DESIGN AND FABRICATION OF A VERTICAL PALM FRUIT DIGESTER FOR PALM OIL PROCESSING

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CERTIFICATION

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DEDICATION

This work is humbly dedicated to God Almighty, the Father of Light, my eternal source, unwavering strength, and guiding light throughout this academic journey. It is with deep gratitude that I extend this dedication to my cherished Mum, whose boundless love, sacrifices, and unwavering support have been the cornerstone of my success. Her relentless commitment played a pivotal role in my completion of the B.Eng. Degree in Agricultural Engineering from the University of Benin. To God and my incredible Mum, this achievement is a testament to your enduring influence in my life.

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I express profound gratitude to my Mother, Mrs. Helen Igedegbe, whose ambitious dream envisioned, through thick and thin, that her son would attain a university degree. Her unwavering belief in my potential has been my driving force.

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Together with the dedicated staff in the workshop, I am deeply thankful for the pivotal roles you have played in my academic journey. May God richly bless you both abundantly. Amen.

ABSTRACT

This project presents the design, material selection, fabrication, and performance testing of a diesel-powered vertical palm fruit digester aimed at supporting small- and medium-scale producers. The design offers a practical, affordable, and locally adaptable solution to enhance palm oil production in underserved regions.

The machine achieved a digestion efficiency of 95.5% during performance testing, indicating its capability to effectively separate the mesocarp from the kernel.

TABLE OF CONTENT

The vertical palm fruit digester is one of the most commonly used configurations in small- to medium-scale palm oil processing. It consists of a cylindrical chamber equipped with a central rotating shaft, to which multiple beater arms or paddles are attached. These arms rotate within the chamber, physically breaking down the fruit to release the oil. Steam or heat may be applied within the chamber to soften the pulp and facilitate the digestion process. A typical digester unit comprises several key components, including a hopper, digester barrel, sealed bearings, main shaft, worm gear, wheel gear, discharge outlet, and a prime mover, either an electric motor or a diesel engine. Parboiled fruits are loaded through the hopper and are macerated by the rotating beater arms. Once the fruits are sufficiently digested, the resulting mash exits the unit through the discharge end by gravity. Vertical digesters are especially favored in palm oil processing due to their high efficiency and throughput, with some models capable of handling up to 740 kilograms

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ASAE – American Society of Agricultural Engineers

ASME – American Society of Mechanical Engineers

NIFOR – Nigerian Institute for Oil Palm Research

FFA – Free Fatty Acid

FFBs – Fresh Fruit Bunches

FAO – Food and Agriculture Organization

ASTM – American Society for Testing and Materials

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The development of a palm fruit digester is a crucial stride in addressing the limitations of traditional palm oil extraction techniques in Nigeria. Historically, palm oil production has relied heavily on laborious manual practices that are not only time-consuming but also yield relatively low oil output. These methods, while still in use in many rural communities, struggle to meet the growing domestic and industrial demand for palm oil (Nwauwa & Asoegwu, 2010). As palm oil remains a significant economic resource in Nigeria, used widely in food production, pharmaceuticals, and cosmetics, there is an urgent need for more efficient and scalable processing systems (FAO, 2019).The palm fruit digester, as a mechanized unit in the palm oil processing line, addresses this need by facilitating the maceration of fruit mesocarp, thereby releasing oil from the cellular structure. This process not only improves extraction efficiency but also reduces the physical strain associated with manual pounding or pressing (Adediran, 2015). Digesters typically consist of a rotating shaft equipped with beater arms that crush and stir the fruit mass. Their design may vary, with horizontal and vertical configurations offering different benefits in terms of total output and maintenance (Fashina, Durodola, & Hammed, 2017). Vertical digesters, for instance, allow gravity-assisted movement of fruit, while horizontal digesters often permit continuous feeding and discharge of processed material (Gblechi & Ige, 2014). The importance of locally fabricated machinery like the palm fruit digester extends beyond productivity. It supports Nigeria's engineering and manufacturing sectors by reducing reliance on imported equipment and encouraging innovation in agro-processing tools (Asoiro & Udo, 2013). MoreoSver, the availability of efficient digesters can contribute to rural development by improving the viability of small-scale processing operations, thus empowering communities economically. As Nigeria's population continues to rise, so too does the demand for palm oil, especially in its red oil form used in everyday cooking. Mechanized solutions such as digesters offer a practical path toward scaling production sustainably while preserving oil quality and nutritional value (Oghenevwaire, 2019). These machines are instrumental in reducing drudgery, increasing oil yield, and ensuring consistent processing standards. With thoughtful design, the digester becomes not just a piece of machinery but a transformative tool in the advancement of the oil palm industry. Therefore, this research aims to design and construct a palm fruit digester that embodies the principles of mechanical efficiency, user accessibility, and environmental consciousness. Through this effort, it is hoped that the resulting device will contribute meaningfully to the modernization and sustainability of palm oil production in Nigeria.

1.2 Statement of the Problem

Despite the increasing demand for palm oil in Nigeria (Sasu, 2022), a substantial portion of local producers, especially small-scale operators, continue to rely on outdated, labor-intensive methods of palm fruit processing. These traditional and semi-mechanical techniques result in low oil recovery rates, prolonged processing durations, and high labor costs. Such inefficiencies have hampered the productivity and profitability of palm oil production, particularly in rural communities where access to modern processing mills and electricity is limited. Moreover, although some mechanized digesters are available, they often come with prohibitive acquisition, maintenance, and repair costs, making them inaccessible to most small-scale producers (Asoiro & Udo, 2013). This lack of affordable and effective technology further deepens the disparity between large-scale operations and smallholder enterprises, preventing the latter from competing in an increasingly demanding market. The result is a stagnation of growth for many rural producers and a missed opportunity for economic empowerment in these regions. The broader implication is that Nigeria remains a net importer of palm oil, despite having the ecological and agricultural potential to be self-sufficient or even an exporter. Enhancing the efficiency and accessibility of palm fruit digesters, particularly for small-scale users, presents a critical opportunity to improve oil yields, reduce production time and labor intensity, and ultimately foster sustainable growth across the industry. Therefore, this study seeks to design and construct a cost-effective, efficient palm fruit digester that addresses these limitations and contributes meaningfully to the advancement of Nigeria's palm oil sector.

1.3 Aim

The aim of this research is to create an economical and effective palm fruit digester specifically designed for small-scale palm oil producers in Nigeria.

1.4 Objectives

The primary objective of this study is to design and fabricate a cost-effective and efficient palm fruit digester specifically tailored for small-scale palm oil producers in Nigeria. This equipment is intended to streamline the processing of palm fruit by integrating both digestion and pressing mechanisms into a single unit, thereby enhancing oil extraction efficiency while reducing operational complexity and costs.

Specific Objectives are to:

I. Design and construct a vertical palm fruit digester that is simple to operate, maintain, and suitable for small-scale processing environments.

II. Integrate the digestion and pressing functions into a unified system to reduce processing time and improve oil recovery.

III. Ensure affordability by selecting locally available materials and optimizing fabrication processes for cost reduction.

IV. Evaluate how design parameters such as size, shape, and material composition affect the machine's performance.

1.5 Scope of Study

This research is centered on the design and fabrication of a vertical palm fruit digester that utilizes a diesel-powered, gear-driven shaft for direct mechanical rotation. The study applies core mechanical engineering principles to develop a machine that is structurally robust, technologically feasible, and economically suitable for small- and medium-scale palm oil producers in Nigeria. The scope covers detailed modeling, design calculations, and simulation of critical parameters such as torsional stress, load distribution, and material deformation. Tools such as SolidWorks will be used to simulate the mechanical behavior of the components under realistic loading conditions. Design dimensions and tolerances will be determined in accordance with established engineering standards including ASME, ASABE, and ASTM, ensuring that the final construction adheres to internationally accepted safety and performance guidelines. This work does not extend into the commercial deployment or long-term field testing of the digester but remains focused on prototype design, fabrication, and preliminary performance evaluation. The study will also identify opportunities for design optimization and provide practical recommendations to support the integration of the digester into local palm oil processing operations.

1.6 Significance of the Study

I. The study will contribute to the body of knowledge on agricultural machinery design, particularly in the context of palm oil processing in Nigeria.

II. The design and fabrication process outlined in this research will serve as a reference for future studies in machine design, rural agro-processing technologies, and small-scale engineering solutions.

III. By focusing on cost-effectiveness and local material sourcing, the project supports efforts toward sustainable engineering practices and import substitution.

IV. The completed palm fruit digester prototype can help small-scale producers improve oil extraction efficiency, reduce processing time, and minimize manual labour.

V. The work encourages the integration of applied engineering in addressing real-world agricultural challenges, bridging the gap between theory and practical innovation.

1.7 Justification of Study

This study is driven by the urgent need to improve the efficiency, affordability, and sustainability of palm oil production in Nigeria. Despite the country's long-standing involvement in oil palm cultivation, a significant number of small- and medium-scale producers still rely on outdated, labour-intensive processing techniques. These methods limit productivity, reduce oil yield, and hinder economic progress. As such, increasing national and global demand for palm oil, empowering small-scale processors has become essential for improving competitiveness and reducing Nigeria's reliance on imports. This study explores innovative design strategies that combine the digestion and pressing phases of palm oil extraction into a single, more efficient system. The result is a solution that reduces manual labour, accelerates processing time, and improves oil yield. In addition to boosting productivity, the project promotes environmental sustainability by encouraging efficient resource use and reducing waste during the extraction process. It also highlights the vital role of engineering solutions in addressing real-world problems, especially in rural communities where access to advanced agro-processing technologies is limited. Ultimately, this research provides actionable insights and design innovations that can inform future studies, guide policy and investment decisions, and support the long-term development of Nigeria's palm oil sector.

1.8 Limitations of Study

While the design and fabrication of a functional vertical palm fruit digester were successfully demonstrated in this study, future attempts to replicate or scale the design may face certain limitations. Identifying these potential challenges is important for informing future improvements and guiding others who may undertake similar fabrication projects.

I. **Limited Access to Resources:** Access to specific raw materials, advanced machining tools, or specialized components may be restricted depending on the fabrication environment. In such cases, designers may need to make substitutions or design adjustments, which could impact the accuracy, durability, or performance of the final machine.

II. **Financial Constraints**: Limited funding may restrict the selection of high-performance materials, the inclusion of enhanced features (such as automated feeding or integrated sensors), or the ability to carry out multiple prototype iterations. These financial constraints could affect both the optimization and longevity of the machine.

III. **Time Constraints:** Time limitations during academic or field-based fabrication projects may prevent extensive performance testing, iterative refinements, or long-term durability evaluations. As a result, the reliability of the digester over prolonged use might remain uncertain unless addressed in follow-up studies.

IV. **Technical and Engineering Limitations**: In environments without access to precision fabrication equipment, some components may need to be manually crafted. This can affect tolerances and alignment, possibly reducing mechanical efficiency. Additionally, the lack of diagnostic tools may limit the ability to conduct in-depth mechanical or thermal analysis.

V. **Environmental and Operational Testing Limitations**: Initial testing may be limited to workshop or semi-controlled environments. Without comprehensive field trials across diverse climatic and infrastructural conditions, such as rural off-grid locations, areas with inconsistent power supply, or humid processing sites, real-world performance may not be fully predictable.

