DESIGN AND FABRICATION OF A SOLAR POWERED GRINDING MACHINE

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CERTIFICATION

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under the supervision of Engr. Dr. H.O EGWARE in the Department of Mechanical Engineering, Faculty of Engineering, University of Benin, Benin City in partial fulfillment of the requirement for the award of Bachelor of Engineering (B.Eng) in Mechanical Engineering

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DEDICATION

We dedicate this report to God Almighty, whose grace has granted us the strength to accomplish all that was necessary for the success of this project. To our families, whose unwavering support and encouragement have been the foundation of our academic journey.

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ABSTRACT

As global engineering practice increasingly prioritizes the elimination of greenhouse gas emissions and environmental pollution, the development of renewable energy-powered equipment represents a critical pathway toward sustainable industrial operations. This project focuses on the design and fabrication of a solar-powered grain grinding machine that harnesses photovoltaic technology to provide an off-grid, zero-emission solution for agricultural processing in rural areas where conventional electricity supply is unreliable and diesel-powered alternatives contribute significantly to carbon emissions and operational costs.

The system employs a 350W brushless DC (BLDC) motor operating at 24V and 1500 RPM, powered by a 200W monocrystalline solar panel with battery backup comprising two 12V lead-acid batteries connected in series. A pulse width modulation charge controller regulates the charging process while providing comprehensive battery protection. The mechanical subsystem features a food-grade stainless steel hopper feeding into a burr-type grinding mechanism with 80mm diameter hardened steel grinding plates, enabling adjustable fineness control for various grain types. Power transmission from the motor to the grinding shaft is achieved through a universal joint coupling, with the complete assembly mounted on a fabricated mild steel frame.

System performance analysis reveals a comprehensive energy conversion pathway from solar input to mechanical grinding output. The electrical subsystem demonstrates strong efficiency with the PWM charge controller achieving approximately 78% efficiency and the BLDC motor operating at 85-90% electrical-to-mechanical conversion efficiency. The mechanical drivetrain, comprising the universal joint, bearings, and shaft assembly, maintains approximately 85% transmission efficiency. These results in a net system operational efficiency of approximately 58% from battery DC output to mechanical grinding power. Under typical operating conditions, the system delivers approximately 315-320W of net mechanical grinding power from the 350W motor rating, accounting for motor efficiency and mechanical losses. Performance testing validated a grinding throughput of 5.0-10.0kg/hr for various grain types including tomatoes, pepper, millet etc with an estimated Specific Energy Consumption (SEC) of approximately

42Wh/kg. Environmental benefits include zero operational carbon emissions, elimination of air and reduced noise pollution, and contribution to sustainable rural development.

The system eliminates recurring fuel costs associated with diesel generators, reduces monthly operating expenses for minimal maintenance, and provides payback periods of 1-3 months for small-scale commercial users.

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Nomenclature

A	area
AC	alternating current
B	breadth
W	width
BEME	Bill of Engineering Material and Evaluation
BLDC	brushless direct current
DC	direct current
E	energy
IDE	integrated development environment
LCD	liquid crystal display
NASA	National Aeronautics and Space Adminstration
Ŋ	efficiency
OSHA	Occupational Safety and Health Adminstration
P	pressure
PWM	Pulse Width Modulation
Rpm	Revolutions per Minute
SOL	solenoid
V	volume
Σ	sigma
π	pi
τ	shear stress

CHAPTER ONE

INTRODUCTION

1.1 Back ground to the study

The grinding is achieved by the application of mechanical forces that alter the structure of the food product (e.g grain, tomato, corn, pepper e t. c) overcoming their cohesive forces after which the state of the solid food product or agricultural products is changed to flour or puree. Agricultural produce from the farm is processed in some form before it is actually consumed.

A major step in this process is a physical transformation that prepares the raw harvest for practical use without involving chemicals. Traditionally, in some part of the world today, grinding is accomplished by rubbing the agricultural produce between two stone. The grinding stone consists of a lower stationary one, called the Queen Stone and an upper stone which is mobile and called the hand stone. The oldest known agricultural milling device is Saddle stone (Williams and Rosentrater, 2007). It is a cradle-shaped hard stone that holds the produce to be ground. The accompanying hand stone, which could either be a cylindrical piece or a fat disc with a vertical handle, is held in one hand and used to crush the material. These stones were traditionally used to process farm products into four or puree (Thomas and Filippov, 1999). In order to make grinding easier, the agricultural product such as grain is normally malted. Malting refers to the process whereby cereal is made to germinate by soaking in water and then have the germination halted by drying in warm air; this method is time consuming and can only be used for small scale production.

According to Culpin (1992), grinding of agricultural produce has been practice since early times when a device like pestle and mortar was used in the production of meal for human consumption. The first mill modification of device is when agricultural produce was put through an opening, in a disc shaped stone which was caused to rotate upon another. The gradual development of this Mills during the years has led to evolution of the burr stone mill.

The earliest record of food production shows that indigenous agricultural produce has long been milled to produce flour or Puree for cooking and other usage. Traditional crops such as maize, millet, tomatoes and pepper have been ground for centuries either with a crude mortar and pestle design from a tree stump and branch or by using a flat stone or rubbing stone. All these types of grinding system are still in practice today.

According to Brian and Rottger (2006), the invention of electric motors in the mid-nineteenth century led to the development of higher-speed machines, like hammer and plate mills, which began to replace traditional stone mills. These modern mills often feature a burr plate mechanism. In some designs, a worm gear is used to crack products, such as tomatoes, before they are transferred to the burr plate for grinding. The commercial grinding machine can be used to grind both soft and hard product due to its capacity.

Fuel powered grinding machine; this involved the use of fuel driven engine to convert chemical energy stored in fuel into mechanical energy for grinding operations. This type of machine is particularly useful in areas where electricity is unavailable or unreliable. The principle of this machine lies in energy conversion where the fuel is combusted in an internal combustion engine, generating heat. This heat drives a piston, creating mechanical motion. The combustion engine is connected to the grinding mechanism, providing the necessary force to operate the grinding process. The mechanical energy produced by the fuel engine is transmitted to the grinding mechanism using a combination of belts, pulleys, or gears. These components ensure that the engine rotational motion is effectively transferred to the grinding component.

Electrically powered grinding machine: this involves the conversion of electrical energy into mechanical energy to process and grind agricultural produce. This machine is widely used for grinding variety of agricultural produce for food production, and other industrial applications.

The electrically powered source ensures more consistent performance, precise control, and high efficiency compared to fuel powered alternatives.

Solar powered grinding machine: is a suitable design solution to address the energy needed to power agricultural grinder of any size, also to address the issues of high cost of fuel and electricity. This machine harnesses solar energy through photovoltaic panels to power the grinding process which convert the agricultural product of large size into smaller pieces or size for food and industrial purpose.

Traditional grinding methods: in many developing countries, rural and off grid communities rely on manual, fuel or electrically powered mills for grinding. Manual grinding is labour intensive, time consuming and inefficient while fuel and electrically powered grinding machine are costly to operate due to high cost of fuel and electricity and also the fuel type also contributed to environmental pollution due to the use of fossil fuel for operation. The use of solar powered grinding machine address these issues by providing clean, renewable, and cost-effective energy source. The core of the solar powered grinding machine is its ability to absorb energy from the sun using photovoltaic panels. These panels convert the sunlight into direct current (DC) electricity, which can either be used immediately or stored in battery for later use. In case of an AC operating motor, inverter is often used to convert the DC electricity into alternating current (AC), which powers the motor of the grinding machine. This setup ensures continuous power supply, even in area where the electrical energy from grid is unreliable or unavailable. This innovative approach seeks to reduce operating costs while also promoting sustainability by using renewable solar energy. It offers a practical solution for rural communities, small businesses, and individuals looking to lower their energy expenses and environmental impact. By developing a solar-powered grinding machine, this study aims to contribute to the creation of more accessible, sustainable, and efficient grinding technologies, ultimately improving the way agricultural products are processed for various purposes.

1.2 Statement of the Problem

Conventional machines used for grinding is quite expensive in operation due to high cost of fuel and electricity and requires more frequent maintenance.

This study therefore tends to explore an alternative means of producing a grinding machine. That is hybrid in nature. Unlike conventional grinding machines, our models combines two-energy sources; solar panels with a battery storage which provides reliable power by using multiple energy types. Using solar panels, battery, charge controller, DC motor, and other sourced materials for the production of cheap, safe, and easy to operate grinding machine.

1.3 Aim and objectives of the research

1.3.1 Aim of the research

The aim of the research is to design and fabricate a solar powered grinding machine

1.3.2 Objectives of the research

The objectives of the research are;

1. To develop a conceptual design for solar powered grinding machine.
2. Carry out detailed design analysis of the machine.
3. Fabrication of a solar powered grinding machine prototype using available materials
4. Carry out test on the fabricated prototype.

1.4 Scope of Work

The scope of the project is to carry out a developmental design, fabricate and implement a solar powered grinding machine capable of efficiently grinding for both domestic and industrial usage, to ensure reliable operation using solar power as primary energy sources. Design a system that is affordable, easy to maintain, and durable for local setting. Conduct a Feasibility study for using solar power as the energy source for grinding. Design the grinding mechanism, incorporating renewable energy principles, selection of materials and components that are durable and appropriate for both domestic and industrial grinding. Determine the power requirements for the grinding operations, select appropriate solar panels, battery storage, and power management systems. Integrate solar components with the grinding machine to ensure continuous operation.

1.5 Significance of the Work

This research work is significant in various aspects including;

1. Solar powered grinding machine can significantly cut operating costs for larger and small-scale users by eliminating electricity and fuel expenses.
2. Where infrastructure and access to power are challenging, solar powered grinding machine make it possible to grind agricultural product without dependency on traditional energy sources, enhancing food processing capabilities.
3. The use of solar powered grinder reduces noise and air pollution, leading to healthy working condition compared to fuel powered machines.
4. Solar powered grinders use renewable energy, which reduces greenhouse gas emissions and lower the overall carbon footprint compared to traditional fuel powered grinding machine.

CHAPTER TWO
LITERATURE REVIEW

2.1 Overview of Grinding

Grinding is a mechanical technique used to reduce solid materials into finer particles or powders. This seemingly simple process plays a critical role in numerous industrial operations, ranging from metalwork and construction to food processing and pharmaceuticals (Gupta & Yan, 2016). To carry out this task effectively, specialized equipment known as grinding machines or grinders are employed. These machines are engineered to deliver precision in shaping, finishing, and pulverizing materials into consistent textures or specifications, whether for polishing metals or producing finely ground flour in the food industry.

Interestingly, the origin of grinding technology can be traced back to nature itself our own teeth. From prehistoric times, human teeth served as rudimentary grinding tools, capable of generating bite forces of up to 200 pounds (about 90 kilograms), sufficient for chewing through tough plant materials and meat (Lucas, 2004). However, as early humans began processing harder materials like grains and nuts more frequently, the limitations of using teeth alone became evident. This pushed early societies to develop external tools better suited for such tasks.

One of the earliest innovations in grinding technology was the **quern-stone**, a manually operated device used by Neolithic humans. These devices, often made of basalt or sandstone, allowed early people to crush and grind grains more efficiently (Wright, 1992). Querns marked a major leap in human ingenuity, transitioning from direct bodily effort to tool-assisted processing. Similarly, mortars and pestles used across ancient civilizations from Mesopotamia to Egypt were among the earliest examples of grinding instruments.

Manual grinding remained dominant for centuries, with techniques like stomping and treading commonly used for tasks such as grape crushing in winemaking or grain milling. However, these labor-intensive methods were limited in productivity, hygiene, and consistency.

With growing societal demands, particularly during the agricultural and industrial revolutions, came the need for mechanized grinding systems. This led to the evolution of larger, powered grinding machines capable of handling industrial-scale material processing. These machines have since become essential tools in modern industries, supporting large-scale operations that require precision, speed, and efficiency. From producing smooth metal finishes to creating powdered medicines, grinding machines have helped shape the industrialized world as we know it today.

The history of grinding technology spans thousands of years, beginning with the early use of natural energy sources to power simple machinery. Waterwheels, for instance, were used by ancient civilizations to automate the grinding of grains and other materials. These early machines harnessed the kinetic energy of flowing water to rotate grinding stones, significantly reducing the need for manual labor in food production and other industries (Wilson, 2002).

Technological development accelerated during the Roman Empire, where engineers began incorporating gears and mechanical systems into water-powered mills. Rotating grindstones driven by horizontal or vertical waterwheels became increasingly common. One of the most sophisticated examples of this advancement is the Barbegal mill complex in southern France. This site featured a cascading arrangement of sixteen overshot wheels, each around two meters in diameter, working in tandem to supply flour for a large urban population estimated at nearly 80,000 people (Greene, 1990; Reynolds, 1983).

As engineering knowledge spread across Europe during the medieval period, water-powered grinding became a critical part of local economies. However, in regions where water was less accessible, wind-powered mills emerged as an effective alternative. These mills were particularly valuable in areas like the Netherlands and parts of the Middle East, where wind was more consistent than flowing water (Glick, 1977). Windmills allowed communities to continue grinding grains and other materials without relying on rivers or streams.

By the 19th century, grinding equipment had evolved to combine old and new technologies. One innovation was the integration of millstones with mechanical rollers.

The stones performed the initial breaking of grains, while the rollers often made of metal or porcelain, handled the final grinding to achieve finer textures. According to Turner (1998), "A well-documented example of this approach was the New Phoenix Flour Mills in Newcastle, England, which started in 1856 with 12 pairs of millstones and later upgraded to include 28 pairs of porcelain rollers alongside 20 millstone sets."

In North America, the use of grinding mills became more established in the early colonial period. The first American gristmill, built in Jamestown in 1621, was designed to support food production for settlers. Before this, Indigenous peoples and early European settlers relied on tools like mortars and pestles for processing grains. In the mid-18th century, George Washington developed a highly productive milling operation at Mount Vernon, eventually expanding it to three functioning mills that produced flour for both domestic use and export (Fischer, 2004).

Fast forward to the modern era, and grinding machines have become indispensable in both domestic and industrial settings. From chefs in kitchens using compact grinders to factories employing large, high-capacity systems, grinding remains central to many production processes. The range of equipment now available allows users to choose machines based on processing capacity, energy consumption, material type, and the desired level of fineness (Gupta & Yan, 2016).

Ultimately, selecting the appropriate grinder involves understanding the specific requirements of the application. Some systems are designed for high-precision tasks, such as pharmaceutical processing, while others are optimized for volume, as seen in food manufacturing or construction material preparation. Whether manual or automated, small-scale or industrial, grinding continues to be a key element in converting raw materials into usable forms across a broad spectrum of industries. Smaller, portable grinders are often lightweight, easy to operate, and suitable for household tasks, such as preparing spices or small material batches. In contrast, industrial-scale grinders are built for efficiency and durability, capable of handling substantial quantities of material in a short time. They are typically used in large manufacturing facilities where precision, speed, and reliability are paramount.

Portable grinders are compact machines designed primarily for domestic and small-scale use, offering a practical solution for individuals and small businesses. Their history can be traced to the innovation-driven period of the 19th and 20th centuries (industrial revolution), when technological advancements made it possible to adapt large industrial equipment into smaller, user-friendly designs. Technological advances in the field of metallurgy and mechanical engineering in the late 19th century paved the way for portable grinding machines. Innovators like Joseph Lee, who patented early milling equipment in the 19th century, and Dr. Royal Lee, who introduced the first electric household grinder in the 1930s (early 20th-century American innovation), played pivotal roles. Dr. Lee's invention allowed individuals to grind materials at home, ensuring freshness and quality.

The breakthrough of portable grinders became particularly significant in rural and post-war societies during the mid-20th century (post-World War II era). In Europe, Asia, and Africa, portable grinders enabled local processing of materials during food shortages and infrastructure devastation. In rural Africa (mid-20th-century Africa), portable grinders reduced the time and physical effort required for tasks traditionally done manually. In the United States during the Great Depression (1930s), household electric grinders helped families reduce reliance on store-bought products. Portable grinders have become tools of resilience, independence, and community support during challenging times. They offer several advantages, such as compactness, ease of use, affordability, and the ability to preserve the quality of materials. However, they are designed for small-scale use and are unsuitable for high-volume industrial settings. Their simpler mechanisms and reliance on electricity may limit their versatility and durability under heavy or prolonged use.

In contrast, commercial and industrial grinders are built for high-volume, continuous production, with advanced grinding technologies and materials that ensure consistent performance and durability. These machines are ideal for large-scale operations but impractical for smaller-scale or domestic use.

Portable grinders fill a unique niche, catering to those who prioritize freshness, control, and small-batch production.

By blending practicality with innovation, portable grinders remain a vital tool in modern industry and daily life.

Additional considerations for choosing a grinder include the type of material being processed, the available energy source (manual, electric, or fuel-powered), and budget constraints.

Evaluating these factors and understanding the specific advantages of each grinder type will ensure optimal performance and cost-effectiveness for any application.

2.2 Evolution of Commercial and Industrial Grinding Machines

The development of commercial and industrial grinders marks a significant milestone in the advancement of material processing technologies, driven by the increasing demands of a growing global population and the continuous transformation of various industries. The origins of this progress trace back to the late 19th and early 20th centuries a pivotal era defined by rapid industrialization and technological innovation. During the late 18th century, Oliver Evans, an innovative American inventor, introduced automated material handling systems, laying the foundation for contemporary grinding techniques. His pioneering concepts were later enhanced during the Industrial Revolution, which brought about the use of steam power, enabling consistent and large-scale grinding operations. This advancement led to the introduction of roller grinding mechanisms in the mid-to-late 19th century, which replaced traditional millstones with more efficient systems capable of delivering finer, more uniform outputs.

By the early 20th century, companies like **Nordyke & Marmon**, based in Indianapolis, emerged as prominent manufacturers of advanced commercial grinding equipment. These machines were tailored for small businesses, bakeries, and local producers, offering a combination of accuracy, longevity, and operational efficiency. Commercial grinders stood out for their ability to produce a variety of textures, meeting the needs of a diversifying market. Unlike portable grinders, commercial units were built to manage greater workloads, making them crucial for businesses serving regional markets.

Simultaneously, industrial grinders gained prominence as vital machinery for large-scale processing in the late 19th and early 20th centuries. Initially powered by steam and later by electricity, these high-performance machines became integral to factory operations and processing centers, particularly in urban areas across Europe and the United States. Advances in engineering and material science during this era enabled the creation of durable, heavy-duty grinders capable of processing multiple tons of material per hour. This capability was essential to support urban expansion and the rising dependency on refined materials, elevating grinding from a localized practice to a critical component of industrial supply chains.

The advantages of commercial grinders include their compact design and suitability for small-scale businesses. They are energy-efficient and versatile, enabling small enterprises to process diverse materials at a manageable cost. However, their limitations lie in their lower capacity compared to industrial machines, which restricts their utility in high-demand scenarios.

On the other hand, industrial grinders are engineered for scalability and efficiency. These machines can process massive quantities of materials continuously, ensuring consistency and minimizing waste. Advanced features, such as automated controls and specialized roller mechanisms, make industrial grinders indispensable for factories and large-scale operations. However, their size, infrastructure requirements, and high energy consumption make them unsuitable for smaller enterprises or domestic use.

The story of commercial and industrial grinders is not only a tale of technological progress but also one of adaptability to societal needs. Figures like Oliver Evans and companies like Nordyke & Marmon paved the way for these innovations, shaping the global processing industry. From the dawn of industrialization to the highly specialized processing plants of today, these grinders have played a vital role in ensuring material efficiency, industrial growth, and economic progress, demonstrating the enduring impact of technological ingenuity on society

2.3 Principle of Operation of Grinding Machine

The working principle of a grinding machine revolves around the application of mechanical forces to break down materials into smaller particles or fine powders. Materials are fed through a hopper into a grinding chamber, where they are subjected to forces such as compression, abrasion, or shearing (mechanical force application). These forces are applied using components like rotating blades, hammers, rollers, or millstones, which leverage principles of mechanical physics, including Newton's Laws of Motion, to achieve the desired particle size. For instance, the high-speed rotation of blades or hammers generates kinetic energy that impacts the material, breaking it apart according to Newton’s Second Law (Force = Mass × Acceleration) (Newton, 1687).

After grinding, fine particles are separated using sieves, filters, or centrifugal force, with coarser residues expelled as waste. This process often employs principles of fluid dynamics in airflow systems or Bernoulli's Principle, which aids in separating lighter materials from heavier particles. Power is provided by manual input, electric motors, or fuel- powered engines, and is transmitted through belts, pulleys, or gears based on Pascal's Law, ensuring smooth and consistent energy transfer across the system (Pascal, 1653).

