophy degree in Agricultural Mechanisation and Machinery Technology.

DECEMBER, 2024.

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature: .... Date: ....

Name: Seth Osei

Supervisors' Declaration

I hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

Principal Supervisor's Signature:................................... Date:.........................

Name: Dr Francis Kumi

ABSTRACT

The study aimed at developing and evaluating a crop residue shredder. The components of the machine include a frame, hopper, shafts, electric motor, blades, sieve, spur gear, and outlet, to convert crop residues into a smaller form. The performance of the developed machine was evaluated using maize, millet and sorghum stalk, as feeding materials, with varying speeds of 55 rpm, 110 rpm and 220 rpm. The machine achieved a maximum shredding efficiency of 82% for maize stalk residues passing through a 20 mm diameter sieve, and the shredding speed was 220 rpm. The maximum throughput capacity attained was 14.6 kg/h of maize stalk at 220 rpm speed, while the minimum throughput was 5.14 kg/h of sorghum stalk at a speed of 55 rpm. The optimization of shredding speeds shows significant energy savings, as demonstrated by reduced power consumption at higher speeds from 0.20 kWh to 0.10 kWh for maize and 0.25 kWh to 0.10 kWh for millet when speeds increase from lower to higher rpm. The particle size distribution of crop residues depends on shredding speed, with lower speeds (55 rpm) producing larger particles, medium speeds (110 rpm) creating balanced distributions ideal for composting, and higher speeds (220 rpm) generating finer particles for rapid decomposition. The machine is user-friendly to small scale farmers and could be useful for carrying around relevant residue size reduction operations in agriculture in Ghana and other Sub-Saharan Africa countries.

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Keywords: Crop residues, shredder, shredding efficiency, Agricultural machinery.

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Finally, I thank my family, especially my parents Mr. and Mrs. Abirem, for their prayers and support, and my siblings Mark Obese, Isaac Nkansah, and others for their constant support throughout this journey.

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DEDICATION

I dedicate this work to my family~~,~~ for their unconditional support.

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LIST OF ABBREVIATIONS

FEA	Finite Element Analysis
RPM	Revolutions per minute

CHAPTER ONE

INTRODUCTION

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Background to the study

Agricultural waste refers to any by-product emanating from the cultivation and processing of agricultural crops and/or animals including fruits, vegetables, meat, poultry, and other dairy products (Nande et al., 2023). These are the non-productive outputs from the production and processing of agricultural commodities, which may include materials beneficial to humans. The costs of collecting, transporting, and processing these materials for beneficial use typically exceed their economic worth (Obi et al., 2016). With the intensification of agricultural production, the volume of agricultural waste has surged, raising concerns about its disposal and adverse environmental effects (Jena & Singh, 2022).

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In Ghana, approximately 60%–70% of agricultural biomass, including stalk, is produced annually (Quartey, 2011), but managing and valorising this biomass effectively remains a challenge, often leading to environmental degradation. Thus, the effective management of crop residues plays a crucial role in maintaining soil health and optimizing crop productivity. It is often observed that farms in Ghana produce substantial amounts of crop residues like maize stalk, sorghum and millet stalk, groundnut haulm, and rice straw (Nuhu et al., 2012). Meanwhile, it has been reported by Antwi‐Agyei et al. (2023) that there is scarcity of crop residues for conservation agriculture practice in smallholdings in the northern part of the country, which calls for ways of coming up with techniques or methods that could be used to salvage the situation for a more sustainable agricultural production.

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One approach is to utilize crop residues shredder machine to facilitate the reduction of the residue into relatively smaller particles for subsequent application These machines are often developed to chop the materials obtained after harvest such as corn stalks and wheat straw (Dattatraya Raut & Bhalgat, 2020). The shredding process offers a significant benefit by enhancing the soil's nutrient content during the initial decomposition stages. To achieve diverse results and improve shredder efficiency, various factors are considered, including blade thickness, cutting angle, shear angle, blade approach angle, blade periphery velocity, and shredder speed (Sridhar et al., 2017).

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Suggestion: "…utilize crop residue shredder devices to…"

Shredded crop residues leave a significant amount of essential nutrients (Udakwar & Sarode, 2023). These residues are nutrient-rich, containing nitrogen, phosphorus, sulphur, and potassium, making them valuable for agricultural use. Properly managing crop residues through recycling for conservation agriculture or nutrient resource utilization technologies can greatly improve soil fertility, enhance soil health, and decrease the reliance on external fertilizers (Yadvinder-Singh et al., 2022). The incorporation of crop residues into the soil, whether through composting, vermicomposting, or direct application can boost crop yields and soil microbial activity, offering a sustainable substitute for mineral fertilizers. The effective use of crop residues is essential for sustainable and economically sound agricultural practices (Carricondo-Martínez et al., 2022).

Problem Statement

In recent years, the agriculture sector has grappled with the issue of crop residue management during harvesting and post-harvest operations. Most farmers generate a substantial quantity of crop residues, amounting to 60% to 70% such as maize stalks, sorghum stalks, and millet stalks of their residues after harvesting (Nuhu et al., 2012). The management of these residues left after harvesting and during the post-harvest process has emerged as a major challenge facing the agricultural sector in recent years. The usual practice of burning crop residues has become increasingly common in Ghana, leading to atmospheric pollution and soil degradation, as indicated by recent research findings (Raza et al., 2022).

The open-air burning of crop residues in fields releases pollutants into the atmosphere, contributing to greenhouse gas emissions. The resulting smoke and soot particles are harmful to human health and can have a detrimental impact on soil properties, leading to the loss of valuable nutrients such as protein, phosphorus, potassium, and sulphur from the soil (Kanokkanjana & Garivait, 2013). Despite the drawbacks, crop residues are burned repeatedly each year. However, they can be utilized for economic benefits and to speed up decomposition, allowing for the return of organic matter to the soil more quickly. Some farmers also manage their crop residues by cutting them manually after harvesting their crops. They use their hands and knives to cut the plant residue into smaller sizes. This method is very low in productivity, time-consuming, labour-intensive, and can be monotonous for workers or farmers (Sreenivas et al., 2017).

The overuse and extended application of agrochemicals like pesticides and fertilizers can adversely affect soil health, which may lead to diminished crop yields and inferior product quality. However, utilization of field crop residues can be achieved through various efficient and simple methods. These methods primarily depend on size reduction mechanisms, which involve chopping or shredding the residues into appropriate sizes. (Megahed et al., 2015). In Sub-Saharan Africa and Asia, small-scale farms measuring less than 5 hectares constitute over 80% of the total agricultural land (Fan & Rue, 2020). It is often observed that crop residue shredding machines are not commonly used on these farms and their adoption has been limited due to various factors such as high costs, large power requirements, and the lack of a rugged design suitable for rural field operations (Ramulu et al., 2023). This is partly because information on crop residueshredder tailor-made for smallholder farmers, especially in Ghana, is scanty. Therefore, it is essential to develop and evaluate its performance to gather information about its effectiveness and potential benefits for farmers.

General Objective

The project's aim is to design, fabricate, and evaluate the crop residue shredder machine for smallholder farmers.

Specific Objectives

1. To design and fabricate a crop residue shredder.
2. To evaluate the performance of the shredder in terms of efficiency, throughput capacity, and power consumption.
3. To conduct a particle size analysis of the shredded crop residue.

Research Questions

1. What is the performance level of the developed crop residue shredder?
2. How fine or coarse are the particles shredded from the crop residue shredder?

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Significance of the study

Developing and accessing an efficient, low-cost, and user-friendly crop residue shredder is a crucial goal since smallholder farmers face severe challenges with managing crop residues after harvesting. Smallholder farmers face challenges in accessing shredding machines due to high costs, energy requirements, low shredding rates, and inadequate designs for rural field operations (Ngoma et al., 2023). Proper crop residue management is necessary, however, crop residue burning remains a widespread practice for farmers in the country with its attendant negative health implications. Crop residue is a resource in various ways, including enriching the soil with soil nutrients, producing bio-energy, and improving feed use. Current manual crop residue-cutting practices, on the other hand, are inefficient and time-consuming.

Therefore, there is demand for novel approaches that overcome existing limitations associated with commercializing excess crop residues by small-scale farmers (Surgude, 2023). Consequently, there is a pressing need for innovative solutions that addresses the challenges faced by smallholder farmers in managing crop residues efficiently and sustainably. The availability of a crop residue shredder could be a turning point for the benefit of smallholder farming communities. By offering a practical and robust equipment for leftover crop management, farmers can lessen the environmental harm from residue burning, enhance soil health, and possibly boost agricultural productivity and income. Additionally, assessing the shredder's capacity and the distribution of particle sizes will confirm its

Commented [KA7]: Suggestion: “Therefore, there is demand for novel approaches that overcome existing limitations associated with commercializing excess crop residues by small-scale farmers.”

Commented [KA8]: Change to: “innovative solutions” suitability for farmers' specific requirements. This study would provide requisite data and information accessible to farmers and the general public.

Delimitations

The research on the development and assessment of a crop residue shredder was conducted in Cape Coast, Ghana. However, the results are relevant to all regions of Ghana that share similar crop residues. The goal is to create a shredder that is appropriate for small to medium-scale farmers. The research included designing the shredder with AutoCAD Mechanical 2022 Version, and subsequently importing into Autodesk Inventor Professional 2023 for the finite element analysis (FEA), constructing the shredder, and evaluating it based on its efficiency, throughput capacity, and cost-effectiveness for local farmers.

Limitations

It is very important to acknowledge the limitations of this study. The project is subject to time constraints that will make it impossible to conduct all durability tests of a shredder. Whereas the intention is to have broad applicability, the finding of the study may not be generally applied to all types of crop residues. The testing and evaluation are also not going to involve comprehensive comparison against all commercially available shredders.

CHAPTER TWO

LITERATURE REVIEW

Crop Residues Management

Crop residues, the leftover plant materials after harvest, have historically been viewed as waste or byproducts in agriculture. However, recent decades have seen a growing appreciation for their value and potential uses in sustainable farming practices. Crop residues play a significant role in sustainable agriculture by providing essential nutrients and promoting soil health. Improper management of crop residues can lead to environmental pollution, reduced soil productivity, and health issues. To valorise crop residues, various strategies have been proposed, including microbial fermentation, in-situ incorporation with microbial consortia, and thermo-chemical conversion Verardi et al. (2023). These strategies aim to transform crop residues into valuable products like single-cell proteins, biofuels, and soil nutrients, supporting a circular economy and reducing waste. Through the use of innovative techniques, farmers can effectively manage crop residues to enhance soil quality, increase crop yields, and mitigate the negative effects of residue burning on the environment and human health (Shah & Valaki, 2023).

Historically, farmers have utilized a range of methods to manage crop residues, such as burning, removal, or incorporation into the soil via tillage. Each method, however, has its challenges and drawbacks. The practice of burning crop residues, widespread in many areas to clear fields for subsequent planting, weed control, and nutrient release for the next crop cycle, presents considerable difficulties. The smoke from burning residues emits dangerous pollutants, including particulate matter, carbon monoxide, and greenhouse gases, adversely affecting human health and the environment (Gadde, 2009). The excessive smoke from burning crop residues contains harmful pollutants like particulate matter, carbon monoxide, and greenhouse gases, which negatively affect human health and the environment (Gadde, 2009). Incorporating these residues into the soil can enhance soil organic matter and nutrient cycling, improving soil health and crop productivity. However, too much residue can hinder seedbed preparation and planting, possibly resulting in poor crop establishment and lower yields (Rathore & Shekhawat, 2022). Effective crop residue management, such as through conservation agriculture, offers sustainable ways to maintain soil health, increase crop productivity, prevent excessive residue buildup, improve nutrient cycling, and reduce soil erosion, thereby leading to better crop yields.

Crop Residue Shredders

Crop residue shredders have become a valuable tool for efficient residue management, as noted by (Ramulu et al., 2023). These machines are engineered to chop and crush crop leftovers into fine pieces, which helps with their integration into the soil or their removal from the field. Shredders contribute to enhanced decomposition by improving soil-residue interaction, reducing the likelihood of blockages in machinery during planting, and facilitating the more effective handling and transport of residues. The advent of crop residue shredders presents a viable solution to the challenges of residue management, promoting agricultural sustainability and environmental conservation (Stoian & Mitrache, 2023). Crop residue shredder technology is essential in reducing the size of crop residues, facilitating their return to the soil or their use in bioenergy production and composting applications.

Shredding plant residues helps improve soil health, boost productivity, and minimize environmental pollution from residue burning (Simha et al., 2022). The development of crop residue shredders has been driven by the need for sustainable farming practices, concerns about the environmental impact of open burning, and the growing recognition of the value of crop residues for various uses such as animal feed, bioenergy production, and soil improvement. To address these issues effectively, a range of shredding equipment, including cutters, rotor platforms, and biter-knife shredders, has been introduced (Naujokienė et al., 2023).

Historical Overview of Crop Residue Shredders

The development of crop residue shredders can be traced back to the early 20th century when farmers and engineers began seeking mechanical methods to manage crop residues more efficiently (Reddy & Raju, 2018). Among the initial innovations was the straw cutter, which was designed to chop straw and other fibrous materials into smaller pieces for use as animal bedding or feed (Resmi & Vinod, 2022). These early developments set the stage for the modern shredding technologies that followed, marking significant progress in the field. Innovations such as the straw cutter led to the creation of more advanced shredding machines, which have contributed to enhanced agricultural practices and waste management within the farming industry. The evolution of shredding mechanisms in agriculture has introduced various innovations, including the flail shredder, which uses hinged flails on a rotating shaft to effectively break down crop residues (Stoian & Mitrache, 2023). Subsequently, rotary shredders with fixed blades on a rotating cylinder and hammer mills with hammers on a rotating shaft emerged as alternatives in the

1940s and 1950 (Ryadnov et al., 2022b). These machines offer efficient methods for shredding coarse materials such as corn stalks and wheat straw into finer pieces, thus improving the digestibility of fodder beet for cattle. Furthermore, contemporary agricultural machinery includes components for cutting crops and conditioning, like macerator assemblies, which further improve the shredding process (Volkhonov et al., 2020).

Early innovations in crop residue shredders faced limitations in efficiency and compatibility with existing agricultural machinery (Stoian & Mitrache, 2023). Nevertheless, continuous research has focused on improving shredding mechanisms to enhance operational performance and minimize energy consumption, in accordance with the developing needs of sustainable agricultural practices. Recent studies have investigated the effects of shredding rollers on the mechanical properties of fibrous cannabis residues, underlining the significance of effective shredding in organic cannabis cultivation. (Naujokienė et al., 2023). Experimental research has also been carried out on machines specifically designed to shred woody plant residues. Moreover, recent advancements in plastic shredding technology have seen the integration of IoT systems, which optimize energy consumption and prevent overheating, indicating a move towards more efficient and safer shredder designs (Setyaningsih et al., 2022).

Recent Developments of Crop Residue Shredders

In recent years, there has been a growing focus on enhancing the effectiveness and efficiency of crop residue shredding systems to maximize the benefits of sustainable farming methods. Improvements in precision agricultural technology, material engineering, and mechanical design have led to advancements in the shredding process. The development of high-efficiency shredders and mulchers with sophisticated cutting mechanisms has been a significant breakthrough in many industries. Research on optimizing shredder blade geometries and orientations to improve wear resistance and performance has shown that double-edge shredder blades with spiral orientation have better recycling and shredding efficiency (Wong et al., 2022).

Moreover, research has been done to evaluate the cutting forces utilized in shredding root crops, emphasizing the significance of reducing cutting forces for effective grinding. To enhance the quality of the final product, innovations such as a planetary transmission system for shredding cutters have been developed to provide differential shearing pressures for comprehensive shredding without dead corners (Warguła et al., 2018). Shredder cutting efficiency is enhanced by improvements in blade design, such as the addition of auxiliary blades with greater thickness and strength and supporting ribs.

According to Sridhar et al. (2017), these advancements do not only facilitate quicker residue breakdown but also better soil integration, which improves recycling and waste management procedures overall. Agricultural equipment with specialized blades or flails may effectively shred a variety of agricultural leftovers, including fibrous and hard materials. These devices are essential to the various uses of agricultural waste processing. For example, a portable shredder was created to cut paddy straw, coconut leaves, and Areca leaves into pieces for vermicompost (Naujokienė et al., 2023).

In addition, a pulveriser machine is made to shred organic wastes without the need for energy, highlighting the significance of effectively using agricultural waste for positive purposes (Ganesh et al., 2017). The incorporation of shredding mechanisms into agricultural gear, such as balers or combine harvesters, has demonstrated encouraging advancements in simplifying processes and minimizing the requirement for independent equipment. This integration enables simultaneous shredding and residue distribution during the harvesting process, enhancing efficiency and productivity (Ramulu et al., 2023).

Evaluation of Shredders

As concerns over sustainable agricultural practices and resource conservation have grown, the effective management of crop residues has become increasingly important. Crop residue shredders have emerged as a promising technology for facilitating the incorporation or retention of residues on the soil surface, offering numerous benefits such as erosion control, nutrient cycling, and improved soil health. Several studies have documented successful implementations of crop residue shredders in various agricultural settings and cropping systems.

Kishan et al. (2014), innovated a machine for extracting areca fibres from the husk. The machine includes a three-phase, 5hp AC motor that is directly connected to the drive shaft. The shaft is enclosed in a casing that is designed to remove dust while allowing fibres to exit through a rectangular duct at the lower side of the casing. The shaft is supported by two bearings and features blades that have been modified from those used in a coconut husk decorticating machine.

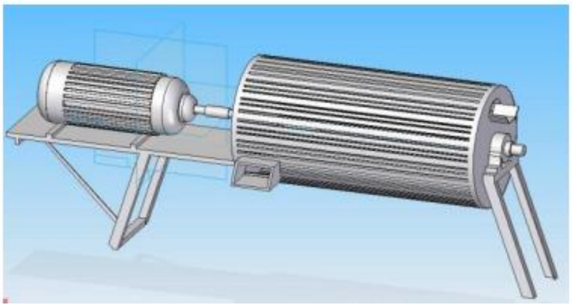


Figure 1: Areca fibre extracting machine

Khatib & Kumar, (2014) proposed a shredder machine that would shred coconut leaves. The machine consists of a cutter mounted on a dual shaft, with a motor attached to the base. A smaller pulley at the motor end provides drive to a larger pulley connected to a gear. This gear in turn drives another gear, causing the barrel to rotate in the opposite direction. They stated that the shaft rotates at 520 rpm, enabling the high rotational speed necessary for the cutter assembly to convert coconut leaves into powder.

Ajinkya & Deshpande, (2014) focused on the developed Portable Organic Waste Chopping Machine. In this machine, organic waste was uniformly fed through a feeding drum and tray, and then an electric motor, operated by pulleys, rotates the shaft at 1440 rpm, causing the chopping drum to cut the waste due to the impact shear obtained from the shearing blades. The cutting process also generated tensile, friction, and impacted the chopping house. The cut pieces were then used to pass through concave holes in the sieve and exit the machine. It allows for different-sized sieves to be used.

Adgidzi, (2007) also developed a forage chopper tailored for crop residues. The machine's cutting blade featured a knife-edge thickness (δ) of 80µm, a knife thickness (t) of 4mm, and a sharpening angle (β) of 25 degrees.

The moisture content of both wet and dry materials was determined using the oven-dry method before chopping. The chopper achieved average efficiencies of 86% for wet materials and 92% for dry materials. It processed 24kg/h of dry materials and 15.6kg/h of wet materials, indicating superior performance with dry materials. The chopped pieces were typically 25mm long. Designed for operation by a single person, this machine is apt for both rural and urban environments and necessitates a diesel or petrol engine with a minimum power output of 8.5kW.

