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Research Article

Production of Bio-Briquettes from Agricultural Waste: A Comprehensive Study on Sustainable Energy Solutions

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A R T I C L E I N F O

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A B S T R A C T

The increasing global energy demand and environmental concerns associated with fossil fuels have intensified the search for sustainable and renewable energy sources. Biomass briquetting offers an effective method for converting low-density agricultural residues into compact, energy-rich solid fuels. This study focuses on the production and characterization of bio-briquettes made from agricultural wastes such as rice husk, sugarcane bagasse, cotton stalk, coconut shell, groundnut shell, banana peel, corn cobs, and sawdust.
The biomass materials were dried, pulverized, and mixed with banana peel powder as a natural binder (5–15%). Briquettes were produced using a hydraulic press under pressures of 10–30 MPa and later air-dried for stability. Proximate analysis was conducted to evaluate key fuel properties including moisture content, volatile matter, ash content, fixed carbon, density, and calorific value.
Results showed that the briquettes had an average moisture content of 10%, volatile matter of 72%, ash content of 6%, and fixed carbon of 12%. The calorific value averaged 15.42 MJ/kg, indicating good energy potential for domestic and small-scale industrial applications. These properties demonstrate that agricultural waste briquettes can serve as a viable and sustainable alternative to conventional fuels.
The study highlights the potential of converting agricultural residues into clean and renewable energy sources, contributing to waste management, rural energy security, and reduced environmental pollution.

1. INTRODUCTION

Biomass has long been recognized as one of the most important and accessible sources of renewable energy, providing a substantial portion of the energy needs of rural populations in developing countries and offering significant potential for expanded utilization in modern energy systems. Bio-briquettes, which are solid biofuels produced by compressing biomass residues into dense, compact forms, represent a particularly attractive technology for converting low-value waste materials into high-value energy products suitable for cooking, heating, and small-scale industrial applications (Kelwade et al., 2025). The production and use of bio-briquettes address multiple interconnected challenges facing contemporary society, including the need for sustainable energy sources, the imperative to manage waste streams responsibly, and the goal of reducing greenhouse gas emissions that drive climate change.

Energy has become one of the most fundamental requirements for human civilization, powering everything from domestic cooking and heating to industrial processes and transportation. The demand for energy has increased rapidly in recent decades, driven by population growth, economic development, urbanization, and improving living standards across the developing world (Chen & Usman, 2025).

This rising demand has been met primarily by fossil fuels, including coal, oil, and natural gas, which together account for approximately eighty to ninety percent of global primary energy consumption. However, the continued reliance on fossil fuels is associated with several profound and interconnected problems that threaten the long-term sustainability of human civilization.

The depletion of finite fossil fuel reserves represents an inevitable long-term constraint on energy availability, with production of conventional oil and gas expected to peak and decline in the coming decades even as demand continues to rise. The volatility of fossil fuel prices, driven by geopolitical tensions, market speculation, and supply disruptions, creates economic uncertainty and disproportionately affects developing countries that are net energy importers. The environmental consequences of fossil fuel combustion are even more severe, with the release of carbon dioxide and other greenhouse gases driving global climate change, while emissions of sulfur dioxide, nitrogen oxides, and particulate matter contribute to air pollution and associated public health crises. Global warming, driven by the accumulation of greenhouse gases in the atmosphere, is already causing observable changes in climate patterns, sea level rise, glacier retreat, and increased frequency and intensity of extreme weather events, with projections indicating that these impacts will intensify substantially in the coming decades without rapid and decisive action to reduce emissions.

In this context, the development of alternative fuels that are renewable, inexpensive, environmentally friendly, sustainable, economically competitive, and characterized by lower greenhouse gas emissions has become an urgent global priority (Ibrahim et al., 2020). Renewable energy sources, including solar, wind, hydroelectric, geothermal, and biomass, offer pathways to meet energy needs while dramatically reducing the environmental footprint of energy production and consumption. By 2040, the contribution of renewable energy to global energy supply is projected to increase substantially, driven by technological improvements, falling costs, supportive policies, and growing recognition of the imperative to address climate change (Owusu & Asumadu-Sarkodie, 2016). The adoption of briquetting technology specifically contributes to achieving the seventh Sustainable Development Goal of the United Nations, which calls for ensuring access to affordable, reliable, sustainable, and modern energy for all (Kpalo et al., 2020).