Adjustable mechanisms, such as varying the distance between rollers or modifying sieve sizes, allow for customization of the grinding process, adhering to the Law of Conservation of Energy, as input energy is efficiently converted into mechanical work for grinding (Robert Von Mayer et.al.1847). Modern machines incorporate safety features, such as guards and emergency shut-offs, following OSHA guidelines, and cooling systems (air or water-based) prevent overheating, ensuring the machine adheres to thermal efficiency principles.

This combination of scientific principles, mechanical engineering, and safety standards ensures that grinding machines operate efficiently, transforming raw materials into usable products while minimizing energy loss and maximizing productivity. The underlying mechanics showcase the application of classical physics and engineering innovations to material processing technology.

2.4 Classification of Grinding Machine

Grinding machines are categorized based on their power sources, design, and scale of operation. This classification ensures that different user needs, ranging from domestic to industrial, are met effectively. Each type of grinder manual, electric, fuel-powered, or commercial and industrial has unique features, advantages, and limitations. Understanding these classifications helps in selecting the appropriate machine for specific processing tasks, whether for small-scale household use or large-scale food production industries.

2.4.1 Classification Base on Power Source;

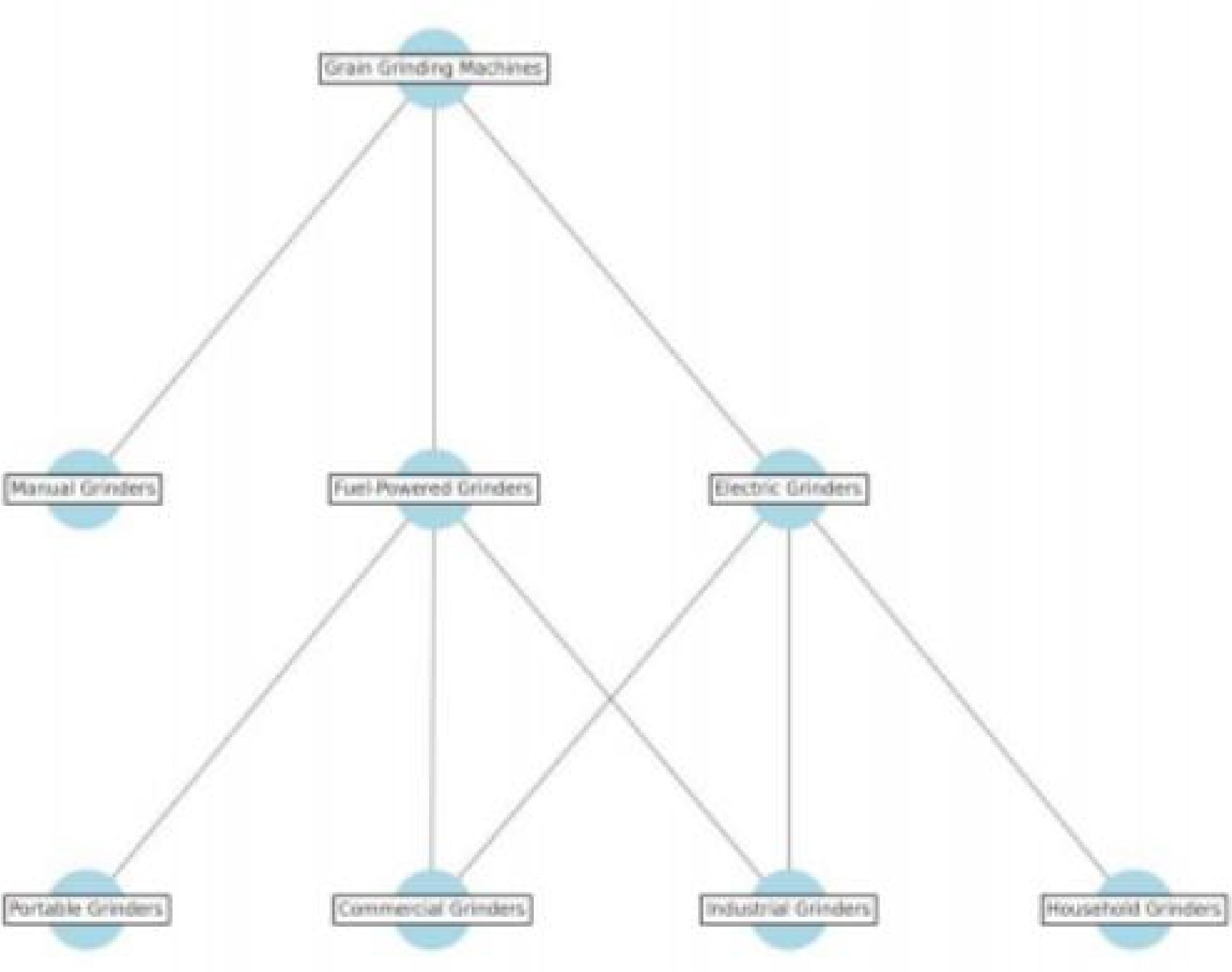


Figure 2.1: Grinding machine chart

(a)Manual Grinding Machine

Manual grinding machines, a type of grain grinding machine as shown in Fig.2.1 is operated by hand or foot pedals, and have been a cornerstone of material processing for thousands of years, allowing people to break down materials into smaller particles with minimal technology.

Their history traces back to early tools like the mortar and pestle (circa 35,000 BC) (early tool development, 35,000 BC) and progressed through significant advancements like the rotary quern (circa 500 BC), which improved efficiency and became common across ancient societies (rotary quern invention, 500 BC). These low-capacity devices are well-suited for small-scale or domestic use and remain an essential part of traditional practices in many cultures. For example, the "chakki" is still widely used in Indian households for material processing (chakki use in India, traditional practice), while similar grinders are vital in sub-Saharan Africa for preparing staple foods like “ugali” and “injera” (traditional African grinders, sub-Saharan cultural use). Although industrialization introduced electric grinding machines, manual grinders retain their appeal for their portability, cost-effectiveness, and independence from electricity, making them ideal for rural areas, off-grid living, and emergency preparedness (manual grinder utility, emergency and rural settings). Recently, manual grinders have experienced renewed interest in artisanal production and homesteading, reflecting their timeless practicality and cultural significance (artisanal trends and homesteading, renewed interest in manual grinders).

(b) Fuel-Powered Grinding Machine

The introduction of fuel-powered grinding machines marked a transformative era in material processing by replacing centuries-old manual and animal-driven grinding methods with more efficient, mechanized systems. This transition gained momentum during the Industrial Revolution, particularly in the late 18th and early 19th centuries, as factories began adopting steam-powered equipment for high-volume production tasks (Reynolds, 1983). Steam engines, fueled by coal or wood, offered continuous mechanical energy, allowing mills to operate independently of water sources or human labor. This advancement was especially crucial in urban and industrialized areas where natural power sources were either inconsistent or unavailable. The ability to drive grinding mechanisms using combustion-based energy revolutionized productivity, laying the groundwork for modern mass manufacturing (Hills, 1989). The foundation for this leap in technology was laid through critical scientific discoveries and engineering breakthroughs.

One notable milestone was Michael Faraday’s 1831 discovery of electromagnetic induction, which, although primarily foundational to electric power generation, catalyzed broader applications in mechanized systems and control technologies (Williams, 1965).Before Faraday’s breakthrough, Thomas Mead had already demonstrated the potential of gas-based mechanical energy through his 1791 invention of the gas-powered generator, an important step toward mobile and off-grid power systems. Another leap forward came in 1870 when Dr. Alphonse Beau de Rochas introduced the four-stroke internal combustion engine design a configuration that remains central to many modern fuel-powered machines today (Petráš & Kotek, 2016). These innovations contributed not only to general industrialization but also to the development of specialized machinery, including grinding equipment used in agriculture and construction.

By the late 19th century, internal combustion engines had started to replace bulky steam engines in a variety of industrial applications, including material processing. These smaller, more efficient engines made it possible to design mobile, standalone grinding machines suitable for deployment in rural or remote areas. Gasoline-powered grinders became practical tools for farmers and small-scale operators, offering dependable and portable solutions where electricity or wind power was unavailable. In contrast, diesel engines, known for their fuel efficiency and longevity, were increasingly used in larger-scale commercial grinding setups due to their ability to handle continuous heavy-duty operations with minimal maintenance.

According to Gupta & Yan (2016), "As engine technology matured, the integration of such systems into grinding machines allowed for a significant boost in processing speed, consistency, and scalability, effectively supporting the growing demands of global food and construction industries." The move from manual or animal-driven grinding toward fuel-powered systems not only enhanced throughput but also improved worker productivity, safety, and control. It is no exaggeration to say that this shift laid the foundation for the emergence of industrial grinding as we know it today. Key breakthroughs such as the four-stroke engine and practical gas generator designs were instrumental in converting combustion energy into reliable mechanical motion, fundamentally reshaping how raw materials were processed on a large scale (Petráš & Kotek, 2016; Williams, 1965).

A modern fuel-powered grinding machine as illustrated in **Fig2.2** typically comprises several key components that operate in coordination to perform efficient grinding. At the heart of the machine lies the internal combustion engine, which can be powered by either gasoline or diesel fuel. The engine generates rotational force to operate the grinding components and typically includes a manual start mechanism, such as a pull-start system, for ignition. A fuel tank is mounted to supply the engine with gasoline or diesel, with a carburetor system in place to mix air and fuel in the correct ratio for combustion for gasoline engines. The engine is further protected by air filters, which prevent dust and particulate matter from damaging internal components.

Grain or other materials enter the system through a hopper typically a funnel-shaped container strategically positioned above the grinding chamber. The chamber houses high-speed rotating components such as burrs, plates, hammers, or discs that reduce the material size by crushing, cutting, or shearing. The feeder mechanism ensures that raw material is introduced gradually and evenly into the grinding chamber, preventing overload and optimizing the grinding consistency (Wills & Finch, 2016).

As material enters the grinding zone, the motion generated by the engine and transferred via a transmission system consisting of belts, pulleys, and gears ensures continuous rotation of the grinding tools. This system allows for torque regulation and speed adjustment, both of which are essential for achieving desired particle sizes. After processing, the finished product exits through a discharge outlet, which may be equipped with mesh screens or sieves to filter out larger particles and ensure uniform output. The machine's frame, usually made of heavy-duty steel, provides structural support and protects internal components from vibration and mechanical stress. To maintain operational integrity during extended use, especially in high-output systems, cooling systems are integrated into the design. Smaller machines typically use air-cooling systems driven by fan blades, while larger models may incorporate water-cooling mechanisms to dissipate heat generated by continuous combustion and mechanical friction (Rajput, 2007).

Additionally, modern fuel-powered grinding machines include safety features such as protective guards over moving parts like belts and pulleys, emergency stop mechanisms, and vibration dampening to reduce operator fatigue and prevent accidents.

The fuel delivery system itself includes a tank, fuel lines, and filters that ensure a clean and steady fuel supply to the engine without introducing contaminants or disrupting flow.

All these components work in unison to provide a reliable, mobile, and efficient grinding solution suitable for a wide range of environments. Whether processing grains for animal feed in rural agricultural settings or crushing minerals on construction sites, the adaptability and power of fuel-driven grinders make them invaluable in many fields. Their ability to operate independently of electrical infrastructure continues to make them particularly vital in off-grid regions, disaster response situations, and temporary construction camps. More importantly, their development has mirrored the broader trajectory of industrial mechanization, from basic manual labor toward highly automated, high-throughput systems. By offering scalable power and flexibility, fuel-powered grinding machines continue to fill a crucial niche in modern material processing systems worldwide

Figure 2.2: Fuel powered grinding machine

(c)Electrically Powered Grinding Machine

The transition from steam to electric power in the late 19th and early 20th centuries marked a pivotal moment in the evolution of grain grinding machines (historical shift: steam to electric power). Electric motors revolutionized the industry by offering enhanced control, reliability, and efficiency, enabling consistent and large-scale production (advantages of electric motors: control, reliability, efficiency).

Unlike steam engines, which relied on fuel sources such as coal or wood and required extensive maintenance, electric motors were compact, cleaner, and simpler to operate (comparison: electric motors vs. steam engines). These innovations reduced energy consumption, eliminated the need for direct fuel combustion, and provided a more reliable power source, especially as electricity became more accessible.

The shift to electric grinding machines was transformative for both industrial and domestic applications (industrial and domestic impact of electric power). Factories benefited from increased precision and speed, while smaller, electrically powered grain grinders brought convenience to households (benefits for factories and households).

One of the most significant milestones in this evolution occurred in the 1930s, when Dr. Royal Lee developed the world's first electric household grain grinder (Dr. Royal Lee, 1930s electric household grinder). His invention allowed families to process fresh flour at home, promoting better nutrition and self- sufficiency during an era of growing health awareness (benefits of home grain grinding: nutrition and self-sufficiency). The machine combined efficiency with ease of use, setting the stage for the widespread adoption of electric grinders in kitchens and small-scale food production (adoption of electric grinders in households).

Electric-powered grain grinding machines also introduced advanced features such as variable speed controls and automated mechanisms to regulate the grinding process (advanced features: variable speed controls and automation). These features allowed users to achieve specific textures and consistency, accommodating various types of grains and applications. From coarse meal for animal feed to fine flour for baking, the versatility of electric grinders expanded the range of possibilities in food processing.

The innovations brought by electric power in grain grinding significantly advanced the milling industry, enabling more precise, scalable, and user-friendly solutions.

This shift not only improved productivity and convenience but also laid the groundwork for further technological developments, including the computer-controlled grinders used in modern food production today.

An electric grinding machine consists of several key components, each serving a specific purpose to ensure efficient and effective operation (component breakdown for electric grinders). The hopper is the upper compartment where materials are loaded; it guides the materials into the grinding chamber in a controlled manner (hopper function: material loading and control). The grinding chamber contains grinding burrs or blades, typically made of hardened steel or stone, which crush or pulverize the materials into finer particles (grinding chamber materials and function). The burrs may be adjustable to produce different levels of fineness (adjustable burrs: fineness control).

The motor is the machine's power source, converting electrical energy into mechanical energy to drive the grinding mechanism (motor function: electrical-to-mechanical conversion). Motors vary in power output, affecting the machine’s grinding speed and capacity (motor power and output variability). The feeder mechanism regulates the flow of materials from the hopper to the grinding chamber, ensuring a consistent feed rate for even grinding (feeder mechanism: feed rate control). The discharge chute collects and directs the ground product into a receptacle, minimizing spillage (discharge chute: product collection).

The cooling system, often integrated into higher-end models, prevents overheating by dissipating heat generated during operation, thus protecting the motor and grinding components (cooling system: overheating prevention). Lastly, the control panel or switch allows the user to power the machine on or off and, in advanced models, adjust settings like grinding speed or fineness (control panel: power and setting adjustments). Together, these components make electric grinders efficient, versatile, and suitable for various materials and processing needs (overall functionality: efficiency, versatility, and material processing suitability).

Figure 2.3: Electric powered grinding machine

(d)Hybrid Grinding Machine

Hybrid grinders represent a modern evolution in food grinding technology, designed for versatility by operating in manual, electric, or fuel-powered modes. These machines emerged in the late 20th century as manufacturers sought to address the limitations of single-mode grinders, particularly in areas with inconsistent power supplies. For instance, in the 1980s, rural electrification projects in developing countries highlighted the need for flexible devices that could function in both electrified and off-grid settings.

Hybrid grinders became particularly relevant in agricultural regions of Africa and Asia, where small-scale food producers required dependable tools for processing various food items regardless of infrastructure. By the 1990s, advancements in engineering allowed for the integration of durable motors for electric and fuel modes, alongside crank handles for manual operation. These grinders, which could switch between modes depending on power availability, became essential for emergency preparedness, disaster relief operations, and remote areas with no access to modern utilities.

Their adaptability makes them invaluable in diverse applications, combining the efficiency of electric systems with the reliability of traditional methods (hybrid grinders' adaptability). Hybrid grinders reflect a response to the growing demand for flexible and sustainable food processing solutions in the face of technological and environmental challenges (demand for flexibility and sustainability).

2.4.2 Classification Based on Grinding Mechanism

(a)Roller Mills

Roller mills brought about a transformative shift in food processing during the late 19th century, setting a new standard for producing fine, refined flour that catered to the growing demands of modern baking and food production industries. The design as illustrated in **fig 2.4** employs cylindrical rollers that rotate at different speeds to shear grains, breaking them down into smaller particles while facilitating the precise separation of bran and germ. This capability not only improves the texture and quality of the flour but also enhances its usability in various culinary applications. As a result, roller mills became indispensable in industrial milling operations, where consistency and efficiency are paramount. Their efficiency and ability to produce uniform, high-quality flour in large quantities have positioned roller mills as the backbone of commercial milling, especially in urban and industrialized settings. However, these machines are not without limitations. They are less suited for coarse grinding or producing whole-grain flour, as the process tends to strip grains of their bran and germ, reducing the nutritional content. Additionally, the high cost of acquisition and maintenance, coupled with their dependence on electricity, makes roller mills less accessible for small-scale farmers or operations in off-grid locations.

Despite these challenges, the advantages of roller mills far outweigh their drawbacks.

Their unmatched precision, speed, and scalability continue to make them the preferred choice for large-scale milling operations.

Their introduction revolutionized the food industry by enabling mass production of refined flour, thereby meeting the needs of a rapidly growing global population. Over time, incremental technological advancements have improved the durability and efficiency of roller mills, solidifying their relevance in modern milling processes while leaving a lasting impact on food production systems worldwide.

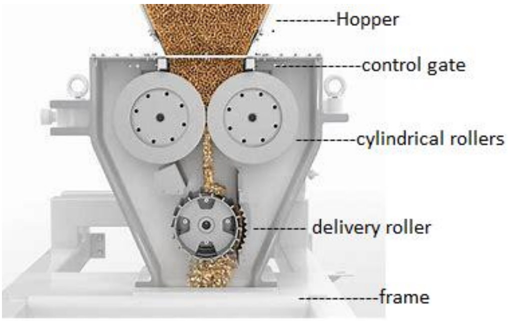


Figure 2.4: Roller mill

(b)Hammer Mills

Hammer mills as illustrated in **fig.2.5** are commonly utilized for rough grinding tasks and are especially suitable for preparing feed for livestock. Their high-speed rotating hammers pulverize grains into rough particles, making them ideal for livestock farming and industrial feed production. Invented in the late 19th century, they gained prominence in the early 20th century due to their simplicity and efficiency.

However, hammer mills are limited in their ability to produce fine or uniform flour, often resulting in inconsistent particle sizes. The heat generated during operation can degrade the nutritional quality of grains, and their high noise levels and energy consumption further restrict their applications in certain settings. Despite these limitations, their ability to process large quantities of grain quickly ensures their relevance in agricultural and industrial uses.

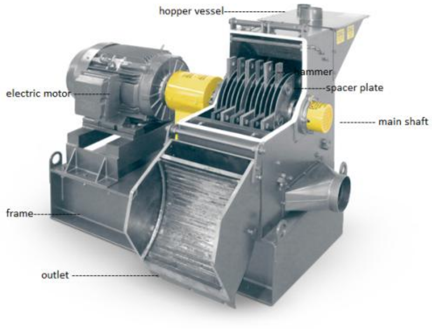


Figure2.5: Hammer mill

(c)Stone Mills

Stone mills as illustrated in **fig.2.6** are among the oldest grinding mechanisms, and trace their origins to ancient civilizations around 6000 BCE. These mills rely on heavy millstones to grind grains at a slow and steady pace, a process that helps retain the nutritional integrity, making them especially suited for producing high-quality whole-grain flour. This traditional method has stood the test of time and remains a cornerstone in artisanal and organic food production, where the focus is on quality and authenticity rather than speed or volume.

The process employed by stone mills is lauded for its ability to preserve the natural oils and nutrients in grains and purees, a key factor for health-conscious consumers. However, these mills come with certain limitations. They typically operate at a lower capacity, requiring more time and effort to process significant quantities of grain. The friction created during grinding generates heat, which, although moderate, can slightly impact the flavor and texture of the flour.

Furthermore, the millstones themselves demand regular maintenance, including sharpening and cleaning, to ensure optimal performance and consistency.