CHAPTER TWO
LITERATURE REVIEW

2.1 Concept of Oil Palm Production

The oil palm (*Elaeis guineensis*), a perennial tropical crop from the Arecaceae family, is notable for producing two major commercially valuable oils: palm oil, derived from the fleshy mesocarp, and palm kernel oil, extracted from the seed or kernel. The fruit, typically a reddish-orange drupe, is botanically structured with a fibrous outer pulp surrounding a hard shell that encloses the oil-rich kernel. These attributes make the oil palm one of the most economically significant crops in the global agricultural sector. Historically, Nigeria was the world's leading producer of palm oil in the early 1960s, accounting for approximately 43% of global output. Although this dominance has since declined due to factors such as outdated processing technologies and limited industrial investment, oil palm cultivation continues to support the livelihoods of millions, particularly in rural communities (FAO, 2019). The crop remains a vital contributor to Nigeria's agricultural economy, with applications in food, cosmetics, pharmaceuticals, and biofuels. Due to rising domestic and international demand, significant attention has been directed toward improving the efficiency of palm oil extraction. Traditional processing methods, while still prevalent, are labour-intensive and yield relatively low-quality oil. This has led to the development of mechanical devices such as palm fruit digesters, which play a crucial role in the modern extraction process by breaking down the mesocarp and facilitating oil release. Several digester designs have been developed over the years, including both horizontal and vertical configurations, each offering distinct mechanical advantages. A typical palm fruit digester comprises key components such as a feed hopper, digester drum, rotating stirrers or beater arms, structural frame, cover, outlet channel, and a prime mover, which is typically an electric motor or a diesel engine (Agbonkhese et al., 2018). For example, Agbonkhese and colleagues reported a vertical digester constructed with locally available materials that achieved an efficiency of 92.31% and a throughput of 740 kg/hr. Owolarafe et al. (2008) observed that processing conditions, especially digestion time and expression pressure, significantly influence oil yield and impurity levels. Similarly, Yeow et al. (2010) explored the use of microwave moisture sensors to assess ripeness, which is a key factor affecting oil quality and yield. These technological advances highlight the critical role of engineering in optimizing palm oil production systems. Consequently, the continued innovation and refinement of palm fruit digesters form the foundation for improving oil extraction efficiency and reducing processing costs.

2.2 Structure of the Oil Palm Industry

The global oil palm industry is a complex and interconnected system comprising both large-scale industrial plantations and smallholder farmers. Its structure spans three major continents: Asia, Africa, and Latin America, with Southeast Asia dominating the production landscape. Indonesia and Malaysia together account for over 85% of global palm oil output, producing approximately 42.5 million and 18.5 million tonnes annually, respectively (Statista, 2020). These countries supply a significant portion of global demand, exporting to major markets in the European Union, China, and the Indian subcontinent, where palm oil is used in food, cosmetics, biofuels, and industrial applications. Modern palm oil cultivation is largely characterized by vertically integrated corporate entities that manage everything from plantation to export. These operations benefit from economies of scale, advanced technology, and streamlined logistics, making them highly efficient. However, a significant portion of global palm oil still comes from smallholder farmers. According to Decals et al. (2020), smallholder plantations occupy approximately 30–40% of global oil palm cultivation land. While less efficient in terms of yield, smallholder units play a critical socio-economic role, especially in rural areas, where they provide employment, local food security, and household income (Hambloch, 2018; Euler et al., 2016In Africa, the structure of the industry differs significantly. Nigeria, which was the world's largest producer of palm oil in the 1960s, now ranks fifth globally with an estimated annual output of about 1 million tonnes, far behind Indonesia and Malaysia (Statista, 2020). The Nigerian oil palm sector is heavily fragmented, with the majority of production still carried out by small-scale producers using traditional or semi-mechanical methods. Most of the palm oil produced is consumed domestically, with limited export activity. Although commercial plantations exist, such as those operated by Presco and Okomu Oil, they account for only a small fraction of the country's total output.

The Nigerian industry's structure can be classified into three main categories:

I. Industrial/Commercial Plantations: Typically, large-scale, vertically integrated companies with access to capital, modern processing facilities, and export infrastructure.

II. Smallholders: Individual farmers cultivating less than 5 hectares, often using manual or rudimentary tools for harvesting and processing.

III. Out-grower Schemes: A hybrid system where smallholders grow oil palm under contract or partnership with commercial firms, supplying fresh fruit bunches (FFB) for centralized processing.

2.3 The Significance of Palm Oil as a Global Commodity

I. Versatility and Widespread Use: Palm oil is a globally significant agricultural commodity, valued for its versatility across numerous sectors. It is used in food products such as margarine, instant noodles, ice cream, and baked goods; in household items like soaps, detergents, and cleaning agents; and in industrial products including lubricants, cosmetics, candles, and bio-based plastics (Rosner, 2018). According to Gough (2013), over half of all supermarket products, from shampoos to packaged snacks, contain palm oil or its derivatives. This widespread use makes it a vital ingredient in both developing and developed economies, where its low cost and long shelf life contribute to its preference over other vegetable oils.

II. Importance in Global Trade and Industry: Palm oil represents a crucial part of international trade, accounting for 0.24% of global trade volume (Descals et al., 2020). Major producers like Indonesia and Malaysia export large volumes to key markets such as China, India, and the European Union. The trade of palm oil is not only economically significant but also politically strategic, affecting the balance of payments and shaping international trade relations (Xu et al., 2020). For countries like Nigeria, improving local production efficiency can reduce reliance on imports and strengthen domestic trade positioning.

III. Influence on the Consumer Goods Sector: The consumer goods industry is deeply intertwined with the palm oil supply chain. Global corporations across the food, hygiene, and cosmetics sectors rely heavily on palm oil for product formulation. Consumer awareness and regulatory shifts toward sustainability have prompted increased scrutiny of how palm oil is sourced and processed (Gough, 2013). This creates opportunities for technologies that ensure traceability, reduce waste, and support environmentally responsible production, emphasizing the need for efficient digesters that minimize resource loss during processing.

IV. Contribution to Renewable Energy and Energy Security: Palm oil plays a growing role in the renewable energy sector, particularly in the production of biodiesel. In the European Union, more than 50% of palm oil imports are directed toward transportation fuel, reflecting its importance in reducing dependence on fossil fuels (Rosner, 2018; Statista, 2020). As global interest in biofuels intensifies, improving the upstream processing of palm fruit, including digestion and oil extraction, becomes increasingly vital to meet demand while maintaining sustainability standards.

V. Socio-Economic Impact and Rural Development: Beyond its industrial applications, the oil palm industry is a driver of rural development and poverty alleviation. Smallholder farmers account for a significant portion of global palm oil production and benefit from stable income, land use efficiency, and employment opportunities. According to Kadandale et al. (2019), the industry supports approximately 6 million direct jobs and 11 million indirect jobs globally. In Nigeria, where palm oil is primarily produced by rural smallholders, access to appropriate technologies such as affordable palm fruit digesters can dramatically improve livelihoods and enhance the country's agricultural productivity.

2.4 Methods of Extracting Palm Oil

In this section, two methods of palm oil extraction methods are discussed:

2.4.1 Traditional Method

Traditionally, palm oil extraction in Nigeria was carried out using manual techniques, often practiced at the community level and primarily driven by women in rural areas. The process typically begins with harvesting ripe fruit bunches using simple tools like sickles or machetes. The fruits are detached manually from the bunch, then boiled or cooked in large pots to soften the mesocarp. Once softened, the fruits are pounded using a mortar and pestle or sometimes even bare feet to release the oil from the oil-bearing cells. The mixture is then washed with water, and the floating oil is skimmed off the surface. This oil is finally boiled again to separate impurities, allowing the oil to be collected from the top. While, historically important, this method is widely acknowledged as time-consuming, physically demanding, and hazardous. Studies such as those by Owolarafe et al. (2002) and Fashina et al. (2021) have highlighted the inefficiency and poor quality of oil obtained through these manual processes. The high labour intensity, low yield, and inconsistent quality of the oil produced limit its suitability for large-scale consumption or export markets.

2.4.2 Mechanical Methods

With the advent of industrialization, the oil palm industry began incorporating mechanical methods to overcome the inefficiencies associated with traditional practices. These modern processes employ machinery to automate and optimize key stages such as sterilization, digestion, pressing, clarification, and purification, ultimately leading to increased oil yield and improved quality. According to Fashina, Durodola, and Hameed (2017), mechanical digesters and extractors have been developed using locally sourced materials to promote accessibility and reduce fabrication costs. Machines such as vertical and horizontal digesters, screw presses, and sterilizers have become commonplace in semi-mechanized and industrial setups. Okafor (2015) also highlighted how thermal insulation was incorporated into digester designs to retain heat, thereby improving oil extraction efficiency. The mechanical oil palm processing line generally comprises the following steps:

I. **Fruit Reception:** Fresh fruit bunches (FFBs) are transported from plantations to processing centers. Efficient reception ensures freshness and minimizes free fatty acid (FFA) development due to delays.

II. **Threshing:** A mechanical thresher is employed to detach the palm fruits from their bunches. Using the principle of vibration or rotary impact, the thresher minimizes manual labor and improves throughput.

III. **Sterilization:** Sterilization is a crucial pre-processing stage in palm oil extraction. It involves the application of heat, either through boiling or steaming, to the freshly harvested palm fruit bunches. This process serves multiple purposes: it deactivates lipolytic enzymes that could otherwise cause oil spoilage, softens the mesocarp (the fleshy part of the fruit), and facilitates the separation of the fruit from the bunch during threshing, as well as the pulp from the nut and fibre during digestion. Two main types of sterilization methods are employed. Steam-based sterilizers expose the fruits to high-pressure steam and are preferred when it is necessary to prevent direct contact between water and the fruit. This method helps preserve the integrity and quality of the oil, especially when mechanical pressing is used without any water dilution. On the other hand, water-based sterilizers involve boiling the palm fruits in water and are suitable when some degree of washing or dilution is acceptable in the process. This method is commonly used in small-scale or traditional processing setups. Proper sterilization greatly enhances the efficiency of the subsequent digestion and oil extraction stages, while also improving the overall quality of the palm oil produced.

IV. **Digestion:** This is the critical phase where palm fruits are mashed to rupture oil-bearing cells, enabling oil release. Modern digesters, either vertical or horizontal, employ rotating shafts with beater arms to macerate fruits. Heating is often applied to aid cell rupture and reduce viscosity. The vertical-cylinder method, the focus of this research, uses a central shaft with radially spaced arms to mash fruits while rotating within a cylindrical chamber.

V. **Pressing:** Once digested, the palm fruit mash is either mechanically pressed (dry method) or subjected to hot water-assisted oil separation (wet method). In both cases, pressure is applied to separate crude oil from fibrous solids and nuts. Hydraulic or screw presses are commonly used, with throughput and extraction efficiency depending on pressure intensity and mash consistency.

VI. **Clarification:** The purpose of clarification is to separate the crude palm oil from water, fibrous matter, and other impurities that remain after the pressing stage. The mixture coming from the digester or press is dense and highly viscous due to the presence of solid particles, cell debris, and water. To facilitate separation, hot water is added in a dilution ratio of approximately 3:1. This step thins the mixture and helps create a physical distinction between oil and non-oil components. The addition of hot water and the application of heat encourage the lighter oil droplets to rise to the surface while the heavier material, including water, fibre, and debris, sink to the bottom. Before settling, the diluted mixture is passed through a screen to remove coarse fibrous material. It is then transferred to a large tank where it is boiled for one to two hours. This heating further reduces the viscosity and enhances the separation process. After boiling, the mixture is left to stand undisturbed, allowing gravity to act on the components. As a result, a clear layer of palm oil accumulates at the top of the tank, while sludge and sediment remain at the bottom. The clarified oil is carefully decanted into a reception tank and is often subjected to further heating in a dryer or purifier to remove any remaining moisture or fine impurities before storage or packaging.

VII. **Purification:** Purification involves further removal of impurities such as gums, pigments, and trace contaminants. The clarified oil may undergo heating or filtering to yield clean crude palm oil suitable for storage and eventual refining.

VIII. **Storage:** Purified oil is stored in insulated, stainless steel tanks to prevent contamination and degradation. Ideal storage temperatures are maintained around 50°C to avoid solidification and oxidation. The oil is later transported to refineries for further treatment.