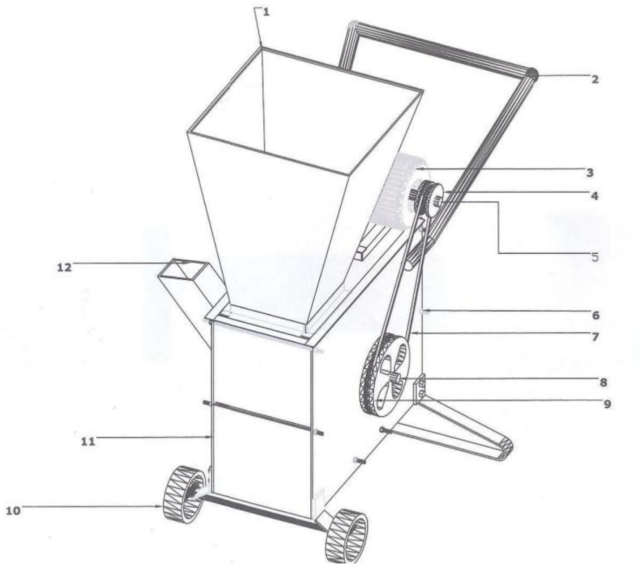


Figure 2: Isometric View of Forage Chopping Machine

Busari et al. (2024) investigated an innovative agricultural waste shredder designed specifically for accelerated composting processes. The research addressed the critical environmental and public health challenges posed by agricultural waste pollution by developing a more efficient conversion system for organic manure production. The study highlighted that existing waste conversion machines suffer from inadequate throughput capacity and insufficient size reduction capabilities, which significantly slow the composting process. To overcome these limitations, Busari developed and evaluated a specialized waste shredder optimized for maize straw processing. The machine featured several key components: a shredding drum with triple blade sets, a feeding tray, sieve mechanism, engine mounting, and discharge outlet. Performance testing evaluated the device across various operational parameters, including rotation speeds (300-1500 rpm) and processing durations (0.5-2.5 hours). Using Response Surface Methodology (RSM), the researchers optimized operational efficiency by systematically varying these parameters. Results demonstrated impressive performance metrics, with peak shredding efficiency reaching 91% and maximum throughput capacity of 585 kg/h when operated at 1,500 rpm for 1.5 hours. Additionally, the machine offers practical advantages including portability, energy efficiency, and ease of operation for processing diverse agricultural waste materials.

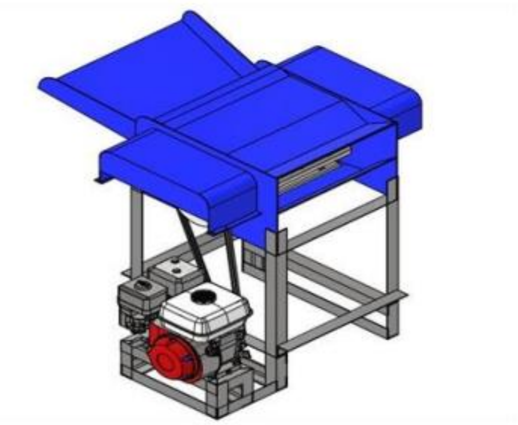


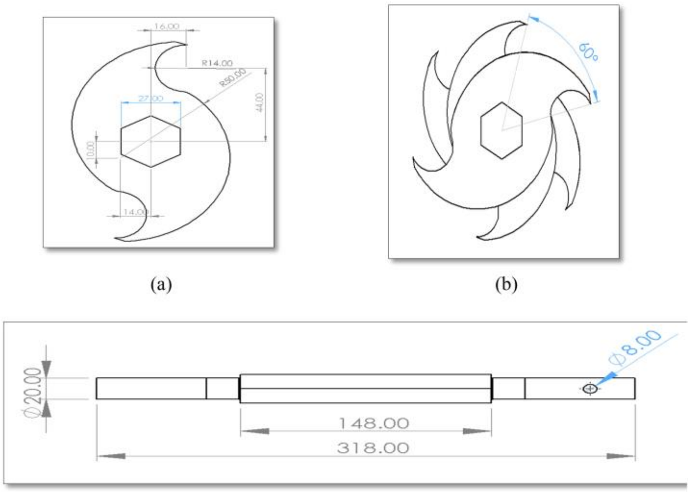
Figure 3: Three – dimensional view of the Designed Shredder

According to Bashir et al. (2011), a stalk chopper was designed with a prime mover that drives the chopping disc with the knives attached. The machine had a throughput capacity of 45.69 kg/h and achieved a cutting efficiency of 91%. Nithyananth et al. (2014) also designed a waste shredder machine that functions as a ploughing attachment. The shredder operates using a tractor's power take-off shaft and is suitable for organic matter shredding, resulting in small pieces that can be used for vermin compost preparation.

Abdulkadir et al. (2020) conducted research which focused on the design, construction, and testing of a shredder machine to shred agricultural waste effectively which can then be used for composting or as animal feed. The performance of the machine was assessed utilizing bean stalks. The performance evaluation was shredding efficiency on different operational speed and sieves apertures and also throughput capacity. The maximum shredding efficiency achieved was 93% at a shredding speed of 975 rpm with a 20 mm sieve aperture. The maximum throughput capacity was 6.10 kg/min at the same speed. The machine's design was found to be effective and suitable for small and medium-scale agricultural operations.

Figure 4: Agricultural Waste Shredder

Trad (2024) significantly advanced plastic recycling technology by optimizing shredder rotor design through structural finite element analysis. The research employed experimental design and response surface methodology to enhance the most critical components of plastic shredders: the rotor, shaft, and rotary blades. The study followed a systematic approach using Ansys Workbench Design Exploration. It began with modal analysis to identify natural frequencies and mode shapes, followed by harmonic response analysis to determine operational frequency constraints. Transient structural analysis then identified key areas for optimization on the rotor. The optimized design achieved remarkable improvements with minimal compromise, increasing mass by only 2.43% while reducing equivalent stress by 9.84% and total deformation by 42.86%. Structural stability was enhanced as evidenced by increases in the first three natural frequencies (21.4%, 4.35%, and 4.48% respectively).



(a) (b)

(c)

Figure 5: (a) Blade geometry and dimensions, (b) configuration of blades, (c) Shaft geometry and dimensions.

Abhay et al. (2019) constructed a shredding machine for recycling and management of organic waste to convert organic waste into smaller particles, facilitating faster composting and reducing environmental pollution. The machine’s performance was assessed based on its shredding efficiency and throughput capacity. It was found to be effective and suitable for composting by recycling organic waste into compost. The machine helps reduce the environmental impact of waste disposal and also promotes sustainable agricultural practices by providing high-quality compost for soil enrichment.

Integration of Crop Residues Shredder with Farming Systems

Maximizing the successful integration of crop residue shredding into farming systems is essential for achieving long-term sustainability and realizing its full benefits. A comprehensive approach is necessary that takes into account various factors, such as crop rotations, tillage practices, and overall farm management strategies. Integrating legume crops or canola into rotations, for instance, can lead to faster decomposition of residues, which is beneficial for effective shredding (Flower et al., 2021). The rate of decomposition of certain crop residues, such as those from leguminous crops or crops with high carbon-to-nitrogen ratios, may vary, which can impact soil fertility and weed suppression. The effectiveness of crop residue shredding is influenced by crop selection and rotation, as different crop residues decompose at varying rates (Naujokienė et al., 2023). In Mediterranean agroecosystems, legume residues like vetch and pea decomposed faster than barley residues, which affected nutrient release dynamics (Almagro et al., 2023).

Additionally, intercropping practices with leguminous crops can enhance soil organic carbon and nitrogen (N) storage and stabilization, which contributes to sustainability. Crop rotations also play a vital role in residue dynamics, as shown in a study in Chile, where residue production and grain yield were influenced by previous crops and residue incorporation levels, highlighting the importance of crop selection and residue management in agricultural systems (Flower et al., 2021). Crop rotation is a vital aspect of residue management, ensuring the continuous availability of shredded residues for soil enhancement (Behera et al., 2022). Combining crop residue shredding with conservation tillage methods, such as no-till or strip-till systems, can significantly improve residue management by minimizing soil disturbance and maintaining shredded residues on the soil surface. This integration leads to increased soil cover, erosion control, and improved moisture retention, ultimately contributing to better soil health and productivity (Sarker et al., 2022). Effective crop rotation planning and the adoption of conservation tillage practices enable farmers to manage residues more sustainably, enhance soil quality, and maintain agricultural productivity in an environmentally friendly and economically viable manner. The use of precision agriculture technologies, such as yield mapping and variable-rate shredding, can further optimize the integration of crop residue shredding by analysing yield data and residue distribution patterns, ensuring efficient residue management across the entire field (Zaman, 2023).

Benefits of Crop Residue Shredding

Enhanced Soil Health and Fertility

Shredding crop residues is an essential agricultural practice that greatly improves soil health and fertility. These decaying residues are fundamental to the nutrient cycle. Returning crop residue to the soil can boost levels of organic carbon, nitrogen, phosphorus, and potassium (Zhao et al., 2019). Farmers who shred and mix residues into the soil can improve soil structure and tilth. As organic matter, shredded residues enhance soil aggregation, boost porosity, and increase water retention. Improved soil structure supports better root development, more effective nutrient absorption, and results in healthier, more robust crop growth. Additionally, crop residue shredding helps in managing crop residues effectively, reducing the need for burning, which can lead to environmental degradation and loss of soil nutrients (Angon et al., 2023).

Traditional crop residue management practices, such as open burning or complete removal, have been linked to increased soil erosion and nutrient depletion. Retaining crop residues on the soil surface is indeed a recognized strategy for mitigating soil erosion and conserving soil nutrients. Crop residues play a crucial role in maintaining soil health as they enhance the soil's organic carbon content, improve its structure, and facilitate nutrient cycling (Ramteke & Vashisht, 2023). The practice of retaining crop residues plays a crucial role in protecting soil from erosion, regulating soil temperature, and improving water and solute movement, which all contribute to the overall health of the soil and the sustainability of the land Gollany, (2022). Additionally, incorporating crop residues into the soil can increase the content of nutrients, organic matter, and humus, leading to improved soil fertility and plant growth.

Weed Suppression and Pest Management

Crop residue shredding presents a significant advantage in controlling weeds and pests by potentially reducing the need for chemical herbicides and pesticides. When crop residues are shredded and left on the soil surface, they form a mulch layer (McKenzie-Gopsill & Farooque, 2023). This mulch layer functions as a physical barrier, inhibiting weed seed germination and growth by altering the conditions of sunlight exposure, temperature, and moisture at the soil surface (Naujokienė et al., 2023). Consequently, the establishment of many weed species is impeded, leading to decreased weed pressure and potentially reducing the reliance on chemical interventions for weed control (Stoian & Mitrache, 2023).

The implementation of cover crop residues following shredding can lead to enhanced weed suppression by means of allelopathic effects and modified nutrient availability. The process of shredding crop residues is crucial for fostering a diverse and balanced ecosystem in both the soil and crop residue layer, thereby strengthening natural pest control methods and diminishing the reliance on chemical treatments (Bansal, 2022b). Additionally, the allelopathic effects of crop residues on weeds and pests bolster weed suppression and pest management capabilities. Incorporating allelopathy as a tool in integrated weed management plans can significantly decrease the need for herbicide application, making it a practical and environmentally friendly approach in agriculture (Khamare et al., 2022).

Additionally, bioherbicidal efficacy of crop residues is enhanced by the synergistic interactions between volatile and water-soluble chemicals released by allelopathic residues, mostly applied as a soil supplement (Pardo-Muras et al., 2022). Although the effectiveness may vary depending on crop type, residue composition, and environmental conditions, farmers can use these advantages to promote more environmentally friendly and sustainable agricultural practices by implementing crop residue shredding procedures (Muhammad et al., 2022).

Economic Considerations and Cost-effectiveness

Crop residue shredding has many agronomic advantages, but its long-term sustainability and farmers' ability to use it depend on the practice's cost-effectiveness and economic effects. The initial outlay for shredding equipment is a major economic factor. The initial investment cost is a crucial consideration when building or buying a crop residue shredder. The developed shredder machines for management of agricultural waste have been the issue of many studies. The complexity of the design, the materials used, labour, and the specialized machinery needed for production are some of the factors that affect the cost. When taking into account operating expenses, cutting efficiency, and fuel consumption, these machines have shown to be economical. Therefore, understanding the initial investment cost is crucial for farmers and industries looking to implement sustainable agricultural waste management practices (Ganesh et al., 2017).

Utilizing a shredder machine is more cost-effective compared to traditional methods of managing crop residues, which include burning or manual removal (Sokhansanj et al., 2023). Because of residue burning, traditional techniques are associated with health expenditures; during the burning season, households pay between USD 13.37 and USD 8.79 on healthcare (Raza et al., 2022). Shredder machines provide a healthier substitute by lowering air pollution and related health problems. Farmers can profit economically from the employment of shredder machines by selling their excess crop residue for the production of electricity, lowering pollution, and lowering greenhouse gas emissions (Devi & Balakrishna, 2022). Therefore, the cost of using a shredder machine for crop residue management can be more economical and environmentally friendly compared to traditional methods.

Other Benefit of Shredder

The milling and processing of agricultural products also result in a substantial amount of crop residues. These residues are not merely natural resources with considerable value to farmers; they also provide an additional source of income. They can be used as animal feed, material for composting, thatching for rural homes, and as fuel for domestic and industrial purposes. Nutrients such as nitrogen, phosphorus, sulphur, and potassium, which are absorbed by cereal crops, remain in the residues, rendering them valuable nutrient sources (Ramulu et al., 2018).

Plant residues can be fed to animals directly or in combination with other additives. Nevertheless, because they are poorly digestible and unappealing, crop residue cannot serve as the exclusive feed for animals. Crop residues consist of low-density fibrous materials with a low lignin content, which serves as a physical barrier and hinders microbial decomposition. They are also deficient in nitrogen, soluble carbohydrates, minerals, and vitamins. These residues have to be processed, enriched with urea and molasses, and supplemented with green fodders and straw produced on legumes to meet the nutrient requirement of the animals (Birla et al., 2020). The use of crop residues such as paddy straw bedding during cold seasons helps the animals keep themselves warm and maintain appropriate body heat loss rates.

Biomass is a highly efficient energy source that is globally sought after due to its environmental benefits. Crop residues are now more often used to generate energy and replace fossil fuels in the production of energy. Biomass energy is more affordable, storable, eco-friendly, and energy-efficient than other renewable energy sources like solar and wind (Birla et al., 2020). Straw and rice crop husks can be effectively used to produce bioenergy. Empirical estimates indicate that 290 kg of rice straw may generate 100 kWh of power, and 1 tonne of rice husk can generate between 410 and 570 kWh (Ahmad et al., 2023).

Challenges of Crop Residue Shredding

Crop Residue Shredders Factors

Crop residue shredding is essential for improving insect control, weed suppression, and soil health. Nevertheless, there are technological obstacles to this practice's implementation, chief among them being the suitability and accessibility of shredding machinery (Kumar et al., 2023). For small-scale farmers, specialized equipment such as shredders, mulchers, or flail mowers can be expensive. Skilled labour is needed to operate and maintain these devices, and it may not always be readily available. Furthermore, variables including residue kind, moisture content, and field conditions can affect how well these machines work, which could hinder efficient shredding processes. Shredders can face technical problems such as clogging, especially if the residue is wet or contains large, tough stalks. These shredders can also cause dust and noise pollution during operation. These difficulties show how creative fixes and effective systems of support are required to encourage the broad use of agricultural residue shredding techniques in agriculture. Managing vast amounts of leftovers is another difficulty, especially in high-yield farming systems or areas with slow rates of residue decomposition. Crop residues that build up excessively on the soil surface can cause problems such as nutrient immobilization, allelopathic effects, and elevated risks of pests and diseases (Kumar et al., 2023). Residue management is essential to avoiding these problems in high-yield cropping systems, such as the rice-wheat combination in India, where large amounts of residue are produced (Korav et al., 2022). To minimize any negative effects and guarantee ideal crop growth, strategies that strike a balance between residue removal and retention as well as the timing and depth of residue integration are crucial (Flower et al., 2022).

Energy Consumption and Emissions

Traditional practices like open burning of crop residues are concerning due to their adverse environmental impacts, which include air pollution, greenhouse gas emissions, and soil degradation (Kumar et al., 2023). The energy consumption of crop residue shredders is indeed influenced by various factors. The type and design of the shredding mechanism, such as disc and drum shredders or biter-knife shredding machines, play a crucial role in determining energy intensity. Additionally, the power source, whether it is an electric motor or a diesel engine, impacts the power consumption of the shredder.

Moreover, the characteristics of the crop residues being processed, like the supply rate and moisture content, significantly affect energy consumption, with higher supply rates leading to increased energy usage. Understanding and optimizing these factors are essential for enhancing the energy efficiency of crop residue shredders (Sarana et al., 2023). Evaluating emissions associated with crop residue shredding is crucial for assessing environmental impact (Kumar, 2023). The shredding process can generate particulate matter and other air pollutants, contributing to atmospheric contamination. Additionally, the interaction of fibrous cannabis residue with soil during cultivation impacts the mechanical properties of the residue and the environment, underscoring the significance of comprehending these dynamics (Mirzaei et al., 2023).

Moreover, the practice of burning crop residue, particularly in developing nations such as India, transforms valuable components in the residue into detrimental air pollutants, underscoring the necessity for sustainable management of such residues. By evaluating the effects of shredding on moisture content, lignin content, and the mechanical properties of breaking and cutting, it is possible to enhance the shredding process's efficiency, thereby reducing emissions and lessening the environmental impact.

Chapter Summary

This literature review has examined the evolution and significance of crop residue management, with particular focus on the development and application of crop residue shredders. Through our exploration of existing research, we have uncovered several interconnected narratives that shape our understanding of this field. The crop residues have undergone a remarkable transformation over time. Once dismissed as mere agricultural waste, these materials are now increasingly recognized as valuable resources that can significantly contribute to sustainable farming practices. Traditional management approaches, particularly the widespread practice of burning, have created substantial environmental and health hazards that affect both rural and urban communities. This recognition has driven the search for more sustainable alternatives, with shredding emerging as a promising solution.

The technological journey of crop residue shredders spans over a century, beginning with simple straw cutters in the early 20th century. These rudimentary machines laid the groundwork for today's sophisticated equipment featuring advanced cutting mechanisms and innovative designs. Recent years have witnessed remarkable advancements, including optimized blade geometries, integration of digital technologies, and specialized mechanisms tailored to different types of crop residues. These innovations reflect the agricultural industry's growing commitment to sustainable resource management. Our review of performance evaluations reveals the practical effectiveness of various shredder designs across different contexts. Researchers have developed and tested numerous machines with shredding efficiencies ranging from 86% to 93%, demonstrating the technical viability of this approach. Particularly noteworthy is the relationship between operational parameters such as rotational speed and processing duration, which significantly influence overall performance outcomes.

The integration of crop residue emphasizes that shredding technology cannot exist in isolation but must be thoughtfully incorporated within broader farming systems. Successful implementation requires careful consideration of crop rotations, tillage practices, and comprehensive farm management strategies. When combined with conservation tillage methods and precision agriculture technologies, shredding practices become even more effective at managing residues sustainably. These brings multiple advantages by enhancing soil health that emerges through improved organic matter content and nutrient cycling. Ecological benefits include effective weed suppression and pest management with reduced chemical dependence. Economic advantages extend beyond soil improvement to include alternative uses of shredded residues as animal feed, composting material, and bioenergy feedstock.

Despite these promising developments, challenges persist. Many farmers, particularly those operating at smaller scales, face significant barriers to adoption, including equipment costs and accessibility issues. Technical challenges around managing large volumes of residues in high-yield farming systems require further attention, as do concerns about energy consumption and emissions associated with shredding operations. The review reveals several important gaps in current knowledge that future research should address. These include the need for more affordable and accessible technologies for small-scale farmers, optimized designs for various crop types and conditions, energy-efficient and low-emission shredding systems, better quantification of long-term benefits, and improved strategies for managing shredded residues across diverse agricultural contexts. As I move forward with the research on crop residue shredder development and evaluation, this comprehensive understanding of existing literature provides crucial context. It highlights both the significant progress already made and the substantial opportunities that remain for advancing sustainable crop residue management practices.

CHAPTER THREE

MATERIALS AND METHOD

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The aim of this project was to design, fabricate, and evaluate a crop residue shredder using feedstock such as maize stalk, millet stalk and sorghum stalk. The steps listed in this chapter were followed to design, construct, and evaluate the crop residue shredder. The design procedure particularly focused on the design considerations, design analyses, conceptual designs, concept evaluation parameters, and analyses of the final design. The major sub-assemblies of the new design are also covered. The materials, procedure, tools, and equipment used in the design and construction of the shredder, are all enlisted in this chapter.

Study Areas

The fabrication of the crop residue shredder took place in a local metal workshop in Cape Coast. This workshop was selected due to its well-equipped facilities, which include all the necessary tools, machinery, and equipment needed for the design and construction of the shredder, such as welding gear and metalworking tools. They have expertise and fabricators who contributed to the development of the machine. It is located in the Central Region of Ghana, within Cape Coast Metropolis. Cape Coast Metropolis is situated along the southern coast of the Atlantic Ocean, known as the Gulf of Guinea.