Despite these challenges, stone mills continue to hold an important place in modern milling, particularly for small-scale and boutique operations that prioritize nutrient preservation, traditional methods, and the rich flavors associated with slow grinding. Their enduring relevance

highlights a balance between historical milling techniques and the growing demand for healthier, natural food products in today's market

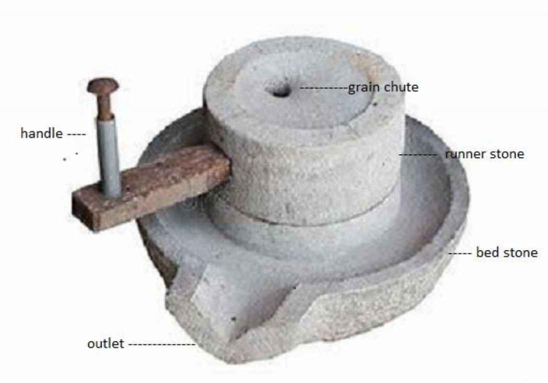


Figure 2.6: Stone mill

(d)Ball Mills

Ball mills as illustrated in **fig.2.7** was developed in the late 19th century for industrial applications, utilize grinding media like steel or ceramic balls in a rotating cylindrical chamber to crush grains into ultra-fine powders. Originally designed for producing precision steel balls, they were later adapted for milling, particularly in industries requiring consistent and ultra-fine outputs, such as pharmaceuticals and specialty baking. Nonetheless, ball mills involve significant investment costs and require substantial energy input, along with frequent maintenance to ensure optimal performance. They are not suitable for small-scale or coarse grinding, as their design is specialized for producing fine powders. Despite these limitations, their precision and effectiveness in industrial-scale operations ensure their importance in advanced milling processes.

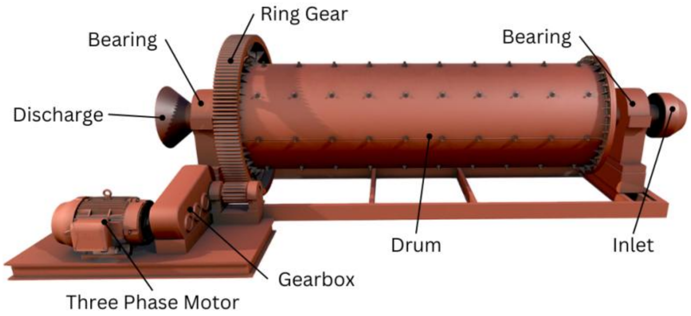


Figure 2.7: Ball mill

2.5 Power and Fuel Option

Grinders are essential tools in various culinary and food processing applications. Traditionally, fuel-powered engines, such as diesel or gasoline, have been the primary power source for these machines. However, with advancements in technology and increasing access to electricity, electric-powered food grinders have emerged as a viable and preferred alternative. This article explores the key differences between electric and fuel-powered food grinders, highlighting the advantages of electric power in terms of noise, maintenance costs, control, and safety (key comparison factors).

Electric grinders can be powered by either AC (alternating current) or DC (direct current) electricity, depending on the type of motor used (motor types). AC-powered grinders are more common and can typically operate on standard household voltages, such as 110V or 220V.

DC-powered grinders often require lower voltages, such as 12V or 24V, and are commonly powered by batteries or external DC power supplies (DC voltage specifications).

Fuel-powered grinders rely on internal combustion engines that burn fuel to generate mechanical power (internal combustion engines). These engines can operate on various fuels, including diesel, gasoline, or even biofuels.

The specific fuel type and engine size determine the power output and performance of the grinder.

One significant advantage of electric food grinders is their lower noise levels compared to fuel-powered machines (noise level advantage). Electric motors produce minimal noise during operation, making them ideal for use in residential or noise-sensitive areas. In contrast, fuel-powered engines generate considerable noise and vibration, which can be disruptive and uncomfortable for operators and nearby residents.

Electric grinders generally require less maintenance than their fuel-powered counterparts. Electric motors have fewer moving parts and are less prone to wear and tear.Routine maintenance for electric grinders typically involves cleaning, lubrication, and occasional belt replacement (routine electric maintenance tasks). Fuel- powered engines require regular oil changes, filter replacements, and other maintenance tasks to ensure optimal performance and longevity.

Additionally, fuel-powered engines may require periodic tune-ups and repairs, which can be costly and time-consuming.

Electric food grinders offer greater control and precision over the grinding process. The speed and power of electric motors can be easily adjusted using variable speed controls or digital displays. This allows for precise control over the texture and consistency of the ground food (texture control). Fuel-powered engines, while capable of high power output, often lack the same level of fine-tuning and control. The speed and power of these engines are typically fixed, limiting the ability to adjust the grinding process to specific needs. Electric grinders are generally safer to operate than fuel-powered machines. Electric motors do not produce harmful emissions or require the handling of flammable fuels (no emissions or fuel handling). Additionally, electric grinders are less likely to spark or ignite combustible materials, reducing the risk of fire hazards.

Fuel-powered engines pose several safety risks, including the potential for fuel spills, fires, and explosions (fuel safety risks). Proper handling and storage of fuel, as well as regular maintenance of the engine, are essential to minimize these risks.

In conclusion, electric-powered food grinders offer several advantages over fuel-powered machines, including lower noise levels, reduced maintenance costs, greater control and precision and improved safety. While fuel-powered grinders may be necessary in areas with limited access to electricity, electric grinders are the preferred choice for most applications due to their numerous benefits. As technology continues to advance and renewable energy sources become more accessible, the use of electric food grinders is likely to increase further, contributing to more sustainable and efficient food processing practices.

2.6 Energy from the Sun

The sun, a colossal sphere of superheated gas primarily composed of hydrogen and helium, serves as Earth's most abundant and renewable energy source. Deep within its core, temperatures soar to approximately 15 million degrees Celsius, where a process known as nuclear fusion takes place (sciencetimes.com). According to Badescu (2008), "In this process, hydrogen nuclei combine to form helium, releasing enormous amounts of energy in the form of electromagnetic radiation." This energy, which encompasses visible light, ultraviolet rays, and infrared radiation, travels across the vacuum of space roughly 150 million kilometers (93 million miles) to reach Earth in just over eight minutes. Once it arrives, this radiation drives vital natural processes such as plant photosynthesis, ocean currents, and weather systems. It also offers humanity an opportunity to harness clean, sustainable energy to meet growing global energy demands.

Modern solar energy harvesting has been made possible through innovations in photovoltaic (PV) and solar thermal technologies. Photovoltaic systems use semiconductor materials, such as silicon, to convert sunlight directly into electricity.

When photons from sunlight strike the PV cells, they dislodge electrons, creating an electric current (Green, 2005). Solar thermal systems operate on a different principle: they absorb solar radiation to generate heat, which is then used to produce steam. This steam can drive turbines, much like in conventional power plants, to produce electricity. In both systems, energy storage is a critical component. As an example, a standard 100-watt solar panel exposed to around five hours of optimal sunlight daily is capable of producing approximately 500 watt-hours of electrical energy. This amount would require several days to fully charge a 12-volt, 100-amp-hour battery, depending on factors such as sunlight intensity, panel efficiency, and system losses

(Kalogirou, 2009). These technologies have been scaled for everything from small off-grid installations to large solar farms capable of powering entire cities.

The concept of solar energy as a practical power source dates back to the early 19th century. In 1839, French physicist Alexandre Edmond Becquerel discovered the photovoltaic effect, showing that certain materials, like silver compounds, could generate electricity when exposed to light (Perlin, 1999). This groundbreaking discovery revealed the possibility of directly converting sunlight into usable electrical energy. A few decades later, in the 1860s, engineer Auguste Mouchout developed one of the earliest solar-powered engines. Using reflective solar collectors, his design concentrated sunlight to boil water and generate steam, which could power mechanical devices such as water pumps—particularly useful in agriculture and early industrial applications (Butti & Perlin, 1980). Although innovative, these early solar technologies remained niche due to high costs and limited efficiency.

The turning point in solar technology came in 1954 when scientists at Bell Laboratories introduced the first commercially practical silicon-based solar cell. This invention significantly improved the efficiency of photovoltaic systems and reduced their production costs (Chapin, Fuller & Pearson, 1954). As a result, solar power began to attract serious attention as a viable energy solution. Initially, these cells powered small devices like calculators and rural water pumps, but by the 1970s, they were also being used in space missions, including NASA's Apollo program, where reliable off-grid power was essential. These advancements firmly established the viability of solar power for use on Earth as well as in space-based technologies.

However, the effectiveness of solar energy systems is heavily influenced by environmental and geographical variables. Elements such as latitude, seasonal variation, atmospheric conditions, and elevation significantly affect solar panel performance. Equatorial regions like the Sahara Desert receive abundant sunlight year-round, making them prime candidates for large-scale solar farms. Conversely, areas with frequent cloud cover, heavy air pollution, or long winters such as parts of Northern Europe may experience reduced solar efficiency (Turchi et al., 2011). To counter these limitations, tracking systems have been developed that allow solar panels to follow the Sun's path across the sky, optimizing the angle of incidence and improving energy capture throughout the day.

In addition to mechanical improvements, there have been significant advances in materials science aimed at boosting solar efficiency and affordability. Innovations such as thin film solar cells, made from lightweight materials like cadmium telluride, and emerging technologies like perovskite-based cells are pushing the boundaries of what solar power can achieve. These next-generation materials promise higher efficiency rates and lower production costs, which could make solar energy more accessible to developing regions and accelerate the transition to renewable energy worldwide (Green et al., 2014).

However, solar energy goes beyond scientific exploration; it stands as a viable and expandable answer to the world's growing energy challenges. From its origins in 19th century experiments to its current role in powering homes, industries, and space missions, solar technology has evolved into a cornerstone of sustainable development. As technological advancements continue to improve efficiency and reduce costs, the potential for solar energy to become a dominant force in global energy supply becomes increasingly attainable. With the growing demand for renewable energy, researchers and companies around the world are working to make solar energy more efficient, affordable, and accessible to a broader population. Despite challenges related to location and weather, solar power remains a superior energy source compared to traditional fuel-powered and electrical systems for several reasons. It is a renewable resource, with an inexhaustible supply of energy, unlike fossil fuels, which are finite and produce harmful emissions.

Solar energy generates no greenhouse gases, thereby helping to reduce the carbon footprint and combat climate change. In fact, it is one of the most environmentally friendly energy sources available today. Unlike fossil fuel-based power generation, which involves extracting, refining, and transporting fuels processes that contribute to air and water pollutions solar power does not require fuel combustion and produces no hazardous by-products. As a result, solar power plays a key role in global efforts to transition to clean energy and mitigate the negative effects of climate change. Furthermore, solar power is cost-effective in the long run. While the initial installation costs of solar panels and related infrastructure can be high, the cost of solar power has decreased dramatically over the past few decades due to technological advances and mass production. Once installed, solar systems require minimal maintenance, unlike traditional fuel-powered systems, which require frequent maintenance such as oil changes, filter replacements, and other costly repairs. With the added advantage of potentially low operating costs, solar power is increasingly viewed as a long-term asset that yields returns gradually. Additionally, solar power systems provide energy independence by reducing reliance on grid electricity and fuel, which can be particularly beneficial in remote or off-grid areas.

Solar systems also offer long-term stability in energy prices, as the Sun is an inexhaustible resource, whereas fossil fuel prices are volatile and subject to geopolitical factors. Another key advantage is safety. Solar power systems do not pose the risks associated with fuel-powered systems, which can result in fire hazards, fuel spills, and environmental contamination. Solar panels are non-toxic, require no handling of flammable fuels, and produce no harmful emissions, making them inherently safer than fossil fuel-based energy generation. The applications of solar power span a wide array of sectors, including residential, commercial, industrial, agricultural, and transportation. In homes, solar panels are used to power everything from lights to refrigerators, while solar water heaters can be used to provide hot water. Solar energy can also be used to run appliances, charge electric vehicles, and provide heating and cooling through passive solar design, where building structures are designed to maximize natural light and heat. Commercial buildings and factories use solar energy for heating and electricity generation, reducing energy bills and minimizing environmental impacts.

The agricultural sector benefits from solar energy through the use of solar-powered irrigation pumps, grain dryers, and even solar-powered vehicles for farm equipment. In addition, solar power has found applications in the transportation sector, where solar-powered vehicles and solar charging stations are becoming increasingly common. Solar energy can even power streetlights and remote infrastructure, reducing the need for diesel generators and extending the reach of power to rural and off-grid areas. Capturing solar energy requires specialized equipment tailored to each application. Photovoltaic panels, the most widely used approach for capturing sunlight involves panels composed of multiple interconnected solar cells. These panels are typically mounted on rooftops, in solar farms, or in large-scale solar power plants, where they can absorb sunlight throughout the day. Solar thermal collectors are used to capture and concentrate sunlight for heating applications or steam generation. Concentrated Solar Power

(CSP) systems use mirrors or lenses to focus sunlight onto a receiver, where the heat is converted into steam that drives turbines for electricity generation. CSP technology is used in large-scale solar power plants in areas with abundant sunlight, such as the Mojave Desert in California, where plants like the Ivanpah Solar Electric Generating System utilize solar thermal power to generate electricity sufficient to meet the needs of thousands of residences.

The energy produced by solar systems is stored using batteries, allowing excess energy to be used during periods of low sunlight. Additionally, inverters are used to convert the direct current (DC) generated by solar panels into alternating current (AC), which is suitable for household and grid use. Solar energy systems are also classified into photovoltaic types, which produce electricity directly, electricity; solar thermal systems, which are used for heating or steam generation; hybrid systems, which combine solar with other energy sources; and passive solar systems, which are integrated into building designs to maximize natural light and heat. Solar power, having evolved from early scientific discoveries, has transformed into a crucial energy resource that powers homes, industries, and vehicles worldwide. As solar technology continues to advance, the global solar capacity has skyrocketed, with countries like China, the United States and India at the forefront of solar energy adoption. In 2020 alone, the world installed over 130 Giga watts of solar power capacity and the cost of solar energy has dropped by more than 80% over the last decade.

Solar power is poised to continue its rapid growth, offering a cleaner, safer, and more cost-effective alternative to conventional fossil fuels. The journey from the early work of pioneers like Becquerel and Mouchout to today's solar breakthroughs exemplifies the enduring promise of harnessing the energy of the Sun to power the future. As technology improves and costs continue to fall, solar power will play an ever more important role in meeting global energy needs, contributing to sustainable development, and helping to address the urgent challenge of climate change (Solar Energy Industries Association, 2020; U.S. Department of Energy, 2021).

2.7 Grinding Machine Designs and Selection

Grinding machines vary in design and usage, serving diverse needs across agricultural

1. Hammer mills employ high-speed rotating hammers to crush and grind materials into coarse or fine powders. They are widely used across industries such as agriculture, food processing, recycling, and mining. In food production, they can break down fruits and vegetables to create pastes or coarse purees.

2. Roller mills use cylindrical rollers to compress and shear materials, producing uniform particle sizes. They are ideal for applications in flour production, mineral processing, and food industries where consistent texture is critical, including the preparation of smooth fruit or vegetable purees.

3. Disc mills use abrasive discs to grind materials through friction, making them versatile for producing powders and fine purees. They are often utilized in the food industry to produce sauces, pastes, or purees, as well as in pharmaceutical and agricultural processing.

4. Stone mills utilize rotating stones to grind materials into powders or semi-liquid pastes. These mills are favored for creating coarse or artisanal purees, such as nut butters, hummus, or traditional fruit pastes, as well as in natural material processing for pigments or flours.

5. Burr mills, featuring adjustable grinding plates or burrs, allow for customizable coarseness and texture. They are ideal for small-scale or home use in industries like food, where they can create smooth or coarse purees and grinds, depending on the user’s needs.-

6. Ball mills use steel or ceramic balls within a rotating drum for fine grinding. They are commonly used in sectors such as ceramics, advanced material processing, and mining. In food production, they can be used to achieve ultra-fine purees or smooth, homogeneous textures.

7. Hand-operated mills rely on manual mechanisms to grind small quantities of materials. They are commonly used in areas without electricity, perfect for grinding grains or preparing fresh fruit and vegetable purees for personal or family use in remote or off-grid settings. Each type of grinding equipment is designed to handle a variety of tasks, from producing powders and pastes to creating smooth purees, tailored to the scale of operation and the specific needs of the user across multiple industries.

Designing a grinding machine requires careful attention to key factors that guarantee its efficiency, long service life, and suitability for its specific purpose. Major considerations include:

I. Type of Material to Be Processed
II. Capacity and Throughput Requirements
III. Grinding Mechanism
IV. Power Source
V. Material of Construction
VI. Energy Efficiency
VII. Ease of operation and maintenance
VIII. Safety Features
IX. Size and Portability
X. Cost and Budget Constraints
XI. Noise and Vibration Levels
XII. Environmental Factors
XIII. Regulatory and Food Safety Standards
XIV. Customization and Scalability
XV. Performance Efficiency
XVI. Integration with Auxiliary Systems

One notable piece of literature which addresses considerations in the design and selection of grinding machines is by Black (1975). The book highlights critical factors such as material characteristics, machine efficiency, power requirements, and environmental adaptability. A key excerpt from the book states: "The design of grinding systems must prioritize the nature of the material to be processed, the energy dynamics of the mechanism, and the ultimate application of the ground product. The durability and ease of maintenance of the machine are essential to its long-term success in varying operational environments. Another significant source in the literature on the design and selection of grinding machines is the textbook Theory of Machines by Khurmi and Gupta (1987), which is widely referenced in mechanical engineering studies. This book emphasizes key mechanical and functional considerations essential for designing machinery, including grinding systems. These considerations are broadly categorized and elaborated as follows:

1. Material Characteristics

The physical characteristics of the material such as its hardness, particle size, moisture level, and brittleness are key factors in selecting an appropriate grinding mechanism. Harder substances demand tougher grinding surfaces and components,

while materials containing more moisture call for designs that minimize clogging or deterioration during the process. Choosing inappropriate materials or designs can lead to suboptimal performance and accelerated wear of the grinding machine components, compromising efficiency and durability.

2. Power Requirements: The energy requirements for operating a grinding machine depend on factors such as the type of grain, seed, fruit, the desired particle size, and the grinding speed. For instance, grinding harder items into finer particles demands more power, as energy is needed to overcome their resistance and maintain the desired speed. Machines can be powered manually, electrically, or by fuel, with power ratings calculated to ensure optimal performance and efficiency. For example, an electrically powered grinder operating at 350 watts (0.35 kW) and used for one hour consumes 0.35 kWh of energy. If grinding a specific material requires 5 kWh per ton and the machine processes 500 kg of the material per hour, its power rating must match the energy demand without overloading the motor or causing excessive energy consumption. Properly understanding and calculating these requirements ensures the machine operates efficiently, prolongs its lifespan, and minimizes energy costs.

3. Capacity and Throughput

The machine's ability to process a specific volume of item over time is a crucial factor in its design, determined by the size of the grinding chamber, the speed of operation, and the grinding mechanism used. High-capacity machines, capable of processing large quantities, are ideal for industrial applications, while smaller machines are more suited for households or small-scale farmers. If the machine’s capacity is mismatched with the intended application, it can lead to inefficiency, wastage, or underutilization of resources. Ensuring the right capacity for the task at hand optimizes performance and prevents unnecessary energy consumption or equipment strain.

4. Durability and Material Selection

Machine parts exposed to high stress, such as the grinding plates or hammers, must be constructed from wear-resistant materials like hardened steel or cast iron to withstand the demands of constant use. Additionally, the outer casing and structural components should be designed to resist corrosion and impact, ensuring that the machine can endure various environmental conditions without deteriorating quickly. Proper material selection is crucial as it extends the machine's lifespan, reduces maintenance costs, and ensures consistent performance, allowing the grinder to operate efficiently over time without frequent repairs or component replacements.

5. Particle Size Control

The design of the grinding machine must incorporate mechanisms that allow for control over the fineness of the ground material, such as adjustable screens, rollers, or burrs. This feature ensures that the machine can meet a wide range of user needs, from producing coarse animal feed to fine flour for baking. The option to control particle size enhances the machine's flexibility, allowing it to process a wider range of materials and meet diverse operational requirements. This adaptability not only broadens the machine's potential applications but also improves its overall efficiency by providing customized output for various tasks.

6. Ease of Maintenance

Machines should be designed with easy access to critical components for cleaning, repairs, and replacements, ensuring that routine maintenance can be performed without difficulty. A simple and user-friendly design minimizes downtime and reduces maintenance costs, as it allows operators to quickly address issues and keep the machine running efficiently.

7. Operational Safety

Safety features such as protective guards, emergency shutoff mechanisms, and ergonomic controls are essential in preventing accidents during the operation of grinding machines. These safety measures not only protect operators from potential injuries but also help create a safer working environment.