2.5 Palm Fruit Digester

A palm fruit digester is a vital machine in the palm oil extraction process, designed specifically to rupture the oil-bearing cells in the mesocarp of the fruit. This action is essential for maximizing oil release before the pressing stage. The digester performs mechanical agitation or maceration on the sterilized palm fruit, significantly improving oil yield and overall extraction efficiency (Owolarafe et al., 2002).

2.5.1 The Vertical Type

The vertical palm fruit digester is one of the most commonly used configurations in small- to medium-scale palm oil processing. It consists of a cylindrical chamber equipped with a central rotating shaft, to which multiple beater arms or paddles are attached. These arms rotate within the chamber, physically breaking down the fruit to release the oil. Steam or heat may be applied within the chamber to soften the pulp and facilitate the digestion process. A typical digester unit comprises several key components, including a hopper, digester barrel, sealed bearings, main shaft, worm gear, wheel gear, discharge outlet, and a prime mover, either an electric motor or a diesel engine. Parboiled fruits are loaded through the hopper and are macerated by the rotating beater arms. Once the fruits are sufficiently digested, the resulting mash exits the unit through the discharge end by gravity. Vertical digesters are especially favored in palm oil processing due to their high efficiency and throughput, with some models capable of handling up to 740 kilograms per hour. They also consume relatively low amounts of energy and are known for their ease of operation and maintenance. An additional advantage is their gentle processing action, which results in minimal damage to the kernels, an important factor for efficient kernel recovery. Moreover, their compatibility with screw presses helps reduce wear and tear on the press unit itself (Owolarafe et al., 2008; Adah et al., 2015).

2.5.2 The Horizontal Type

The horizontal digester is another common design in palm oil processing, featuring beater arms arranged horizontally along a rotating shaft within a cylindrical chamber. These arms simultaneously perform the dual function of digesting the palm fruits and conveying the macerated mash toward an outlet for discharge. While the design is effective in breaking the oil-bearing cells and allows for continuous output, it is not without mechanical inefficiencies. Issues such as belt slippage, shaft whirling due to the extended length of the shaft, and the complexity of the pulley system can hinder optimal performance. Nevertheless, despite these limitations, horizontal digesters continue to play a significant role in larger-scale operations where the emphasis is on continuous processing (Ogblech & Ige, 2014).

2.6 The Role of Palm Fruit Digesters in the Overall Palm Oil Extraction Process

The palm fruit digester plays a critical role in the palm oil extraction chain, serving as the intermediate stage that prepares sterilised palm fruits for efficient oil release. Once the fruits have been sterilised to soften the mesocarp and deactivate enzymes that would otherwise raise the free fatty acid (FFA) levels, the digester steps in as the mechanical solution for rupturing the oil-bearing cells within the fruit. The primary function of the digester is to mash or pulp the palm fruits, converting them into a homogeneous mixture where oil can be more easily separated in the subsequent pressing stage. This process not only increases oil yield but also reduces the energy requirements during pressing, as the mechanical breakdown performed by the digester facilitates smoother oil flow and better separation of fibres and nuts. Vertical palm fruit digesters, in particular, have been preferred for their efficiency in this role. They use rotating beater arms inside a heated cylindrical drum to ensure even maceration of the fruit. This configuration enhances processing speed, improves oil quality, and minimizes residual oil in the fibre, thereby contributing to both operational efficiency and product yield. For small- and medium-scale producers, digesters are indispensable for reducing labor intensity and processing time. They offer a scalable and semi-automated solution to what would otherwise be a highly laborious manual task. In essence, the digester serves as the mechanical heart of the oil palm processing line. Its performance significantly influences not just the quantity but also the quality of oil extracted, making it a central focus of innovations aimed at boosting productivity, reducing waste, and improving the overall sustainability of palm oil production systems.

2.7 Problems Affecting the Development of the Nigerian Oil Palm Industry

The Nigerian oil palm industry faces a range of entrenched structural and systemic challenges that significantly hamper its growth, modernisation, and global competitiveness. A predominant issue is the dominance of small-scale farmers who rely heavily on manual labour and outdated traditional processing methods. These inefficient practices not only limit productivity but also compromise the quality of the palm oil produced, reducing the industry's ability to meet international standards or effectively compete in the global market. Another major hindrance is the frequent inconsistency in government policies. Unstable regulatory frameworks and abrupt policy changes introduce uncertainty, discouraging both local and foreign investment. This policy volatility impedes long-term planning and undermines stakeholder confidence in the sector's sustainability. Moreover, there exists a pervasive negative perception of agricultural labour, particularly among the youth. This sentiment contributes to a declining interest in palm oil farming and processing as a viable economic pursuit, thereby stalling the entry of new talent and innovation into the industry. Compounding these issues is a lack of adequate regulatory oversight and enforcement mechanisms. The absence of strong quality control systems and sustainability standards results in variable product quality and environmentally unsustainable practices. Poor infrastructure, such as dilapidated road networks, inadequate storage facilities, and limited access to modern milling technologies, further restricts the flow of raw materials and finished goods, raising transaction costs and lowering overall efficiency. Access to financing remains another critical barrier. Smallholder farmers and agro-entrepreneurs often face difficulties securing affordable credit or investment capital, limiting their capacity to adopt improved technologies, expand operations, or invest in modern processing facilities. Without comprehensive and well-coordinated interventions, these multifaceted challenges will continue to suppress the growth potential of Nigeria's oil palm sector. The country risks increased dependence on palm oil imports to satisfy domestic demand, an outcome that undermines national food security and diminishes the sector's contribution to economic development. Addressing these constraints will require a holistic approach involving targeted policy reforms, infrastructural investments, financial inclusion strategies, and the promotion of modern, sustainable agricultural practices.

2.8 In-Depth Analysis of the Problems Affecting the Development of the Nigerian Oil Palm Industry and Recommendations

The Nigerian oil palm industry faces a complex web of interrelated challenges that have hindered its growth and productivity. Numerous studies have pointed to issues ranging from outdated processing technologies and poor infrastructure to weak government policies and limited access to credit. Each of these obstacles contributes to a cycle of underperformance and stagnation. To achieve sustainable growth and unlock the full potential of the industry, these challenges must be systematically addressed.

2.8.1 Dependency on Outdated Technology and Small-Scale Processing

According to Izah and Ohimain (2016), Nigeria's oil palm sector operates at three primary scales: smallholder, semi-mechanised, and mechanised. Smallholder processors dominate the sector, accounting for approximately 80%, typically operating on plantations of 1–5 hectares. Semi-mechanised processors occupy 16% of the sector (5–20 hectares), while mechanised processors account for just 4% (>20 hectares). While mechanised processors employ modern equipment, the majority of smallholders still rely on crude, manual tools. This results in batch-based processing that is both time-consuming and labour-intensive, especially when compared to the continuous processing of mechanised systems. Processing takes 6–10 days for smallholders and 4–8 days for semi-mechanised operations, involving stages such as fruit fermentation (2–3 days), sterilisation and boiling, digestion and pressing (1–2 days), fibre separation (1 day), and palm press fibre fermentation (2–4 days). Orewa et al. (2009) reported that extended fermentation of fresh fruit bunches (7–9 days) led to a 42% decrease in palm oil yield. Similarly, Ohimain et al. (2013b) observed that smallholder mills processing the Dura variety achieved oil yields of only 9.4–12.8% of fresh fruit bunch weight, with some as low as 8–9%. Consequently, outdated methods remain a significant barrier to domestic supply growth.

Recommendation: Modernising the smallholder sector is essential for improving yields and reducing labour intensity. This can be achieved through subsidised access to semi-mechanised equipment via loans or leasing programs, similar to successful models in Indonesia (Sukma, 2020). Additionally, training initiatives are needed to equip smallholders with the skills required to operate new technologies (Wibowo et al., 2017). Public-Private Partnerships (PPPs) can drive investment in large-scale mechanised mills and infrastructure, as seen in Malaysia (Salleh et al., 2017). Increased funding for R&D, especially in genetic improvements of palm varieties, and the adoption of modern fermentation methods like bioreactors (Surya et al., 2018) can further enhance quality and sustainability.

2.8.2 Poor Work Ethics and Ineffective Government Policies

Following the post-independence realisation of rising demand, Nigeria initiated several development plans to boost oil palm production. The First National Development Plan

(1962–1968) aimed to address this, but its progress was halted by the civil war. The Second Plan (1970–1974) mandated the Nigerian Institute for Oil Palm Research (NIFOR) to replace wild groves with high-yield varieties (Ugbah and Nwawe, 2008), with partial success in southern regions. The Third Plan (1975–1980) emphasized smallholder expansion, but outcomes were undermined by weak work ethics. Subsequent efforts, such as planting 1 million hectares for 15 million metric tonnes of fresh fruit bunches (FFB) annually, were poorly implemented. Initiatives like the World Bank Tree Crops Program, the Agricultural Development Programme (ADP), and the Public/Private Sector Investment Drive also fell short due to mismanagement and poor execution.

Recommendation: A coherent and stable policy framework is essential. This should include campaigns to improve perceptions of agricultural labour, targeted training programs for smallholders, and streamlined access to tools and modern techniques (Ugbah & Nwawe, 2008). Improved accountability and transparent oversight are also critical for effective implementation (Adams & Oladele, 2016). Engaging international partners and private stakeholders will further bridge the production-consumption gap.

2.8.3 Limited Access to Credit Facilities and Uneven Resource Distribution

The majority of oil palm processors, especially smallholders, are located in rural areas where access to credit remains a critical issue. Many lack assets that can be used as collateral for formal loans. Existing credit schemes have often been skewed by favouritism, and recipients frequently divert funds away from palm oil production. As a result, many smallholders are unable to scale their operations or invest in modern tools.

Recommendation:

A more inclusive and transparent credit policy is needed, one that prioritises smallholder farmers and provides low-interest, collateral-free loans. Financial literacy programs should be integrated to ensure that recipients understand how to manage credit effectively (Ugbah & Nwawe, 2008). Strengthening rural financial institutions can also enhance accessibility to financing for processors (Olomola, 2010).

2.8.4 Poor Infrastructural Facilities

Most oil palm cultivation occurs in rural areas that are poorly served by basic infrastructure. Inadequate roads, erratic electricity supply, and lack of basic amenities such as health care and education all contribute to inefficiencies in production. In particular, the use of diesel-powered equipment and organic waste for sterilisation is prevalent among smallholder processors, increasing costs and limiting productivity.

Recommendation:

Government-private partnerships should prioritise infrastructure development in rural areas, especially transport and electricity (Fashina et al., 2021). Solar and renewable energy systems offer sustainable alternatives to diesel-powered operations (Owolarafe et al., 2008). Holistic rural development will reduce operating costs and boost livelihoods, thereby encouraging greater participation in the sector (Agbonkhese et al., 2018).

2.8.5 Frequent Changes in Government Policies

Policy inconsistency due to changes in political leadership has undermined long-term progress. For example, the 2008 initiative to expand oil palm estates to 1 million hectares by 2010, with NIFOR expected to boost seed output, collapsed due to lack of continuity by successive administrations (Ugbah & Nwawe, 2008). Although 2.5 million hectares were projected by 2020, poor follow-through caused the initiative to stall.

Recommendation:

To ensure continuity, a constitutionally backed national agricultural framework is essential (Fashina et al., 2017). Strengthening institutions like NIFOR and building policy resilience through monitoring and evaluation systems will reduce reliance on transient political agendas and support long-term growth (Orewa et al., 2009).