Materials and Instrumentation

The primary materials utilized in constructing the crop residue shredder included: 50 mm x 25 mm mild steel angle iron for the frame, a mild steel plate for the hopper, mild steel for the blades and spacers, and diameter of 25 mm mild steel pipe. Additional components were 206 pillow bearings, a

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spur gear, an electric motor, and various bolts and nuts. The machinery utilized in constructing the shredder were: an electric arc welding machine, a drilling machine, and an electric hand grinding machine. The hand tools employed in conjunction with these machines were vernier callipers, a tape measure, a try square, spanners, a hacksaw, hammers, and a centre punch.

Design considerations

In designing the shredder, the primary mechanical factors considered were the strength, rigidity, and the availability of materials used for fabricating the machine. Economically, the focus was on using locally available raw materials for fabrication, ensuring low fabrication costs, and minimizing maintenance cost.

Conceptual designs

Regarding standard design processes, three conceptual designs were developed.

Concept 1 (Dual shredding shafts with direct gear drive)

This conceptual design consists of an electric motor, spur gear, dual shredding shafts, bearings, blades, outlet and the frame~~ (Figure 6Figure 6)~~. The frame carries the load of the machine, and provides support for the machine during operation, and the blades shred the crop residues into smaller sizes. The machine is powered by an electric motor with an in-built gearbox. The output shaft of the motor is directly coupled to a pair of spur gears on the shredding shafts to cause their rotation.

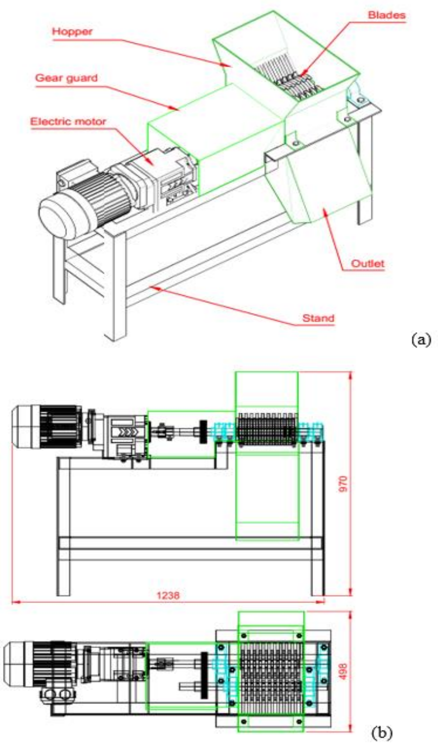

Figure 6: Concept 1 (a) Isometric View (b) Orthographic Views

Concept 2 (Dual Shaft with Sprocket and Chain Drive)

This concept is made up of an electric motor, chain drive, gear drive, bearing, frame, outlet and hopper~~ (Figure 7Figure 7)~~.~~ Figure 6~~The process begins at the hopper where the residues are fed into the machine. Inside the hopper are the blades which shred the residues into small sizes. The electric motor is located at the bottom. Power is transmitted from the electric motor to the shredding shafts through a chain and sprocket drive system. A pair of Spur gears is used to drive the dual shafts in opposite directions. The bearings support and allow the rotation of the shaft and the blades. The frame supports the whole machine together and the outlet is where the shredded residues are discharged.

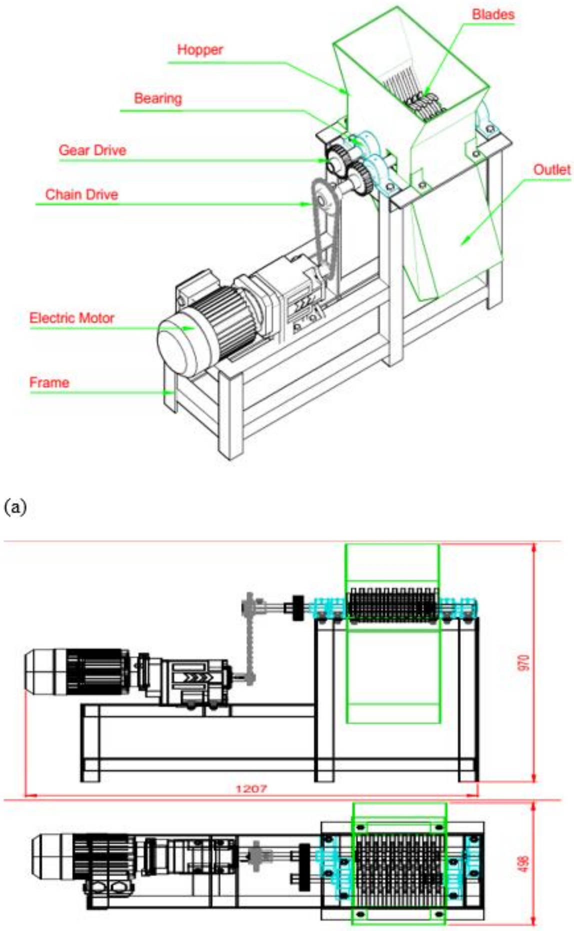

Figure 7: Concept 2 (a) Isometric View (b) Orthographic views

Concept 3 (Single Shredding Shaft with Direct Drive)

This concept consists of an electric motor, a shaft with blades arranged on it, bearings, a frame, outlet and a hopper~~ in (Figure 8Figure 8)~~. The process begins at the hopper where the residues are fed into the machine. Inside the hopper are the blades which shred the residues into small sizes. The electric motor is located at the top and directly coupled to the single shredding shaft. Unlike concepts 1 and 2, this concept does not use spur gears since the shaft is only one. The bearings support and allow the rotation of the shaft and the blades. The frame supports the whole machine together and the outlet is where the shredded residues are discharged.

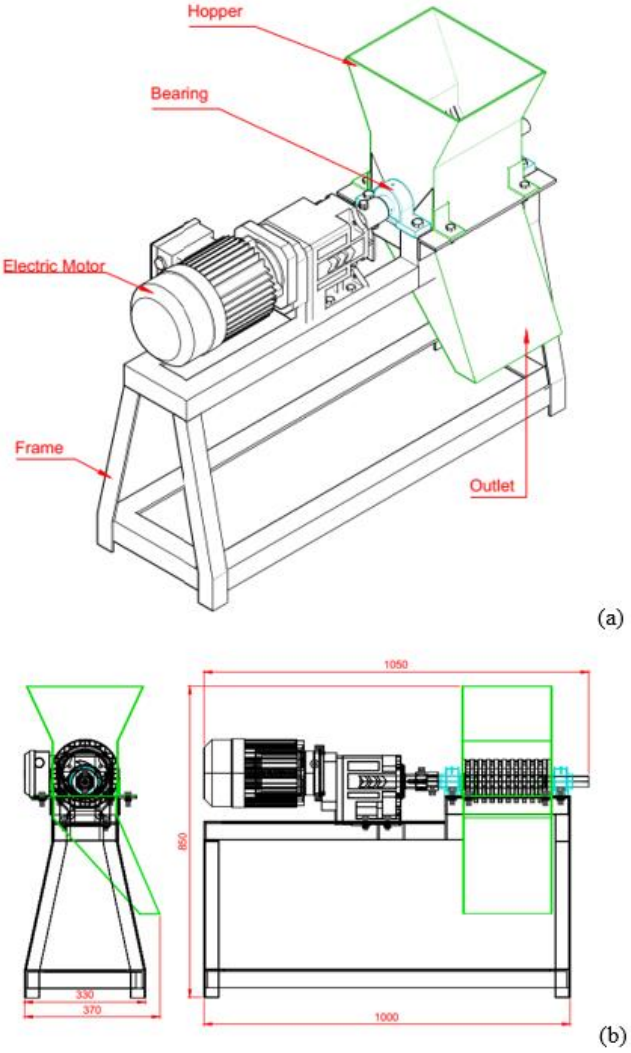

Figure 8: Concept 3 (a) Isometric view (b) Orthographic Views

Conceptual Evaluation Parameters

The cost of fabrication, ease of operation, ease of maintenance, shredding capacity, and ergonomics were the parameters used to evaluate the conceptual designs.

Cost of fabrication

This parameter considered and estimated cost of fabrication in each conceptual design with special emphasis on the materials costs, labour expenses, and tooling requirements. These components were evaluated using a decision matrix for the machine, offering a detailed perspective on the financial impact of each design alternative. By examining these cost elements, decision-makers can gain insights into the economic viability and possible compromises of the various conceptual designs, leading to more informed decisions in the machine development process.

Ease of operation

This particular parameter shows how easily or difficult the chosen design can be operated. This parameter evaluated how efficiently each of the three conceptual designs could operate under normal conditions. It also took into account the technical knowledge involved in the operation of the selected design.

Ease of maintenance

The ease of maintenance of the machine is a critical factor in the decision-making matrix, emphasizing the simplicity and efficiency of machine maintenance. This aspect covers key elements that affect overall maintainability, including the ease with which technicians can access and service different parts, and the availability of spare parts in the market.

Shredding Capacity

The shredding capacity parameter provides a comparative analysis of features across different conceptual designs of crop residue shredders. This evaluation focuses on assessing the fundamental capabilities that directly impact the machine's core performance in shredding crop residues.

Ergonomics

The operation of the machine involves humans. Therefore, the height of the shredder, location of control handles and safety issues were considered under this parameter.

Evaluation criteria

The three conceptual designs were assessed based on the evaluated parameters discussed above, and the criteria with which these parameters were evaluated have been elaborated in Table 1~~Table 1Table 1~~ and Table 2 below~~Table 2 below.~~

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Table 1: Evaluation Criteria

Parameters	**Magnitudes**		
Cost of fabrication	≤GH¢7,000	GH¢7,100-8,000~~8000~~	≥GH¢8,100~~8100~~
Score	3	2	1~~1~~
Ease of Operation	Easy	Moderate	Difficult
Score	3	2	1
Ease of Maintenance	Easy	Moderate	Difficult
Score	3	2	1
Shredding capacity	High	Medium	Small~~Low~~
Score	3	2	1
Ergonomics	Excellent	Acceptable	Needs improvement
Score	3	2	1

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Table 2: Decision Matrix

Parameters	**Concept 1**	**Concept 2**	**Concept 3**
Cost of fabrication	GH¢7,0~~2~~00.00	GH¢7,600.00	GH¢6,400.00
	3~~2~~	2	3
Ease of operation	Easy~~Moderate~~	Easy~~Moderate~~	Easy
	3~~3~~	3~~3~~	3
Ease of Maintenance	Easy	Easy	Easy
	3	3~~2~~	3~~1~~
Shredding capacity	Medium~~High~~	Medium	Small~~Low~~
	2~~3~~	2~~3~~	1~~2~~

Ergonomics	Excellent	Excellent	Excellent~~Acceptable~~
	3	3	3~~2~~
Total	(14~~4~~/15) * 100	(13/15) * 100	(13~~1~~/15) * 100
	93.33~~93.3~~%	86.67%	86.67~~73.33~~%

Selection of Final Design

Each conceptual design includes a frame, hopper, electric motor, outlet, gear drive system, bearings, and blades. The majority of the components were made from carbon steel, including flat bar, mild plate, and angle iron. They however differed in their frames, gear drive systems, shafts, blades, and hopper sizes. In the end, the concept 1 was selected due to its practical scores across various critical evaluation parameters. The design showed significant practical benefits, achieving high scores in cost of fabrication, ease of operation, ergonomics and ease of maintenance. These performance metrics made the concept 1 as the most feasible and optimized option among the designs considered.

Description of Final Design

The prototype of the selected conceptual design is made up of an electric motor, spur gear, dual shaft, bearings, blades, outlet, hopper and the frame. The frame carries the load of the machine, and provide support during operation while the blades shred the crop residues into smaller sizes. The shredder is powered by the electric motor through the gears to cause the rotation of the shaft to shred the crop materials.

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Design Analysis

Determination of the volume of the hopper

The shape of the hoppers is trapezoidal and the following formulae were used for the design calculation:

$$\mathrm{A_1 = L_1 \times W_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

Where $\mathrm{A_1}$ = Area of the top rectangle

$\mathrm{l_1}$ = length of the top opening

$\mathrm{w_1}$ = width of the top opening

$$\mathrm{A_2 = L_2 \times W_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Where $\mathrm{A_2}$ = Area of the bottom base

$\mathrm{l_2}$ = length of the bottom base

$\mathrm{w_2}$ = width of the bottom base

h = height of the hopper

$$\text{The volume of the hopper} = \frac{h}{3}\left(A_1 + A_2 + \sqrt{A_1 \text{ x } A_2}\right) \ldots\ldots\ldots\ldots (3)$$

Power transmission

The selected crop residue shredder concept chosen for the machine showed it was to be powered by an electric motor. The motor will provide the necessary power to drive the cutting mechanism to cut or slice the residues into small pieces.

Power transmitted by shaft in watt was determined as;

$$\mathrm{P = F \times V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where: $P = \text{power } (\text{Nms}^{-1})$

$F = \text{force of shredding (N)}$

$V = \text{velocity } (\text{ms}^{-1})$

The force required for the shredding is given as;

$F = m\omega^2 r$ ……………………………………………………. (5)

$F = \text{force required to shred the crop residue}$

$m = \text{mass of shredding blades}$

$\omega = \text{angular velocity of the shaft}$

$\omega = \frac{2\pi N}{60}$, N is the speed of shredding(rpm) …………… (6)

The = power delivered by the shaft is given by:

$P = F\omega r$ ………………………………………………….. (7)

The Shaft diameter

The diameter of the machine's shafts was estimated using the maximum shear stress theory, which, according to Khurmi & Gupta, (2005), is suitable for shafts experiencing combined bending and twisting moments, as with the shafts in this machine. These shafts are constructed from mild tough steel. The diameter was calculated based on the maximum stress theory (Hall et al., 1980), and the following formula was used to determine its size:

$$d^3 = \frac{16}{\pi\, Ss}\sqrt{(kt\ \times mt)^2 + (kb\ \times mb)^2} \qquad \text{……….} \ (8)$$

Where, d = diameter of the shaft (mm)

Ss = Allowable shear stress of metal with key

Mb = maximum bending moment (Nmm)

Mt = torsion moment (Nmm)

Kb = combined shock and fatigue factor applied to bending moment

Kt = combined shock and fatigue factor applied to torsional moments.

The shredder shaft is rotating within the shredder chamber and it is equipped with blades and spacers. These blades were arranged on the shaft with the spacers to allow the shredding of the crop residues materials.

Shear force and bending moment

Driving shaft

The vertical forces acting on the driving shaft of the shredder are represented by the diagram shown in Figure 9~~Figure 9Figure 9~~.

Determining the Reactions at the bearings supporting the driving shaft

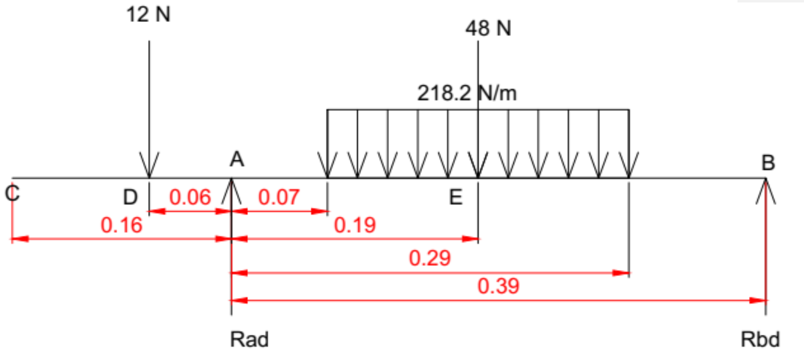

Figure 9: Vertical Loading of the Driving Shaft

Taking moments about point A and equating the sum of Clockwise Moments to the sum of Anticlockwise Moments in Figure 9~~Figure 9Figure 9~~. the reaction R_{bd} was calculated to be 21.54 N. For equilibrium, total upward forces must be equal to total downward forces. Applying this rule to Figure 9~~Figure 9Figure 9~~ the reaction R_{ad} was determined to be 38.46 N

Taking point C as the reference, and employing the singularity function in Microsoft Excel, the shearing forces at points C, D, A, E, and B were determined to be 0, -12 N, 26.46 N, -21.54 N, and 0 respectively in Figure 10~~Figure 10Figure 10~~. The moments at the same points were found to be 0, -0.3 Nm, -0.6 Nm, 4.3074 Nm, and 0 respectively Figure 10~~Figure 10Figure 10~~. The maximum bending moment on the driving shaft was 4.3074 Nm and it occurred at point E (the middle of the length covered by the shredding blades.

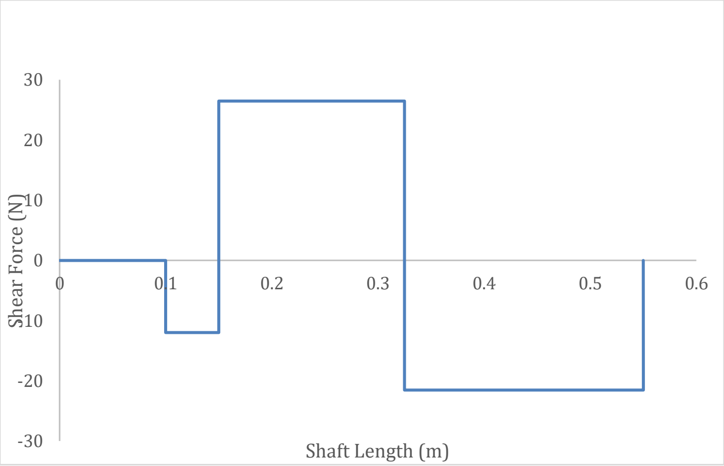

Figure 10: Shear Force Diagram for the Driving Shaft

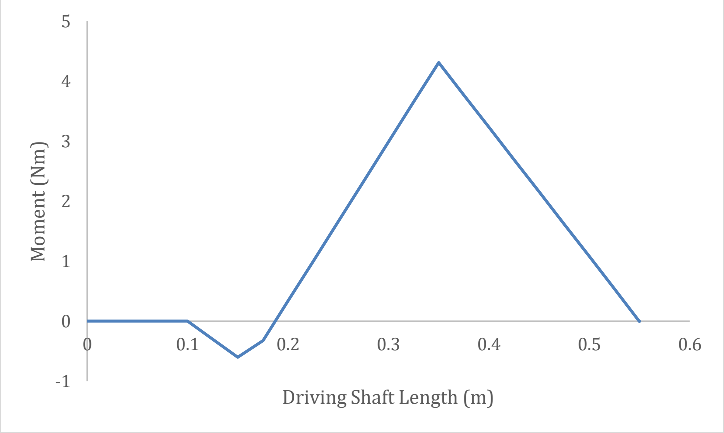

Figure 11: Moment Diagram for the Driving Shaft

Driven Shaft

The vertical forces acting on the driven shaft of the shredder are displayed in diagram shown in Figure 12~~Figure 12Figure 12~~.

Determining the Reactions at the bearings supporting the driven shaft

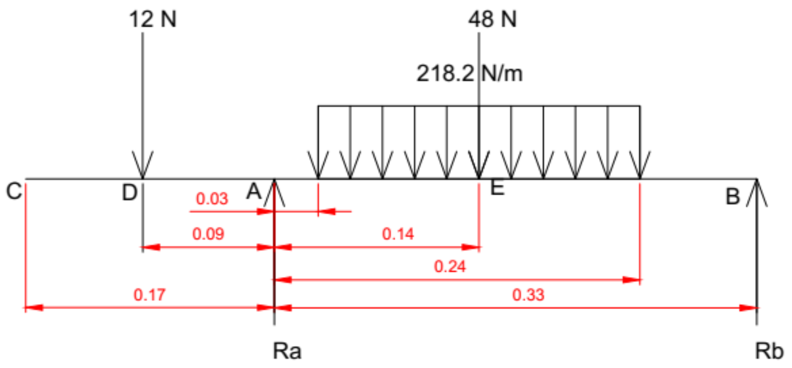

Figure 12: Vertical Loading of the Driven Shaft

Taking moments about point A in Figure 12~~D~~ and equating the sum of Clockwise Moments to the sum of Anticlockwise Moments, the reaction R_b was calculated to be 17.09 N. For equilibrium, total upward forces must be equal to total downward forces. Applying this rule to Figure 12~~Figure 12Figure 12~~, the reaction R_a was calculated to be 42.91 N.

Taking point C as the reference point, and using the singularity function in Microsoft Excel, the shearing forces on the driven shaft at points C, D, A, E, and B were found to be 0, -12 N, 30.91 N, -17.09 N, and 0 respectively Figure 13~~Figure 13Figure 13~~. The moments at the same points were found to be 0, -0.24 Nm, -0.84 Nm, 2.9383 Nm, and 0 respectively Figure 14~~Figure 14Figure 14~~. Therefore, the maximum bending moment on the driving shaft is 2.9383 Nm and it occurred at point E (the middle of the length covered by the shredding blades.