8. Environmental Adaptability

Machines should be designed to operate effectively in a variety of environmental conditions, such as dusty fields or humid storage facilities. This can be achieved by incorporating features like sealed bearings, rust-proof coatings, or ventilation systems to protect sensitive components from environmental damage.

9. Cost-Effectiveness

The balance between a machine's initial cost and its operational benefits is crucial for its long term success in the market. Designers must carefully ensure that the machine is affordable without compromising on essential functional requirements such as efficiency, durability, and overall performance.

10. Energy Efficiency

Energy-saving features, such as optimized motor designs or efficient grinding mechanisms, should be integrated into grinding machines to reduce operational costs and enhance overall performance. Incorporating energy-efficient technologies helps lower electricity costs and reduces dependence on costly and inconsistent power sources.

11. Noise and Vibration

Excessive noise and vibration in grinding machines can lead to operator fatigue, environmental complaints, and potential structural damage to the machine itself. Dampening systems or well-optimized components help reduce these problems while enhancing the overall user experience. machine durability.

12. Modularity and Scalability

Modular designs in grinding machines offer significant advantages by allowing for easy upgrades or reconfiguration to meet evolving demands.

These designs incorporate scalable features that enable the machine to be customized for both large industrial operations and smaller-scale applications.

13. Compliance with Standards

Grinding machines must comply with local and international safety, health, and food hygiene regulations to ensure they are safe for use in food processing environments. Adhering to these standards ensures operator safety and avoids potential legal issues.

2.8 Application of Grinding Machines

Grinding machines have a wide array of applications across various industries, from food production to agriculture, each benefiting from their unique grinding capabilities. Below are the key applications are as follows:

1. Food Processing: Grinding machines are essential in the food processing industry, where they are used to mill grains such as wheat, corn, rice, barley, and oats into flour, meal, or powder. These processed products are the foundation for many food products, including bread, pasta, cakes, cereals, and snacks. The machines ensure that items are finely ground to the required particle size, allowing for consistent texture and quality in the final food product. In addition, grinding machines help in creating customized flour blends for specific food recipes or dietary requirements, making them vital for both commercial food production and home-based food processing.

2. Animal Feed Production: Grinding machines are extensively used in the production of animal feed, processing raw materials such as corn, wheat, barley, and other cereals into smaller, more digestible particles suitable for various types of livestock. The ability to finely grind materials ensures better nutrient absorption, which directly contributes to improved animal health and productivity. This application is particularly crucial in the poultry, swine, and cattle industries, where precise control over particle size is essential to maximize growth rates and enhance feed conversion ratios. By optimizing feed texture and consistency, grinding machines help ensure efficient and cost-effective feeding strategies.

3. Flour Milling: Flour milling is one of the most traditional and widespread applications of grinding machines. These machines are utilized in large-scale industrial mills as well as smaller-scale operations to produce fine flour from wheat and other cereals. The milling process typically involves multiple stages, including cleaning, conditioning, and grinding, to ensure the production of high-quality flour used for baking bread, pastries, cakes, and other bakery products. The efficiency of grinding machines plays a critical role in the overall productivity of flour mills, directly impacting both the yield and quality of the flour produced.

4. Spice and Herb Grinding: Grinding machines are used for processing spices, herbs, and seeds into fine powders. This application is crucial for the food and pharmaceutical industries, where powdered spices and herbs are used in cooking, medicine, and cosmetic products. Machines used for grinding spices need to ensure that the particles are fine and uniform, as the quality of the grind can affect the flavor, aroma, and potency of the product. These machines can handle a variety of tough materials, including pepper, turmeric, coriander, and ginger, contributing to a diverse range of culinary and medicinal products.

5. Coffee and Cocoa Processing: Coffee and cocoa beans require grinding to extract their flavors and oils, making grain grinding machines a key component in the coffee and chocolate industries. These machines are used to grind raw coffee beans into coffee grounds or cocoa beans into cocoa powder, which are then used in the production of beverages, confections, and other products. The uniformity and consistency of the grind are vital for producing high-quality coffee and chocolate, as the particle size can directly impact the extraction process and the final taste.

6. Biofuel Production: In recent years, grinding machines have found a role in the production of biofuels, particularly in the grinding of grains and other organic matter for bioethanol production. Grains such as corn are ground into a fine powder to increase the surface area for fermentation, a key step in bioethanol production. The efficiency of the grinding process can influence the yield of ethanol, making it an important step in the biofuel production chain. As the demand for renewable energy sources increases, grinding machines play a crucial role in advancing biofuel technologies.

7. Traditional and Small-Scale Milling: In rural and small-scale operations, grain grinding machines are essential for local farmers and communities. These machines are often used to grind grains for personal consumption or for small businesses such as local bakeries and food vendors. They are designed to be more compact and affordable, providing an accessible means for communities to process their own grains and produce flour, meal, or other ground products. This application is especially important in developing countries where access to large industrial mills may be limited, making small-scale grinding machines critical for food security and economic independence.

8. Pharmaceutical and Nutraceutical Applications: Grinding machines also have applications in the pharmaceutical and nutraceutical industries, where they are used to process grains, herbs, and other botanicals into fine powders for medicine or dietary supplements. In these industries, consistency and precision are key to ensuring that the active ingredients are adequately extracted and that the dosage is uniform across batches.

Grinding machines used in these applications must meet strict hygiene and material specifications, ensuring that the products are safe and effective for consumption.

2.9 Related Literatures

Several researchers have investigated solar-powered grain grinding and milling machines, exploring different design configurations, energy systems, and operational strategies. This section reviews the most relevant prior studies in this field.

Study 1: Solar-Powered Grinding Machine with Flywheel

A significant contribution to the field was made through solar powered grinding machine with flywheel energy storage system (ResearchGate,2022). The researchers designed and fabricated an auto charging grinding machine powered by solar energy, which incorporated a flywheel mechanism for energy storage and release. The machine was designed to grind various shapes of objects including circular, square and polygonal materials. The grinding mechanism was driven by a single phase induction motor, which received power from a 12V DC battery charged by solar panels and an alternator coupled to the grinding shaft. The key design feature was the incorporation of a flywheel energy storage system that stored rotational kinetic energy during periods of excess power generation and releases it during peak demand. The alternator , coupled to the grinding shaft via spur gear drive , continously charged the battery during operation , creating a self sustaining system. The machine could acheieve speeds exceeeding 10,000rpm by varying pulley sizes, making it sustainable for various industrial grinding applications.

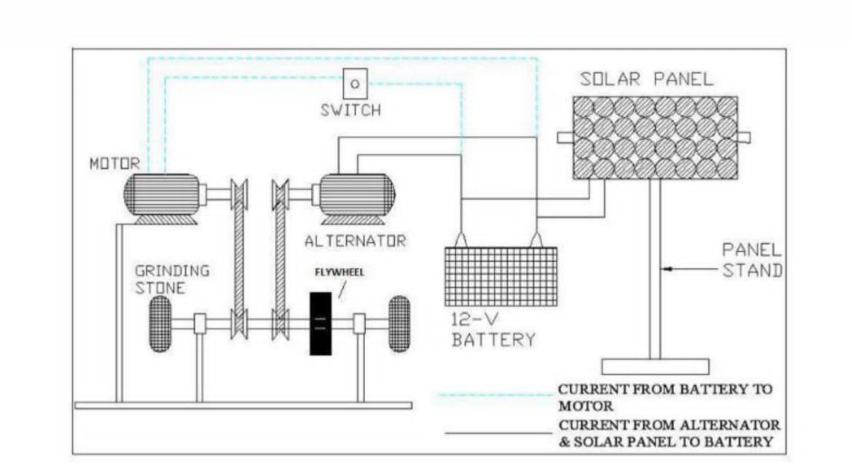
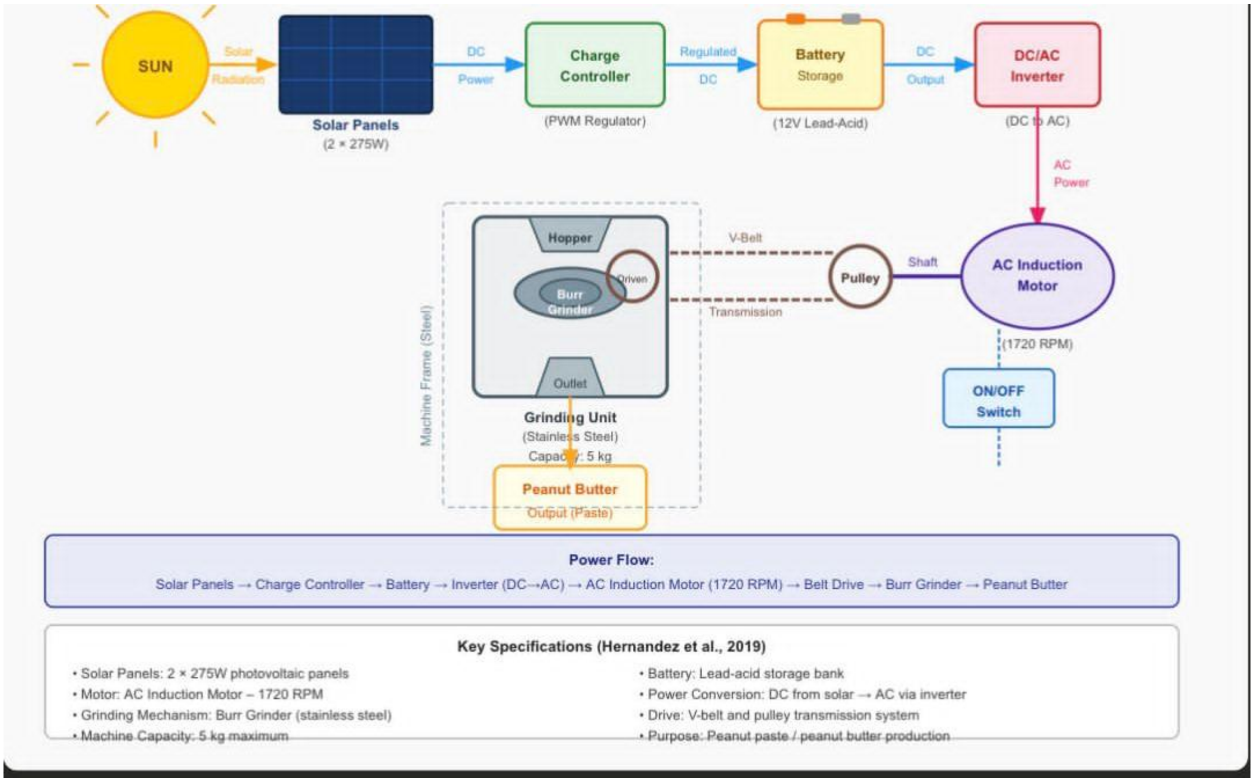


Fig 2.8: layout of the solar powered grinding machine

Study2: Solar Powered Peanut Grinding Machine

Hernandez et al. (2019) developed and installed a solar powered grinding machine designed specifically for peanut butter production. The machine featured a maximum grinding capacity of 5kg and utilized a burr grinder mechanism to produce fine ground peanuts suitable for paste production. The design incorporated stainless steel components to prevent contamination and ensure food safety compliance. The system employed two solar panels rated at approximately 275 watts each (550 watts total) to ensure continuous operation and increased production capacity. An AC induction motor operating at 1720rpm drove the grinding mechanism. This researchers highlighted several advantages including continuity of power supply, increased production, reduced production costs.



Power Flow:
Solar Panels → Charge Controller → Battery → Inverter (DC→AC) → AC Induction Motor (1720 RPM) → Belt Drive → Burr Grinder → Peanut Butter

Key Specifications (Hernandez et al., 2019)

- Solar Panels: 2 × 275W photovoltaic panels
- Motor: AC Induction Motor – 1720 RPM
- Grinding Mechanism: Burr Grinder (stainless steel)
- Machine Capacity: 5 kg maximum
- Battery: Lead-acid storage bank
- Power Conversion: DC from solar → AC via inverter
- Drive: V-belt and pulley transmission system
- Purpose: Peanut paste / peanut butter production

Fig 2.9: schematic diagram of solar powered grinding machine

Study3: Design and Development of a Solar Energy-Powered Maize Milling Machine

Sharma et al. (2020) designed and developed a PV- powered maize milling machine intended for off-grid rural development. Their study demonstrated that electric milling powered by solar photovoltaic (PV) energy is a technically and economically viable option for both grid-connected rural areas. The machine integrated a PV array, charge controller, battery storage, and an electric motor to drive the milling Mechanism. The author concluded that the energy cost per kilogram of milled grain was competitive with diesel-powered milling systems when full lifecycle costs were considered. The system used a conventional Lead-Acid battery bank and a standard PWM charge controller, with limited energy conversion efficiency. No provision was made for microcontroller based load management or dynamic speed control (Sharma et al., 2020).

Study4: Solar-Powered BLDC Motor Grinder.

Research advances in motor technology have led to the development of solar-powered grinding machines utilizing Brushless DC (BLDC) motors (IEEE,2024). This system was specifically designed for the spice grinding industry in Bangladesh, addressing the large market demand for ground products. The machine utilized an 800W BLDC motor, which demonstrated 1.5 times higher efficiency compared to conventional induction motors used in industry.

The system achieved a production capacity of 5-6kg of maize per hour, significantly out performing traditional motor driven grinders. The use of BLDC motors provided several advantages including higher efficiency, lower maintenance requirements.

Summary Comparison Table of Related Studies

Table 2.1: Comparison of Related Studies on Solar-Powered Grinding Machines

Study/Project	Power System	Motor Type	Capacity	Key innovation
Flywheel Grinding Machine(2022)	12V battery + solar + alternator	Single phase AC	Variable (10,000rpm+)	Flywheel energy storage
Peanut Grinder (Hernandez et al., 2019)	2×275W solar panels	AC induction (1720rpm)	5kg battery	Burr grinder for paste
Sharma et al. (2020)-PV maize mill	Solar PV + Lead-Acid battery +PWM charge Controller	DC electric motor	8-10 kg per hour	PV maize mill without grid access
BLDC Grinder (IEEE,2024)	Solar + BLDC motor	Slow BLDC	5-6kg/hr	1.5×efficiency vs conventional
This Project (2025) solar BLDC grain grinder	200W solar panel +24V Lead – Acid Battery +PWM charge controller	Brushless DC hub motor (350W,1500rpm)	7-8kg/hr	Hybrid system with wet grinding

2.10 Limitations of Previous Research and Novelty of Present Research

A critical review of the related literature reveals a number of significant gaps and limitations that collectively motivated the design approach adopted in this project. These limitations are discussed below under five key areas.

i. Absence of Microcontroller-Based Intelligent Energy Management

The majority of the reviewed studies, including those by Nikhil Pati et al. (2022), Sharma et al. (2020), and Hernandez et al. (2019) did not incorporate a microcontroller-based energy management system. These machines operated without real-time monitoring of battery state-of-charge, solar panel output voltage, or motor load conditions. As a result, the systems were susceptible to battery over-discharge, uncontrolled motor start-up surges, and inefficient power delivery. The IEEE (2024) study made progress by integrating a Field-Oriented Control (FOC) speed controller, but did not include an overarching Arduino-based supervisory control layer. The present project addresses this gap by integrating an Arduino microcontroller that monitors system parameters and coordinates the operation of the charge controller, motor speed controller, and protection fuse, providing a more responsive and intelligent power management system.

ii. Use of Inefficient Motor Technologies

Several earlier studies, most notably Nikhil Pati et al. (2022), employed conventional AC induction motors powered via inverter systems. This approach introduces additional energy conversion losses (DC from solar to AC via inverter), reduces overall system efficiency, and increases component complexity and cost. Hernandez et al. (2019) peanut grinding study used a 12V brushed DC motor, which suffers from brush wear over time and lower power density compared to modern BLDC motors. The present project directly addresses this limitation by using a Brushless DC (BLDC) Hub Motor rated at 350W and 1500 RPM — a motor type proven to offer higher efficiency, better torque characteristics, reduced heat generation, and longer service life, as also demonstrated in the IEEE (2024) study.

iii. Limited Power System Voltage and Battery Capacity

The works of Hernandez et al. (2019) utilized a solar powered battery system to store energy for the peanut grinding machine's operating which provided insufficient for extended operation beyond 4 hours per day and could not sustain operation under cloudy conditions.

iv. High Capital Cost and Lack of Scalability for Rural Communities

A 2020 study by Energy 4 impact and the efficiency for access coalition reported that solar-powered milling costs approximately twice as much as comparable diesel-powered units at the point of purchase ($2000 vs $1000) presating a major adoption barrier in rural off-grid communities. Studies such as those Nikhil Pati et al. (2020) and the solar milling SL platform also noted that many rural operators could not afford the large upfront investments required for high- capacity solar systems. The present project responds to this challenge by prioritizing low-cost (approx.$250), totally available components including a 200W solar panel, standard Lead-Acid batteries, and a universal joint transmission system to produce a functional grain gravity machine at a significantly reduced the total cost.

v. Absence of Fuse-Based Electrical Protection in Small-Scale Systems

Most of the small-scale solar grinding machine designs reviewed in the literature did not include dedicated circuit protection devices such as fuses or circuit breakers. This absence creates a significant safety risk, particularly in cases of motor winding short circuits, battery terminal shorts, or peak current surges during motor start-up. The Energypedia Grain Mill database also noted that high start-up currents in DC solar mills frequently led to failure of starter components. The present project integrates a 10-amp fuse as part of its electrical protection scheme, thereby safeguarding the battery, charge controller, and BLDC motor from overcurrent damage — a feature absent from most comparable designs in the reviewed literature.

CHAPTER THREE
MATERIALS AND METHOD

3.1 Materials

Materials required for the design and fabrication of grain grinding machine include the following

i. Brushless DC Hub motor of 350 WATTS and 1500 RPM
ii. DC motor speed controller (field oriented control_FOC)
iii. 24VOLTS PWM Charge Controller
iv. 12VOLTS Lead acid battery (x2)
v. 24 VOLTS 200 WATTS Solar Panel
vi. 23mm Universal Joint
vii. Arduino Microcontroller
viii. 10 AMPS Fuse
ix. Cables
x. Connectors
xi. Male and Female headers
xii. Dignity box
xiii. Hopper
xiv. Grinding Shaft

3.2 Method

The design and Fabrication of solar powered grain grinding machine using solar energy to power the motor that drives the grinder. This is done by the help of solar panels that capture sunlight and convert it into electrical energy; the photovoltaic cells within the panels absorb the sunlight and generate direct current electricity through the photovoltaic effect.

The generated DC electricity passes through a charge controller; the charge controller regulates the flow of the electricity, ensuring that the battery connected charged properly and preventing overcharged or damage. The electricity is stored in a rechargeable battery, allowing the machine to operate when sunlight is insufficient.

A DC motor is then connected to the battery that receives power from the solar panel and drives the grinding mechanism. The DC speed controller (regulator) is placed between the battery and motor to adjust the speed of the motor or stop the motor if needed. The power from the motor is transmitted to the grinder with the help of direct shaft connection (Universal joint)

3.3 Conceptual Design

Conceptual design is the preliminary phase of the design process where different design alternatives are generated and evaluated to identify the most suitable solution. In this project, the conceptual design phase involved developing two distinct configurations for the solar-powered grinding machine. The first concept utilized a DC motor with direct coupling to the grinding wheel, while the second concept employed an AC motor with belt and pulley transmission system. Both concepts incorporated solar panels, charge controllers, and battery storage for power generation and storage. The purpose of generating multiple concepts was to explore different approaches to power transmission and energy conversion, allowing for systematic comparison based on key criteria such as cost, efficiency, ease of fabrication, and maintenance requirements. Through weighted decision matrix analysis, the most appropriate concept was selected for detailed design and fabrication.

3.3.1 Concept 1: DC drive system with direct coupling

This concept as illustrated in **Figure3.1** utilizes a direct current (DC) motor powered by solar energy through a battery storage system. The solar panel converts solar radiation into electrical energy, which is regulated by a charge controller to prevent overcharging and deep discharge of the battery.

The stored energy in the battery powers a DC motor that is mechanically coupled to the grinding wheel through a universal joint. This configuration provides a compact and efficient power transmission system with minimal energy losses. The universal joint allows for angular misalignment between the motor shaft extension and the grinder shaft, ensuring smooth operation and reducing vibration. The system operates entirely on DC power, eliminating the need for power conversion from DC to AC, thereby improving overall system efficiency.