Agricultural residues represent a particularly promising feedstock for bio-briquette production due to their abundance, renewability, and current underutilization. Materials such as rice husk, sugarcane bagasse, groundnut shell, coconut shell, cotton stalk, corn cobs, banana peel, and sawdust are generated in enormous quantities, especially in rural and agricultural regions of developing countries like India. These materials are often treated as waste products with little or no economic value, and are commonly disposed of through open burning, uncontrolled dumping, or simply left to decompose, practices that result in severe environmental pollution, release of greenhouse gases, and loss of potentially valuable energy resources (Widjaya et al., 2022). Converting these residues into bio-briquettes provides an effective solution for waste management while simultaneously producing a clean and renewable source of energy that can displace fossil fuels and reduce net carbon emissions (Sanchez, 2022).

The production of high-quality bio-briquettes depends on a range of factors that must be carefully controlled and optimized. The moisture content of the feedstock affects both the briquetting process and the combustion characteristics of the final product, with optimal levels typically falling between eight and twelve percent. Particle size influences the density and strength of briquettes, with smaller and more uniform particles generally producing stronger and more durable products. The type and proportion of binder material affects the mechanical integrity of briquettes, with natural binders such as starch-rich biomass and lignin-containing materials often providing adequate binding without the need for synthetic additives (Idris et al., 2021). Compaction pressure determines the density and energy content of briquettes, with higher pressures generally producing denser and more energy-rich products, though the relationship is not linear and optimal pressures depend on the specific feedstock characteristics (Kaliyan & Morey, 2009). The composition of the feedstock, including the relative proportions of cellulose, hemicellulose, lignin, and other components, influences both the briquetting behavior and the combustion characteristics of the final product (Marreiro et al., 2021).

The quality and performance of bio-briquettes are evaluated through a range of analytical methods that characterize their physical, chemical, and combustion properties. Proximate analysis, which determines moisture content, volatile matter, ash content, and fixed carbon, provides essential information about the combustion behavior and energy content of the fuel. Calorific value, measured directly or calculated from proximate analysis, quantifies the energy released during complete combustion and serves as a primary metric for comparing different fuels. Density affects handling, storage, and transportation efficiency, as well as the volumetric energy density of the fuel. Mechanical durability determines the ability of briquettes to withstand handling and transportation without breaking or producing dust.

India presents a particularly compelling case for the promotion of bio-briquette technology. With approximately sixty-seven percent of the population relying on traditional biomass fuels for their cooking and heating needs, the potential market for improved biomass fuels is enormous (Jadhav et al., 2016). The country generates vast quantities of agricultural residues, much of which is currently underutilized or disposed of in environmentally harmful ways. The development of a bio-briquette industry could create rural employment opportunities in waste collection, processing, and briquette production and marketing, while simultaneously improving energy access for rural populations and reducing the environmental footprint of both waste management and energy consumption.

Several studies have demonstrated the feasibility and benefits of producing briquettes from various agricultural residues. Oladeji (2010) reported that briquettes produced from corncob and rice husk residues exhibited favorable fuel properties, including high calorific value and low ash content. Oyebamiji and colleagues (2025) evaluated biochar and briquettes from agricultural wastes and confirmed their suitability for sustainable energy production. Arachchige (2021) discussed the potential of briquette production as an alternative fuel source, highlighting the role of lignin in facilitating natural binding during compaction. Nikiforov and colleagues (2023) analyzed the characteristics of bio-coal briquettes produced from agricultural and coal industry waste, demonstrating the potential for co-utilization of different feedstocks.