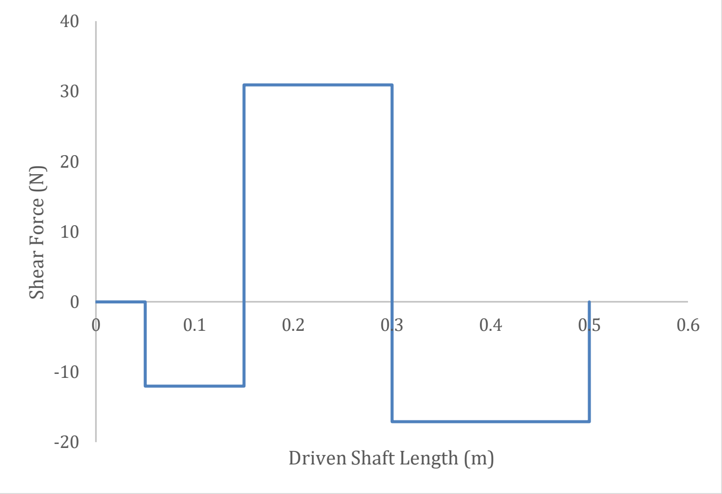

Figure 13: Shear Forces on the Driven Shaft

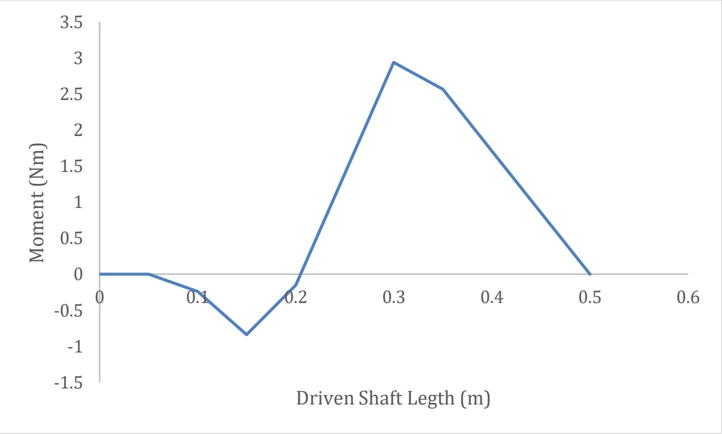

Figure 14: Bending Moments on the Driven Shaft

Factor of safety

The machine's design integrity is verified by ensuring the safety factor exceeds 1, which guarantees the machine will not structurally fail under load. Here, (FoS) is the factor of safety, 'YS' represents the yield strength of the material used, and 'WS' denotes the working stress or the maximum stress. The computation was performed using the equation below:

$$\mathrm{FoS} = \frac{\mathrm{Y_S}}{\mathrm{W_S}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Finite Element Analysis (FEA) of the Shredder

Finite Element Analysis (FEA) enables the prediction of a machine component's response to real-world forces, vibrations, heat, fluid flow, and various physical effects. The steps followed in conducting FEA in Autodesk Inventor are illustrated by the block diagram in ~~(~~Figure 15~~Figure 15Figure 15)~~.

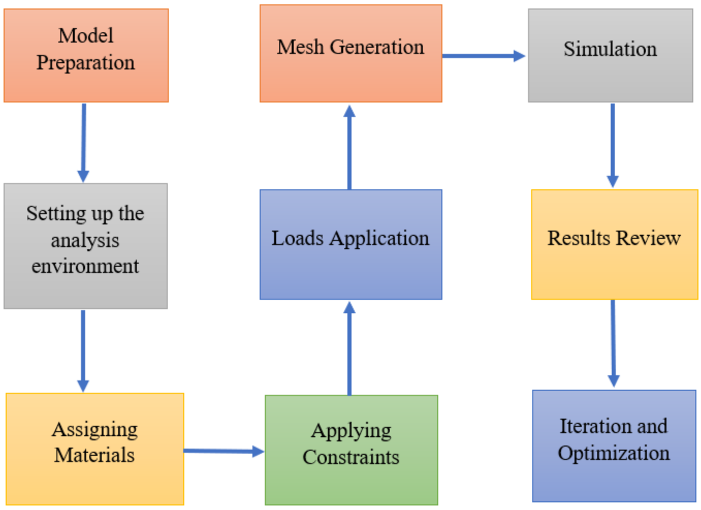

Figure 15: Steps Involved in Finite Element Analysis

Model Preparation

The three-dimensional (3D) model of the structure or machine component using AutoCAD Mechanical 2022 Version, and subsequently imported into Autodesk Inventor Professional 2023 for the FEA.

Setting up the Analysis Environment

After the model was imported into the Autodesk interface, "stress analysis" was selected from the ribbon under the "environment" tab. In the stress analysis ribbon, "create study" was selected followed by the selection of "static analysis" from the opened study dialogue box.

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Note: Discuss with your supervisor

Assigning Materials

After setting up the analysis environment, the next step in the analysis is to assign material to the model. If the model is made up of different parts with different materials, all the appropriate materials would be assigned to the appropriate parts. Autodesk Inventor provides a library of materials with predefined properties. Under the "Assign Material" button, there is a provision for original material and overriding material. The mechanical properties of the original material were applied in the analysis. The overriding material only gave the colour of the model.

Applying Constraints

This involved fixing or constraining certain faces or edges to simulate real-world boundary conditions. The constraints in Inventor are Fixed, Pin, and Frictionless. The fixed constraint restricts motion in all directions. The pin constraint restricts motion in radial, axial or tangential directions, depending on the options you set. The frictionless constraint restricts motion of a face in the direction normal to the face.

Loads Application

This had to do with the application of the appropriate loads to the respective components or points in the model during the simulation. The loads applied on the frame, shaft and blade were 765N, 9463 N, and 492.670 N respectively must be the maximum forces exerted on the components during the actual operation of the machine.

Mesh Generation

The shredder has several components with varying geometries, some having irregular shapes and sizes. Calculating the total deformation of these elements or determining the stress produced during operation would be extremely laborious. Meshing simplifies these calculations by dividing the geometry into smaller elements for which specific formulas and functions exist to compute these outcomes. All these results are then integrated to get the total solution for the geometry.

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Simulation

After the setup was complete, the simulation or analysis was made to run to solve for the behaviour of the model under the defined loads and constraints. Inventor uses algorithm solutions to calculate displacements, stresses, strains, and other relevant results.

Simulation results review

After the completion of the analysis, the results were assessed to get to know how the model behaved under applied conditions. Inventor provides visual feedback through contour plots, deformation animations, stress plots, and more.

Machine description

Table 3: Machine description

No.	Description	Specification
1.	Name of machine	Crop residues shredder machine
2.	Mechanism	Spur Gear
3.	Target Customer	Small scale Farmers
4.	Manufacturing	Machining, Bending and Fabrication
5.	Safety	Avoid sharp corners, Safety guard
6.	Cost	7,000
7.	Life of the machine	10 years
8.	206 Pillow block bearing	Cast steel
9.	Working RPM	220RPM
10.	Weight of machine	109.9kg
11.	Shredding rate	15kg /h
12.	Volume	14.78liters

Machine Component Description

Table 4: Machine Components Description

Item No.	Name of the components	Description	QTY.
1	Frame	Mild Steel angle iron	1
2	Hopper	Mild Steel Plate	1
3	Blades	Mild Steel	16
4	Shafts	Mild Steel	2
5	Spacer	Mild Steel	16
6	Outlet/Discharge	Mild Steel (Steel metal)	1

7	Spur Gear	Carbon steel	2
8	206 Pillow Bearing	Cast iron	4
9	Electric Motor	3 Hp (2.24 kW), 1350 rpm	1
10	M10 Bolt and nuts	Mild Steel	13
11	M8 Bolts and nuts	Mild Steel	8
12	Sieve	Mild steel	1
13	Guard	Mild steel	1
14	Coupling	Mild steel	1

Manufacturing of the main components

The construction of the crop residue shredder took place in a local metal workshop in Cape Coast. The main manufacturing steps included measuring, marking, punching, drilling, hammering, cutting, welding, shaping, bending, grinding, and bolting. The sub-assemblies consisted of the frame, hopper, blades, shaft, sieves, and the outlet. The processes are described as follows:

The frame sub-assembly

The fabrication of the frame Figure 16~~Figure 16Figure 16~~ was made by using mild steel angle iron of 4mm thickness cutting them into various heights and lengths: four pieces at 600mm for the legs, two at 670mm for the long side rails, four at 300mm for the short cross members, and four at 400mm for the width supports. Additionally, a mild steel plate measuring 300mm x 346mm and 4mm thick was cut for the motor seat, along with four 400mm pieces of angle iron for the hopper seat. The assembly begun by welding the long side rails to the legs to form a basic rectangular frame with dimensions of 1055mm in length, 300mm in width, and a height of 670mm. Cross members were then placed between the long rails for extra support, and supports attached at the top and bottom for enhanced stability. The hopper seat was constructed into a square frame with an interior opening of 400mm x 435mm, which was then centred and attached to the top end of the stand. The motor seat was created to support brackets under the specified area and securing the steel plate on top. Subsequently, drilling mounting holes was created: four in the hopper seat frame and four in the motor seat. An additional eight holes were drilled into the frame to hold the bearings connected to the two shafts. Post-drilling, all welds are smoothed with a grinding machine. The final stage involves cleaning to remove any oil, applying a steel coat, and then painting.

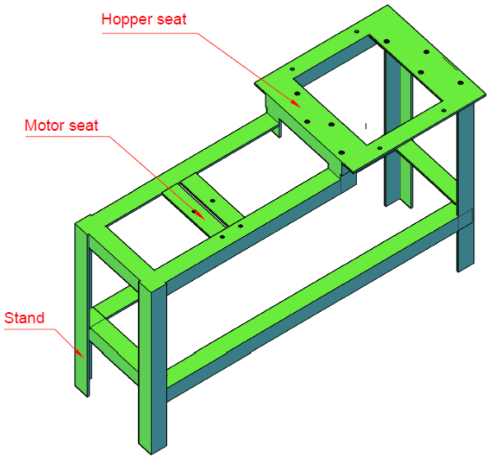

Figure 16: Frame sub-assembly

H~~The h~~opper sub-assembly

The manufacturing process of the hopper (Figure 17~~Figure 17Figure 17~~) began with the selection of a 3mm thick mild steel plate. It continued with cutting the metal sheet into specific panels: two trapezoidal pieces for the front and back measuring 440mm at the top, tapering to 350mm at the bottom, with a height of 150mm, and two rectangular side panels measuring 250mm by 150mm. Once the main panels were cut, the next crucial step was the bending process. The plate was then bent into a U-shape, with 90-degree bends 150mm from each long edge. These parts were welded together, attaching the side pieces to the main body to form the hopper's shape. Four mounting flanges were fixed onto the bottom corners, checked for level and alignment. The hopper opening sides, measuring 50mm by 65mm were then cut near the bottom to accommodate two shafts. All welds were subsequently smoothed, to eliminate sharp edges. Four 10mm diameter holes were drilled into the mounting flanges for fastening. The finished hopper was inspected to check all welds and bends, and to confirm the dimensions and alignment of the mounting holes.

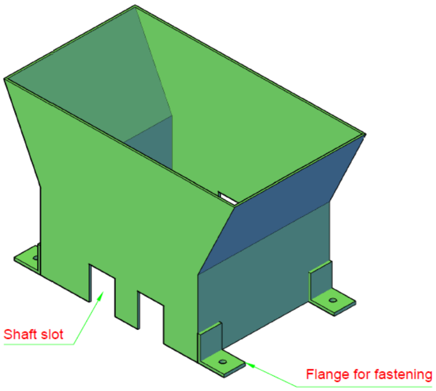

Figure 17: Hopper sub-assembly

The shaft sub-assembly

The two shafts were crafted from carbon steel, known for its strength and durability. The material was cut to lengths of 705mm with a diameter of 35mm for the longer shaft, and 545mm for the shorter one. After cutting, the shafts underwent heat treatment to improve their mechanical properties. Surface polishing was also performed to minimize friction and enhance corrosion resistance. Finally, a keyway of width of 10mm, height of 8mm and depth 5mm was created on both shafts to ensure a proper fit with the gear shaft, effectively supporting the cutting blades.

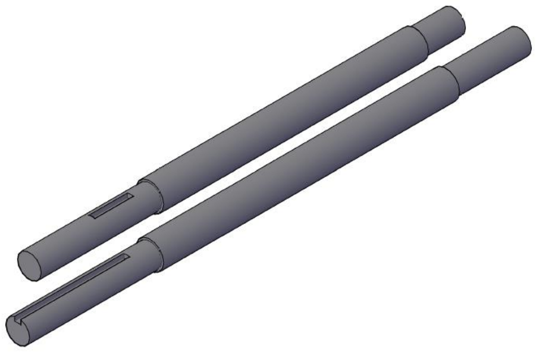

Figure 18: Shaft sub-assembly

The blades sub-assembly

The blade is a crucial component of the shredder machine which is meant for cutting the crop residues into fine particles. It was manufactured from hardened carbon steel flat, chosen for its durability. The blade was crafted using a heat treatment furnace, which shaped the three curved arms, created a central hole with a diameter of 35mm, and formed the outer edges with precise radii—50.21mm for the larger curves and 14.44mm for the smaller ones. Additionally, a blade's tip was designed with a 10.29mm edge.

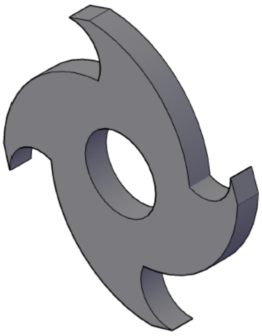

Figure 19: Blade sub-assembly

Sieves sub-assembly

The sieve was located beneath the cutting blade assembly housing in order to allow the shredded waste materials (less than 20mm in length) to pass through the holes. The sieve was constructed using mild steel material with a length of 300mm long, and the width of the holes of 40mm which was formed into a concave shape.

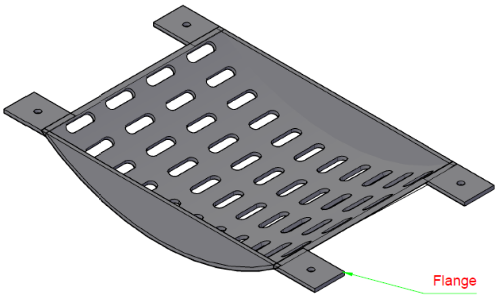

Figure 20: Sieve sub-assembly

Bearing sub-assembly

Two standard bearings readily available and cannot be constructed in the workshop were used. They were selected based on the required inner and outer diameter of the shaft.

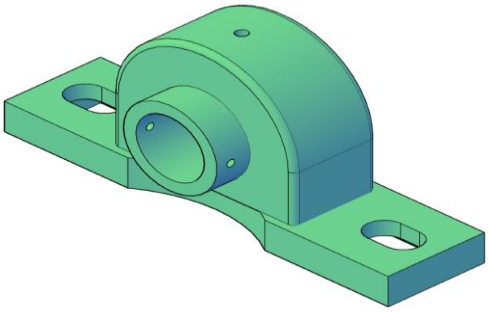

Figure 21: Bearing sub-assembly

Spur gear sub-assembly

Two commercially available external spur gear pairs (Figure 22~~Figure~~ 22~~Figure 22~~) were used, as they could not be fabricated in the workshop. These gears were selected specifically to match the required shaft inner diameter and were mounted on parallel shafts to ensure efficient power transmission.

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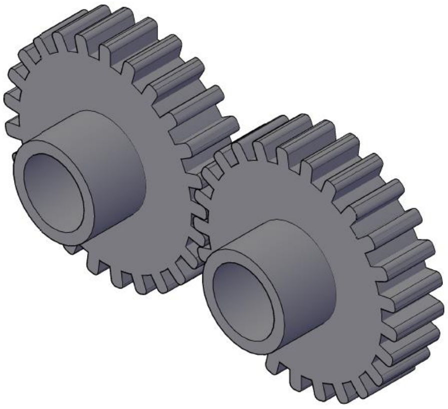

Figure 22: Spur gear sub-assembly

Performance Evaluation of the Manufactured Crop Residue Shredder

The crop residue shredding machine was developed and evaluated to assess its performance in terms of shredding efficiency, power consumption, and throughput capacity. A factorial arrangement in completely randomized design (CRD) was used as the experimental design for the study. The two factors tested were: crop residues and rotational speeds, each with three levels. The three crop residues used (see Figure 23~~Figure 23Figure 23~~) were maize stalk, sorghum stalk, and millet stalk and rotational speeds were 55rpm, 110rpm, and 220rpm. In all, there were nine treatment combinations and having three replications, which gave twenty-seven (27) total runs.

The crop residues used for the evaluation

Figure 23: crop residues

Moisture Content

To determine the moisture content, three types of crop residues maize stalk, millet, and sorghum-were gathered from Tamale in the northern region. These residues were air-dried to ascertain their moisture content before shredding. To determine the moisture content, samples from the stalks of the three different crops were selected. These samples were weighed and recorded before being placed in the dryer. They were put into an oven at temperature of 105°C for a period of twenty-four (24) hours. Post-drying, the samples were weighed again, and the moisture content was determined using the following formula:

$$\text{Moisture content} = \frac{\text{Initial weight} - \text{final weight}}{\text{Initial weight}} \times 100\% \text{........}(10)$$

Results of the moisture content presented in table 5

Table 5: Moisture content

Crop residues	Weight before drying (g)	Weight after weight after (g)	Moisture content (%)
Maize stalk	7.7	6.8	11.69%
Millet stalk	3.8	3.4	10.53%
Sorghum stalk	14.1	12.3	12.77%

The shredding efficiency

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The shredding efficiency was determined by first weighing and recording the total weight of the crop residue input. Then, after shredding, the weight of the shredded crop residues was measured. This weight was divided by the total weight of the input crop residue and multiplied by 100%.

$$\text{Shredding efficiency} = \frac{\text{Mass of output crop residue (kg)}}{\text{Mass of input crop residue (kg)}} \times 100\% \ldots (11)$$

$$\text{Throughput capacity} = \frac{\text{Mass of shredded crop residue (kg)}}{\text{Time taken to shred the crop residue (hr)}} \ldots.(12$$

The power consumption

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Calculating the power consumption of a shredder is essential for understanding its impact on the energy used and the electricity cost when using the shredder. The power consumption is determined by the device's wattage and the amount of time it is in operation.

The formula to calculate the power usage in kilowatt-hours (kWh) is:

$$\text{Energy (kWh)} = \text{Power(kW)} \times \text{Time (h)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(13)}$$

Particle Size Analysis

The particle size distribution was evaluated using five standard sieves and a bottom pan to collect the remnants passing through the fifth sieve. The sieves were organized in descending order, from the largest to the smallest in hole sizes in (millimetres). An average weight of 100g was recorded for all the samples prior to sieving. The sample was placed into the first sieve, covered with its lid, and manually shaken for 10 minutes. The particles retained in each sieve were weighed and the corresponding data documented.

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Statistical analysis

Data on shredding efficiency, shredding time, and throughput were collected from the shredder's evaluation and analysed using the 2021 version of Minitab. The data was subjected to an analysis of variance (ANOVA), with means separated at a 5% significance level. Where differences exist, the Tukey HSD test was used to separate the mean. Also, basic statistical methods in Microsoft Excel (2020), which involved calculating the percentages, means and plotting graphs were done.

CHAPTER FOUR

RESULTS AND DISCUSSION

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The primary objective of this study was to develop a crop residue shredder and evaluate its performance. This chapter details the results and discussion of the study. It consists of the results of the construction as well as the outcome of the structural simulation of the key components of the design and the evaluation of the constructed shredder.

Design and construction of crop residue shredder

The shredder which was designed and manufactured for smallholder farmers was aimed at facilitating the shredding of crop residues. The fabrication was done using local materials and the final product is presented in Figure 25~~Figure 25Figure 25~~. The machine component was first modelled in three dimensions using AutoCAD Mechanical 2022, then imported into Autodesk Inventor Professional 2023 for finite element analysis (FEA).