2.8.6 Exploitation and Cost of Palm Oil

Locally produced palm oil faces challenges related to pricing and quality. Studies have shown that Nigerian palm oil is nearly twice as expensive as imported alternatives (Ugbah & Nwawe, 2008). Additionally, some traders adulterate products to maximise profits. Nnorom (2012) notes that pressure from importers has led to reduced tariffs, further undercutting local producers.

Recommendation:

To protect consumers and producers, the government must enforce quality standards and penalise adulteration (Agbaire, 2012). Policies aimed at lowering input costs and improving access to affordable technologies can reduce production expenses and increase competitiveness. Tariffs on imported oil, alongside campaigns for ethical practices and consumer awareness, will support market stability and public health (Nnorom, 2012; Ugbah & Nwawe, 2008).

2.9 Empirical Studies

Over the years, a growing body of empirical research has focused on the design, fabrication, and performance evaluation of palm fruit digesters, particularly with regard to improving efficiency, reducing labour intensity, and addressing the unique challenges faced by small-scale palm oil producers in Nigeria. Traditional palm oil extraction methods, characterised by low yields, high labour requirements, and significant processing times, have necessitated the development of mechanised solutions that are affordable, sustainable, and adaptable to rural environments. A prominent innovation in this regard is the dual-powered palm fruit digester developed by Alade, Obiakor, Okoro, Ojukwu, Eneh, Onah, Willoughby, and Ojo (2021). Their machine features both motorised and pedal-driven operations, with reported efficiencies of 81.50% and 48.17%, respectively. This hybrid system is particularly advantageous in rural regions where erratic power supply, high diesel costs, and fuel shortages frequently hinder productivity. The machine is designed with key components such as a shaft, gearbox, digesting chamber, and support structures, all engineered for reliability and ease of maintenance. Its adaptability and cost-effectiveness make it highly suitable for small- and medium-scale producers. Similarly, Utu, Erhimona, and Onyenanu (2023) applied Response Surface Methodology (RSM) to optimise a locally fabricated palm fruit digester by examining four variables: motor speed, number of blades, weight of cooked fruit, and digestion time. Their experimental design demonstrated high accuracy, as indicated by the regression coefficients (R^2), and yielded an optimal efficiency of 81% with a throughput capacity of 0.133 kg/min. Their findings reinforce the need for data-driven design approaches to improve local processing technologies and align them with global standards. Further contributions to the field include Aideloje et al. (2018), who developed a vertical mobile palm fruit digester designed to solve the transportation bottlenecks associated with hauling palm fruits from farms to processing locations. The machine, fabricated from locally sourced materials, achieved a digestion capacity of 1090.47 kg/h and an efficiency of 89.82%. Earlier tests of the same model reported a capacity of 740 kg/h and an efficiency of 92.31%, reflecting its high performance and suitability for decentralised operations in remote communities. In another notable study, Asoiro and Udo (2013) designed a motorised rotary digester that achieved a throughput of 117.93 kg/h and a performance efficiency of 64.88% at an optimal operating speed of 621.4 rpm. Although lower in efficiency compared to more recent innovations, their study represented an important step in mechanising oil palm processing. Likewise**,** Durodola et al. (2017) undertook the development and evaluation of an oil palm fruit digester that emphasised cost-effectiveness and local adaptability, while Okafor (2015) developed a vertical digester designed to feed a screw press using gravitational flow, achieving an oil extraction efficiency of 95.7% at an optimal operating temperature of 98°C. Further improvements have also come from studies exploring thermal and mechanical optimisation**.** Wondi et al. (2016) examined the thermal characteristics of vertical digesters and found that regulated heating significantly improved oil release from the mesocarp, suggesting that temperature control is a key variable in efficient digestion. In the same vein, Akpan et al. (2017) developed and tested a vertical digester with a rotating drum, which achieved a 91% oil extraction rate. Their design aimed to improve mechanical separation of pulp and kernel, resulting in greater processing throughput and oil yield. Despite these advancements, a large proportion of Nigeria's rural population continues to rely on traditional and inefficient processing methods. As Sasu (2022) reported, the country produced 1.4 million metric tonnes of palm oil in 2022, yet still faces challenges in meeting domestic demand due to outdated practices. These empirical studies provide critical benchmarks and design frameworks for future innovations aimed at closing the gap between traditional and modern palm oil extraction processes.

CHAPTER 3
METHODOLOGY

3.1 Design Preliminaries

The design of the palm fruit digester was guided by the goal to develop a machine that ensures efficient digestion of palm fruits while reducing the physical demands typically associated with traditional processing methods. In addition, the design aimed to minimize direct contact with the fruit during processing, thereby improving hygiene, safety, and process consistency. The following factors were carefully considered:

I. **Cost:** Given that the intended users are smallholder farmers with limited financial resources, affordability was a critical consideration. Every component and process in the machine's fabrication was evaluated to ensure cost-effectiveness without compromising essential performance features. Locally available materials and simplified assembly methods were prioritized to keep production costs low.

II. **Load Capacity:** The machine was designed to handle two medium-sized palm fruit bunches per cycle, with an estimated weight of 8–12 kilograms each. This results in a target processing capacity of approximately 16–24 kilograms per hour, which aligns with the scale of operations typical among smallholder farmers and allows for practical throughput without requiring industrial-level energy input.

III. **Material Selection:** Mild steel was selected as the primary construction material for the digester due to its strength, availability, and affordability. To enhance its resistance to corrosion, especially considering the moist and acidic environment associated with palm fruit processing, the steel surfaces were treated and painted appropriately.

IV. **Maintainability:** A key aspect of the design was ensuring ease of maintenance and serviceability. The digester's components are arranged in a straightforward layout, allowing users with limited technical expertise to carry out routine cleaning, repairs, or part replacements without requiring specialized tools.

3.2 Design Consideration

Having examined the limitations of primitive processing techniques and the operational benefits of mechanized systems, the following key considerations guided the machine's design:

I. **Increased Processing Capacity:** The design had to have a result of significantly improving output compared to the traditional/manual digestion approach. Hence allowing the user achieve a higher capacity that meets smallholder processing needs efficiently within a shorter time frame.

II. **Reduction of Labour Intensity:** By automating the digestion process, the machine minimizes human effort and promotes ease of use, particularly for rural users.

III. **Material Strength and Thermal Conductivity:** Materials were chosen not only for their mechanical strength, ensuring the digester can withstand forces during operation, but also for their ability to tolerate high processing temperatures. This is critical in preserving machine integrity under extended use.

IV. **Weight and Portability:** The overall weight was optimized to make the digester stable during operation, yet light enough to be relocated by users in rural settings without requiring complex equipment.

V. **Simplicity and User Suitability:** The machine was designed to be as simple as possible, both in structure and operation. This ensures that users with minimal technical skills can operate and maintain it safely, without causing harm to themselves or the environment.

VI. **Durability and Corrosion Resistance:** Given the acidic and oily conditions of palm fruit processing, materials with high corrosion resistance, such as mild steel with protective coating, were selected. This increases the equipment's lifespan and reduces maintenance frequency.

VII. **Noise and Vibration Control:** To improve the operator's comfort and preserve the machine's integrity, noise and vibration levels were minimized through proper design alignment and component balancing.

VIII. **Ease of Maintenance:** Component accessibility was emphasized to allow routine servicing, cleaning, and part replacement without specialized tools. This reduces downtime and extends the life of the equipment in the field.

IX. **Surface Finishing:** Attention was given to surface finishing for both protective and practical purposes. Painted surfaces improve corrosion resistance and contribute to ease of cleaning, enhancing both hygiene and aesthetic appeal.

X. **Power Requirements and Efficiency:** The power rating of the diesel engine or motor to be used was carefully matched to the expected operational load. This ensures that the machine functions effectively without excessive fuel consumption or mechanical strain.

3.3 Design Calculations and Analysis

To calculate the power requirement of the palm fruit digester, the following parameters were considered:

3.3.1 Rupture Strength of a Single Palm Fruit

The power requirement calculations of the machine start from determining the rupture strength required for a single palm fruit that has been sterilized at 100 degrees Celsius under a pressure of 1 atm for 45 minutes.

According to American Society of Agricultural Engineers (ASAE, 2019), this value is 1.082N/mm2.

This value was obtained using the formula

$$S_R = {}^{F_R}/_{A_M} \tag{3.1}$$

Where,

$S_R = rupture\ strength$

$F_R = rupture\ \ force(N)$

$$A_M = area\ \ of\ \ \ palm\ \ \ fruit\ \ mesocarp\ (mm^2)$$

3.3.2 Rupture Force of a Single Palm Fruit

The rupture force for a single palm fruit can be obtained from $eqn\ (3.1)$ by making F_R the subject formula:

$$F_R = S_R\ \ x\ \ \ A_M \tag{3.2}$$

Assuming that the palm fruit is a sphere, the area is determined as follows:

$$A_M = 4\pi(r_m)^2 \tag{3.3}$$

Where,

r_m = approximate radius of deformation of fruit (mm)

Hence, A_M = $254.5mm^2$ According to American Society of Agricultural Engineers (ASAE, 2019). So, from equation 3.2, the value for the rupture force for a single palm fruit is:

$$F_R = S_R\ \ x\ \ A_M$$

$$F_R = 275.37N$$

3.3.3 Torque Transmitted Per Digester Arm

According to American Society of Agricultural Engineers (ASAE, 2019), the relationship is expressed by the given equation:

$$Td = F_R\ \ x\ L_d \tag{3.4}$$

Where, L_d = length of digester arm

So, T_d = 60.581Nm

Hence, Total torque in the digester of 6 beater arms is given by

$$T = T_d\ \ x\ \ \ n \tag{3.5}$$

Where,

n = number of digester arm

n = 6

So, the Total torque (T) transmitted in the digester is:

T = 363.48Nm

3.3.4 Angular Speed of the Shaft

According to American Society of Agricultural Engineers (ASAE, 2019), the relationship is expressed by the given equation:

$$F_R = mw^2 L_d \tag{3.6}$$

The required angular speed of the shaft (w) to support the beater arms of the digester is deduced as in equation (3.10) below:

$$w = \sqrt{\left(\frac{F_R}{mL_d}\right)} \tag{3.7}$$

$$F_R = mg \tag{3.8}$$

$$M = F_R/g$$

(3.9)

$$w = \sqrt{g/L_d} \tag{3.10}$$

Hence, the required angular speed of the shaft is,

$$w = 8rad/sec$$

3.3.5 Diameter of Digester Arm

According to American Society of Agricultural Engineers (ASAE, 2019)

The diameter of a shaft subjected to bending and torsion is obtained from the formula below:

$$d^3 = 16/\pi S_{smax} \sqrt{(K_b\, M_b)^2 + (K_t M_t)^2} \tag{3.11}$$

Where, S_{Smax} = maximum allowable shear stress

K_b = combined shock and fatigue factors applied to the bending moment

K_t = combined shock and fatigue factors applied to the torsional moment

M_b = bending moment

M_t = torsional moment

But since the digester's arms are mainly subjected to bending moment, equation (3.14) reduces to,

$$d^3 = 16/\pi S_{smax} \sqrt{(K_b\, M_b)^2} \quad (3.12)$$

With the bending moment on the digester arm determined by

$$M_b = F_R\ x\ L_d \quad (3.13)$$

M_b = 60.581Nm

According to ASME, bending stress for shafts without keyway is $55MN/m^2$ and $K_b = 2.0$

Hence, making the relevant substitution, we get the shaft diameter as d = 25mm

3.3.6 Load Carry Capacity of the Pulley

The load carry capacity of a pair of pulleys is determined by the relation:

$$e^{\Theta\mu} \quad (3.14)$$

For the choice of the value of which pulley's Θ to use, we use the smaller value Θ that returns the smaller value of $e^{\Theta\mu}$

Using the values of Θ_1 and Θ_2: from equations (3.20) and (3.21), we determine the pulley that the load carrying capacity of the design:

i. Using Θ_1:

$$e^{\Theta\mu} = e^{0.3 \times 2.58} = 2.16$$

ii. Using Θ_2:

$$e^{\Theta\mu} = e^{0.3 \times 3.70} = 3.03$$

Hence, using equation (3.18):

$$T_1/T_2 = \quad e^{\theta\mu}$$

$$T_1/T_2 \ = \ 2.16$$

$$T_1 \ = \ 2.16\,T_2 \qquad (3.15)$$

Therefore, for the palm fruit digester, power to be transmitted by the belt is equals

$$P_a = 2544.23W = 2.544KW$$

Referencing a belt selection table, the maximum power that can be transmitted by a belt at a pulley ratio of 2:1 is 1.7 kW.