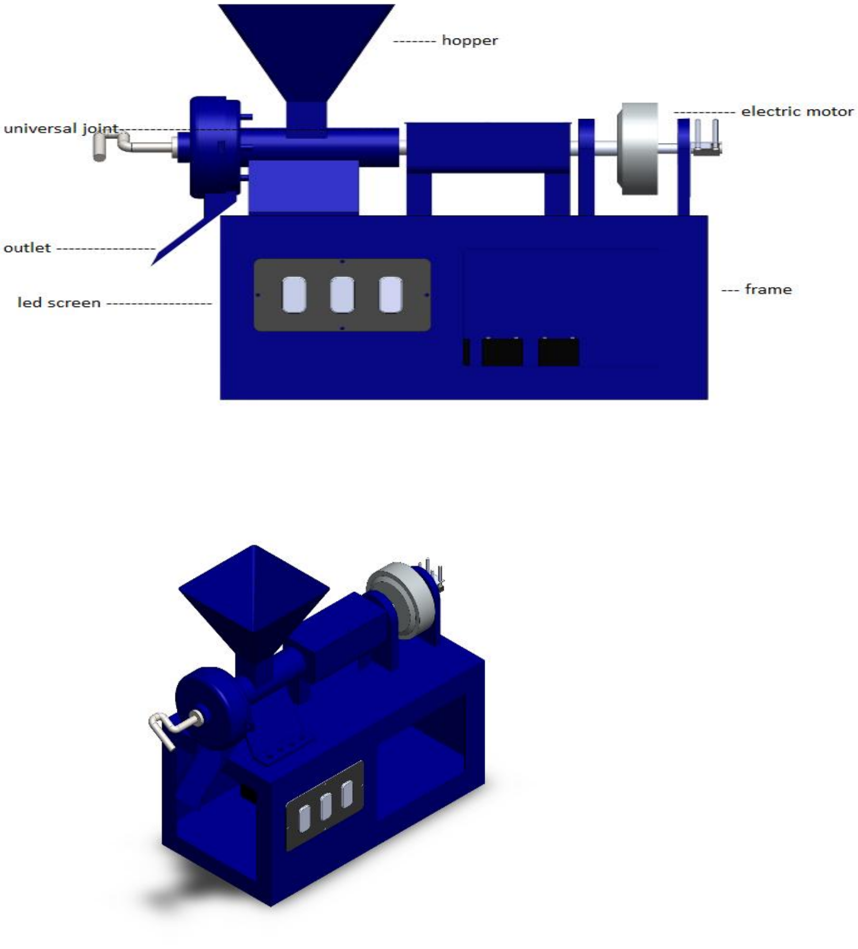


Figure 3.1: Concept 1

The assembly drawing that shows how the component parts of concept 1 design fit together to form a complete unit is illustrated in **Fig.3.2**

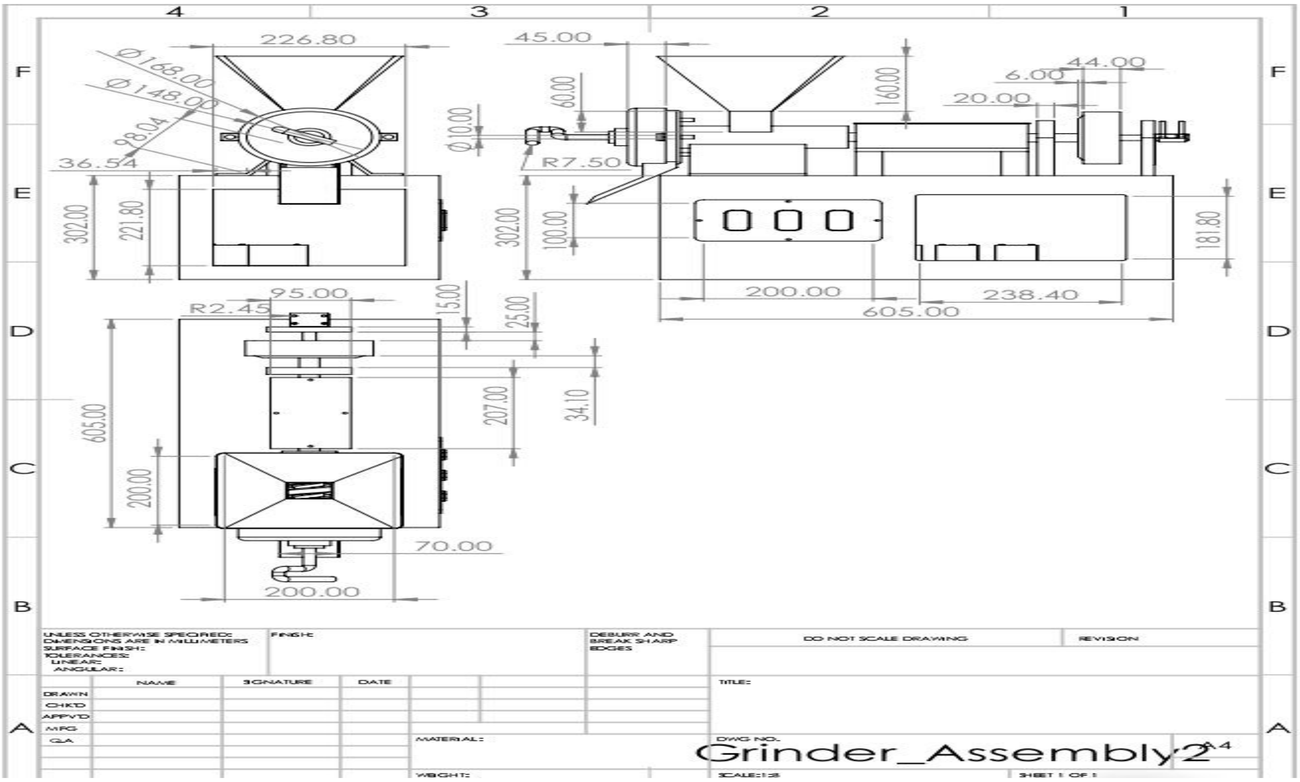


Figure 3.2: Concept 1 Assembly drawing

3.3.2 Concept 2: AC Drive System with Belt and Pulley Transmission

This concept employs an alternating current (AC) motor to drive the grinding wheel through a belt and pulley mechanism. The solar panel charges the battery through a charge controller, similar to Concept 1. However, the DC power stored in the battery is converted to AC power using an inverter before supplying the AC motor. The motor is connected to the grinding wheel via a belt and pulley drive system, which allows for speed reduction or adjustment by varying the pulley diameters. This configuration provides flexibility in terms of motor selection since AC motors are widely available and generally more robust. The belt drive also acts as a shock absorber, protecting the motor from sudden load variations during grinding operations.

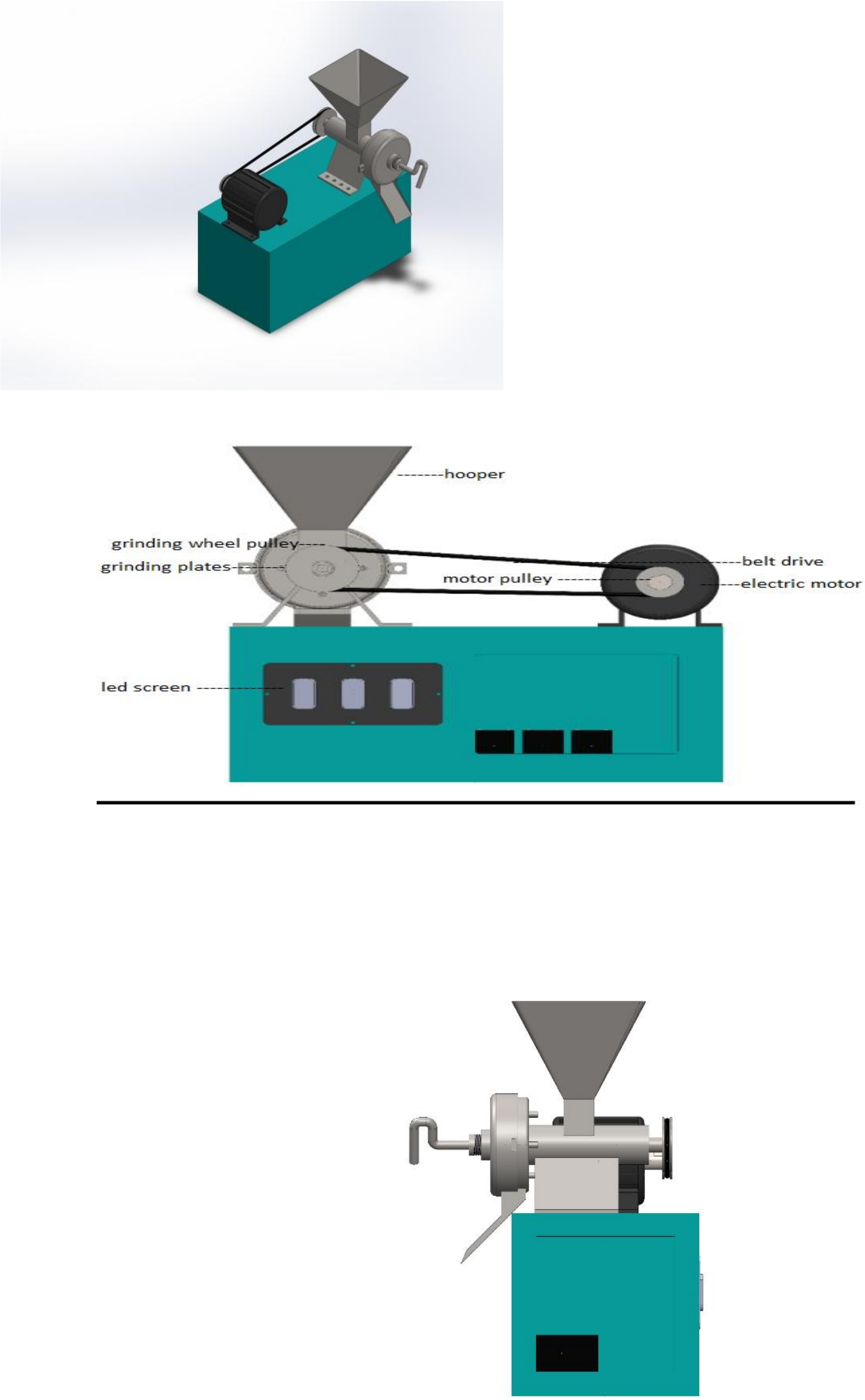


Figure 3.3 Concept 2 split diagram

The assembly drawing that shows how the component parts of concept 2 design fit together to form a complete unit is illustrated in **fig. 3.4**

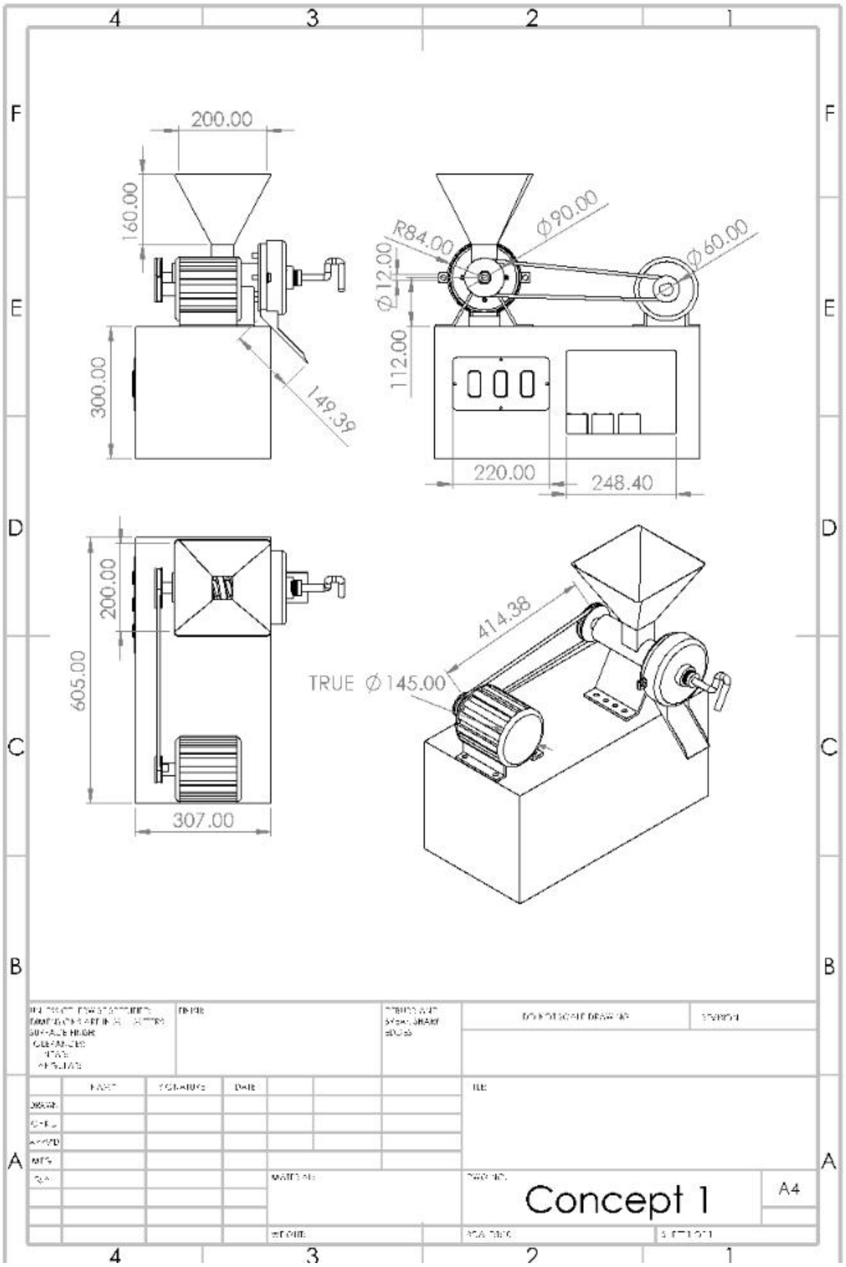


Figure 3.4 Figure 3.2: Concept 2 Assembly drawing

Table 3.1 Decision Matrix Table for Concept Selection

Weighed Criteria	Weighting	Concept 1 Score	Concept 1 Total	Concept 2 Score	Concept 2 Total
Versatility	7	4	28	5	35
Ease of Production	6	4	24	3	18
Low cost of Production	5	3	15	2	10
Total			67		63

From the decision matrix in Table 3.1 using weight scale of 7 to 5 in order of importance of the considered criteria, the concept 1 with total weighted criteria average of 67 was selected as against the concept 2 with total weighted criteria average of 63, hence concept was selected.

3.4 Design Specification

A product Design specification is a detailed statement of the functional and technical requirements that a system or machine must meet. The design specification for the performance objective of the solar power grain grinding machine are as follows:

I. One 200Watts Solar Panel
II. 50Ah, 12VOLTS Battery
III. 24V, 350watts Dc Motor (power of the machine)
IV. The machine uses 23mm universal joint for transmission
V. 24V PWM Charge Controller

3.5 Material selection

In selecting materials for the design, the following factors were considered

1. Availability of the material.
2. Suitability of the materials for the working condition in service.
3. The cost of materials

Shaft:

Material used; stainless steel

Reason:

1. High strength
2. High wear resistant properties
3. Good machinability.

Hopper:

Material used; mild steel

Reason:

1. Good ductility.
2. High strength.

Universal joint:

Material used; Chrome-vanadium alloy

Reason:

1. High strength
2. Good resistance to corrosion

Dc Motor

Material used; Aluminum

Reason:

1. Light weight

ii. Paramagnetic

3.6 Detailed Design

3.6.1 System components and design detail

3.6.2 Solar panel

The 200 W solar panel used in this project as shown in **fig.3.5** serves as the primary source of electrical power for operating the grinding machine. It converts sunlight into electrical energy through photovoltaic cells, producing a maximum output of about 200 watts under standard test conditions. The panel typically delivers around 18 V to 20 V and 10 A of current at peak sunlight. It is connected to a charge controller that regulates power flow to the battery and load. This ensures stable and efficient operation of the solar-powered grinding machine even under varying sunlight conditions.

Figure 3.5: Solar panel

3.6.3 Charge controller

It is a voltage or current regulator to keep battery from overcharging. It regulates the amount of voltage or current coming from the solar panel to the battery, the basic function of charge controller is to.

I: Accept incoming power from solar panel

II: control the amount of power sent to the battery.

III: monitor the voltage of battery to prevent overheating.

IV: Allow power to flow only from the solar panel to the battery

The image shown below in fig 3.6 is a charge controller of 24V.

Figure 3.6: Charge Controller

3.6.4 Battery

The lead-acid battery as illustrated in fig3.7 is a rechargeable energy storage device that converts chemical energy into electrical energy through an electrochemical reaction. It consists of lead dioxide (positive plate) and spongy lead (negative plate) immersed in sulfuric acid electrolyte**.** This battery delivers a nominal voltage of 12 volts and can supply 20 ampere-hours of current. It is commonly used for solar power systems, small machines, and backup applications. The battery is designed for deep discharge and recharge cycles without damage. The 12V 20amps battery is required to power the motor. The battery storage capacity is the amount of energy the battery can store and discharge before needing to be recharged.

Battery storage capacity = power of battery × time duration

Battery power = battery voltage rating × battery current rating

Figure 3.7: Lead acid battery

3.6.5 Brushless DC Hub Motor

The brushless DC hub motor as illustrated in Fig 3.8 is an electrical machine that convert electrical energy into mechanical energy. In a Brushless DC motor, the input electrical energy is the direct current which is transformed into the mechanical rotation. This motor is used to drive the grinder with the help of a universal joint (direct transmission) that transmit the energy from the motor to grinder.

Figure 3.8 Dc Brushless Hub Motor

i. Motor torque; is the rotational force that the motor develops. The torque of an electric motor is commonly measured in Newton meters.

$$\text{Torque} = \frac{60\ x\ power\ rating}{\pi x RPM} \qquad (3.1)$$

RPM = speed of the motor in revolution per minute

ii. Motor efficiency; is the ratio of the mechanical work a motor performs to the electrical work it uses to do that work. It's expressed as a percentage.

Motor Efficiency = $\frac{motor\ power\ rating}{input\ power} \times 100$ Q (3.2)

Input power = motor voltage rating × motor current rating (3.3)

3.6.6 Grinder Shaft and Bearing Design

The grinder shaft is the main mechanical component that transfers torque from the motor to the grinding disc. A 23mm universal joint as illustrated in Fig 3.9, which compensates for small misalignment permits smooth rotation, connects it. Precision roller bearing chosen to manage the 1,500 rpm output of the 350-watts brushless Dc Hub motor support the shaft, ensuring stability and lowering friction. These parts were selected in order to sustain mechanical integrity under load and endure continuous operation.

Figure 3.9: Universal drive shaft

3.6.7 Hopper Design; A Hopper is a container similar to a large funnel into which the product is loaded from the top.

Volume of the Hopper V = $\frac{h}{3}(A_1 + A_2)$ (3.4)

Where h= height of hopper

A_1 = area of the upper base

A_2 = area of the lower base

Figure 3.10: Hopper Pictorial view

3.6.8 Arduino Microcontroller

Arduino microcontroller as illustrated in fig 3.11 is an open-source electronics platform consisting of a programmable microcontroller board and software (IDE - Integrated Development Environment) used to write and upload code to the board. It executes instructions that are programmed into it. It role in the grinding machine includes

i. It coordinates both drivers to drive the Dc Hub motor
ii. It measures the speed and temperature of the Dc hub motor
iii. It measures the voltage of the battery
iv. It calculate and display the battery percentage on the LCD screen (State of Charge_SOC)

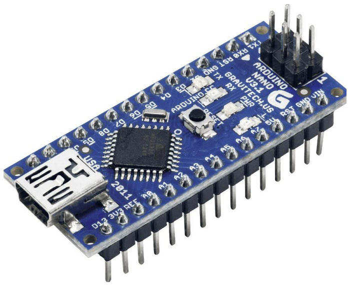


Figure 3.11: Arduino Microcontroller

3.7 Solar power system design

3.7.1 Load Analysis and Power Calculation

The total power requirement of the system was determined by calculating the energy consumption of all electrical components.

(a)Grinding Capacity:

i. Target grinding capacity 7-8kg/hr
ii. Material type: Tomatoes/Pepper (soft to medium hardness)
iii. Fineness: Medium grind (paste/puree consistency)
iv. Application: Food processing (wet grinding)

The grinding capacity range 7-8 kg/hr (with design average of 7.5kg/hr) was determined through, Technical assessment: a 350W motor can theoretically achieve 7.5kg/hr (at 32Wh/kg specific energy) with optimized design reaching 7-8 kg/hr range.