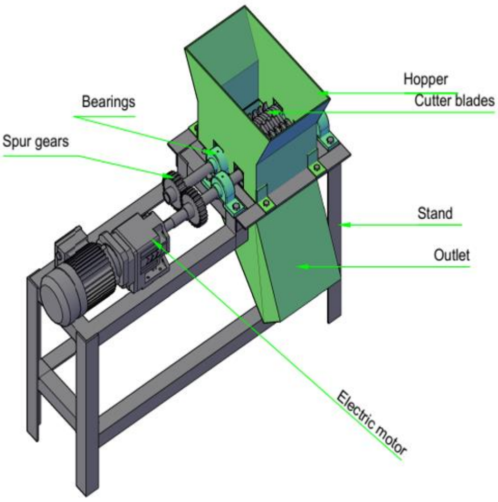


Figure 24: Dimensional view of the shredder

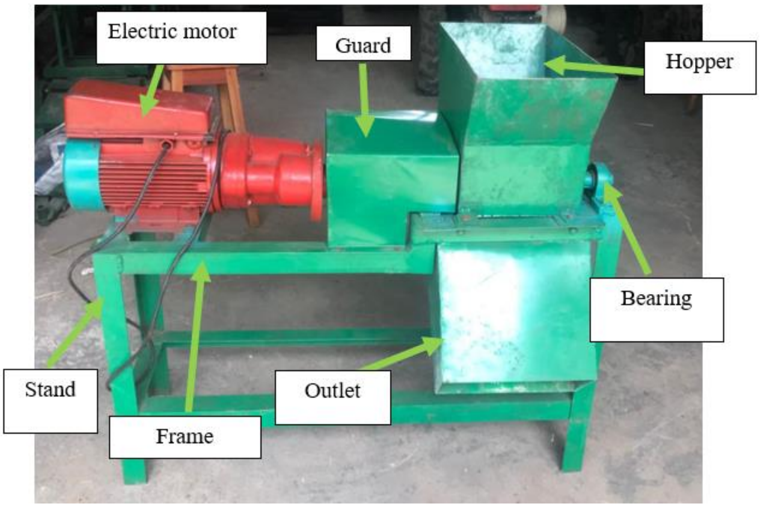


Figure 25: The manufactured crop residue shredder

Simulation Results

The Frame

The Figure 26~~Figure 26Figure 26~~ shows the output of the simulation where ~~that~~ the maximum Von Mises stress (12.26 MPa) is well below the yield strength of mild steel (207 MPa) used for the frame, indicating that the frame is not likely to experience any plastic deformation or failure under the given load.

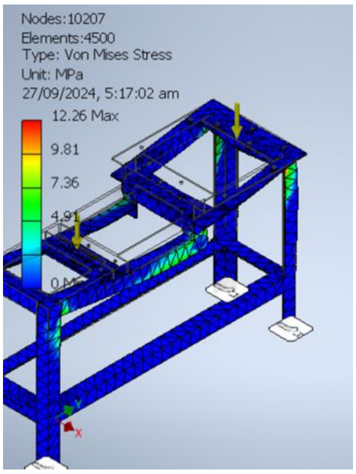
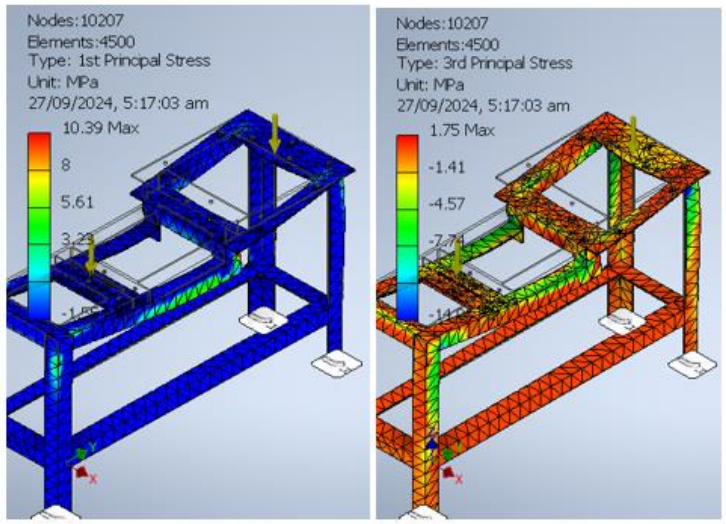


Figure 26: Von Mises Stress on the Frame

The Figure 27~~Figure 27Figure 27~~ shows the tensile and compressive stresses in specific directions. The maximum values of the 1st and 3rd Principal Stresses are 10.389 MPa and 1.74634 MPa, which are still much lower than the yield strength, indicating safe operation.



(a) (b)

Figure 27: Principal stresses (a) 1st principal Stress (b) 3rd Principal Stress

The frame experienced minimal displacement under the applied load (0.099 mm), a good indication of structural stability. A factor of safety~~safety factor~~ of 15 was recorded which gives a good high safety margin since it implies the structure can handle 15 times the applied load before failing.

The Shredder Blade

Figure 28~~Figure 28Figure 28~~ shows the simulation results of~~n~~ the blade where the maximum Von Mises stress (184.96 MPa) is below the material's yield strength of the high-strength steel with low alloy (275.8 MPa) used for the blade, meaning the blade is strong enough to bear the load without deforming.

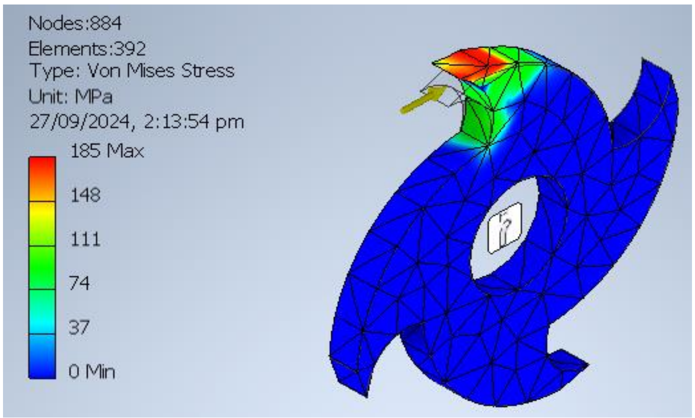


Figure 28: Von Misses stress on the blade

The results for the shredder blade indicate that the displacement is minimal, measuring ~~-~~(0.064 mm). Additionally,~~, and~~ the factor of safety (15~~1.49~~) as shown in Figure 29~~Figure 29Figure 29~~ is above one (1), indicating that the design is~~a~~ safe.~~ design.~~ The simulation further suggests that the shredder blade will operate effectively~~perform well~~ under the applied force of 4912.67 N while~~en~~ shredding millet stalks, without any risk of failure or excessive deformation.

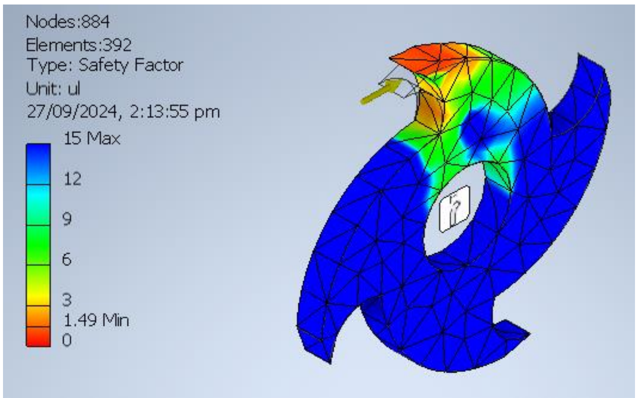


Figure 29: The Factor of Safety of the blade

The Driving Shredding Shaft

Figure 30~~Figure 30Figure 30~~ shows the simulation results of the driving shredder shaft. The results indicate~~d~~ that the maximum Von Mises stress on the shaft (0.247 MPa) is well below the yield strength of mild steel (207 MPa), meaning the shaft is highly unlikely to experience any permanent deformation under this load.

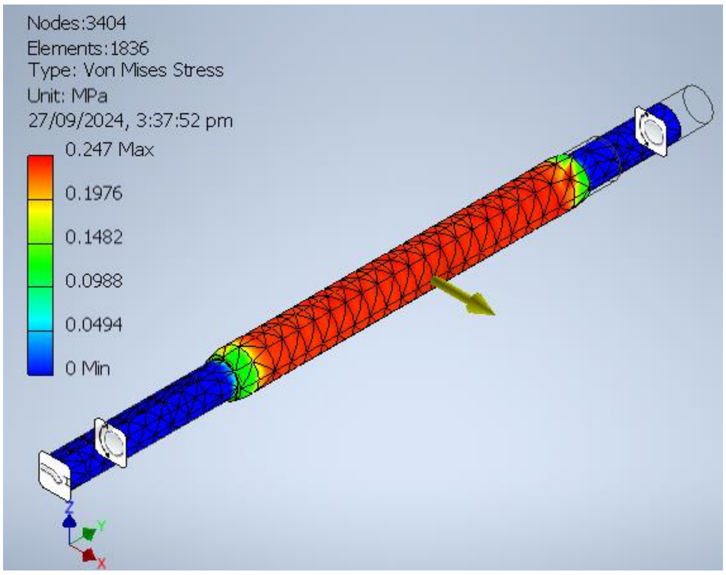


Figure 30: Von Mises Stress on the Driving Shredder Shaft

The displacement result in Figure 31~~Figure 31Figure 31~~ is very small shows ~~the displacement result which is extremely small~~ (0.214 micrometres), indicating that the shaft remains rigid and stable under the applied load.

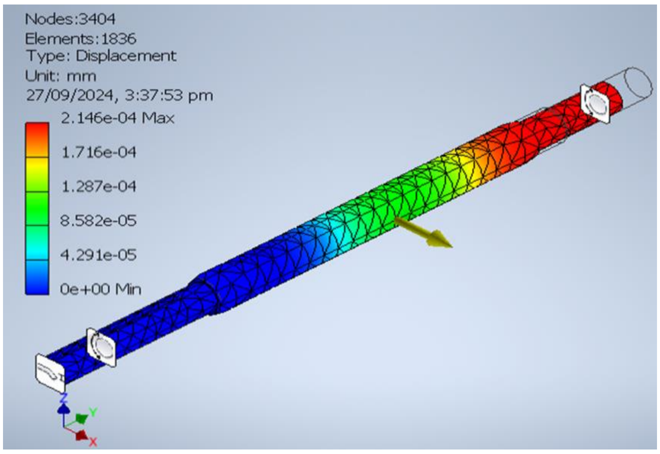


Figure 31: Displacement of the shaft

The Figure 32~~Figure 32Figure 32~~ shows the output of the factor of safety analysis and in this case a maximum factor of~~-~~ safety of 15 for the shaft was realised, indicating that the design is safe to use. The shaft can withstand loads far greater than what is currently applied, making the design extremely safe.

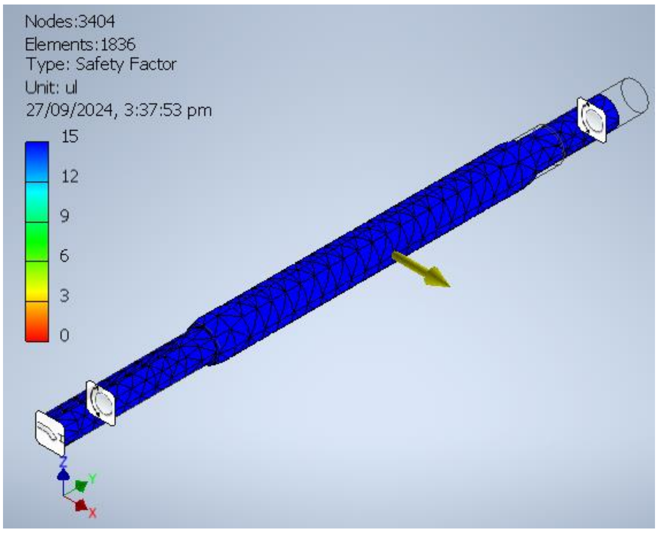


Figure 32: Safety Factor of the Driving Shredder Shaft

Discussion of the Simulation Results

The simulation results demonstrate that the designed crop residue shredder exhibits robust structural integrity across all critical components. The frame, constructed from mild steel, demonstrated a good resilience under applied loads. With a maximum Von Mises stress of (12.26) MPa significantly below the material's yield strength of 207 MPa. The frame showed minimal displacement of 0.099 mm and a factor of safety was 15 which gives a good high safety margin since it implies the structure can handle 15 times the applied load before failing. The shredder blade, crafted from high-strength low-alloy steel, showed a good result with the maximum Von Mises stress of 184.96 MPa which is lower than the material yield strength of 275.8 MPa. The blade’s minimal displacement is 0.064 mm and a safety factor of 1.49. The blade showed it can shred crop residues without risk of deformation. Stress distribution across the blade is crucial for its operational efficiency. Studies show that improper blade orientation can lead to increased resistance forces, affecting the shredding quality (Sheichenko et al., 2023). Finite Element Analysis (FEA) has shown that stress levels in blades can vary widely based on design and operational conditions, with some studies reporting stress levels as low as 5.070 MPa (Celik et al., 2024).

The driving shredding shaft showed low maximum Von Mises stress of 0.247 MPa, a displacement of 0.214mm and factor of safety of 15 which ensures that there would be no unexpected operational stresses. A factor f safety of 15 ensures that the machinery can withstand unexpected loads and stresses, reducing the likelihood of failures (Akhtar Khan et al., 2023). Hwang et al. (2024) stated that factor of safety greater than 1 are essential for predicting the fatigue life of machinery components, ensuring they can withstand operational stresses over time.

The colour-coding system in Finite Element Analysis (FEA) visualization is crucial for interpreting stress distributions, particularly Von Mises stress. This system enhances understanding of stress concentration and load distribution, which is vital for engineering design and structural integrity. The spectrum from dark blue to red effectively communicates varying stress magnitudes, allowing engineers to quickly identify critical areas. The colour spectrum in the FEA visualization provides a clear representation of stress levels, transitioning from dark blue (low stress) to red (maximum stress). The red regions indicate high stress concentrations, often found in geometric transition zones, while orange and yellow signify moderately high stress areas. Green represents medium stress levels, and light blue shows lower stress intensity, facilitating a comprehensive understanding of the stress gradients (Ma, 2024; Wang et al., 2023).

Performance Evaluation of the Shredder

The developed crop residue shredding machine and its were evaluated based on shredding efficiency, power consumption and throughput capacity using three speeds (55, 110, and 220 rpm) and three feedstocks (millet stalk, sorghum stalk and maize stalk).

Shredding Efficiency

~~The Figure 33~~Figure 33 presents the shredding efficiencies of the shredder for three types of crop residues: maize stalk, millet stalk, and sorghum stalk, across different speeds of 55~~rpm~~, 110, and 220 revolutions per minute (rpm). The efficiency graph indicates that shredding performance improves markedly with increased rotational speed. At 220 rpm, the maize stalks achieved the highest efficiency of 82.5 %, followed by millet (79.2 %) and sorghum (77.5 %). The relationship between speed and efficiency is consistent with Zhao's (2012) findings, which indicate that higher speeds applied tend to increase the mechanical forces, thereby enhancing shredding efficiency. Moreover, Abdulkadir et al., (2020) observed a maximum efficiency of 93 % at 975 rpm, further corroborating that machine speed impacts the efficiency in shredding. It was observed that while the type of crop residue and speed were found to be statistically significant (p<0.05), the interaction effect is not statistically significant (p>0.05), which suggests that crop-specific physical properties and speed individually are key to determining the efficiency of shredders as reported by Busari et al. (2024).

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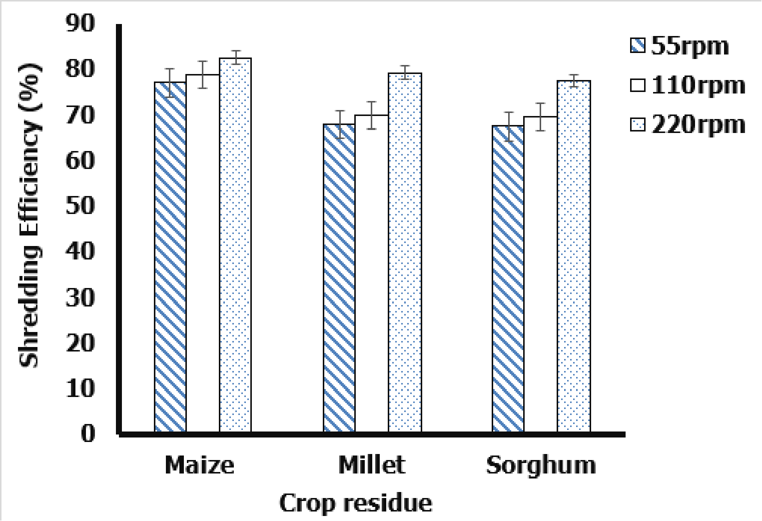

Figure 33: Shredding efficiency (%)

Shredding Time

Figure 34~~Figure 34Figure 34~~ displays the shredding time durations for the three different crop residues: maize, millet, and sorghum stalk, at varying speeds of (55, 110, and 220 rpm). The data in Figure 34~~Figure 34Figure 28~~ shows an inverse relationship between the speed and shredding time. At higher speeds, shredding time decreased across all crop types, with maize showing the most rapid processing. Sorghum, by contrast, consistently recorded the longest duration, nearly 600 seconds at 55 rpm, most likely due to its fibrous resilience. Millet had 520 seconds at 55 rpm while 260 seconds at 220 rpm. Lastly maize had 440 seconds at 55 rpm and 260 seconds at 220 rpm. It was observed that the type of crop residue and the speed had statistically significant effects ($p<0.001$), however, the interaction effect between them was not statistically significant ($p>0.399$), suggesting that the effect of speed remained consistent across different crop residue types, and vice versa.

The inverse relationship however, reveals that increased speed directly reduces time requirements, enhancing overall throughput potential and efficiency which was documented by Pintens et al. (2023) and Awgichew, (2020) who both emphasized the merits of optimizing shredder designs to accommodate variable speeds in response to different crop types. Also, the time reduction at higher speeds agrees with Jančík et al. (2022) suggesting that increasing speed improves shredding efficiency across crop types. However, the relatively longer times for sorghum even at high speeds underlines that material properties still play a crucial role as emphasized in studies by Awgichew, (2020) and (Salo et al., 2021).

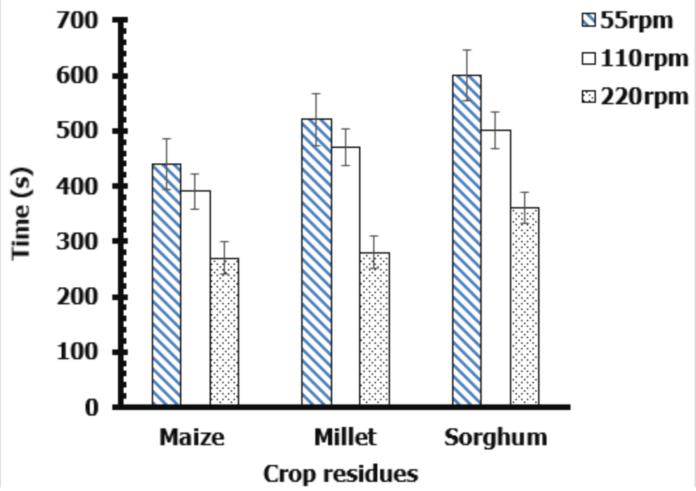

Figure 34: Time duration for shredding

Shredder's throughput capacity

~~The graph below~~Figure 35 ~~Figure 35~~ presents the throughput capacity in kg/h for three crop residues: maize stalk, millet stalk, and sorghum stalk, measured at three rotational speeds: 55rpm, 110, and 220 rpm. In ~~Figure 29~~figure 35, the throughput capacity mirrors the trend of efficiency, showing a clear positive relationship with rotational speed. Maize and millet achieved approximately 14.4 kg/h and 14.0 kg/h at 220 rpm, whereas sorghum had approximately 10.0 kg/h. The results showed that the speed and the crop residue had a statistically significant effect ($p<0.005$), indicating that varying speeds had a substantial impact on the throughput. However, the interaction between speed and crop residues (Speed*Crop Residues) were not statistically significant ($p>0.05$), implying that the influence of speed is consistent across different types of crop residues.

Awgichew, (2020) in a comparative analysis of maize and sorghum highlighted a similar trend, emphasizing that higher speeds yield enhanced throughput by reducing the frictional resistance within the shredder mechanism. The substantial jump in throughput capacity from 110 rpm to 220 rpm shows that higher rpm rates favour the processing of less dense residues like maize and millet.