Hence, the number of belts (N_b) = 2.544/2.3

= 1.1

So, the number of belts required equals 1

3.3.7 Selection of Pulleys and Determination of Their Speeds

Power is transferred from a driving shaft to a driven shaft using a pulley and belt system. The relationship expression provided by Kurmi and Gupta (2005) is utilised to calculate the transmission speed.

The equation (3.16) below is used to determine the transmitted speed:

$$N_1D_1 = N_2D_2 \qquad (3.16)$$

Where:

N_1 = Speed of motor shaft = 850rpm

D_1 = Diameter of driver pulley = 180mm

N_2 = Speed of Digester shaft = 480rpm

D_2 = Diameter of driven

Hence,

$D_2 = 850 \times 180/480 = 320$mm

3.3.8 Designs for Belt

The belt is required for the transmission of the required power. The total power transmitted by a belt drive is a function of the belt tensions and belt speed. According to American Society of Agricultural Engineers (ASAE, 2019), the relationship is expressed by the given equation:

$$Power(P_m) = (T_1 - T_2)V \tag{3.17}$$

Where,

T_1 = belt tension on the tight side

T_2 = belt tension on the slack side

V = belt speed (m/s)

The equation (3.18) below gives a relationship between T1, T2, and the angle of wrap of the belt around the pulley,

$$T_1/T_2 = e^{\theta\mu} \tag{3.18}$$

Where,

μ = coefficient of friction between pulley and belt

Θ = angle of wrap i.e. angles of contact of the belt on the pulley

3.3.9 Determination of Angle of Wrap

According to American Society of Agricultural Engineers (ASAE, 2019), the angle of wrap for an open loop belt may be determined using equation (3.13)

$$Sin\,\beta = (R - r)/c \tag{3.19}$$

Hence β = 15.96°

$\theta_1 = 180° - 2\beta = 180° - 2\,sin^{-1}\,(R - \text{ r})/c$ (3.20)

$\Theta_1 = 180 - 2(15.96)$

$\Theta_1 = 148.08 = 2.58$ rad

$\theta_2 = 180° + 2\beta = 180° - 2\,sin^{-1}\,(R - r)/c$ (3.21)

$\Theta_2 = 180 + 2(15.96) = 211.92 = 3.70$ rad

Where, C = distance between pulley centres

This C is selected based on the assumption that

1. The smaller diameter is 1/3 of the larger pulley diameter
2. The difference between the pulley diameter

As such, the difference between the two pulleys is (320 - 180) mm = 140mm

And C = 400mm

3.3.10 Length of Belt

According to American Society of Agricultural Engineers (ASAE, 2019), the length of the belt is determined by the equation:

L = $\pi(r_1 + r_2) + 2C + \frac{(r_1+r_2)^2}{C}$ (3.22)

Hence, L = 0.6549m

3.3.11 Velocity of Belt

According to American Society of Agricultural Engineers (ASAE, 2019), the velocity of the belt is determined using the formula:

$V = \frac{\pi D_1 N_1}{60}$ (3.23)

3.3.12 Determination of T_1 an T_2 of belt

The maximum and minimum tension of the belt can be determined using equation (3.17):

$$Power(P_m) = (T_1 - T_2)V$$

$$2544.2 = (T_1 - T_2)5.89$$

So by substituting the values of Pm and V into it the above equation:

T1 = 372.41N and T2 = 804.40N

3.3.13 Determination of Belt Width

The width of the belt can be obtained from the equation

$$T_1 = F_b \; x \; b \; x \; t \; x \; N_b \tag{3.24}$$

Where,

F_b = tensile strength of belt = 2.7MN/m2

b = width of belt

t = belt thickness = 12mm (standard value)

N_b = number of belts

Hence substituting values into equation (3.25) we have

b = 25mm

3.3.14 Shaft Loading

The solid shaft is chosen for the digester to satisfy the strength and rigidity requirements. When the shaft is transmitting power under various operating and loading conditions, shafts are usually subjected to torsion, bending and axial loads. (Allen *et al*, 2002)

I. **Maximum shear stress:** the maximum shear stress for a circular shaft is given by

$$T_{\max} = 16M_t/\pi d^3 \tag{3.25}$$

II. **Bending stress**: the bending stress (S_b) is given by

$$S_b = 32M_b/\pi d^3 \tag{3.26}$$

III. **Axial loading:** tensile or compression stress is given by

$S_a = 4f_a/\pi d^2$ (3.27)

IV. **Combined torsion and bending:** the maximum shear stress theory is used for shafts subjected to twisting and bending. This is given by

$$S_{Smax} = \sqrt{\delta_b{}^2 + 4\tau^2} \quad (3.28)$$

$$S_{Smax} = 16/\pi d^3 \sqrt{M_b{}^2 + M_t{}^2} \quad (3.29)$$

When fatigue and combined shock factor is applied to bending (K_b) and torsional moment (K_t) equation (3.31) becomes,

$$S_{Smax} = 16/\pi d^3 \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad (3.30)$$

In a belt drive machine such as a palm fruit digester, the torsional moment is given by the relation

$$M_t = (T_1 - T_2)R \quad (3.31)$$

In designing the shaft, the following assumptions were made

I. The weight of the shaft is negligible

II. Length of the shaft = 720mm

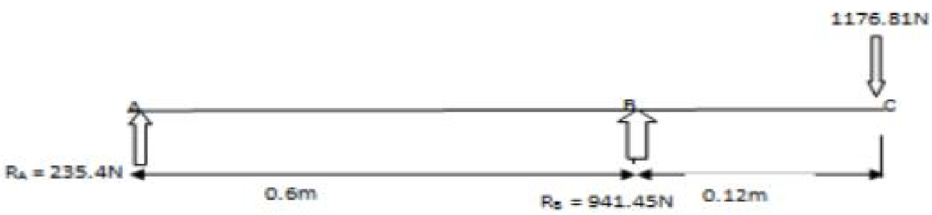

Figure 3.1**:** Drive shaft with applied forces illustrated

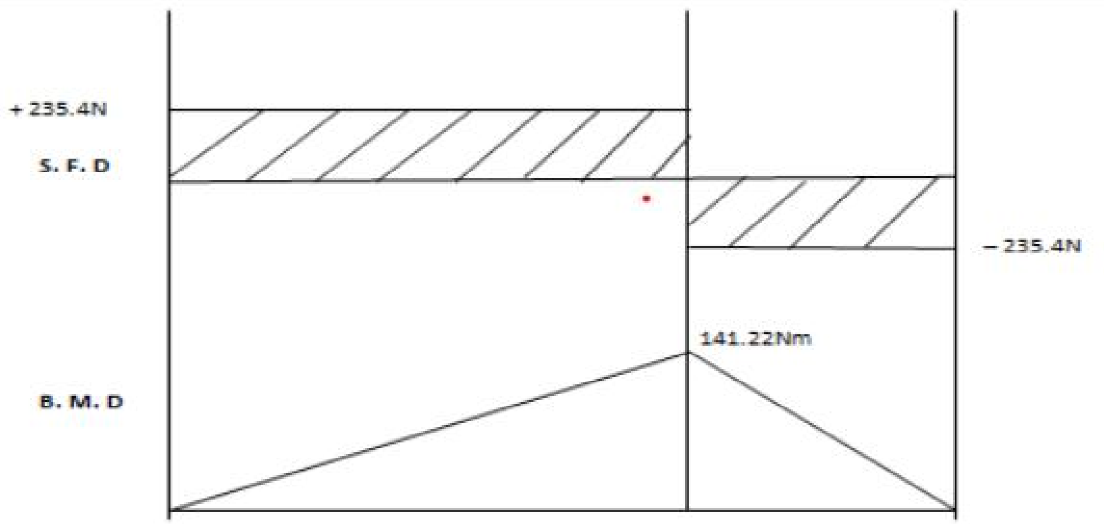

Figure 3.2**:** Shear force and bending moment diagram of the drive shaft under static conditions

To determine the reactions R_A and R_B at points A and B which are the support, moment is taken about point B.

$600R_A$ – 1116.81 x 120 = 0

R_A = 235.36N

The sum of upward forces = sum of downward forces

$R_A + R_B$ = 1176.81

R_B = 1176.81 – R_A

R_B= 1176.81 – 235.36

R_B = 941.45N

Maximum bending moment occurs at point B, therefore

$M_b = (T_1 + T_2)BC$

M_b= (804.4 + 372.41) 0.12

M_b = 141.22Nm

The torsional moment from equation (3.33) is

$M_t = (T_1 - T_2)R$

M_t = (804.4 – 372.41) 0.16

M_t= 69.12Nm

3.3.15 Determination of Shaft Diameter

According to the ASME code (Allen *et al*, 2002), the allowable stress for a shaft with a keyway is 40MN/m^2 , K_b = 1.5 and K_t = 1.0

From equation (3.32), the diameter of the shaft can be determined as follows

$d^3 = 16/\pi S_{smax} \sqrt{(K_b M_b)^2 + (K_t M_t)^2}$

Substituting values into the above expression, we have

$d^3 = 16/\pi\, x\, 40\, x\, 10^6 \sqrt{(1.5\, x\, 141.22)^2 + (1\, x\, 65.12)^2}$

d = 0.030499m

d ≈ 30mm

3.3.16 Required Power of the Digester

The power required by the digester was determined with the expression by Kurmi and Gupta (2005) which states that the power is the product of torque (T) and angular velocity (w) as

$$P_d = Tw \tag{3.32}$$

Hence, $P_d =$ 2544.43W

According to the ASME code (Allen *et al*, 2002), assuming 12% of power is used to overcome friction and a further 15% of power is required to overcome electrical losses in the system, therefore the required power for the machine is used,

$$P_m = P_d + P_f \tag{3.33}$$

Hence, the required power of the digester is,

$P_m =$ $P_d + 0.12P_d + 0.13P_d = 3231.415W$

The engine purchased for the digester is rated at 5 hp (3677.49 W). This engine was selected because its capacity (3677.49 W) exceeds the required power (3231.415W), ensuring reliable operation.

3.4 Material Selection

One of the foundational steps in the design of a mechanical system such as the palm fruit digester is the careful selection of appropriate materials for each component. The material choice directly affects the digester's strength, durability, cost, manufacturability, and operational efficiency.

3.4.1 Factors Affecting Material Selection

The material selection process was guided by several critical factors, each contributing to the functionality, longevity, and feasibility of the digester:

I. **Strength and Durability**: Materials must possess sufficient tensile and yield strength to resist deformation or failure under mechanical loads during operation.

II. **Corrosion Resistance**: Since palm oil and its byproducts have mildly acidic properties, materials in direct contact with the fruit must be resistant to corrosion to prolong equipment life.

III. **Cost Effectiveness**: Given that the target users are small-scale producers, cost is a major constraint. Selected materials must offer a favorable balance between performance and affordability.

IV. **Availabili**ty**:** Locally available materials reduce procurement challenges and costs, enabling widespread adoption and maintenance of the machine.

V. **Manufacturing Compatibility**: Materials must support processes such as welding, machining, and forming, without requiring overly complex fabrication methods.