(b)For Medium Grinding (Paste/Puree Consistency):

i. Fresh tomatoes: **30 W·hr/kg**
ii. Fresh pepper: **35 W·hr/kg**
iii. Average for tomato/pepper mix: **32 W·hr/kg** (Specific power consumption)

The specific energy consumption values of 30W.hr/kg and 35W.hr/kg for grinding fresh tomatoes and peppers respectively were obtained through industry benchmarks for vegetable processing; Energy Star guide for fruit and vegetable processing industry published by Lawrence Bakelen National Laboratory (Masanet et al., 2007, OSTI 10: 927884).

For target capacity of 7.5 kg/hour (middle of 7-8 range):

$$\text{Power Required} = \text{Capacity} \times \text{Specific Power Requirement} \qquad (3.5)$$

$$P = 7.5 \text{ kg/hr} \times 32 \text{ W·hr/kg}$$

P = 240W

(c)Safety Factor for Variable Feed and Peak Loads:

Design Power = $\frac{required\ power}{grinding\ Efficiency}$ (3.6)

P_design = $\frac{240}{0.75}$(wet grinding efficiency, accounting for friction of grinding plates and moisture); Alpha grinding media,(2025).

P_design = 320W

Required grinding power = 320W

Therefore 350W motor selected for 5-10 kg/hour tomato/pepper grinding capacity

(d)DC Motor:

1. Motor Power Rating: 350W
2. Operating Voltage: 24V
3. Motor Speed: 1500 RPM
4. Motor Current at rated load: I = $P/_{V} = 350W/_{24V}$= **14.58A**

For a motor efficiency of 87.5% (85-95%), the actual input power required:

$$\boldsymbol{p_{input} = p\_rated/_{\eta} = 350W/_{0.875} = 400W}$$

For a motor efficiency of 87.5% (80% -95%), the actual input power required:

$p_{input} = \frac{p\_rated}{\eta}$, =$\frac{350W}{0.875}$=410W. (calculator academy, 2023; Steefo group,2025)

i. Motor Torque:

$\text{Torque} = \frac{\text{output power}}{\text{speed of roation}}$

$T = \frac{p}{w}$

$w = \frac{2\pi \times RPM}{60}$

$w = \frac{2\pi \times 1500}{60}$

w = 157.08 Rad/s

Grinding torque

$T = \frac{350}{157.08} = 2.228Nm$

ii. **Required grinding torque:**

$T = \frac{320}{157.08} = 2.037Nm$

Auxiliary Loads:

Microcontroller : 1W

Total auxiliary load =1W

The microcontroller system power consumption is estimated at 1W based on published measurements showing arduino uno R3 boards consumer approximately 1.04W during active operation(Al showman et.al, 2018).

iii. Total System Power:

P_total = 400W + 1W = 401W

iv. Total System Current:

I_total = 401W / 24V = 16.7A

3.7.2 Daily Energy Requirement

Assuming the grinding machine operates for 2-3 hours per day:

Daily Energy Consumption:

E_daily = P_total × Operating hours E_daily = 401W × 2.5 hours = 1002.5 Wh/day **= 1.O25 WAh/day kWh/day**

Battery Energy Requirement (Ah):

E_battery = $\frac{E\_daily}{battery\ voltage} = \frac{1002.5}{24V}$ = **41.77Ah** **(3.7)**

3.7.3 Battery Bank Design and Capacity

Battery Configuration: Two 12V, 20Ah lead-acid batteries connected in series to achieve 24V system voltage.

Total Battery Capacity:

i. Configuration: Series connection (voltage adds, capacity remains same)
ii. System Voltage: 12V + 12V = **24V**
iii. Total Capacity: 50Ah (at 24V)

Battery Energy Storage:

E_stored = Voltage × Capacity = 24V × 50Ah = **1200 Wh** **(3.8)**

Available Energy (considering 50% Depth of Discharge for lead-acid batteries):

E_available = 1200Wh × 0.5 = **600 Wh**

Operating Time on Battery**:**

Operating time = $\frac{E\_available}{P_{total}operating\ time} = \frac{600Wh}{401W}$≈ 1.5 hours **(3.9)**

3.7.4 Solar Panel Specification and Analysis

Solar Panel Specifications:

i. Power Rating: 200W
ii. Voltage: 24V
iii. Panel Current: I_panel = 200W / 24V = **8.33A**
iv. Type: Monocrystalline

Time for panel to completely charge the battery:

$$= \frac{\text{battery storage capacity}}{\text{panel energy storage capacity}}$$

$$= \frac{1200\text{Wh}}{200\text{W}} = 6 \text{ hours}$$

Solar Panel Energy Generation:

Based on average peak sun hours in Benin City (approximately 4.5hours per day based on minimum season); profile SOLAR (2024)

$$E_{solar} = P_{panel} \times peaksunhours \times system\ efficiency$$

Battery Discharge Rate/ 558.8Wh.1 day deficit

Accounting for:

i. PWM charge controller efficiency: 78%
ii. Battery charging efficiency: 85%
iii. Dc motor efficiency: 85-90%
iv. Transmission drive train efficiency: 85%
v. Cable losses: assuming it is negligible

Overall system efficiency = 0.78 × 0.85 x 0.875 x 0.85 = 0.493 (49.3%)

E_solar = 200W × 4.5 hours × 0.493 = **443.7 Wh/day**

Energy Balance Analysis**:**

Daily Energy Requirement = 1002.5 Wh/day

Daily Solar Energy Generation = 443.7 Wh/day

Energy Deficit = 1002.5 – 443.7 = 558.8 **Wh/day**

Analysis: The 200W solar panel generates approximately 44% of the daily energy requirement (443.7Wh out of 1002.5Wh needed).

> During Operation**:** The solar panel can supplement the motor operation by providing approximately 200W × 0.493 = 98.6W of usable power during peak sun hours, reducing battery discharge rate.

Qualitative Analysis

Case1: without Solar Panel (Battery only)

If the motor operates without solar panel assistance:

I. Motor power requirement :350W
II. Operating time 2.5hours/day

Battery discharge rate: 350W continuous 2.5hours

Case2: with Solar Panel (Hybrid Operation)

Solar Panel contribution: 200W×2.5h=628.5Wh

Operating time: 2.5 hours

Energy from battery during Operation:

251.4W×2.5h=628.5Wh

Battery Discharge Rate Reduction

I. Without Solar: 350W discharge rate
II. With Solar: 251.4W discharge rate
III. Reduction: 98.6W (28.6% lower discharge rate)

Total daily energy requirement: 1002.5Wh/day, solar energy generation 443.7 Wh/day Energy deficit of 558.8 Wh/day comes from battery.

3.8 Mechanical System Design

3.8.1 Hopper volume

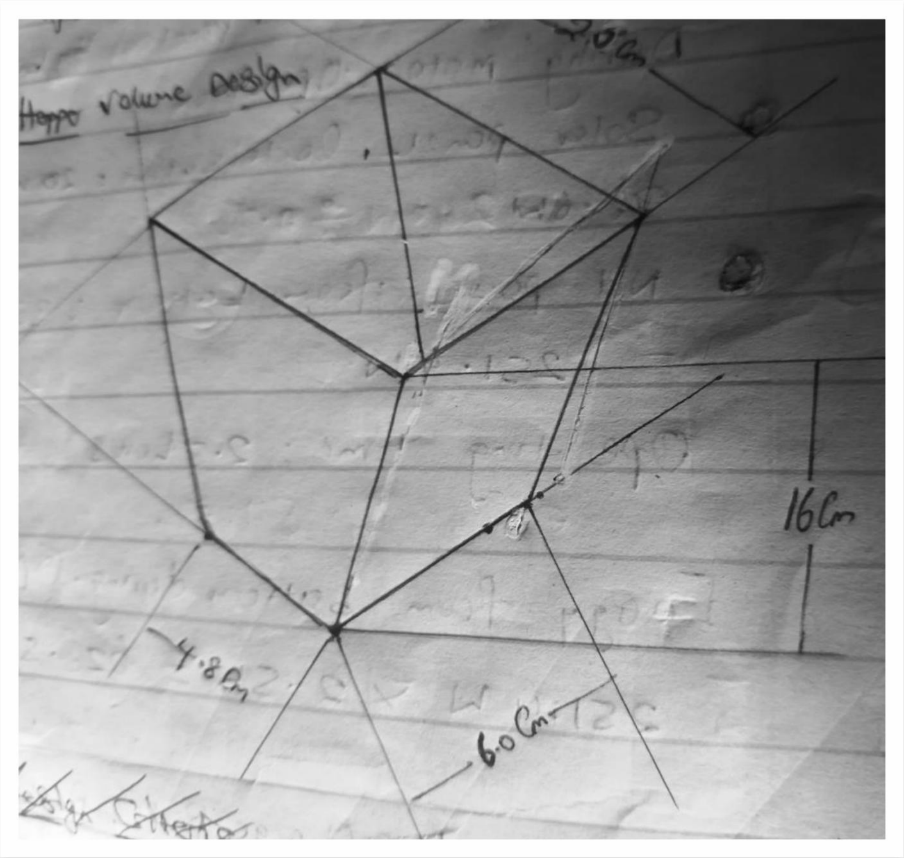


Fig3.12: Dimensional Diagram of the Hopper

Table 3.2:Dimension Selection Rationale

s/n	Dimension	Value	Justification
1	Height (h)	16.0c.m	I. Provides adequate vertical clearance for material flow II. Creates sufficient angle for gravity assigned discharge
2	Top Length(L_1)	20.0 c,m.	I. Square opening (20×20 c.m) provides $400cm^2$ feeding area which is adequate for loading 1-105kg batches. II. Wide enough to prevent spillage during loading
3.	Bottom Length (L_2)	6.0. c.m.	I. Facilitates controlled material feed to drinding plates II. Prevents overflow or clogging at grinding chamber entrance.
4.	Bottom Breadth (b)	4.8 c.m	I. Outlet size limits feed rate to prevent grinding overload. II. Smaller breadth creates slight restriction for the control.

Height of hopper h = 16.0cm

Length of the top base = L_1

L_1= 20.0cm

Area of the top base = L_1 2

$A_1 = (20.0)^2 = 400cm^2$

Length of bottom base = L_2

$L_2 = 6.0\text{cm}$

Breadth of bottom base = b

b= 4.8cm

A_2= area of bottom base

$A_2 = L_2 \times b = 6.0 \times 4.8 = 28.8\ cm^2$

Volume of hopper = V

$V = \frac{h}{3} \times (A_1 + A_2)$

$V = \frac{16.0}{3} \times (400 + 28.8)$

$V = 2286.93cm^3$

3.8.2 Shaft Design Considerations:

The hopper shaft transmits torque from the motor to the grinding teeth while supporting the rotating grinding element. The shaft was designed to withstand:

- i. Torsional Stress from power transmission
- ii. Bending Stress from grinding forces
- iii. Axial loads from grain flow and grinding pressure

Torsional Shear Stress:

$$\tau = \frac{16T}{\pi d^3}; \qquad (3.10)$$

where:

T= torque =2.28N.m = 2280N.mm

d = shaft diameter = 25mm

$$\tau = \frac{16T}{\pi d^3} = \frac{16(2280)}{\pi(25^3)} = \frac{36480}{49087}$$

$\tau = 0.743N/mm^2$ or 0,743mpa

The shaft as shown as below is modeled as a cantilever beam with:

- Fixed support at motor end (ptovides r×n force)
- Simple support at bearing (provide r ×n force only)
- Concentrated load at grinding plate position.

Fig3.13: Shaft configuration design

Load Calculations

Weight of Grinding plate

Wg= m×g

Wg=2.5Kg×9.81m/s^2

Wg=24.52N

Total radial load at grinding plate

Ftotal = Fgrinding+Wg

Fgrinding = F.r =Radial(normal force)

Determination of Radial (normal force)

Using power based approach:

Power, P=F_t ×V_t

V_t = $\frac{\pi \times D \times N}{60}$

Where; P is the power of the motor in watts.

F_t is tangential force of the grinding disc in newton

V_t is the tangential velocity of the grinding disc m/s

D is the diameter of the disc in mm

N is the rotational speed of the motor in r.p.m.

When; D=100mm, N=1500rpm

$V_t = \frac{\pi \times 0.1 \times 1500}{60}$=7.854m/s

F_t = $\frac{P}{V_t} = \frac{350}{7.854} = 44.86N$

$F\_r = F_t \times \frac{cos\emptyset}{sin\emptyset}$

Where;

F_r is the radial (normal) force

Ø is the grinding/shear angle (typically 25°to40° for pulpy food: Mohsenin;Physical Properties of Plant and Animal materials 1986)

F_r = $44.56 \times \frac{cos35}{sin35}$ (using ø=35° average of 25°-40°)

The above design specifications were obtained through systematic calculations based on target grinding capacity of 7.5kg/hr and specific energy consumption of 3.5 W.hr/kg for wet grinding over 2.5 hours daily operation resulting in 1002.5Wh daily energy requirement.

F_r = 77.18 N

F_total = Fgringing + Wg

=77.18N+24.52N

F =101.71N

∴ Total Radial load F at grinding plate is 101.7N

<u>Free Body diagram Analysis</u>

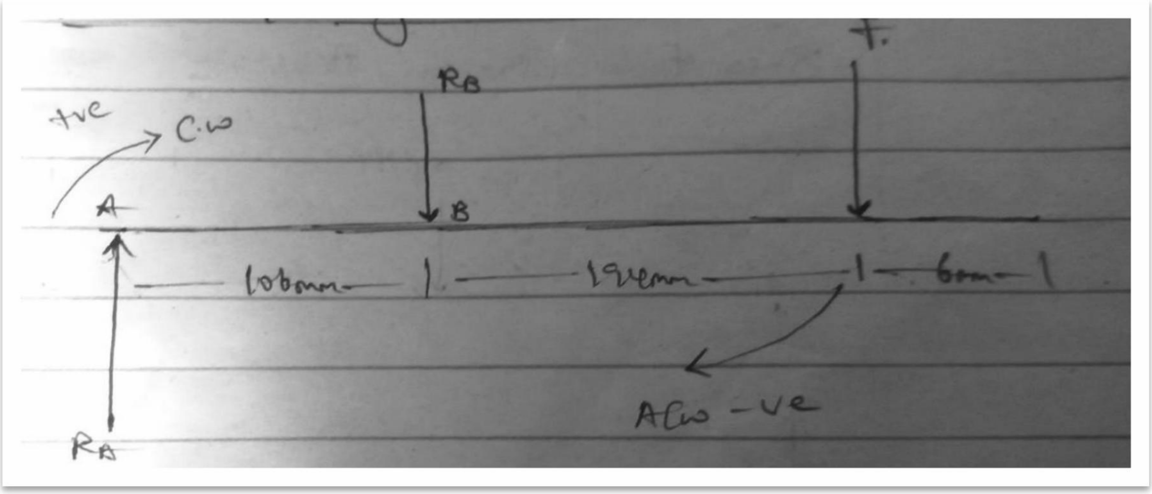


Fig3.14: Free body diagram

Taking moment about point B

$R_A \times 106 - F \times 194 = 0$

$106R_A = 194F$

$106R_A = 194(101.71)$

$R_A = \frac{194(101.71)}{106} = 186.15N$

$\Sigma fy = 0$

$R_A + R_B - F = 0$

$186.15 - R_B - 101.71 = 0$

$84.44 - R_B = 0$

$R_B = 84.44N$(this shows that R_B is in the right direction).

<u>Shear Force Diagram Analysis</u>

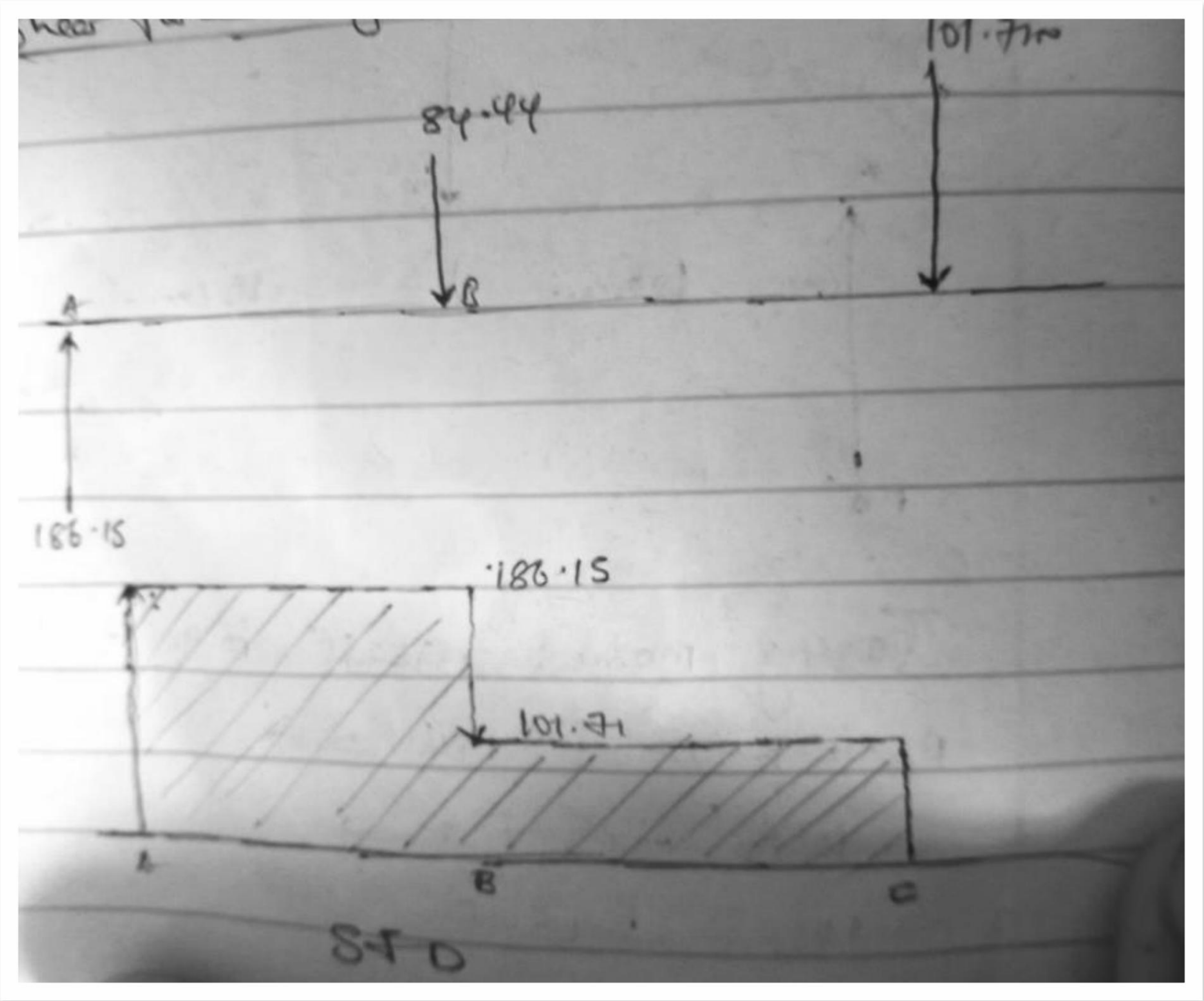


Fig 3.15: Shear Force Diagram

Bending Moment Diagram Analysis

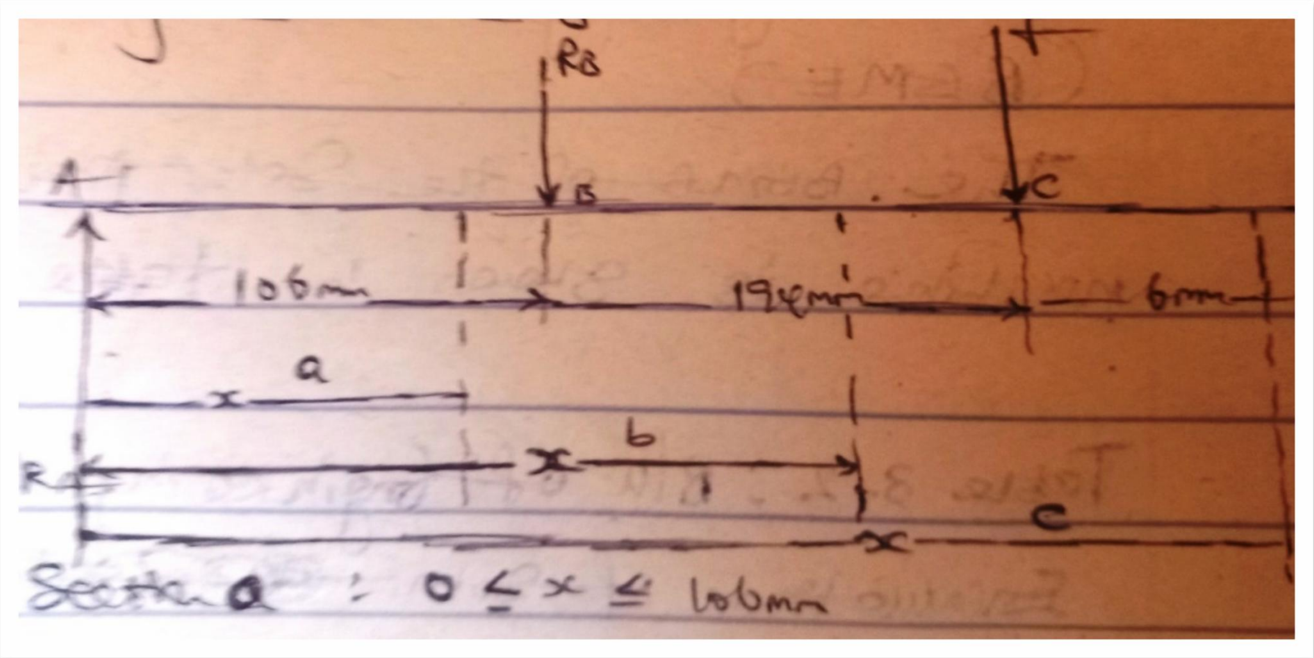


Fig 3.16: Bending Moment diagram

Taking moment about the section

$M(x) = +R_A \times x$

$= +186.15 \times x$

$= 186.15x$

At $x=0$

$M(0) = 0$Nmm

At $x = 106$ mm

$M(106) = 186.15 \times 106 = 19{,}731.9$Nmm $= 19.73$Nm

Section b: $106 < x \leq 300$mm

Taking moment about the section

M(x) = +R_A ×x- R_B ×(x-106)