Coconut shell and groundnut shell-based briquettes have been shown to possess particularly high fixed carbon and calorific value, making them suitable for both domestic and industrial energy applications. The high lignin content of these materials contributes to their excellent binding properties and combustion characteristics. Sawdust, another common feedstock, provides good binding due to its lignin content and produces briquettes with consistent quality and high energy density. Banana peel, often overlooked as a feedstock, contains both starch and lignin that can contribute to binding while also adding to the energy content of the final product (Emaga et al., 2007).

The present study was undertaken to contribute to the growing body of knowledge on bio-briquette production by systematically evaluating the feasibility of producing briquettes from a diverse range of locally available agricultural residues in the Namakkal region of Tamil Nadu, India. The specific objectives were to collect and characterize eight different agricultural residues, to develop a reproducible methodology for briquette production incorporating natural binders, to evaluate the physical and fuel properties of the produced briquettes through proximate analysis, and to compare the characteristics of the bio-briquettes with conventional fuels including fuel wood and coal briquettes. By demonstrating the viability of producing high-quality briquettes from locally available waste materials, this study aims to support the development of sustainable energy solutions that can contribute to rural development, environmental protection, and climate change mitigation.

2. MATERIALS AND METHODS

2.1 Collection of Raw Materials

The success of any biomass conversion process depends fundamentally on the availability and quality of the feedstock materials. For this study, eight different types of agricultural residues were collected from diverse sources across the Namakkal and Tiruchirapalli districts of Tamil Nadu, India. These materials were selected based on their local abundance, current underutilization or problematic disposal, and their potential suitability for briquette production based on previous research and preliminary testing.

Rice husk, one of the most abundant agricultural residues in rice-producing regions, was collected from the Dr. M. S. Swaminathan Field Laboratory at Paavai Engineering College. This material is generated in large quantities during rice milling operations and is often considered a waste product, though it has some limited uses as animal bedding or fuel in industrial boilers. The husk consists primarily of silica and lignin, giving it good combustion properties but also creating challenges for disposal and utilization.

Sawdust was collected from sawmills located in the vicinity of Pachal Village in Namakkal District. This fine, powdery material is generated during wood processing operations and is often accumulated in large piles that can pose fire hazards and environmental concerns. Sawdust has excellent binding properties due to its lignin content and produces briquettes with high density and good combustion characteristics.

Coconut shell was collected from domestic sources in Pachal Village, where it is typically discarded as waste after the coconut meat has been removed. Coconut shell is a hard, dense material with high lignin content and excellent fuel properties, including high calorific value and low ash content. However, its hardness also makes it more difficult to process than softer biomass materials.

Cotton stalk was obtained from farmers in Puthuchathiram Village, Namakkal District. This material is generated in large quantities after cotton harvesting and is often burned in the fields, contributing to air pollution and loss of potentially valuable biomass. Cotton stalk has a fibrous structure that can contribute to briquette strength and good combustion properties.

Groundnut shell was collected from a processing mill in Kattuputhur Town, Tiruchirapalli District. This material is generated in large quantities during groundnut decortication and is often treated as waste, though it has some limited uses as fuel or animal feed. Groundnut shell has good combustion properties and contributes to briquette strength.

Sugarcane bagasse, the fibrous residue remaining after sugarcane crushing, was obtained from the Salem Co-operative Sugar Mill located on the Velur-Mohanur Road in Namakkal District. This material is generated in enormous quantities during the sugarcane crushing season and is often used as fuel in the sugar mill boilers, though there is often surplus material available for alternative uses. Bagasse has excellent fibrous structure that contributes to briquette strength and good combustion properties.

Banana peel was collected from farmers in Puthuchathiram Village, Namakkal District. This material is typically discarded as waste and can create odor and pest problems if not managed properly. Banana peel contains starch and other carbohydrates that can serve as natural binders in briquette production, in addition to contributing to the energy content of the final product.

Corn cobs were collected from the Namakkal Farmer Producers Union near Paavai Engineering College. This material is generated in large quantities during corn processing and is often treated as waste, though it has some limited uses as animal bedding or fuel. Corn cobs have a porous structure that can affect briquetting behavior but contribute to good combustion properties.