VI. **Weight Considerations**: Lightweight materials ease transport, installation, and operation, especially in rural areas where handling facilities are limited.

VII. **Environmental Impact**: Materials with lower toxicity, recyclability, and minimal environmental degradation during use and disposal were preferred.

3.4.2 Evaluation of Candidate Materials

Four materials, mild carbon steel, stainless steel, aluminium, and high carbon steel, were evaluated based on their mechanical, thermal, and chemical properties, as well as economic and environmental factors.

I. **Mild Carbon Steel:** Mild steel (low carbon steel) contains less than 0.3% carbon and is widely used for structural and fabrication purposes due to its excellent weldability, ductility, and affordability. It has a tensile strength between 400–550 MPa and good machinability. While its corrosion resistance is relatively low, protective coatings (e.g., paint) can significantly improve durability in corrosive environments. Its moderate thermal conductivity and ease of forming make it ideal for the structural framework of the digester.

II. **Stainless Steel:** Stainless steel provides excellent corrosion resistance due to its chromium content, making it ideal for food and oil-contact surfaces. It has comparable or higher tensile strength than mild steel and maintains structural integrity under high-temperature conditions. However, its higher cost and more difficult machining make it less ideal for cost-sensitive projects like smallholder palm fruit digesters.

III. **Aluminium:** Aluminium is a lightweight metal with excellent corrosion resistance and thermal conductivity. It is easily formed and machined, but its strength is lower than that of steel, limiting its use in structural components subject to high stresses. Moreover, galvanic corrosion can be a concern when used in contact with other metals.

IV. **High Carbon Steel:** High carbon steel offers excellent hardness and wear resistance but is brittle and difficult to weld or machine. Its strength exceeds 700 MPa, making it suitable for tools and components subject to high wear. However, its low ductility and complex fabrication requirements limit its suitability for this application.

3.5 Manufacturing Process.

The process began with the careful selection of materials and adherence to precise design specifications, followed by the structured construction of individual components and final assembly. All fabrication activities were performed using locally sourced materials and standard workshop equipment.

3.5.1 Fabrication Process

The fabrication process included the following stages:

I. **Measurement**

Materials were measured according to design specifications using calibrated measuring tools to ensure accuracy.

II. **Marking**

The measured sections were marked on the metal sheets or bars to serve as guides during cutting, using scribers and chalk lines for visibility.

III. **Cutting**

Cutting was executed using mechanical saws and metal shears to shape components into their required dimensions and forms.

IV. **Joining**

Electric arc welding was used to make permanent joints for structural stability, while temporary joints were created using bolts and rivets where disassembly might be required.

V. **Drilling**

Drill presses were employed to bore precise holes for bolts and shaft fittings at pre-marked positions.

VI. **Finishing**

Grinding and filing tools were used to smoothen edges and surfaces, enhancing safety, aesthetics, and corrosion resistance.

3.5.2 Fabrication of Each Component of the Digester

3.5.2.1 Digester Drum

The digester drum was fabricated from mild steel, formed into a cylindrical shape with a diameter of 440 mm and a height of 757 mm. A plate rolling machine was used to roll a flat metal sheet into a cylinder, and the edges were joined using electric arc welding. The drum serves as the main chamber where palm fruits are digested.

3.5.2.2 Sludge Outlet

Fabricated from mild steel, the sludge outlet is rectangular with dimensions 160 mm × 80 mm, projecting 217 mm from the digester drum. It includes a removable cover (154 mm × 90 mm) to facilitate waste discharge and cleaning.

3.5.2.3 Chaff Outlet

Also constructed from mild steel, the chaff outlet was created by cutting an opening measuring 416 mm × 240 mm from the digester drum and extending it 238 mm outward. This component ensures the separation and expulsion of chaff during the digestion process.

3.5.2.4 Hopper

The hopper, shaped from mild steel sheet measuring 400 mm × 290 mm, was formed into an octagonal structur**e** slanted at 45° to the horizontal. It serves as the feed entry point for loading cooked palm fruits into the digester chamber.

3.5.2.5 Digester Stand

The digester stand was made using mild steel bars. It measures 500 mm in height with a square base of 480 mm. It has four vertical legs for stability and elevation, allowing the machine to operate at a suitable working height and facilitating drainage.

3.5.2.6 Rotating Digestion Shaft

The digestion shaft consists of two rods: an inner rod with a radius of 15 mm and a length of 770 mm, which connects to the gearbox and bearing, and an outer rod with a radius of 40 mm and a length of 757 mm that carries the digestion blades. Each blade measures 160 mm by 50 mm and is welded to the shaft at a 45° angle to improve agitation and facilitate the separation of pulp from the nuts during operation.

3.5.2.7 Pulley System

The pulley, with a radius of 25 mm, is a key component for transmitting mechanical power from the diesel engine to the digestion shaft. The system employs a belt drive mechanism for smooth and adjustable operation.

3.5.2.8 Gearbox

A gearbox unit, purchased from the local market, was affixed to the digester using electric arc welding. It includes a bevel gear mechanism with a 125 mm diameter pulley. The driver gear has 11 teeth, and the driven gear has 42 teeth, providing a reduction ratio that increases torque while reducing operational speed, ideal for digesting palm fruits.

3.5.2.9 Diesel Engine

A 5-horsepower diesel engine, operating within 1500–3600 RPM, was used to power the digester. It was connected to the pulley system via a belt, offering a flexible power source suitable for rural conditions with limited access to electricity.

3.5.2.10 Bearing

A pillow bearing was integrated into the design to support the rotating shaft and reduce friction during operation. This ensures smooth rotational movement and prolongs the lifespan of the shaft assembly.

3.6 Working Principle

The digestion process begins with the loading of parboiled palm fruits through the hopper into the digester drum. The drum, fabricated from mild steel, houses a central shaft assembly with mounted digester blades (or beater arms) angled at 45°, strategically welded along the shaft to ensure optimal agitation. The diesel engine, rated at 5 horsepower, generates mechanical power, which is transmitted via a belt and pulley system to the gearbox. The gearbox, equipped with bevel gears, adjusts the speed and torque of rotation, reducing the engine speed from about 2600 rpm to a safe operating speed of approximately 130 rpm at the shaft. This reduction is essential to avoid nut breakage while ensuring thorough maceration of the mesocarp. (Adah *et al*., 2015). As the shaft rotates, the beater arms stir and agitate the palm fruit mass, applying shear and impact forces. This rotary impact action effectively loosens the pulp from the nut, breaking down the fruit mass without damaging the kernels. Frictional forces occur between the drum wall and the palm fruit mass, among the fruit particles themselves, and between the blades and the fruit mass. This controlled agitation increases as the load inside the drum increases, thereby improving the extent of digestion. Experimental observations show that higher quantities of palm fruits result in more effective maceration. After sufficient mixing and disintegration (typically over a few minutes), the digested material (macerate) is automatically discharged through the sludge outlet via gravity, minimizing manual handling and contact with the product. The digester's overall configuration ensures efficient operation, reduced labour, and minimal contamination, making it particularly well-suited for small- and medium-scale processors in regions with limited infrastructure.

3.7 Parts and Assembly Drawings

Refer to the appendices for the part list, assembly drawings, and part drawings.

CHAPTER 4
RESULT ANALYSIS AND DISCUSSION

4.1 Performance Test

Three fresh palm fruit bunches of about 12 kilograms each were sourced from a local market (New Benin market) in Benin, Edo State, Nigeria. The fruits were removed from the bunch (the fruits weighed 10 kilograms after being removed from the bunch) washed and cleansed for dirt and other impurities before being boiled for approximately 20 minutes. The mass of the palm fruit after boiling was weighed to be 12 kilograms. After proper assembly and installation of the digester machine, the digestion drum was carefully inspected, washed and cleaned to prevent any health hazards. The palm fruits were weighed using a spring-mass weighing scale. The total weight of the three bunches was approximately 36 kilograms and was split into 4 parts 7 kilograms, 9 kilograms, 10 kilograms and 10 kilograms. Each part was digested one at a time, and the following results were obtained;

Table 4.1: Mass of boiled palm fruit and corresponding digestion time

Test	Mass of boiled palm fruit (kilograms)	Approximate time taken to digest (s)
1	7	180
2	9	240
3	10	300
4	10	300
Total	36	1020

From Table 4.1 it is observed that the approximate time taken for the palm fruit to digest increases with an increase in the quantity of palm fruit.

4.2 Error Testing

Table 4.2: Mass of boiled palm fruit, digested output, and undigested residue

Test	Mass of boiled palm fruit (kilograms)	Mass of digested palm fruit (kilograms)	Mass of undigested palm fruit (kilograms)
1	7	6.7	0.3
2	9	8.7	0.3
3	10	9.5	0.5
4	10	9.5	0.5
5	36	34.4	1.6

From Table 4.2 we can deduce the efficiency of digestion.

Mass of palm fruit (input): 36 kilograms

Mass of properly digested palm fruit: 34.4 kilograms

Mass of undigested palm fruit: 1.6 kilograms

Efficiency = (mass of digested fruit/mass of total boiled fruit) *100

Efficiency of test 1: $\frac{6.7}{7} \times 100 = 95.7\%$

Efficiency of test 2: $\frac{8.7}{9} \times 100 = 96.6\%$

Efficiency of test 3: $\frac{9.5}{10} \times 100 = 95\%$

Efficiency of test 4: $\frac{9.5}{10} \times 100 = 95\%$

The average efficiency of digestion = $\frac{95.7+96.6 + 95.0+95.0}{4}$ = 95.5%

From the result above, it is concluded that the efficiency of digestion is 95.5%.

4.3 DISCUSSION OF RESULT

The testing was carried out on the 16th of April, 2024, to evaluate the efficiency of the machine in carrying out the digestion of palm fruit.

It was discovered that the machine has a very high efficiency of about 95.5%.

This testing was done with carefully selected palm fruits, in which no bad or spoilt fruit was allowed into the machine to get an accurate value.

Meanwhile, in realistic situations, the farmers may not have the time to sort out the palm fruit, therefore there may be situations of more undigested fruits than proposed in the testing.

Some factors that cause an increase in the number of undigested fruits, therefore reducing the efficiency of the machine include;

I. Spoilt fruit: when the fruit is spoilt, it will not be properly digested, no matter how much force is exerted on it.

II. Uncooked fruit: when uncooked fruits find their way into the digester, they will not be properly digested

III. Semi-cooked fruit: when the fruit is not properly cooked, it takes longer time to digest.

4.4 Bills of Engineering Quantity

4.4.1 Material Cost

The table below shows the average cost of all materials used for the fabrication of the palm fruit digester

Table 4.3: Material cost breakdown

S/N	DESCRIPTION	QUANTITY	UNIT PRICE	TOTAL COST
1	Metal sheet	2	80,000	160,000
2	5hp diesel engine	1	250,000	250,000
3	Pillow bearing	2	10,000	20,000
4	Mechanical gearbox	1	25,000	25,000
5	Angle bar	1	26,000	26,000
6	Electrode (pack)	5	15,000	75,000
7	Belt	1	1000	1000
total				557,000

4.4.2 Production Cost

The table below shows a summary of the cost of production incurred.