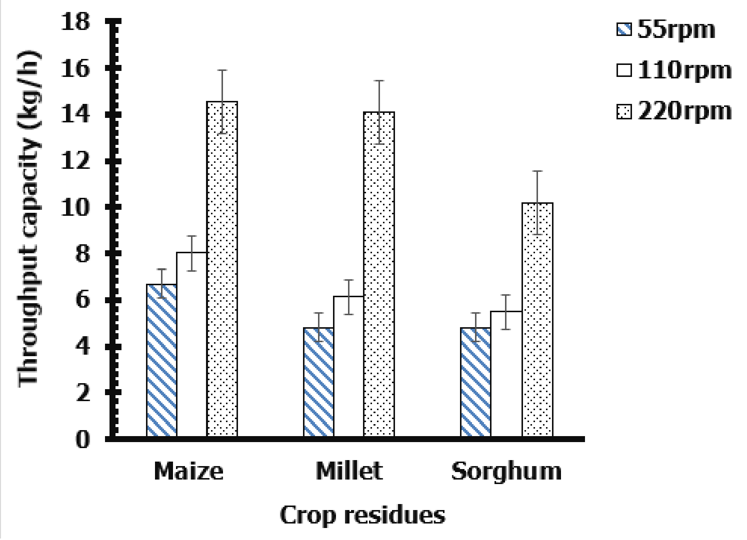

Figure 35: Throughput capacity (kg/h)

Shredder's power consumption

From ~~From Figure 36~~Figure 36,~~,~~ the power consumption was observed to have decreased as speed increased, with maize requiring 0.20 kWh at 55 rpm but only 0.10 kWh at 220 rpm. Millet on the other hand requires 0.25 kWh at 110 rpm but only 0.1 kWh at 220 rpm. Sorghum, however, consistently demanded more energy, consuming 0.26 kWh at 55 rpm and 0.14 kWh at 220 rpm. This trend reflects how prolonged shredding times at lower speeds lead to higher power usage aligning with findings that extended processing times significantly could affect energy consumption in machinery operations as noted by Beniak et al. (2012). The type of material being shredded also affects energy consumption, as different materials exhibit varying mechanical and physical properties that influence the energy required for shredding as stated by (Yu-jin, 2012) .

Thus, the faster the shredding process, the lower the cumulative energy demand, a principle also advocated by (Salo et al., 2021) in their exploration of power dynamics within agricultural shredding systems. Overall, the shredding speed reduced energy consumption, especially for less fibrous residues like maize and millet, reinforcing the value of calibrating shredding speeds to match specific crop properties. This reduction in power usage at higher speeds is a significant finding, especially from a sustainability perspective, as it suggests a way to balance energy efficiency with processing effectiveness.

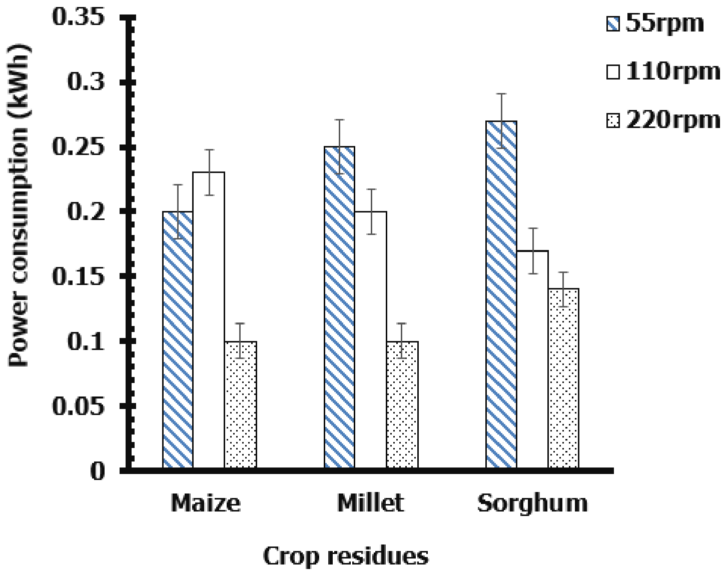

Figure 36: Power consumption (kWh)

Particle Size Distribution of the shredded crop residues

Particle Size Distribution at 55 rpm

~~Figure 37~~Figure 37 indicates the analysis of particle size distribution of the shredded crop residues (maize, millet, and sorghum). It shows that at 55rpm rpm a unique pattern is observed that reflects the structural properties of each crop. The curves show increasing weight percentage with increased particle size, especially within the 2-4 mm range which is vital for understanding their composting potential and impact on crop production. At 55 rpm, the larger particle sizes of maize, millet, and sorghum primarily fall within the 2 - 4 mm range, with sorghum showing the highest retention of 82 % at 4 mm, followed by maize 55 % and millet 45 %.

According to Kuehn et al. (2000), particle sizes between 1 and 4 mm are ideal for composting because they provide a balance of surface area and porosity, essential for microbial activity and adequate aeration. The observed trend aligns with the findings of Stetson et al. (2018), who noted that larger particle sizes contribute to improved soil structure over time by decomposing gradually and sustaining microbial communities longer. This slow decomposition aids in nutrient retention, crucial for improving soil health, as noted in the work of Stegarescu et al. (2020) which emphasizes that long-term benefits of larger particle sizes enhance soil aggregate stability and microbial biodiversity.

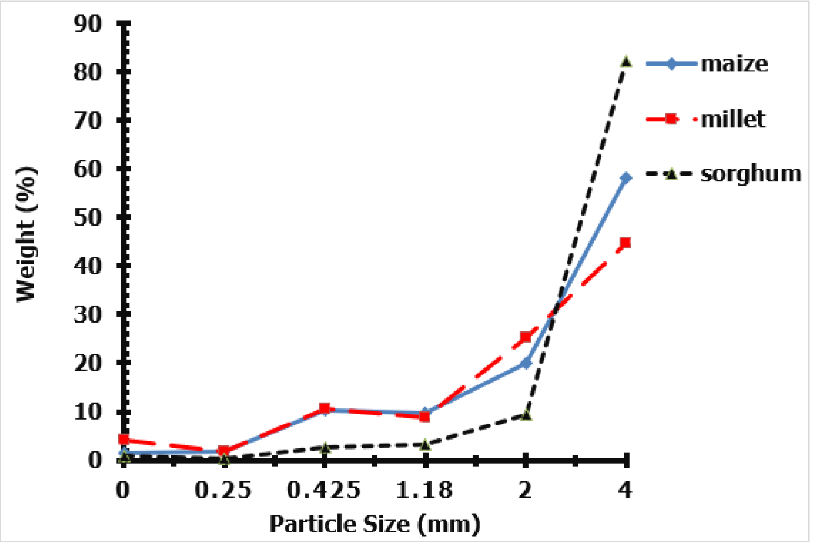

Figure 37: Particle size distribution of shredded crop residues at 55rpm.

Particle Size Distribution at 110 rpm

~~The Figure 38~~Figure 38 shows the particle size distribution of shredded crop residues (maize, millet, and sorghum stalks) at a shredding speed of 110 rpm. As the particle size increases, the weight percentage (%) increases for all three crops. At a particle size of 4 mm, 71% of shredded sorghum stalks were retained, followed by 67.5% for millet and 57.5% for maize. The trend towards medium-sized particles is consistent with the observations of Jagadabhi et al. (2019), who reported that uniform, medium particles enhance microbial activity due to improved aeration and facilitate faster composting cycles. This distribution reflects a balance between stability and breakdown, allowing particles to resist compaction and maintain air channels within the compost pile (Ahn et al., 2024). Such a structure is particularly beneficial for residues that will decompose in mid-length composting durations, as they allow for moderate microbial interaction while preserving bulk.

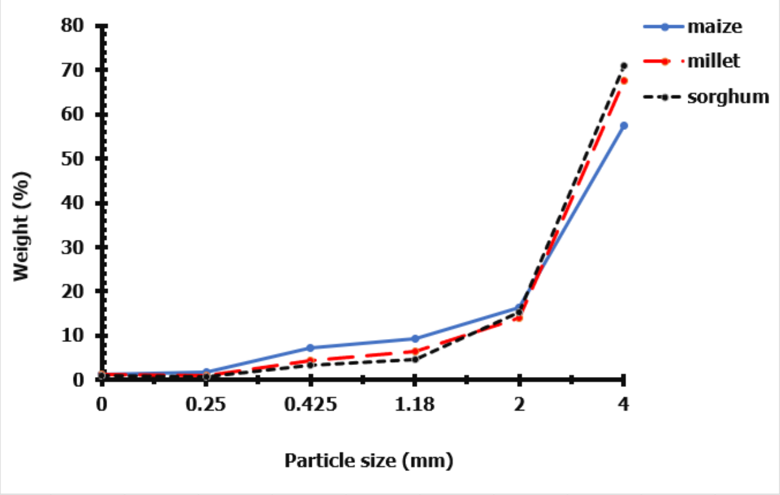

Figure 38: Particle size distribution of shredded crop residues at 110rpm.

Particle Size Distribution at 220 rpm

~~Below is Figure 39~~Figure 39 shows~~ing~~ the results of the particle size distribution of crop residues shredded at the speed of 220rpm. There were significant differences ($p<0.05$) among the stalks at different sieves mesh size. The highest shredding speed of 220 rpm resulted in a further shift toward smaller particles, especially with maize, where a higher proportion of residues passed through finer sieves. Sorghum continues to retain larger particles (81.4 % at 4 mm), while millet and maize exhibit smaller particle sizes, with 57.7 % and 44.1 % at 4 mm, respectively. Studies by Acosta-Martínez et al. (2007) emphasize that smaller particle sizes enable faster decomposition, as smaller particles decompose rapidly, releasing nutrients quicker into the soil. This rapid breakdown is beneficial for short-term composting needs, although it may immobilize nitrogen initially, as observed by Stetson et al. (2018). Fine particles are useful for short-term composting and application where faster decomposition rates are necessary, though they might require nitrogen supplementation for balance due to rapid mineralization.

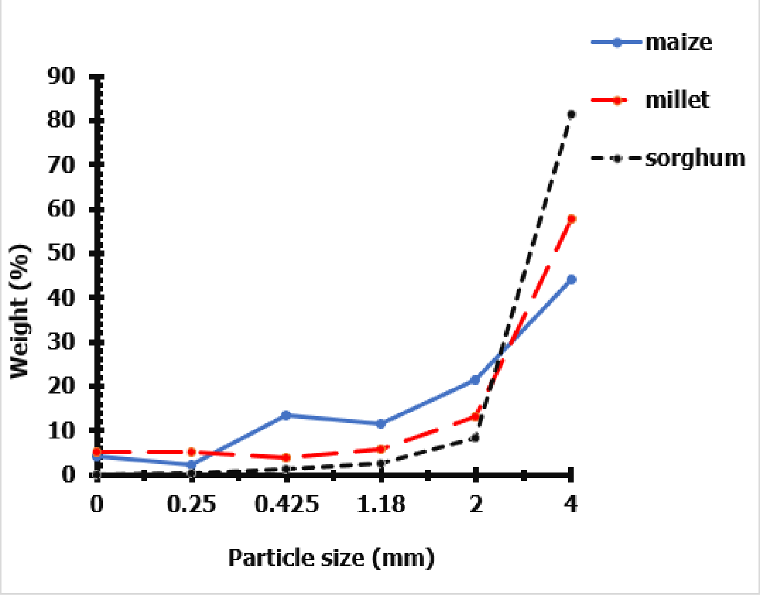

Figure 39: Particle size distribution of shredded crop residues at 220rpm.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

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Conclusion

A shredder for crop residues machine has been developed and its performance was evaluated using various crop residues like maize, millet, and sorghum stalks at three different rotational speeds. This shredder was made using locally available materials, equipment, and technology. The shredder achieved a maximum throughput capacity of 14.5 kg/h at a machine speed of 220 rpm with an overall efficiency being 82%. The data showed that the optimization of the shredding speed can lead to great reduction in the energy consumption used in crop residue shredding. There appears to be a trend of decreasing power consumption as the speed increase with maize going from 0.20 kWh in 55rpm to 0.10 kWh in 220 rpm and millet going from 0.25k~~Kw~~Wh at 110rpm to 0.10 kWh at 220rpm. This shows that adjusting the shredding speeds to match crop properties can be an effective way to balance energy efficiency and processing effectiveness, which is valuable for sustainability.

The particle size distribution of maize, millet, and sorghum residues varied depending on the shredding speed. At lower speeds 55 rpm, the residues exhibit larger particle sizes, with sorghum retaining the highest proportion of 2-4 mm particles. These larger particles are beneficial for long-term soil health, as they decompose gradually and support microbial communities. As shredding speed increases to 110 rpm, the residues fall in a medium particle size range 2-0.425 mm, which could enhance microbial activity and increases the speed of composting when the residues are used for a purpose. This balanced distribution helps maintain soil structure and air channels in the compost. At the highest shredding speed 220 rpm, the residues, especially maize, trend towards smaller particle sizes. These fine particles decompose rapidly release nutrients quickly but can momentarily immobilize nitrogen. The smaller particles are more suitable for short-term composting applications where faster decomposition is desired. Future studies could consider evaluating the performance of the machine using other crop residues and under wider machine speed ranges.

Recommendations

Based on the comprehensive analysis of the crop residue shredder, several promising avenues for future investigation have been identified to enhance the machine’s performance and expand its application. The following recommendations outline key directions for further research:

1. Further research could be done to assess the effect of different blades and the spacers on the machine’s efficiency.
2. The study focused on maize, millet, and sorghum stalk. Future studies are recommended to evaluate the performance of the machine using other agricultural residues.
3. The current study examined three specific shredding speed 55 rpm, 110 rpm, and 220 rpm. Future research could be done to explore wider or higher speed ranges to identify the optimal settings for producing a desired particle size distributions for composing.

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APPENDICES

Appendix A1: General Linear Model: Efficiency (%) versus Speed, Crop residues

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed	2	393.06	196.528	10.85	0.001
Crop residues	2	340.63	170.313	9.40	0.002
Speed*Crop residues	4	35.07	8.767	0.48	0.747
Error	18	326.04	18.113		
Total	26	1094.79			

Tukey Pairwise Comparisons: Speed

Grouping Information Using the Tukey Method and 95% Confidence

Speed	N	Mean	Grouping
220	9	79.7222	A
110	9	72.7778	B
58	9	70.8333	B

Tukey Pairwise Comparisons: Crop residues

Grouping Information Using the Tukey Method and 95% Confidence

Crop residues	N	Mean	Grouping
maize stalk	9	79.4444	A
millet stalk	9	72.3611	B
sorghum stalk	9	71.5278	B

Appendix A2: General Linear Model: Throughput capacity versus Speed, Crop residues

Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Speed	2	301.37	150.685	70.01	0.000
Crop residues	2	41.20	20.602	9.57	0.001
Speed*Crop residues	4	11.71	2.926	1.36	0.287
Error	18	38.74	2.152		
Total	26	393.02			

Tukey Pairwise Comparisons: Speed

Grouping Information Using the Tukey Method and 95% Confidence

Speed	**N**	**Mean**	**Grouping**
220	9	12.9322	A
110	9	6.5383	B
58	9	5.3118	B

Tukey Pairwise Comparisons: Crop residues

Grouping Information Using the Tukey Method and 95% Confidence

Crop residues	N	Mean	Grouping
maize stalk	9	9.74482 A	
millet stalk	9	8.31699 A	B
sorghum stalk	9	6.72043	B

Appendix A3: General Linear Model: Power com versus Speed, Crop residues

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed	2	0.075970	0.037985	91.98	0.000
Crop residues	2	0.011553	0.005777	13.99	0.000
Speed*Crop residues	4	0.001770	0.000442	1.07	0.399
Error	18	0.007434	0.000413		
Total	26	0.096727			

Tukey Pairwise Comparisons: Speed

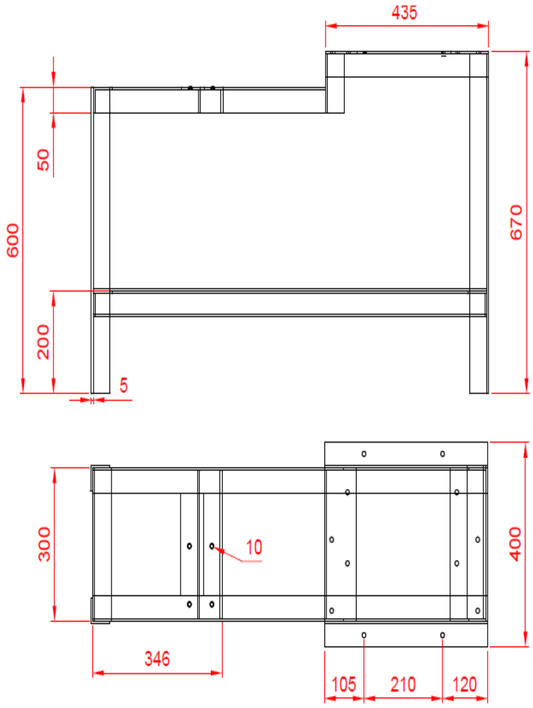
Grouping Information Using the Tukey Method and 95% Confidence

Speed	N	Mean	Grouping
220	9	12.9322 A	
110	9	6.5383	B
58	9	5.3118	B

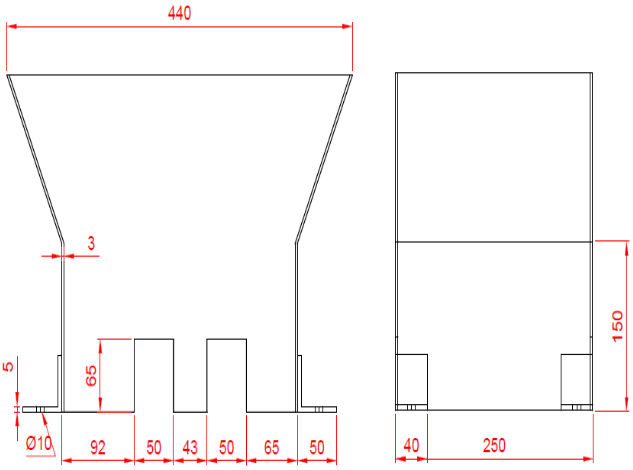
Grouping Information Using the Tukey Method and 95% Confidence

Crop residues	N	Mean	Grouping	
maize stalk	9	9.74482	A	
millet stalk	9	8.31699	A	B
sorghum stalk	9	6.72043		B

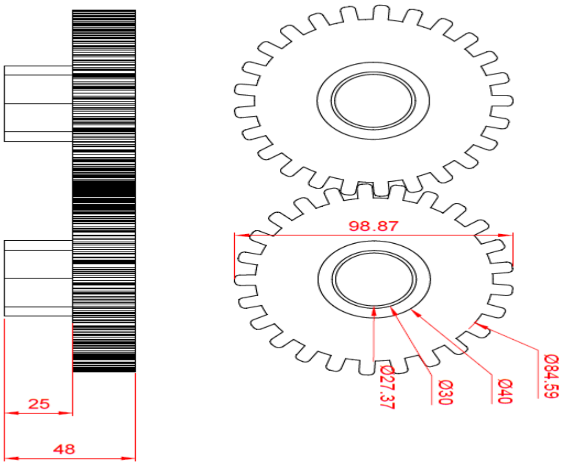
Appendix B: Detailed drawing of the frame sub-assembly



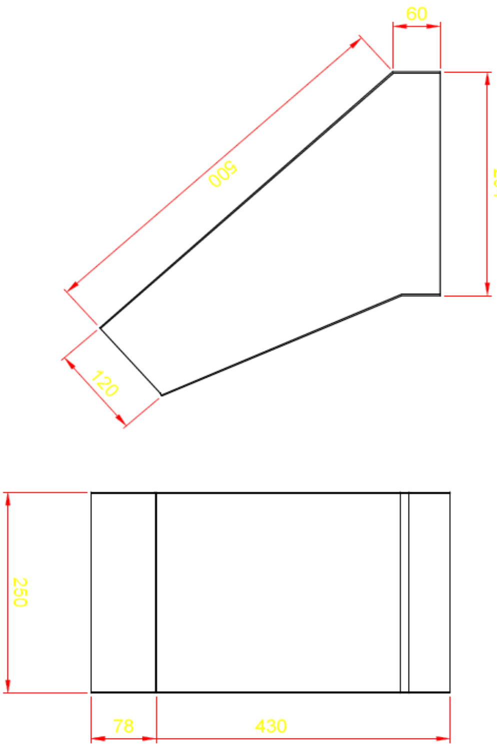
Appendix B2: Detailed drawing of the hopper sub-assembly