2.2 Drying of Raw Materials

The moisture content of biomass materials is a critical parameter affecting both the briquetting process and the quality of the final product. Excessively high moisture content can interfere with particle bonding during compaction, lead to the growth of mold and fungi during storage, and reduce the calorific value of the fuel by replacing combustible material with water that must be evaporated during combustion. Conversely, excessively low moisture content can make particles too dry to bond effectively, resulting in weak and friable briquettes.

The collected biomass materials were initially spread in thin layers on clean, dry surfaces and exposed to direct sunlight for several days. This sun drying process takes advantage of solar radiation to evaporate moisture from the materials, reducing their water content substantially without the expenditure of energy for heating. The duration of sun drying varied depending on the initial moisture content of the materials and the ambient weather conditions, but generally continued until the materials felt dry to the touch and showed no visible signs of moisture.

Following sun drying, the materials were subjected to further drying in a hot air oven maintained at a temperature of one hundred degrees Celsius for a period of one hour. This oven drying step was designed to remove any remaining moisture and to ensure that all materials achieved the uniformly low moisture content required for optimal briquetting. The use of elevated temperature accelerates the drying process and ensures that even the most moisture-retentive materials are thoroughly dried. After oven drying, the materials were removed from the oven and allowed to cool to room temperature in a desiccator to prevent reabsorption of moisture from the air. The dried biomass materials were then stored in airtight containers to maintain their low moisture content until further processing.

2.3 Size Reduction

The particle size of biomass materials has a profound influence on the briquetting process and the properties of the final briquettes. Smaller and more uniform particles generally produce stronger and more durable briquettes because they pack more efficiently and present more surface area for particle-particle bonding during compaction. Larger particles can create weak points within the briquette structure and may lead to uneven combustion.

The dried biomass materials were subjected to size reduction using a pulverizer, a machine that uses high-speed rotating blades to grind materials into fine particles. The materials were fed into the pulverizer hopper and passed through the grinding chamber, where they were impacted repeatedly by the rotating blades until they were reduced to the desired size. The pulverized material was then passed through a sieve with a mesh size of zero point five zero millimeters to separate particles that met the size specification from those that required further grinding. The sieving process ensures that all particles used for briquette production fall within a narrow size range, promoting consistent compaction and uniform briquette properties. The sieved biomass powder was collected and stored in airtight containers until the mixing and briquetting stages.

2.4 Mixing and Binder Addition

The production of strong, durable briquettes often requires the addition of binding materials that promote adhesion between biomass particles and increase the mechanical integrity of the final product. While some biomass materials contain sufficient natural binders, particularly lignin, to form adequate bonds under high pressure, the addition of supplementary binders can improve briquette quality and consistency, especially when using mixtures of different feedstocks.

For this study, banana peel powder was used as a natural binder. Banana peels, which are typically discarded as waste, contain significant amounts of starch and other carbohydrates that can gelatinize when mixed with water and form strong bonds between particles upon drying. The use of banana peel as a binder represents an additional waste utilization opportunity, converting a second waste stream into a valuable input for briquette production.

The dried banana peels were pulverized to a fine powder using the same pulverizer used for the other biomass materials. The banana peel powder was then mixed with water at a proportion of ten to twenty percent of the binder weight to form a uniform, workable paste. This paste was added to the pulverized biomass, with sawdust serving as the primary biomass component, at proportions ranging from five to fifteen percent by weight of the total mixture. The mixture was thoroughly blended to ensure uniform distribution of the binder throughout the biomass, which is essential for producing consistent briquettes with uniform properties.

The binding mechanism in this system relies on multiple factors. The lignin present naturally in the sawdust and other biomass materials softens under the heat and pressure of compaction and acts as a thermosetting binder that bonds particles together upon cooling. The starch from the banana peel powder gelatinizes when mixed with water and forms adhesive bonds between particles that strengthen upon drying. The combination of these natural binding mechanisms produces briquettes with good mechanical strength without the need for synthetic, non-renewable binders.