Table 4.4: Cost of labour and associated services

SN	DESCRIPTION	PRICE
1	Fabrication workshop service	30,000
2	transportation	20,000
3	Miscellaneous	30,000
Total		80,000

Bill of quantity = Production cost + material cost

Bill of quantity = 80,000+557,000

= #637,000

CHAPTER 5
CONCLUSION

This project focused on creating and building a working model of a vertical palm fruit digester designed specifically for small- and medium-scale producers. The main objectives included improving processing efficiency, minimizing manual labor, and providing an affordable, easy-to-use solution for rural oil palm processors. Testing of the machine showed an encouraging average digestion efficiency of 95.5%, highlighting its effectiveness in separating the mesocarp from the kernel. The design also proved to be cost-efficient, relatively straightforward to manufacture and operate, and well-suited to the typical processing conditions found in Nigeria and similar palm oil-producing areas. Introducing this vertical digester model could lead to greater productivity, less waste, and more environmentally responsible processing methods. Beyond these benefits, widespread use of such technology has the potential to strengthen local economies, reduce reliance on imported equipment, and support sustainable farming practices. With ongoing improvements and technological advancements, vertical palm fruit digesters like this one could significantly transform palm oil production, especially in rural communities that face power limitations or lack access to modern processing tools.

Recommendation

Despite its promising performance, there remains room for improvement. The following are recommended to enhance the functionality, efficiency, and sustainability of the vertical digester:

I. Adoption of Electric Motor Drives: In areas with a stable electricity supply, replacing the diesel engine with an electric motor would offer a more cost-effective and eco-friendly solution. Electric motors produce no emissions, reduce operational noise, and contribute to a cleaner farm environment.

II. Integration with a Water Supply System**:** Incorporating an automated water delivery system to supply water at the appropriate temperature can streamline the cleaning process, particularly the removal of sludge from the shaft. This addition would reduce manual labor and increase process hygiene and efficiency.

III. Fixed Installation for Enhanced Stability**:** To minimize vibration-induced displacement during operation, the digester should be permanently installed using a concrete base (cement and sand mix). This fixed setup also reduces wear and tear, prevents theft, and enhances operational stability.

IV. Continued Research and Design Optimization: Further research is encouraged to improve both the structural and functional aspects of the digester. Future efforts could focus on using alternative materials to enhance corrosion resistance, developing improved blade designs to increase output, and exploring modular configurations that allow for easier transport and maintenance.

V. Training and Awareness Campaigns: To encourage widespread adoption of this innovation, it is recommended that sensitization and training programs be organized for local farmers and cooperative societies. Demonstrations and community-based trials can help demystify the technology and show its benefits firsthand.

In conclusion, the fabrication of a vertical digester for palm oil processing offers a promising solution for enhancing efficiency and sustainability in the palm oil industry, by efficiently extracting oil from palm fruit bunches, this technology can contribute to increased productivity, reduced waste, and improved environmental practices. With further research and development, vertical digesters have the potential to revolutionize palm oil processing, leading to a more sustainable and profitable future for the industry.

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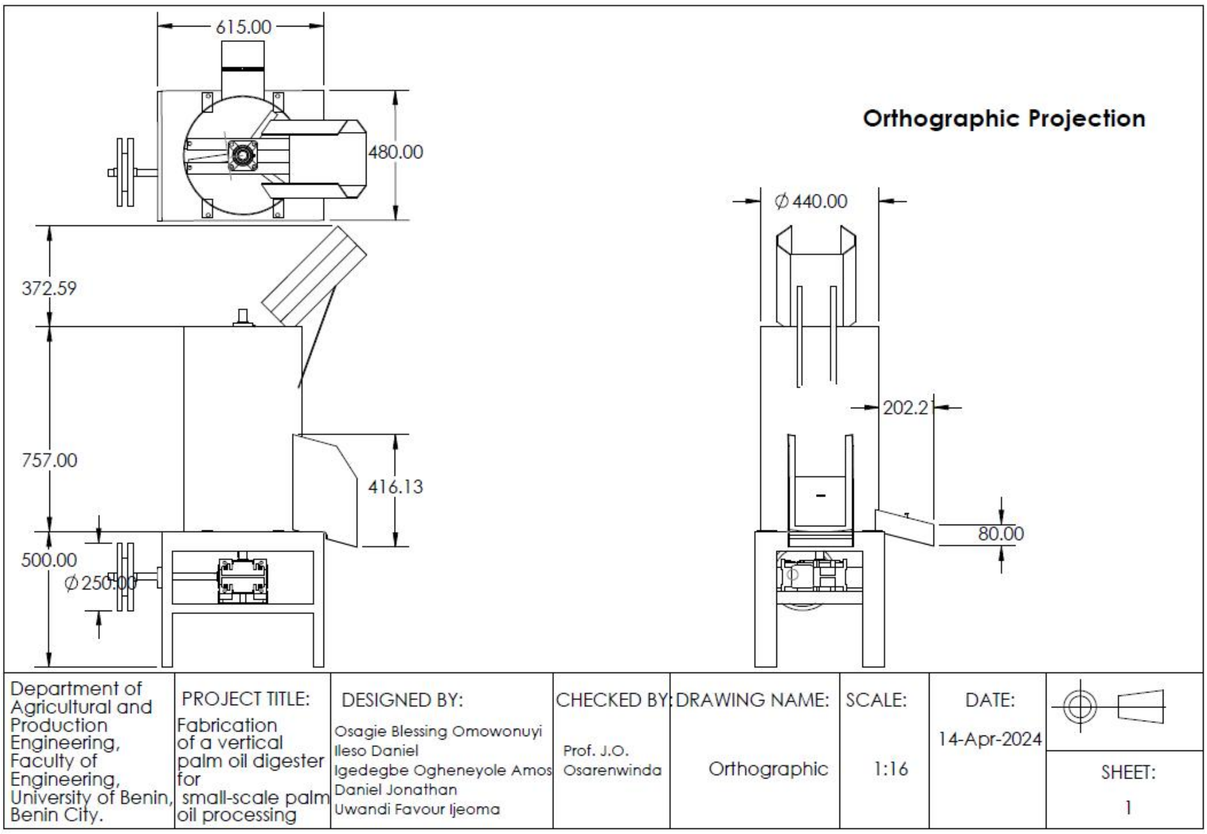
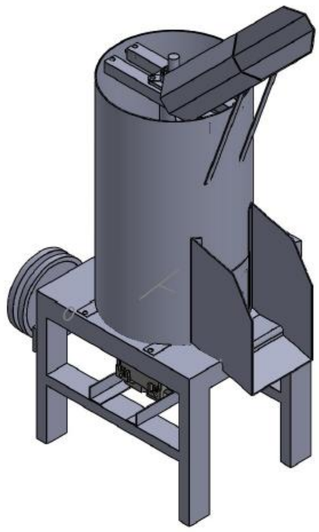
APPENDICES

Appendix I: Orthographic Projection



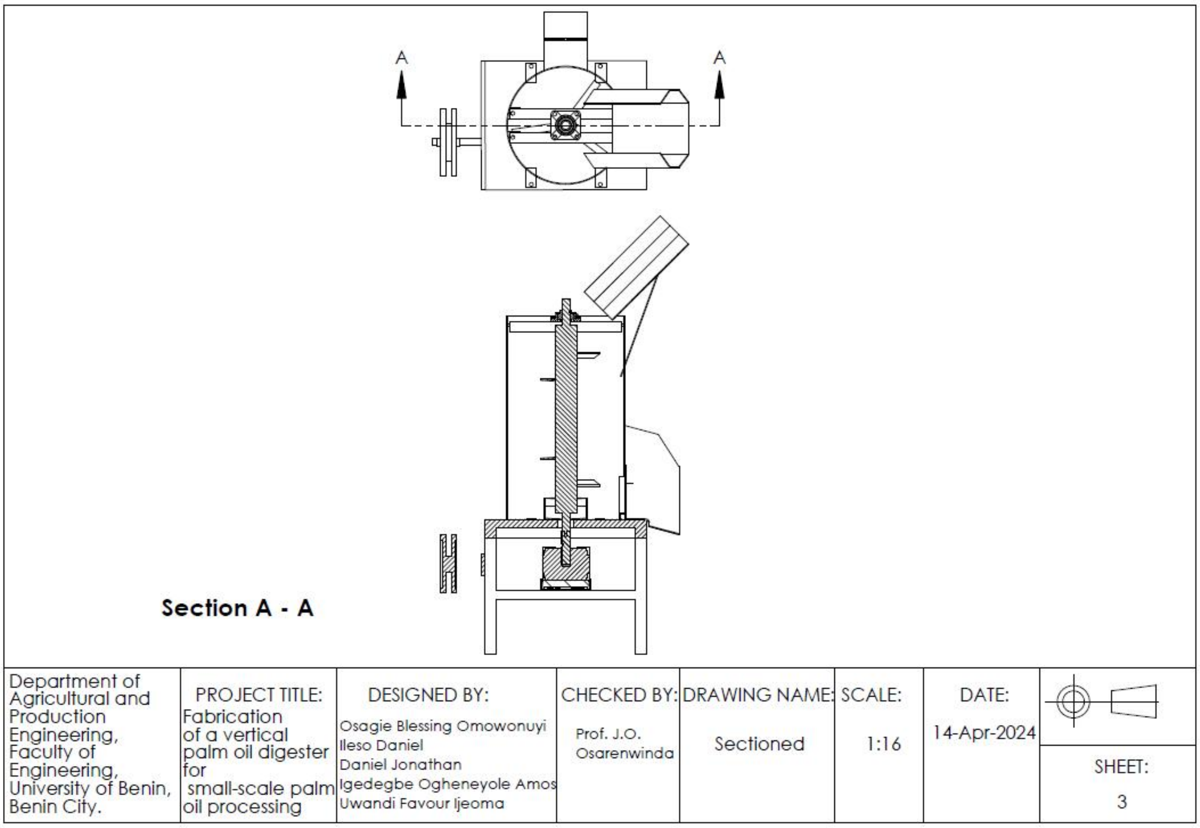
Appendix II: Rendered View

Rendered view

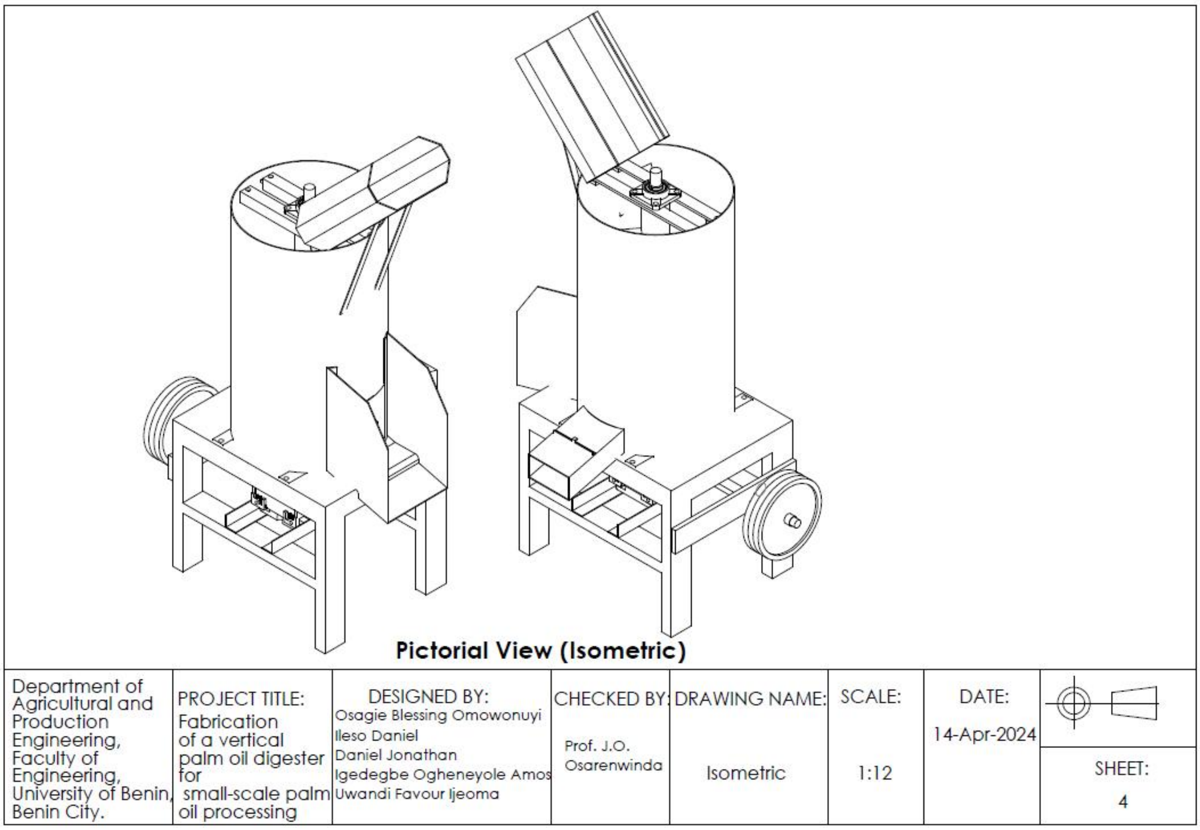


Department of Agricultural and Production Engineering, Faculty of Engineering, University of Benin, Benin City.	PROJECT TITLE: Fabrication of a vertical palm oil digester for small-scale palm oil processing	DESIGNED BY: Osagie Blessing Omowonuyi, Ileso Daniel, Daniel Jonathan, Igedegbe Ogheneyole Amos, Uwandi Favour Ijeoma	CHECKED BY: Prof. J.O. Osarenwinda	DRAWING NAME: Rendered	SCALE: 1:12	DATE: 14-Apr-2024	SHEET: 2