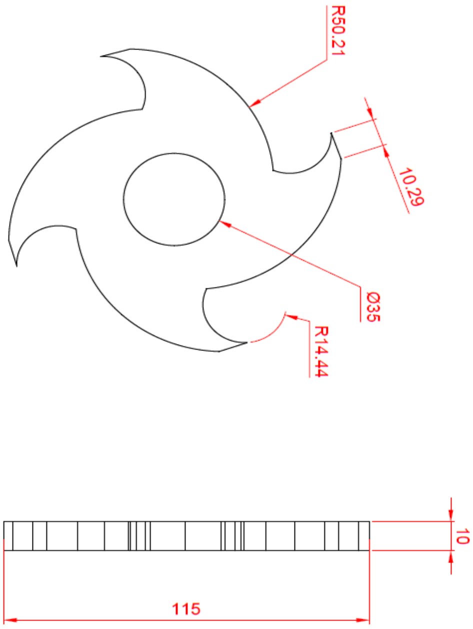
Appendix B3: Detailed drawing of the gears



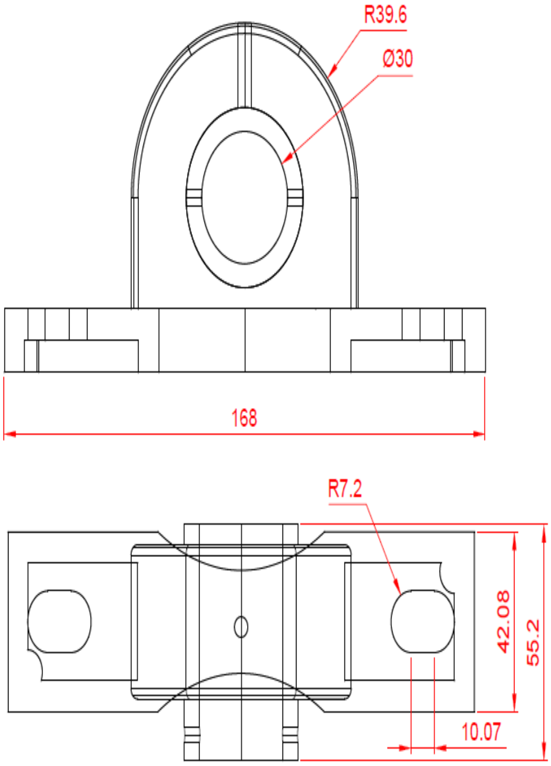
Appendix B4: Detailed drawing of outlet sub-assembly



Appendix B5: Detailed drawing of the blade sub-assembly

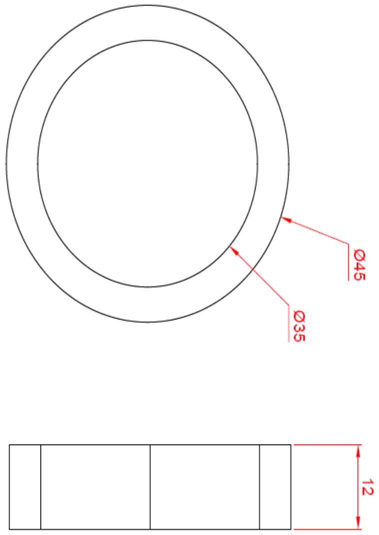


Appendix B6: Detailed drawing of the bearing sub-assembly

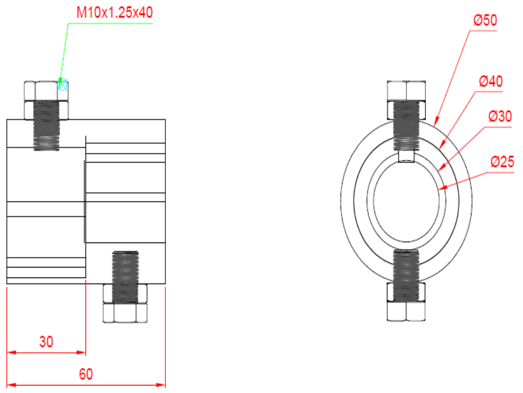


Standard 206 Pillow Block Bearing

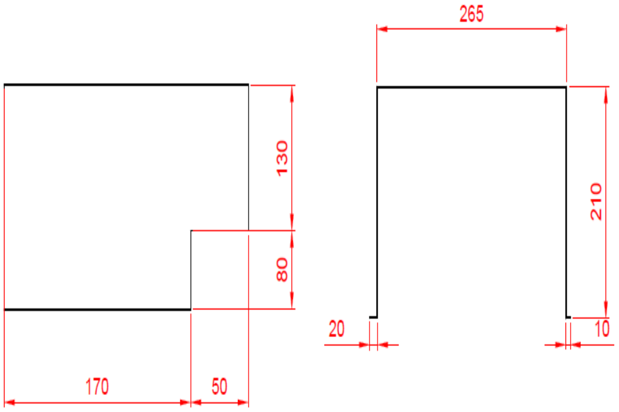
Appendix B7: Detailed drawing of the spacers sub-assembly



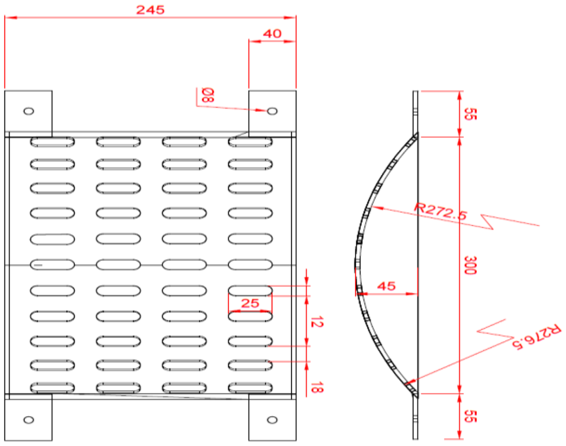
Appendix B8: Detailed drawing of the bolt and nut sub-assembly



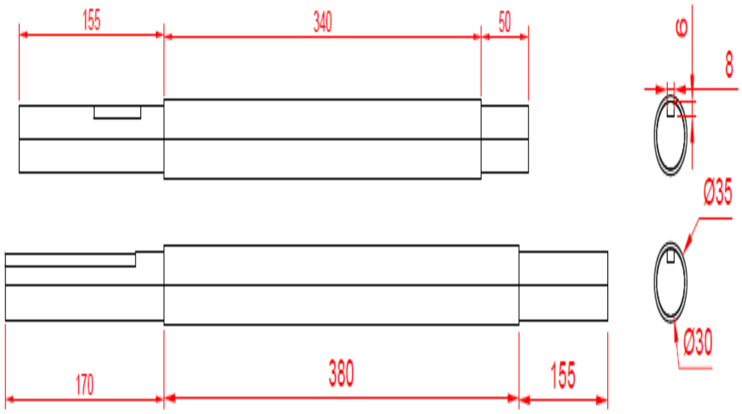
Appendix B9: Detailed drawing of the guard sub-assembly



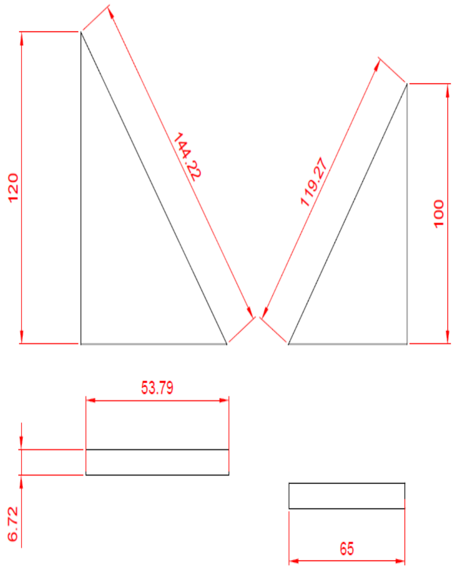
Appendix B10: Detailed drawing of the sieve sub-assembly



Appendix B11: Detailed drawing of the shaft sub-assembly



Appendix B12: Detailed drawing of the wadges



Detail calculations of reactions at the bearing supports

Driving Shaft

Taking moments about point A and equating the sum of Clockwise Moments to the sum of Anticlockwise Moments in Figure A, the reaction R_{bd} was calculated as:

$$(48 \times 0.19) = (Rbd \times 0.39) + (12 \times 0.06)$$

$$9.12 = 0.39Rbd + 0.72$$

$$Rbd = \frac{(9.12 - 0.72)}{0.39} = 21.54\ N$$

For equilibrium, total upward forces must be equal to total downward forces. Applying this rule to Figure A, the reaction R_{ad} was calculated as

$$Rad + Rbd = 12 + 48$$

$$Rad + 21.54 = 60$$

$Rad = 38.46$ N

Driven Shaft

Taking moments about point A and equating the sum of Clockwise Moments to the sum of Anticlockwise Moments in Figure D, the reaction R_b was calculated as

$(48 \times 0.14) = (Rb \times 0.33) + (12 \times 0.09)$

$6.72 = 0.33Rb + 1.08$

$Rb = \frac{(6.72-1.08)}{0.33} = 17.09$

For equilibrium, total upward forces must be equal to total downward forces. Applying this rule to Figure A, the reaction R_a was calculated as

$Ra + Rb = 12 + 48$

$Ra + 17.09 = 60$

$Ra = 42.91$ N

Table A: Driving Shaft Shear Forces and Momentss

Shaft Length (m)	Shear Force (N)	Bending Moment (Nm)
0	0	0
0.025	0	0
0.05	0	0
0.1	0	0
0.10001	-12	-0.00012
0.125	-12	-0.3
0.1250001	-12	-0.3000012
0.15	-12	-0.6
0.1500001	-12	-0.6000012
0.1500001	26.46	-0.6000012

0.175	26.46	-0.3231
0.2	26.46	0.3384
0.225	26.46	0.9999
0.25	26.46	1.6614
0.275	26.46	2.3229
0.3	26.46	2.9844
0.325	26.46	3.6459
0.3250001	-21.54	3.645902646
0.35	-21.54	4.3074
0.375	-21.54	3.7689
0.4	-21.54	3.2304
0.425	-21.54	2.6919
0.45	-21.54	2.1534
0.475	-21.54	1.6149
0.5	-21.54	1.0764
0.525	-21.54	0.5379
0.55	-21.54	-0.0006
0.550001	0	-0.0006

Shaft Length (m)	Shear Force (N)	Bending Moment (Nm)
0	0	0
0.05	0	0
0.050001	-12	0
0.1	-12	-0.24
0.15	-12	-0.84
0.150001	30.91	-0.84001
0.2	30.91	-0.1527
0.25	30.91	1.3928
0.3	30.91	2.9383

0.30001	-17.09	2.938609
0.35	-17.09	2.5638
0.4	-17.09	1.7093
0.45	-17.09	0.8548
0.5	-17.09	0.0003
0.50001	0	0.0003

SHREDDER FRAME STRESS ANALYSIS REPORT

Analyzed File:	Frame only1.ipt
Autodesk Inventor Version:	2023 (Build 270158000, 158)
Creation Date:	27/09/2024, 5:17 am
Study Author:	hp
Summary:	

Static Analysis:1

General objective and settings:

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	27/09/2024, 5:15 am
Model State	[Primary]
Detect and Eliminate Rigid Body Modes	No

iProperties

Summary

Author	hp

Project

Part Number	Frame only1
Designer	hp
Cost	US$0.00
Date Created	23/08/2024

Status

Design Status	WorkInProgress

Physical

Material	Steel, Mild
Density	7.85 g/cm^3
Mass	33.3691 kg
Area	1712870 mm^2
Volume	4250840 mm^3
Center of Gravity	x=-2192.78 mm y=1281.61 mm z=-2191.78 mm

Note: Physical values could be different from Physical values used by FEA reported below.

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

Material(s)

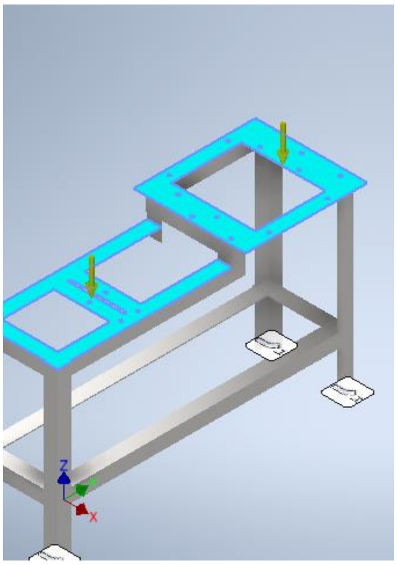
Name	Steel, Mild	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0.275 ul
	Shear Modulus	86.2745 GPa
Part Name(s)	Frame only1.ipt	

Operating conditions

Force:1

Load Type	Force
Magnitude	765.000 N
Vector X	0.000 N
Vector Y	0.000 N
Vector Z	-765.000 N

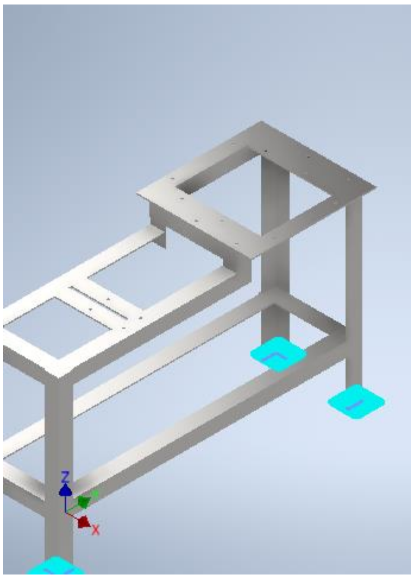
Selected Face(s)



Fixed Constraint:1

Constraint Type	Fixed Constraint

Selected Face(s)



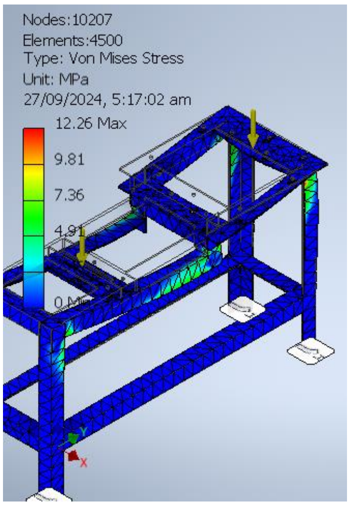
Results

Result Summary

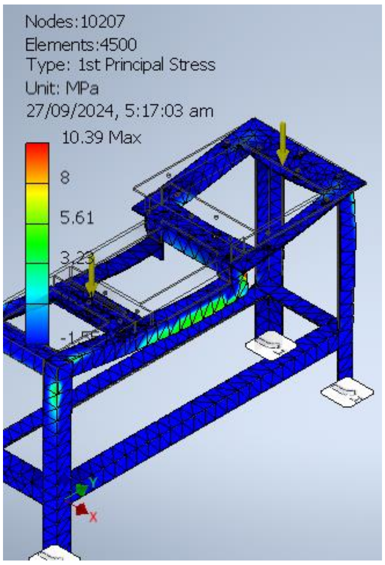
Name	**Minimum**	**Maximum**
Volume	4250840 mm^3	
Mass	33.3691 kg	
Von Mises Stress	0.00435627 MPa	12.26 MPa
1st Principal Stress	-1.5493 MPa	10.389 MPa
3rd Principal Stress	-14.0565 MPa	1.74634 MPa
Displacement	0 mm	0.0992293 mm
Safety Factor	15 ul	15 ul

Figures

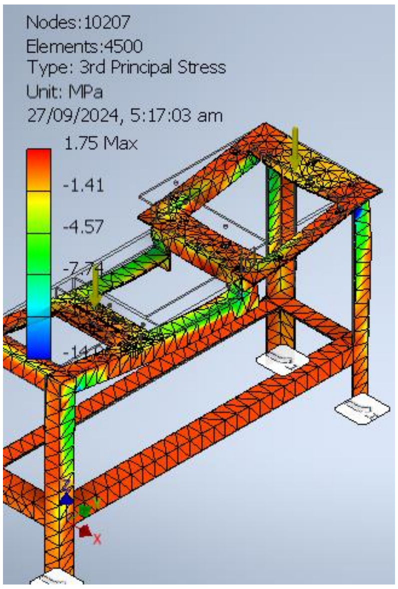
Von Mises Stress



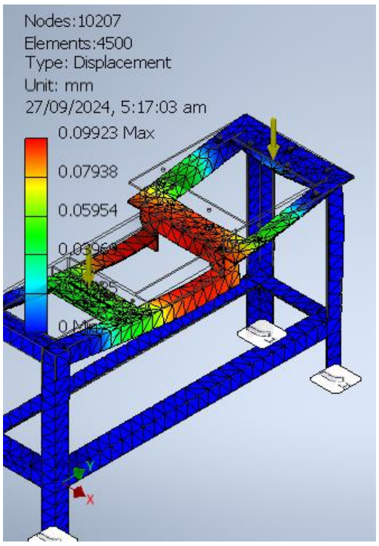
1st Principal Stress



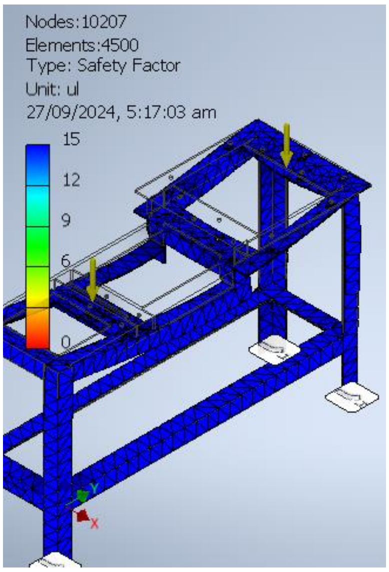
3rd Principal Stress



Displacement



Safety Factor



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Elements:4500
Type: Safety Factor
Unit: ul
27/09/2024, 5:17:03 am

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SHREDDER BLADE STRESS ANALYSIS REPORT

Analyzed File:	Shredder Blade1.ipt
Autodesk Inventor Version:	2023 (Build 270158000, 158)
Creation Date:	27/09/2024, 2:13 pm
Study Author:	hp
Summary:	

Static Analysis:2

General objective and settings:

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	27/09/2024, 2:08 pm
Model State	[Primary]
Detect and Eliminate Rigid Body Modes	No

iProperties

Summary

Author	hp

Project

Part Number	Shredder Blade1
Designer	hp
Cost	US$0.00
Date Created	26/07/2024

Status

Design Status	WorkInProgress

Physical

Material	Steel, High Strength, Low Alloy
Density	7.85 g/cm^3
Mass	0.46801 kg
Area	17595.9 mm^2
Volume	59619.1 mm^3
Center of Gravity	x=989.208 mm y=-560.776 mm z=704.38 mm

Note: Physical values could be different from Physical values used by FEA reported below.