2.5 Compaction

Compaction is the core step in briquette production, during which the loose biomass mixture is transformed into dense, coherent fuel units through the application of high pressure. The pressure applied during compaction forces particles into close contact, promotes inter-particle bonding, and reduces the volume of the material, increasing its density and energy content per unit volume.

The prepared biomass mixture, with moisture content maintained below ten percent, was filled into cylindrical molds of a briquetting machine. The molds determine the size and shape of the final briquettes, with cylindrical shapes being the most common due to their ease of production and handling. The filled molds were placed in a hydraulic press capable of applying controlled, high pressures to the material.

Compaction was performed at pressures ranging from ten to thirty megapascals, depending on the specific characteristics of the mixture being processed. Higher pressures generally produce denser and stronger briquettes but also require more robust equipment and consume more energy. The pressure was applied gradually and maintained for a sufficient duration to allow for particle rearrangement and bond formation. After the compaction cycle was complete, the compressed briquettes were ejected from the molds and transferred to drying racks for subsequent processing.

2.6 Drying and Cooling

The freshly produced briquettes contain residual moisture from the binder addition and may also have absorbed some moisture from the air during processing. This moisture must be removed to achieve final strength and stability, as excessive moisture can lead to mold growth, reduced strength, and poor combustion performance.

The briquettes were initially placed on drying racks under ambient conditions with adequate ventilation. This natural air drying allows for gradual moisture removal, which helps prevent the development of cracks and surface defects that can occur with too-rapid drying. The drying racks were positioned in a clean, dry area protected from direct sunlight, which could cause uneven drying and surface checking.

The drying process continued until the briquettes reached constant weight, indicating that they had achieved equilibrium moisture content with the ambient air. The duration of drying varied depending on ambient temperature, humidity, and air movement, but typically ranged from several days to a week. After drying was complete, the briquettes were allowed to cool naturally to room temperature before being handled or tested.

2.7 Proximate Analysis

The quality and performance characteristics of the produced briquettes were evaluated through proximate analysis, a set of standardized tests that determine the key fuel properties of solid materials. Proximate analysis provides information on moisture content, volatile matter, ash content, and fixed carbon, which together characterize the combustion behavior and energy potential of the fuel. All proximate analysis tests were conducted following the relevant ASTM standards to ensure accuracy and reproducibility of results.

2.7.1 Moisture Content Determination

Moisture content is a critical parameter that affects both the storage stability and combustion characteristics of solid fuels. High moisture content reduces the calorific value of the fuel by diluting combustible material with water that must be evaporated during combustion, consuming energy that would otherwise be available for useful heating. Excessively dry fuels, on the other hand, may produce more dust and can be prone to spontaneous combustion during storage.

The moisture content of the briquettes was determined by oven drying method following ASTM D-3174. Clean, dry crucibles were weighed and recorded, and representative samples of the briquettes were placed in the crucibles and weighed to obtain the initial weight. The crucibles with samples were placed in an electric hot air oven maintained at one hundred five degrees Celsius, plus or minus five degrees, and dried for a minimum of one hour. After drying, the crucibles were removed from the oven, cooled in a desiccator to prevent moisture reabsorption, and weighed again. The drying, cooling, and weighing process was repeated until a constant weight was achieved, indicating that all moisture had been removed. The moisture content was calculated using the following formula:

Moisture Content Percentage = [(Weight of sample before drying - Weight of sample after drying) / (Weight of sample before drying)] × 100

2.7.2 Volatile Matter Determination

Volatile matter consists of the gaseous components released when a fuel is heated in the absence of air. High volatile matter content promotes easy ignition and rapid flame formation, making fuels suitable for applications where quick heat release is desired. However, very high volatile matter can also lead to smoky combustion if adequate air supply is not maintained.