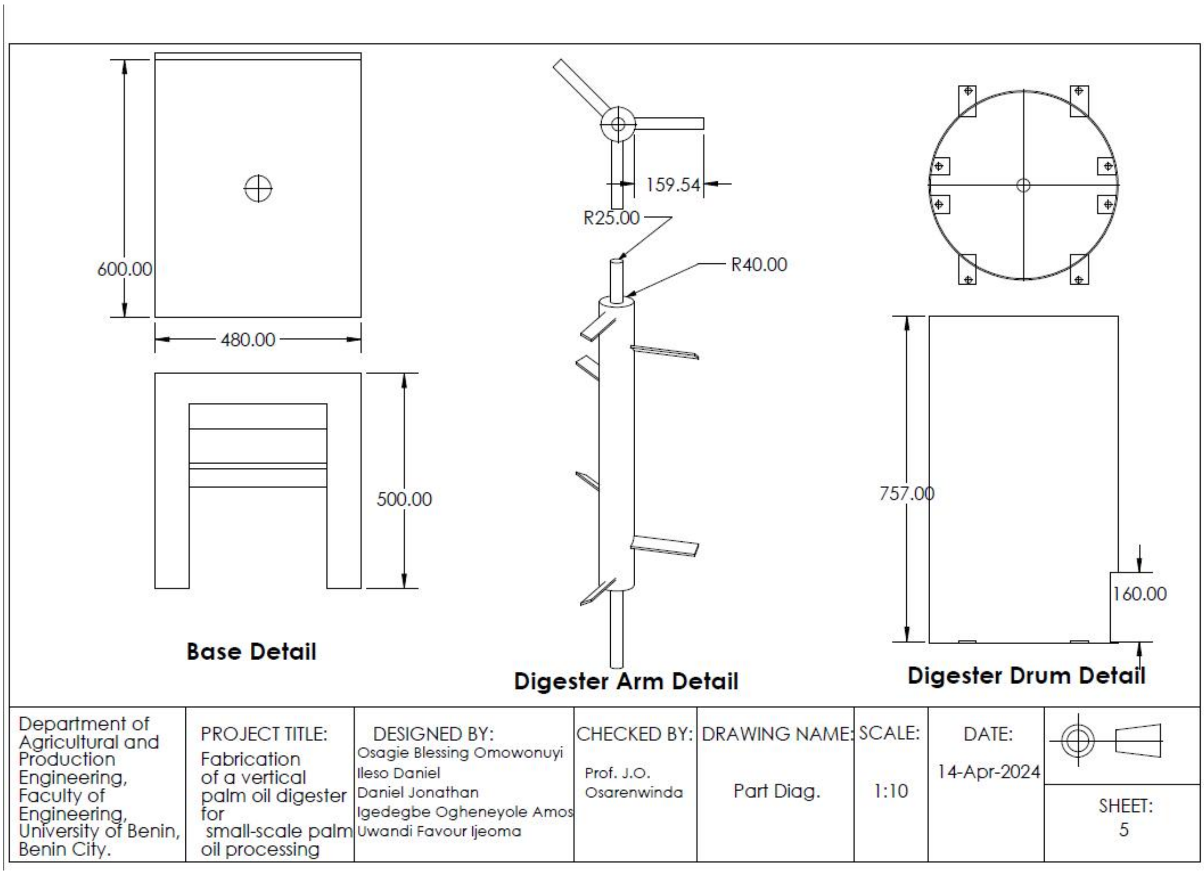
Appendix III: Section A-A



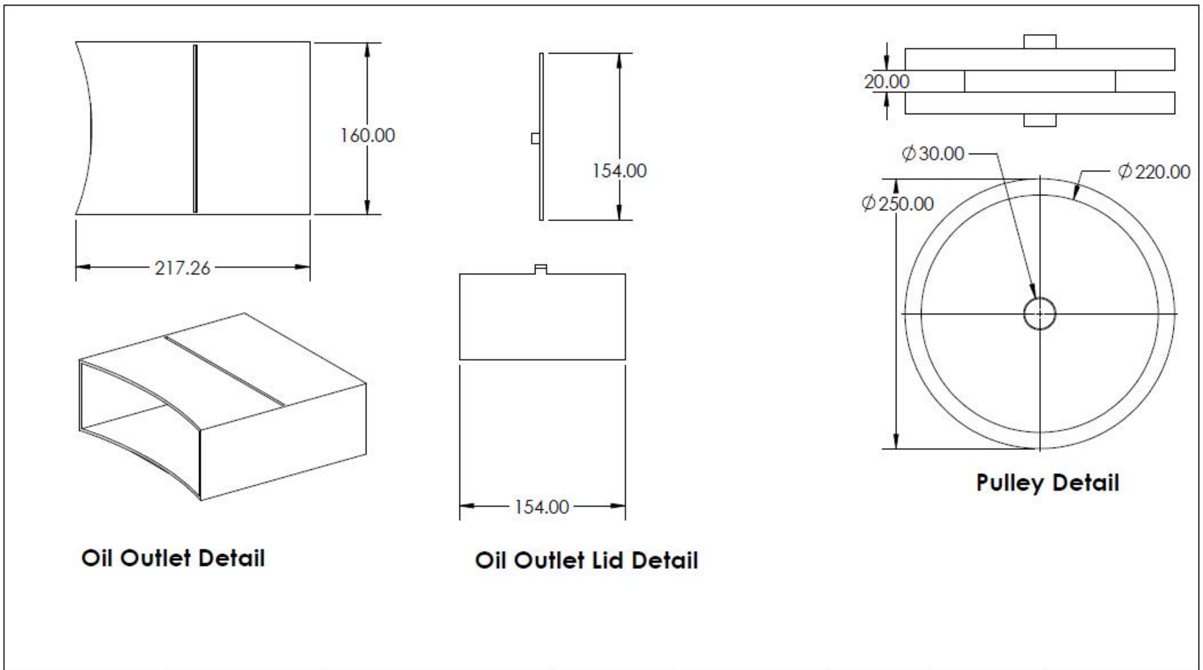
Appendix IV: Pictorial View (Isometric)



Appendix V: Parts Diagram 1

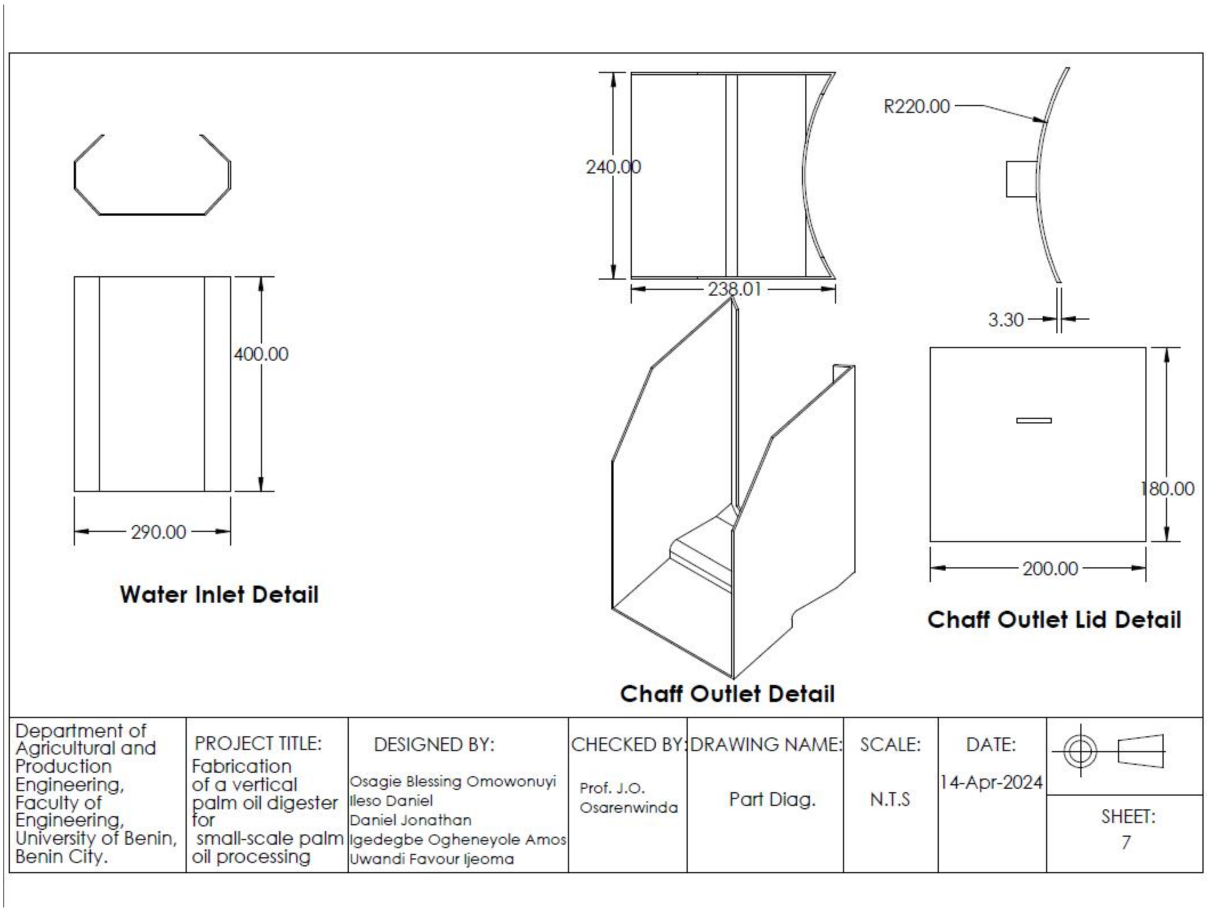


Appendix VI: Parts Diagram 2



Department of Agricultural and Production Engineering, Faculty of Engineering, University of Benin, Benin City.	PROJECT TITLE: Fabrication of a vertical palm oil digester for small-scale palm oil processing	DESIGNED BY: Osagie Blessing Omowonuyi, Ileso Daniel, Daniel Jonathan, Igedegbe Ogheneyole Amos, Uwandi Favour Ijeoma	CHECKED BY: Prof. J.O. Osarenwinda	DRAWING NAME: Part Diag.	SCALE: 1:4	DATE: 14-Apr-2024	SHEET: 6

Appendix VII: Parts Diagram 3



Appendix VII: Parts Diagram 4