=186.15x- 84.44(x-106) + 8950.64

M(x) = 101.71x+8950.64

At x=106mm

M(106) = 101.71(106) + 8950.64 = 19731.9Nmm = 19.73Nm

At x=300mm

M(300) = 101.71(300) +8950.64 = 39463.64Nmm = 39.463Nm

Section C; x>300mm

Taking moment about the section

M(x) = +R_A ×x –R_B × (x-106) - F×(x-300)

=186.15x-84.44(x-106)-101.71(x-300)

= 186.15x-84.44x+8950.64-101.71x+30,513

=(186.15-84.44-101.71)x +8950.64+30513

= 0x+39463.64

M(x)=39463.64Nmm =39.463Nmm

At x=300

M(300)=39.463Nmm

At x=306

M(306)=39.463Nmm (Constant bending moment force)

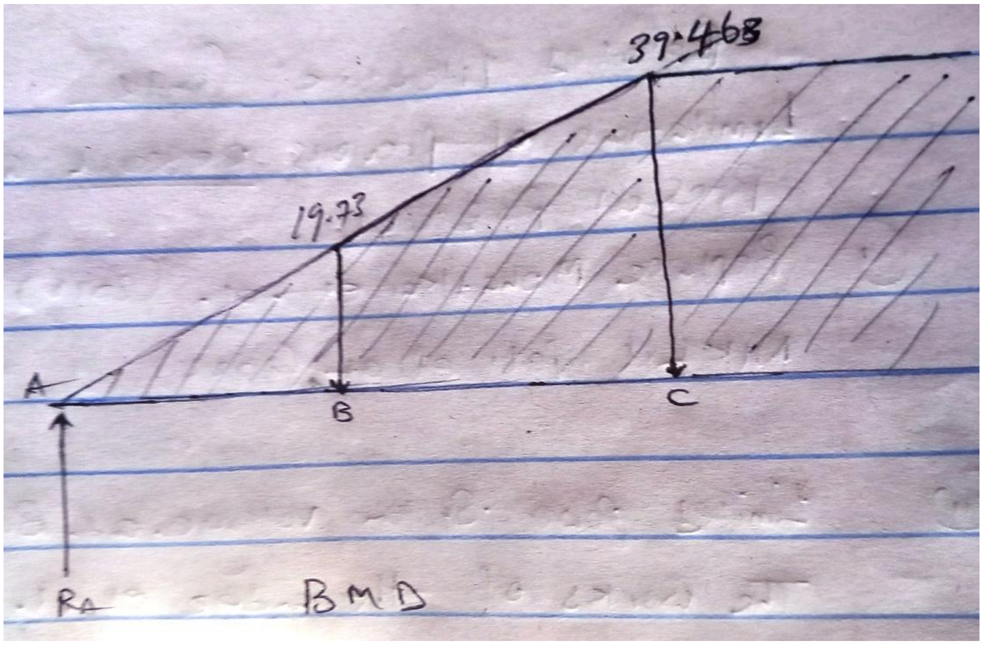


Fig 3.17: Bending moment diagram

3.8.3 Safety features

i. Emergency Stop Button**:** A prominently located emergency stop (E-stop) button is integrated into the control circuit. When activated, it immediately cuts power to the motor, bringing the grinding operation to a halt. The E-stop button is:

  i. Red colored for easy identification
  ii. Positioned within easy reach of the operator
  iii. Requires manual reset after activation

ii. Electrical Safety:

  i. All electrical connections properly insulated
  ii. Frame grounded to prevent electric shock
  iii. Fuses and circuit breakers for overcurrent protection

iii. Operational Safety:

  i. Motor enclosed to prevent accidental contact
  ii. Universal joint covered with protective housing
  iii. Smooth edges on all exposed surfaces

iv. Stability

  i. Low center of gravity design prevents tipping
  ii. Adequate base area for stability during operation
  iii. Provision for bolting to floor if needed

3.9 Fabrication process

3.9.1 Cutting, Welding, and Assembly Operations

Precision cutting of metal sheets and structural elements was the first step in the fabrication process. The frame and housing were then assembled using MIG welding. To guarantee mechanical balance and dimensional accuracy, the hopper, motor mount, and grinding shaft were installed in accordance with the Solid Works model. To preserve structural integrity and operational effectiveness, every component was positioned and fastened.

3.9.2 Electrical Wiring and Connections

To cut down on clutter and make maintenance easier, electrical components were wired in a neat and orderly manner. For protection, the Arduino, charge controller, motor controller, and fuse were installed inside a dignity box. Standard headers and connectors were used for all connections, making upgrades and replacements simple. The charge controller, which supplies power to the motor system and feeds the batteries, was connected to the solar panel.

3.10Bill of Engineering Materials and Evaluation of Solar powered grinding machine (BEME)

The BEME of the solar powered grinding machine is shown in table 3.2

Table 3.3: Bill of Engineering Materials and Evaluation of Solar powered grinding Machine

S/N	COMPONENT	SPECIFICATION	QUANTITY	UNIT COST (₦)	TOTAL COST (₦)
1	Solar panel	Photovoltaic cell, 24V, 200W	1	40,000	40,000
2	Battery	Lead acid battery, 24V, 20amp	2	15,000	30,000
3	Dc Motor	Brushless dc motor, 350W, 24V, 1500rpm	1	87,000	87,000
4	Charge controller	P.W.M, 24V	1	20,000	20,000
5	Arduino	Nano	1`	13,000	13,000
6	Dc motor speed controller	F.O.C brushless driver, 24V – 42V	1	66,000	66,000
7	Hopper	Mild steel hopper	1	50,000	50,000
8	Universal joint	23mm	1	17,000	17,000
9	Cables	Copper wire, 1.5mm	2 yards		
10	Fuse	10 amps fuse	2		
11	Male and female headers	½ in a	5	1,000	1,000
12	Connectors	25amps			
13	Shaft extension	22mm	2	4,000	8,000
14	Dignity box	80×40 mm	1	2,500	2,500
15	LCD screen	16x2 liquid crystal display	1	5,000	5,000
16	Oil paint	Alkyd paint blue	1 litre	6,000	6,000
17	Bolts and nuts	Stainless	$\frac{1}{2}$ inch	200	200
18	Delivery/shipping fee		Couple of items	5,000	5,000
19	Total				350,700

3.11 Testing Procedures

Mechanical and electrical assessments were part of the testing procedures. To check shaft stability and controller response, the motor was operated at different speeds. To guarantee consistent output, sample materials were used to evaluate grinding performance. Electrical tests included examining fuse integrity, current draw, and voltage levels. To verify battery charging effectiveness and overall system dependability, the solar charging system was put through testing in the sun.

3.12 Detail Drawing

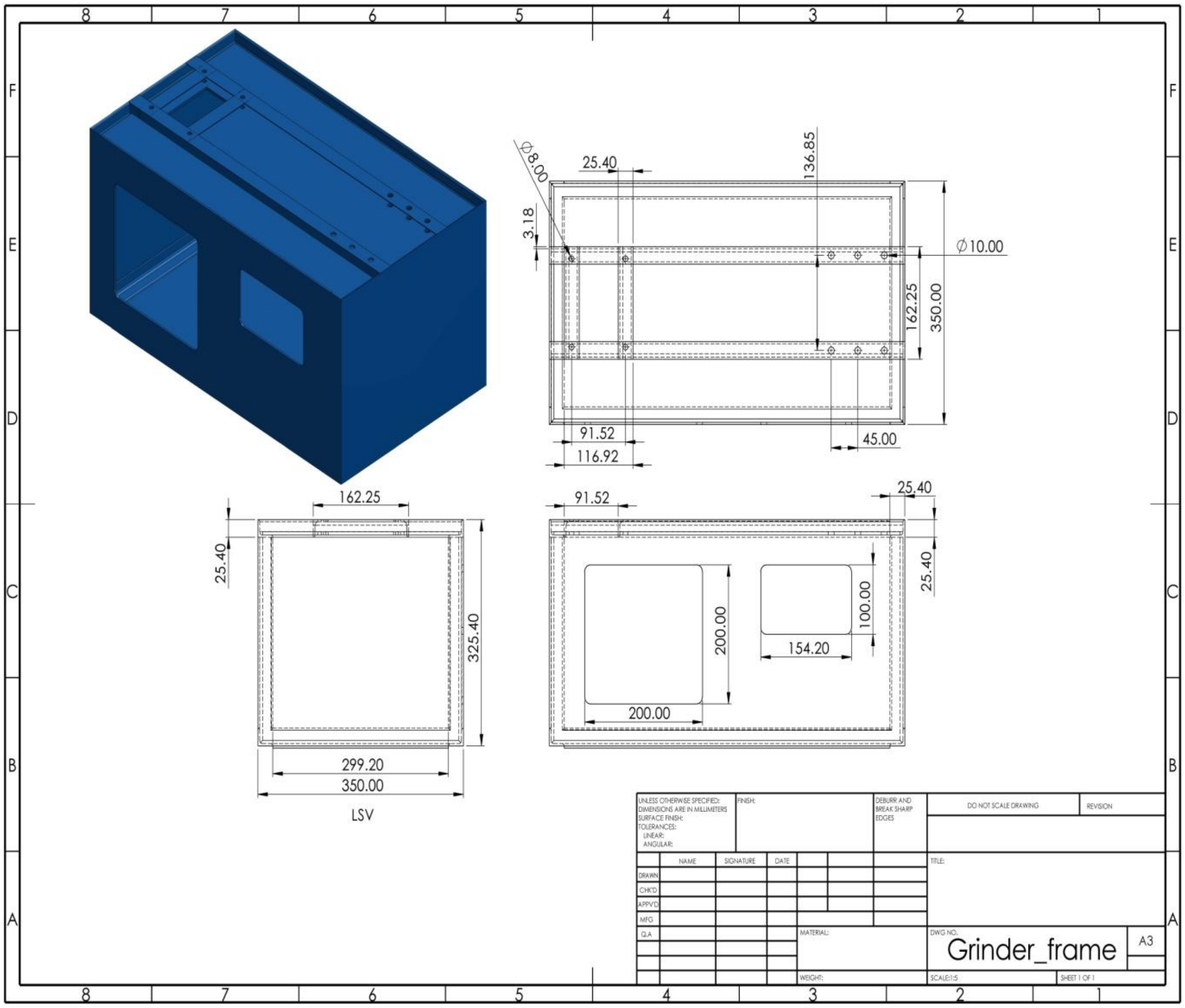


Fig 3.18: Assembly Drawing of grinder Frame

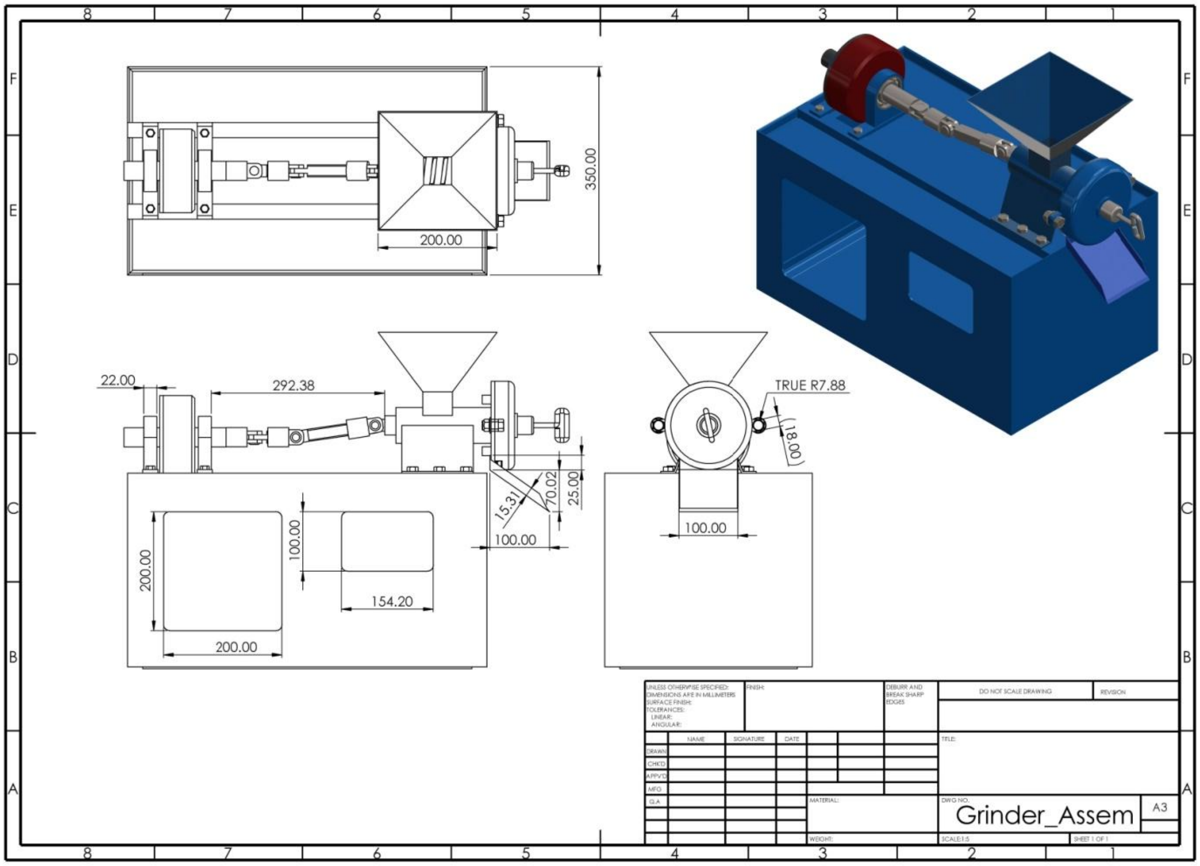


Fig 3.19: Assembly Drawing of Grinding machine

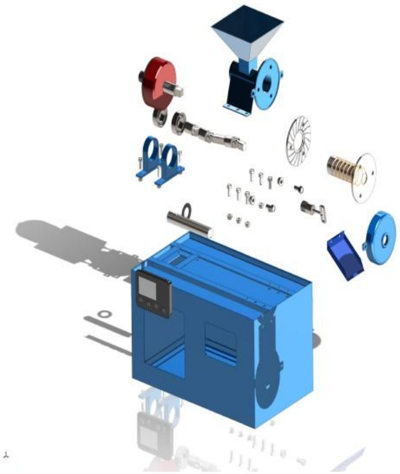


Fig 3.20: Fron tExploded View of Grinding Machine.