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

Material(s)

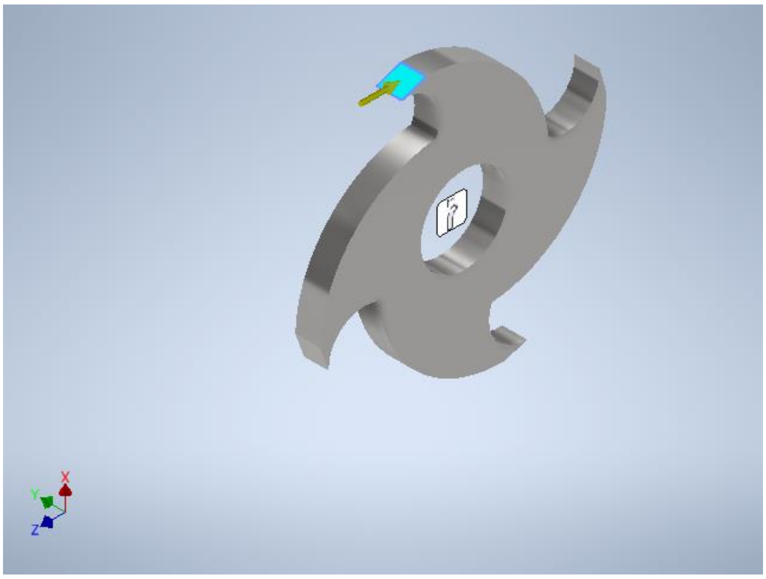
Name	Steel, High Strength, Low Alloy	
General	Mass Density	7.85 g/cm^3
	Yield Strength	275.8 MPa
	Ultimate Tensile Strength	448 MPa
Stress	Young's Modulus	200 GPa
	Poisson's Ratio	0.287 ul
	Shear Modulus	77.7001 GPa
Part Name(s)	Shredder Blade1.ipt	

Operating conditions

Force:1

Load Type	Force
Magnitude	4912.670 N
Vector X	0.000 N
Vector Y	0.000 N
Vector Z	-4912.670 N

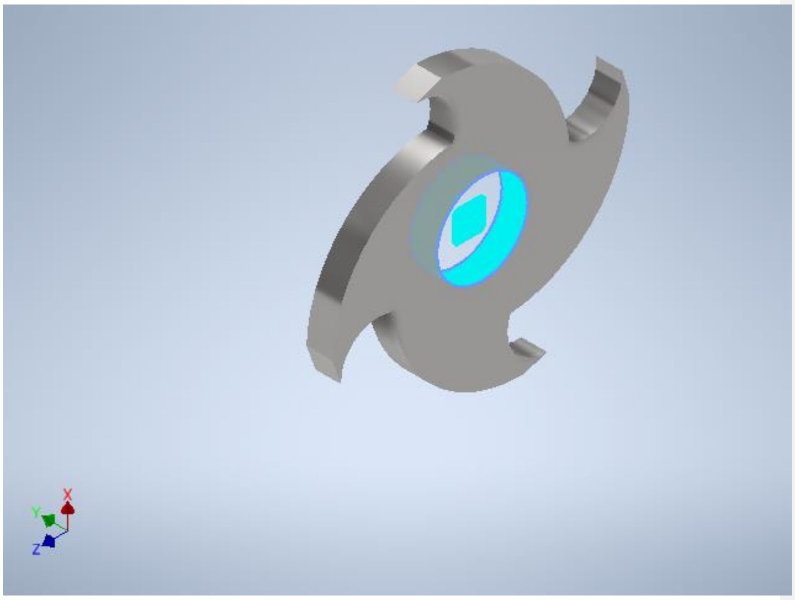
Selected Face(s)



Fixed Constraint:1

Constraint Type	Fixed Constraint

Selected Face(s)



Results

Reaction Force and Moment on Constraints

Constraint Name	**Reaction Force**		**Reaction Moment**	
	Magnitude	**Component (X,Y,Z)**	**Magnitude**	**Component (X,Y,Z)**
Fixed Constraint:1	4912.67 N	0 N 0 N 4912.67 N	275.54 N m	0 N m -275.54 N m 0 N m

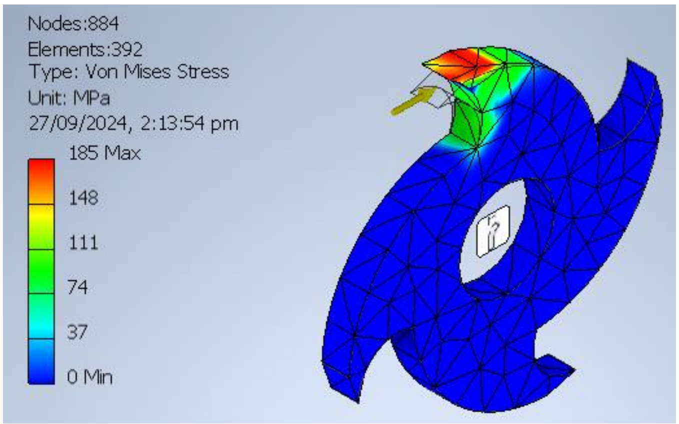
Result Summary

Name	**Minimum**	**Maximum**
Volume	59619.1 mm^3	
Mass	0.46801 kg	
Von Mises Stress	0.00300325 MPa	184.96 MPa
1st Principal Stress	-8.66739 MPa	127.448 MPa
3rd Principal Stress	-184.846 MPa	9.4289 MPa

Displacement	0 mm	0.0642416 mm
Safety Factor	1.49114 ul	15 ul

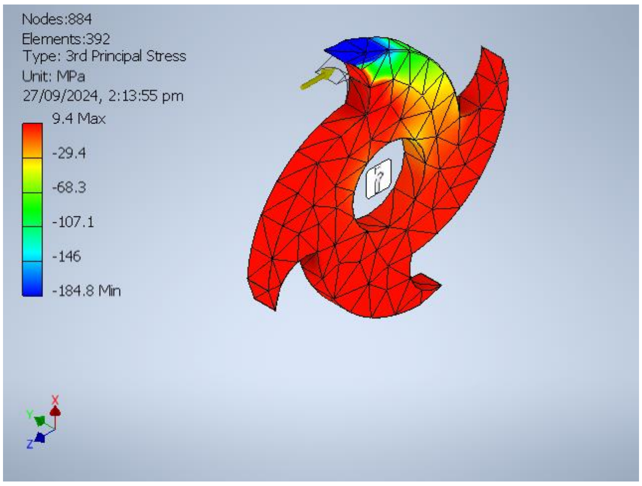
Figures

Von Mises Stress



1st Principal Stress

3rd Principal Stress



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Elements:392
Type: 3rd Principal Stress
Unit: MPa
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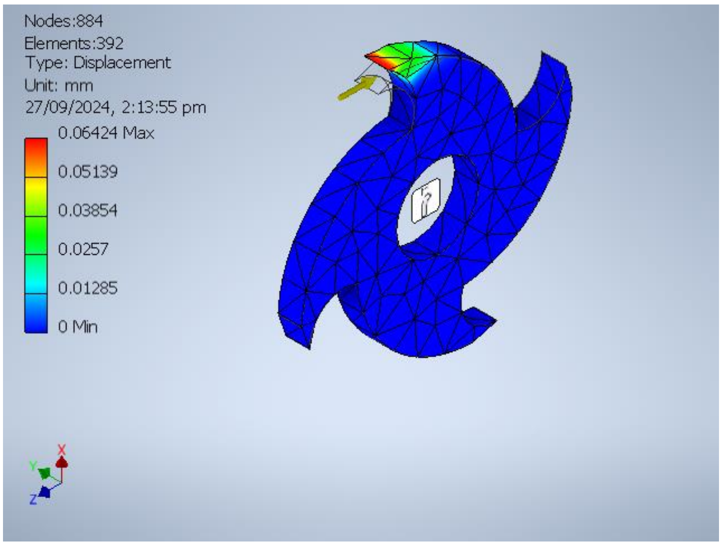
Displacement



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Elements:392
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Unit: mm
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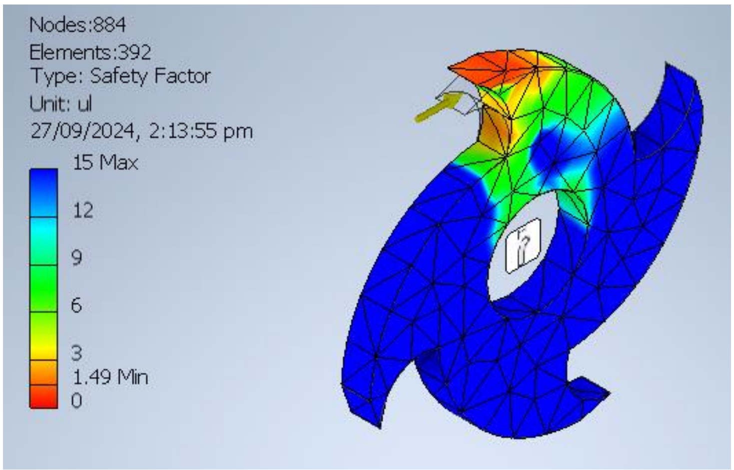
Safety Factor



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SHREDDER SHAFT STRESS ANALYSIS REPORT

AUTODESK

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Creation Date:	27/09/2024, 3:37 pm
Study Author:	hp
Summary:	

Static Analysis:1

General objective and settings:

Design Objective	Single Point
Study Type	Static Analysis
Last Modification Date	27/09/2024, 3:12 pm
Model State	[Primary]
Detect and Eliminate Rigid Body Modes	No

iProperties

Summary

Author	hp

Project

Part Number	Long Shaft only1
Designer	hp
Cost	US$0.00
Date Created	24/08/2024

Status

Design Status	WorkInProgress

Physical

Material	Steel, Mild
Density	7.85 g/cm^3
Mass	4.28925 kg
Area	70197.3 mm^2
Volume	546402 mm^3
Center of Gravity	x=444.513 mm y=3.4099 mm z=227.715 mm

Note: Physical values could be different from Physical values used by FEA reported below.

Mesh settings:

Avg. Element Size (fraction of model diameter)	0.1
Min. Element Size (fraction of avg. size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	Yes

Material(s)

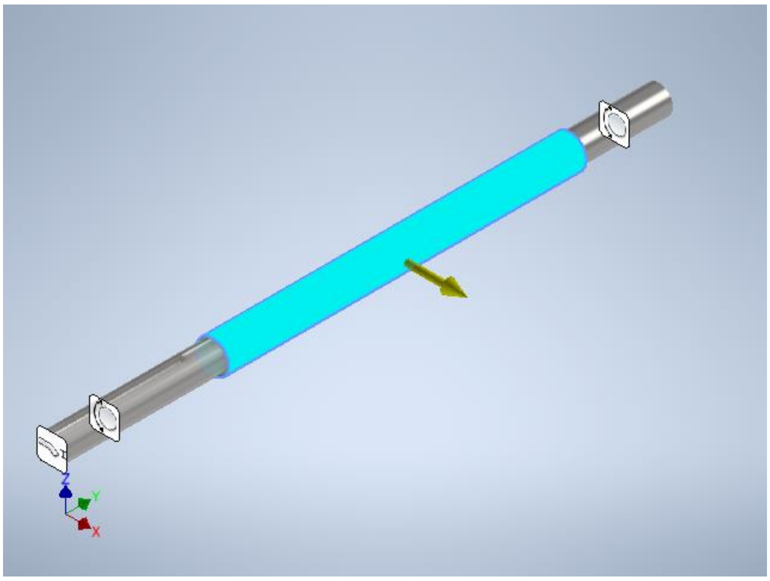
Name	Steel, Mild	
General	Mass Density	7.85 g/cm^3
	Yield Strength	207 MPa
	Ultimate Tensile Strength	345 MPa
Stress	Young's Modulus	220 GPa
	Poisson's Ratio	0.275 ul
	Shear Modulus	86.2745 GPa
Part Name(s)	Long Shaft only1.ipt	

Operating conditions

Force:1

Load Type	Force
Magnitude	9463.000 N
Vector X	0.000 N
Vector Y	9463.000 N
Vector Z	0.000 N

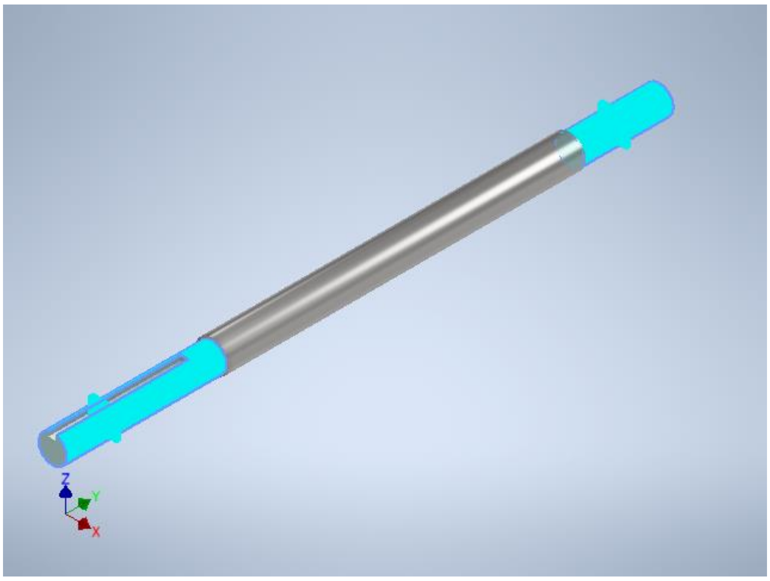
Selected Face(s)



Pin Constraint:1

Constraint Type	Pin Constraint
Fix Radial Direction	Yes
Fix Axial Direction	No
Fix Tangential Direction	Yes

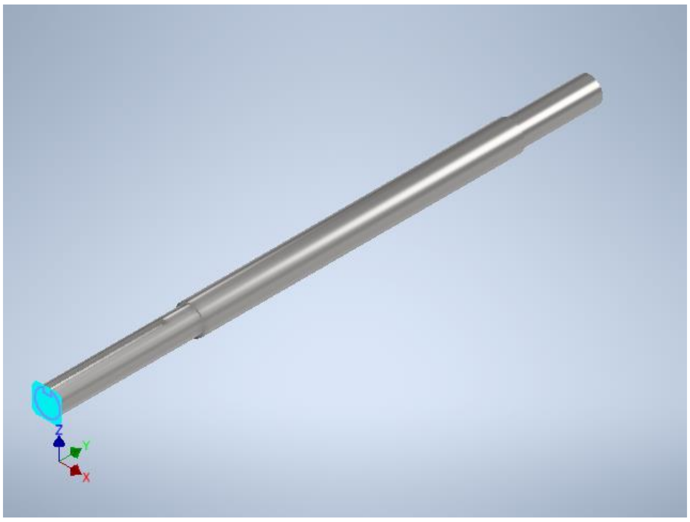
Selected Face(s)



Fixed Constraint:1

Constraint Type	Fixed Constraint

Selected Face(s)



Results

Reaction Force and Moment on Constraints

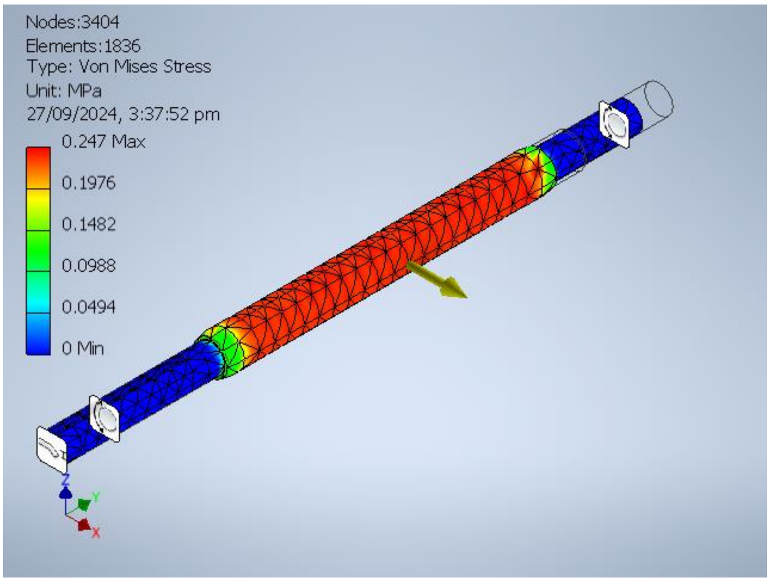
Constraint Name	**Reaction Force**		**Reaction Moment**	
	Magnitude	**Component (X,Y,Z)**	**Magnitude**	**Component (X,Y,Z)**
Pin Constraint:1	0.478825 N	0 N	0.0769722 N m	-0.064844 N m
		0.460855 N		0 N m
		0.129947 N		0.0414726 N m
Fixed Constraint:1	4.66772 N	0 N	0.00112319 N m	-0.00112214 N m
		4.66565 N		-0.0000485991 N m
		-0.138877 N		0 N m

Result Summary

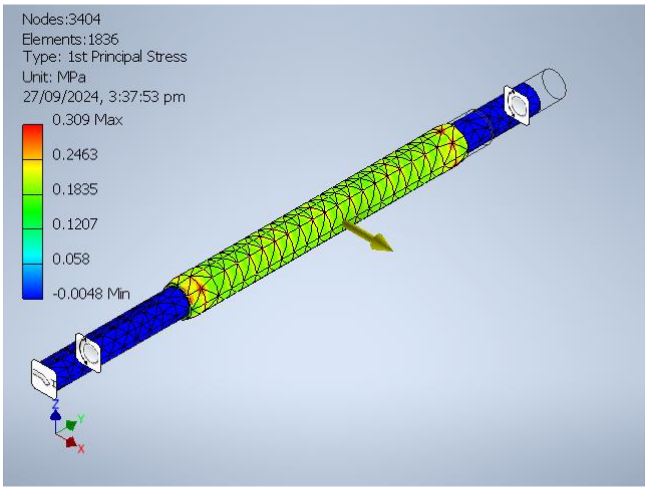
Name	**Minimum**	**Maximum**
Volume	546402 mm^3	
Mass	4.28925 kg	
Von Mises Stress	0.000000183492 MPa	0.246986 MPa
1st Principal Stress	-0.00480039 MPa	0.309032 MPa
3rd Principal Stress	-0.0839155 MPa	0.105678 MPa
Displacement	0 mm	0.000214554 mm
Safety Factor	15 ul	15 ul

Figures

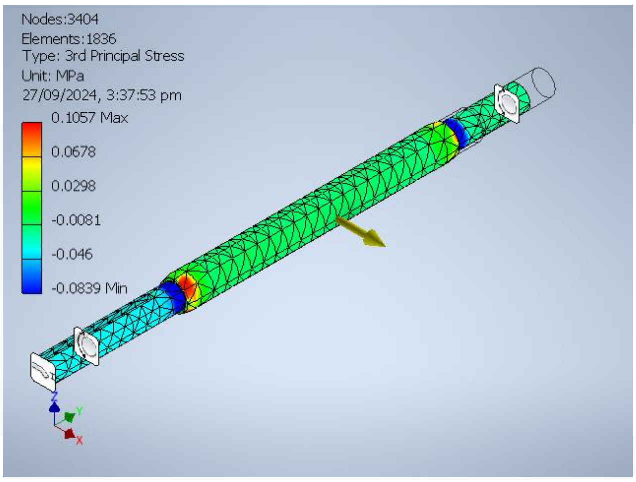
Von Mises Stress



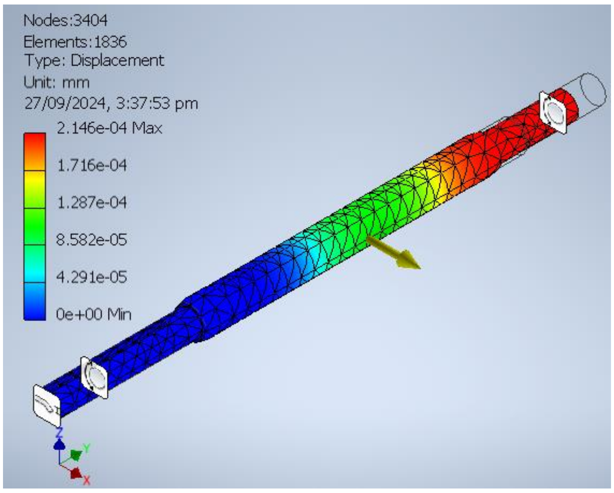
1st Principal Stress



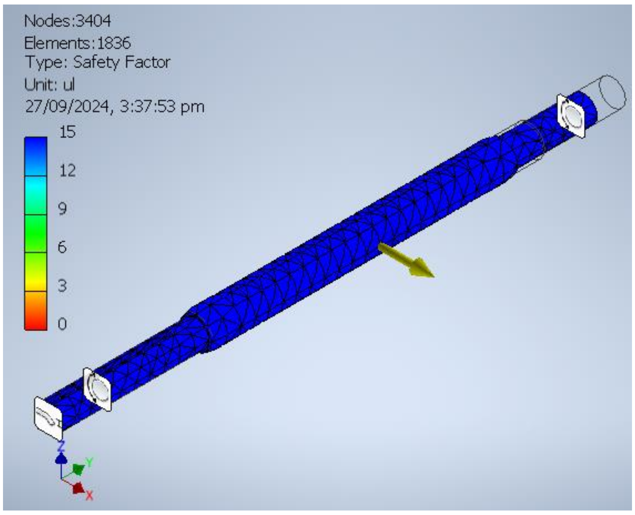
3rd Principal Stress



Displacement



Safety Factor



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Appendix …: Bill of Quantities

S/No.	ITEM	UNITS	QTY	UNIT COST (GHȻ)	AMOUNT (GHȻ)
1	Mild Steel angle iron (50 mm x 50 mm)	pcs	2	200	400.00
2	Mild steel Plate (3 x1200 x 2400 mm)	pcs	0.25	1500	375.00
3	Carbon steel flat bar (90 x 10 mm)	pcs	1	1000	800.00
4	Mild steel shaft (tø40 mm x 1200 mm)	pcs	1	500	500.00
5	Pillow bearings (206)	pcs	2	45	90.00
6	Mild steel electrode (G10)	pkt	1	90	90.00
7	Cutting disc (9 inches)	pcs	2	20	40.00
8	Oil paint	ltrs	2	50	100.00
9	Thinner	ltrs	2	30	60.00
10	M10 Bolts and nuts	pcs	13	3	39.00
11	M8 Bolts and nuts	pcs	8	2	16.00
12	Gear Electric Motor	Pcs	1	3000	3,000.00
Subtotal (Material Cost)					**5,510.00**
13	Transportation			490	490.00
14	Labour				1000.00
Grand total (Material Cost)					**7,000.00**