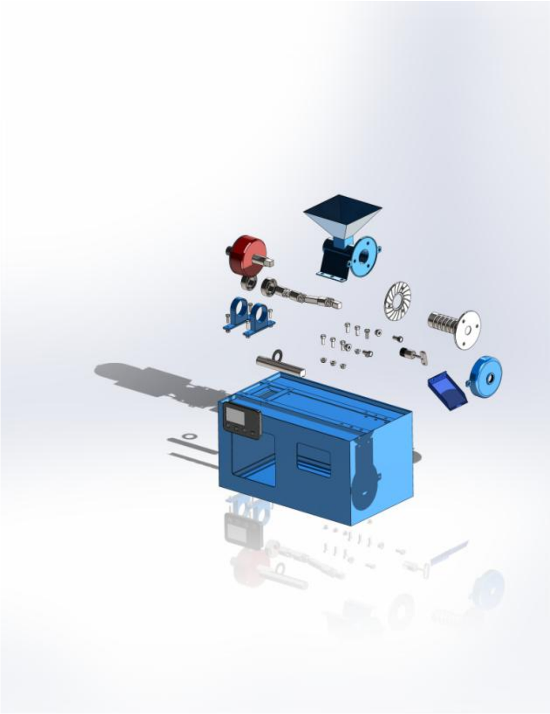


Fig 3.21: Side Exploded view of Grinding machine

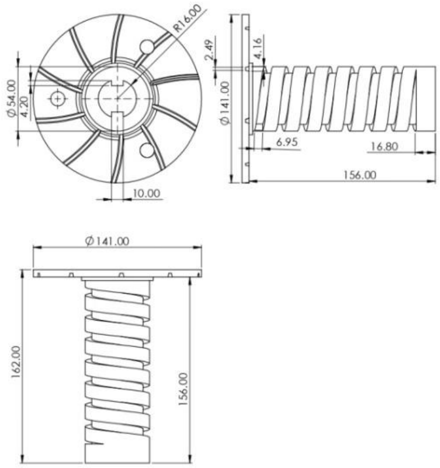


Fig 3.22: Othographic View Of the Rot Burr

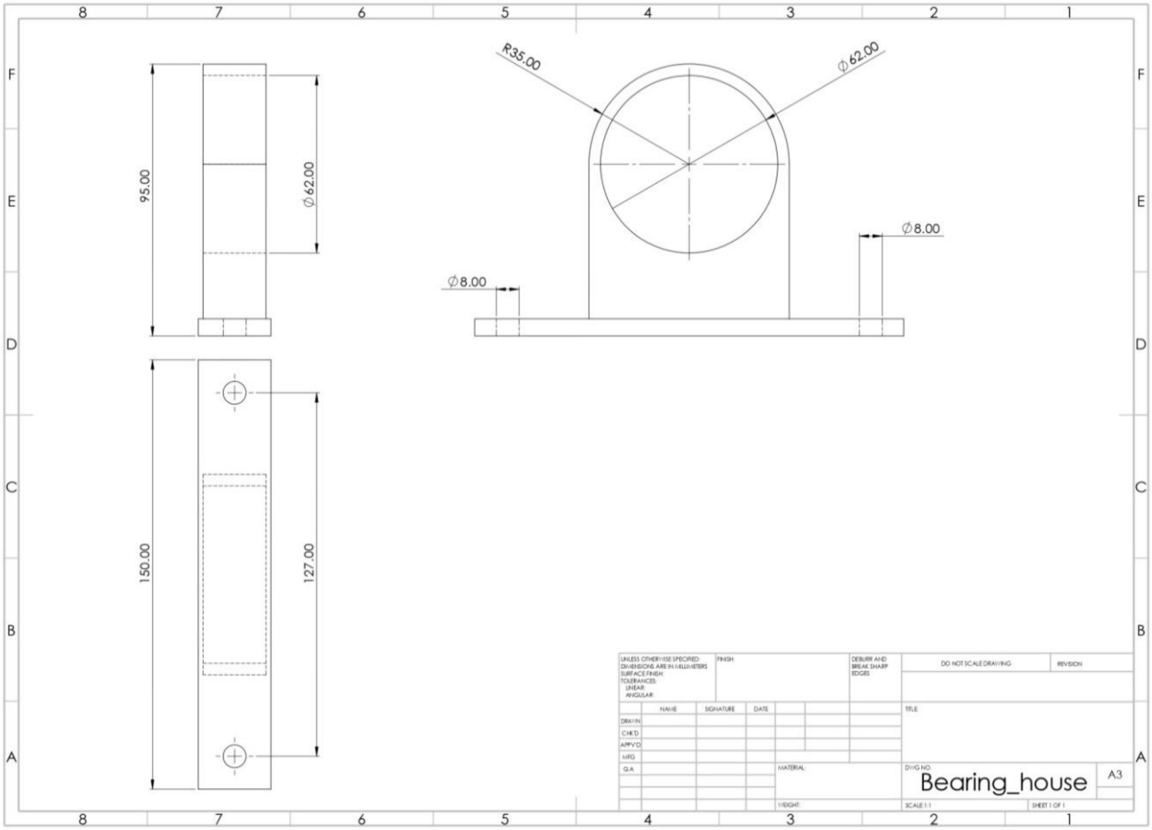


Fig 3.23: Assembly Drawing of the bearing house

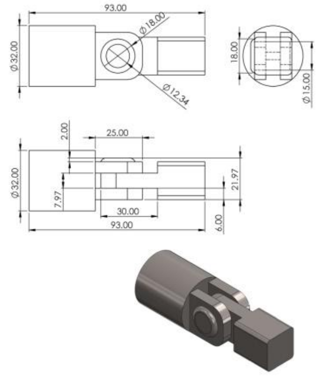
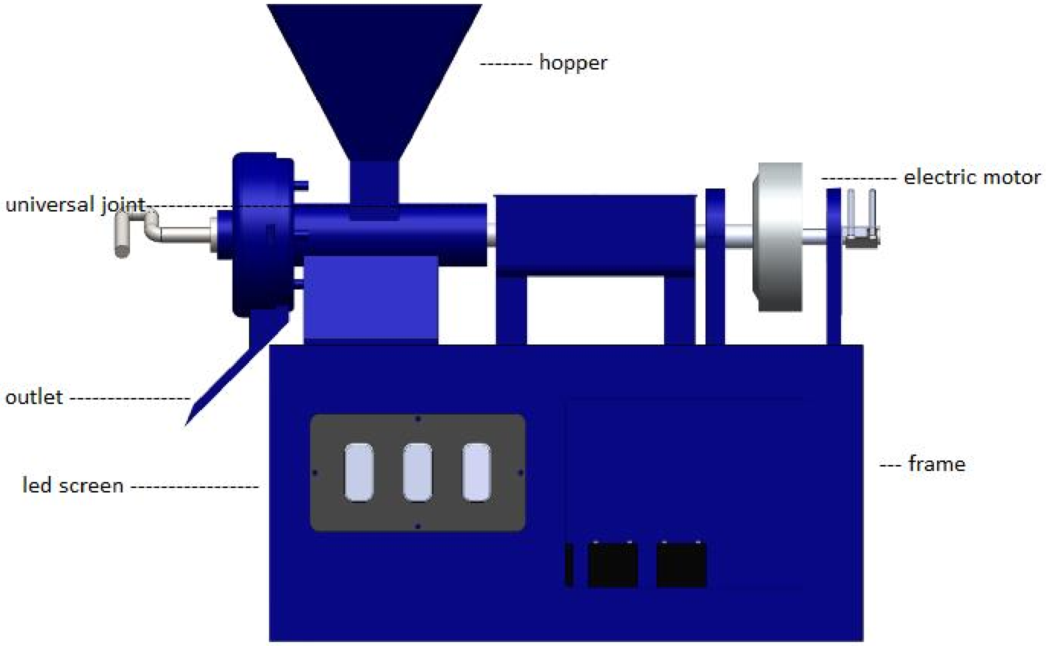


Fig 3.24: Othographic view of the U Joint.



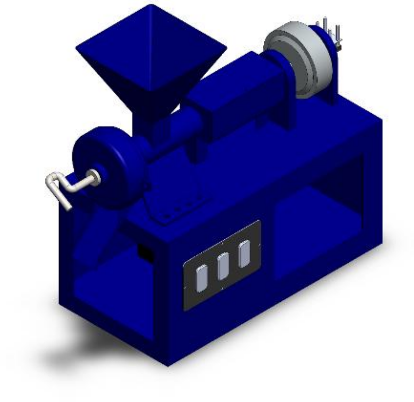


Fig3.25: Isometric drawing of the Grinding Machine

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 RESULTS

The performance of the grinding machine was tested and evaluated under different load conditions. During the testing process, the machine was operated using battery supply only and also using both battery and the solar panel

4.1.1 OPERATION USING BATTERY ONLY

Different quantities of tomatoes ranging from 1kg to 4kg were introduced into the grinder and the time taken for grinding as well as voltage drop were recorded. The purpose of this test was to determine how the grinding load affects the time required for the grinding and the voltage drop of the battery during the operation. The results obtained from the experiment are presented in table 4.1

Table 4.1: Performance of the grinder when operating on battery only

TIME(S)	VOLTAGE DROP(V)	LOAD(kg)
50.0	0.4	1.0
100.0	0.8	2.0
150.0	1.2	3.0
200.0	1.6	4.0

From Table 4.1, it can be observed that the grinding time increases as the load increases. This is expected because larger quantities of tomatoes require more mechanical effort and time to process.

Similarly, the voltage drop increases increases with increasing load. This occurs because the motor draws more current from the battery when higher loads are applied.

GRAPHICAL REPRESENTATION OF RESULTS

The graphs below show a linear relationship between the load and grinding time, and also grinding time and voltage drop. As the load increases from 1kg to 4kg, the time required for grinding increases from 50 seconds to 200 seconds and the longer the time, the more the voltage drop. This indicates that the machine performs consistently under increasing load conditions.

Figure 4.1: Graph of Time against Load (Battery only)

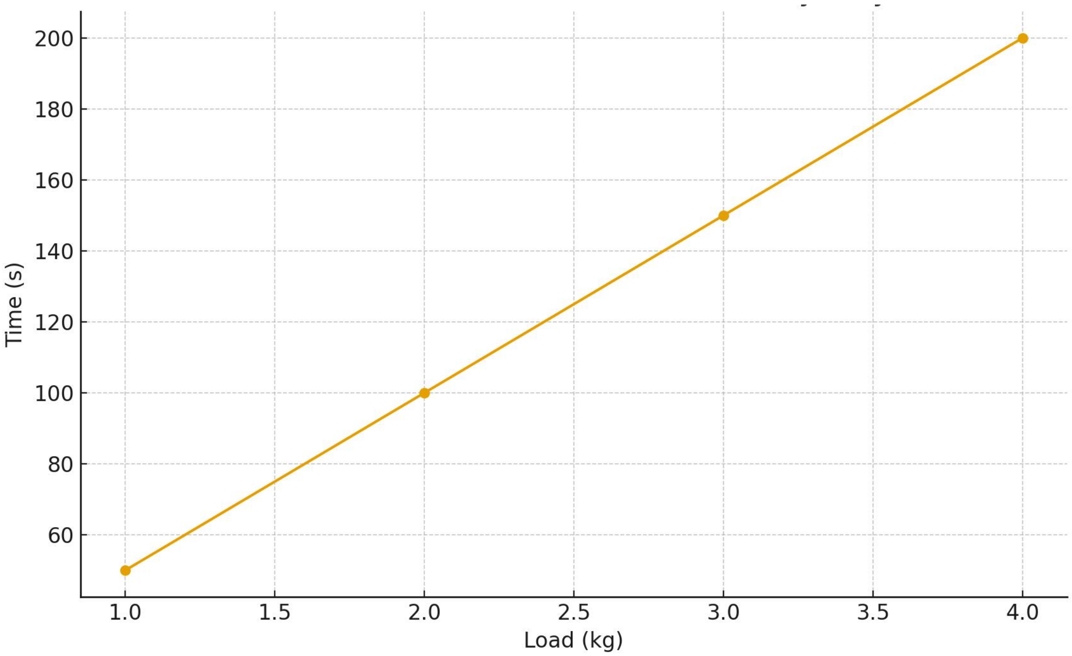
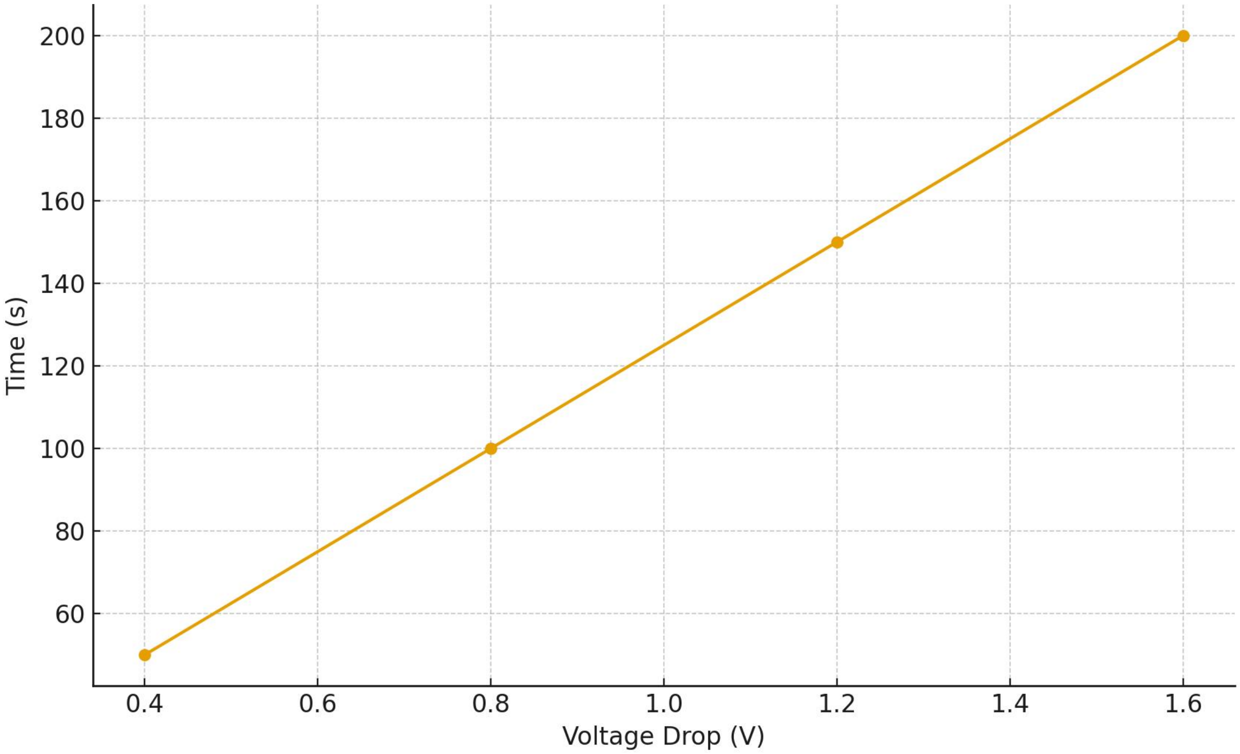


Figure 4.2: Graph of Time against Voltage drop (Battery only)



4.1.2 OPERATION USING BATTERY AND SOLAR PANEL SUPPLY

The machine was also tested using a combination of battery and solar panel supply to observe the voltage behavior during operation. The results obtained from the experiment are presented in table 4.2.

Table 4.2 Performance of the grinder when operating on battery with solar panel supply

TIME(S)	VOLTAGE DROP(V)	LOAD(kg)
50.0	0	1.0
100.0	0	2.0
150.0	0	3.0
200.0	0	4.0

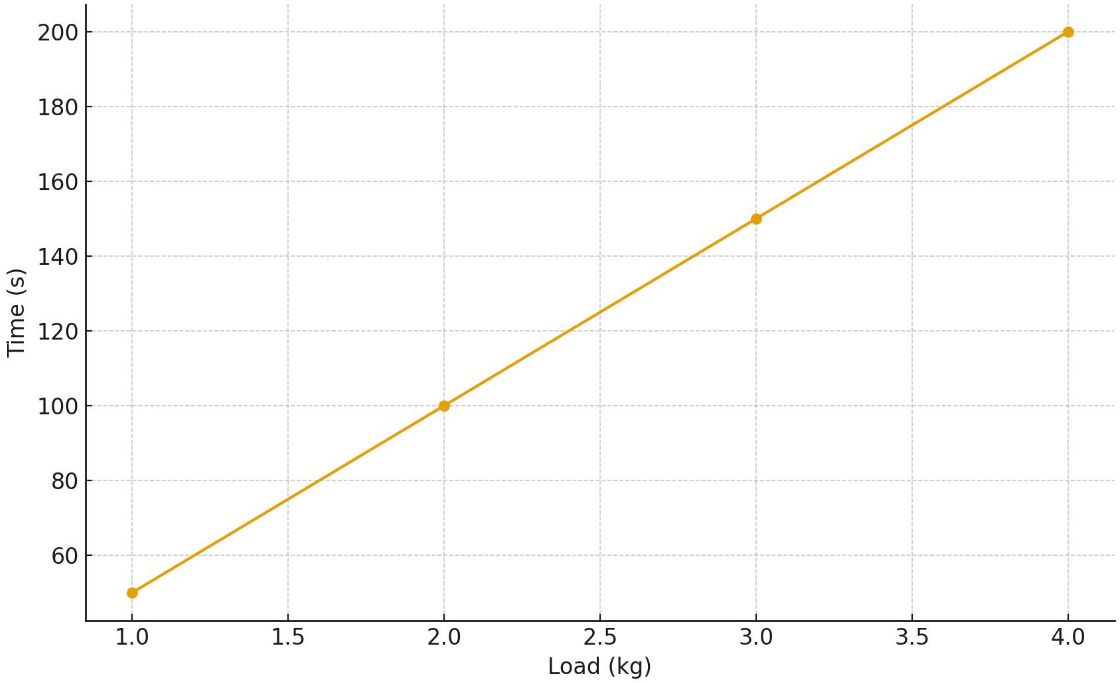
From table 4.2, it can be observed that there was no noticeable voltage drop when the solar panel was connected to the battery during operation. This indicate that the solar panel helped in maintaining a stable voltage supply while the grinding process was taking place.

This result demonstrates that integrating a solar panel into the system improved energy stability and reduces the load on the battery.

GRAPHICAL REPRESENTATION OF RESULTS

The graph below shows a linear relationship between the load and grinding time. From the table it is seen that there was no voltage drop. As the load increases from 1kg to 4kg, the time required for grinding increases from 50 seconds to 200 seconds and this has no effect on the battery voltage as it is maintained by the connected solar panel.

Figure 4.3: Graph of Time against Load (Battery and Solar panel)



4.2 DISCUSSION OF RESULTS

The results obtained from the tests show a clear relationship between the grinding machine's performance, the applied load, and the type of power supply used. When operating solely on battery power, the grinding time increases proportionally with the load. It takes approximately 50 seconds to grind 1 kg of tomatoes as shown in table 4.1, and this time rises steadily to 200 seconds for 4 kg. This linear trend indicates that the machine's performance is consistent and predictable as the load increases, with the longer grinding time attributed to the higher volume of material being processed.

A corresponding increase in voltage drop was also observed with increasing load from 0.4 V at 1 kg to 1.6 V at 4 kg as shown in table 4.1. This suggests that higher mechanical loads demand more electrical energy, leading to greater current draw and subsequent voltage reduction in the battery. This behavior is typical of DC-powered equipment under load variations and reflects the expected relationship between electrical and mechanical performance.

In contrast, when the machine was powered by a combined solar and battery system, the grinding times remained identical, but no voltage drop was recorded across all load conditions as shown in table 4.2. This indicates that the solar panel effectively supplemented the power supply, maintaining a stable voltage throughout operation. Consequently, the hybrid power setup enhances energy efficiency, reduces battery strain, and ensures more stable operation over time.

The linear patterns seen in the time versus load, and time versus voltage graphs (figure 4.1 and 4.2) confirm the system's stable and consistent performance. The absence of voltage drop in the solar-assisted setup further demonstrates the potential of renewable energy integration for small-scale food processing.

Overall, the tomato grinding machine exhibits reliable performance and stable operation across different load conditions. The use of solar-assisted power significantly improves efficiency and sustainability, making the system well-suited for off-grid or rural environments where continuous power supply is essential.

The results obtained from the experimental evaluation indicate that the developed tomato grinding machine operates efficiently within the tested load range. The observed increase in grinding time with increasing load confirms that the machine responds to load variations in a predictable manner, which is consistent with the operational characteristics of most mechanical grinding systems. The gradual increase in voltage drop during battery operation further indicates that the motor requires higher electrical energy as the grinding load increases. However, the integration of the solar panel with the battery system significantly improved the stability of the power supply by minimizing voltage fluctuations during operation. This demonstrates that the hybrid power configuration enhances the overall efficiency and reliability of the machine. Therefore, the developed system is capable of performing effectively in practical applications, particularly in rural and off-grid environments where access to stable electricity supply is limited.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The experimental analysis of the tomato grinding machine demonstrates the critical influence of the power source on system performance and voltage stability. When the grinding operation is powered solely by the battery, a steady voltage drop is observed as the load increases. This occurrence aligns with Ohm's Law ($V = IR$), which explains that an increase in current draw leads to a proportional voltage decrease due to the internal resistance of the battery. As the sole energy source, the battery is unable to sustain a constant voltage under heavy load conditions, resulting in reduced electrical stability during prolonged operation.

In contrast, when the solar panel is integrated into the system, the overall performance becomes more stable and efficient. The solar panel supplements the battery by continuously supplying additional electrical energy, thereby reducing the strain on the battery. This process adheres to the Law of Conservation of Energy, where the total energy provided by both the solar panel and the battery equals the energy consumed by the machine. Consequently, the system maintains a consistent voltage throughout the grinding process, ensuring smooth and uninterrupted operation.

In summary, the hybrid configuration of solar and battery power provides a balanced and sustainable energy supply for the tomato grinding machine. This setup not only enhances operational efficiency and voltage stability but also extends battery lifespan and supports environmentally friendly energy use. Therefore, the solar-assisted grinding system offers a dependable and energy-efficient solution for food processing applications, particularly in remote or off-grid communities where access to stable electricity is limited.

5.2 RECOMMENDATIONS

Based on the fabrication and testing of the solar-powered tomato grinding machine, several improvements have been identified to enhance its overall efficiency, durability, and operational reliability. Implementing these refinements will ensure smoother operation, greater user safety, and longer service life for the machine.

1. Minimizing Vibration in the Grinding System: During testing, excessive vibration was observed, which affected the stability and consistency of the grinding process while contributing to early wear of mechanical components. To address this issue, the machine frame should be reinforced, and vibration-damping materials—such as rubber mounts or shock-absorbing buffers—should be incorporated. These measures will reduce noise, improve balance, and enhance the comfort and safety of operation.

2. Sealing the Grinder Bearings: Water leakage into the grinder bearing area poses a risk of corrosion, frictional wear, and premature failure. Installing high-quality rubber seals is recommended to prevent moisture entry and protect internal components from contaminants. This adjustment will promote smoother operation, reduce maintenance costs, and prolong the lifespan of the machine, especially in humid or outdoor conditions.

3. Optimizing Rotational Speed and Torque: The grinder currently operates at a relatively high speed, resulting in unnecessary noise, increased mechanical stress, and reduced grinding efficiency. Increasing the size of the driven pulley will lower the machine's speed while enhancing torque. This modification will allow more effective grinding of tougher materials, reduce motor strain and noise, and improve the system's energy efficiency.

4. Upgrading the Solar Power System: To achieve consistent and reliable power supply, the capacity of both the solar panels and the battery storage system should be increased. This enhancement will ensure stable operation even under low sunlight conditions and enable longer grinding durations. A larger energy system will improve overall efficiency, reduce dependence on direct sunlight, and support continuous machine productivity.

5. Incorporating Safety and Overload Protection: For enhanced user safety and equipment protection, an automatic shutdown and overload protection circuit should be integrated into the system. This will prevent overheating, electrical damage, and mechanical failure during extended use, ensuring that the machine operates safely and reliably under all load conditions.

In conclusion, implementing these improvements—reinforcing the frame, sealing the bearings, optimizing speed and torque, upgrading the solar power system, and adding safety features—will significantly enhance the performance, efficiency, and sustainability of the solar-powered tomato grinding machine. These modifications will result in a more stable, energy-efficient, and user-friendly machine, ideal for domestic, agricultural, and small-scale industrial applications.

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APPENDIX

Figure 1: Setup view of working prototype

Figure 2: Top view of working prototype

Figure 3: Several views of working solar powered grinding machine prototype