Volatile matter was determined following ASTM D-3175. The dried samples obtained from the moisture content determination were placed in covered crucibles and heated in a muffle furnace at nine hundred twenty-five degrees Celsius, plus or minus twenty degrees, for exactly seven minutes. The covered crucible prevents air from entering and allows the volatile matter to escape without combustion. After heating, the crucibles were removed, cooled in a desiccator, and weighed. The loss in weight during this process represents the volatile matter released. The volatile matter percentage was calculated using the following formula:

Volatile Matter Percentage = [(Loss in weight due to volatile matter removal) / (Weight of sample taken)] × 100

2.7.3 Ash Content Determination

Ash content represents the non-combustible mineral residue remaining after complete combustion of the fuel. High ash content reduces the calorific value of the fuel and can create operational problems such as slag formation, fouling of heat exchange surfaces, and increased maintenance requirements for combustion equipment.

Ash content was determined following ASTM D-3174. The residual samples obtained after volatile matter determination were placed in open crucibles and heated gradually in a muffle furnace to a temperature of seven hundred degrees Celsius, plus or minus fifty degrees, and maintained at this temperature for half an hour. The gradual heating prevents mechanical loss of ash due to too-rapid combustion. After heating, the crucibles were removed, cooled first in air and then in a desiccator, and weighed. The heating, cooling, and weighing process was repeated until constant weight was achieved, indicating complete combustion of all combustible material. The weight of the residue was reported as the ash content. The ash content percentage was calculated using the following formula:

Ash Content Percentage = [(Weight of ash left) / (Weight of sample taken)] × 100

2.7.4 Fixed Carbon Determination

Fixed carbon represents the solid combustible residue remaining after volatile matter has been driven off, excluding ash. It is the fraction of the fuel that burns in the solid state and is responsible for the sustained, glowing combustion that follows the initial flaming stage. Higher fixed carbon content generally indicates longer burn duration and more stable combustion.

Fixed carbon is not measured directly but is calculated by difference, subtracting the sum of moisture content, volatile matter, and ash content from one hundred percent. The calculation assumes that these three components, together with fixed carbon, account for all of the material in the fuel sample. The fixed carbon percentage was calculated using the following formula:

Fixed Carbon Percentage = 100 - (Moisture Content Percentage + Volatile Matter Percentage + Ash Content Percentage)

2.7.5 Calorific Value Determination

Calorific value, also known as heating value, is the most fundamental property for evaluating the energy potential of a fuel. It represents the total amount of heat released during the complete combustion of a unit mass of fuel and provides a direct measure of the fuel's energy content. Calorific value is essential for comparing different fuels and for designing combustion systems to match specific energy requirements.

While direct measurement using a bomb calorimeter provides the most accurate determination of calorific value, it can also be estimated with reasonable accuracy from proximate analysis data using established empirical correlations. For this study, the calorific value was calculated using the formula developed by

Parikh and colleagues, which relates calorific value to fixed carbon, volatile matter, and ash content:
Calorific Value (MJ/kg) = 0.3536(Fixed Carbon Percentage) + 0.1559(Volatile Matter Percentage) - 0.0078(Ash Content Percentage)
This formula was developed specifically for biomass materials and has been validated against direct measurements for a wide range of feedstocks. The results were converted from megajoules per kilogram to kilocalories per kilogram using the conversion factor of one megajoule per kilogram equals two hundred thirty-eight point eight four six kilocalories per kilogram, providing values in units commonly used in the Indian context.

3. RESULTS AND DISCUSSION

3.1 Moisture Content of Produced Briquettes

The moisture content of the bio-briquettes produced in this study was determined through triplicate measurements on representative samples, with the results presented in Table 1. The individual measurements showed moisture contents of nine, ten, and eleven percent respectively, yielding an average value of ten percent. This average moisture content falls squarely within the optimal range of eight to twelve percent that is generally considered desirable for commercial biomass briquettes.

Table 1. Moisture Content of Produced Briquettes

Sample Number	Weight Before Oven Drying (g)	Weight After Oven Drying (g)	Moisture Percentage (%)
1	100	91	9
2	120	108	10
3	150	133.5	11
Average			**10**

The moisture content of a solid fuel has profound implications for its handling, storage, and combustion characteristics. Fuels with excessively high moisture content are prone to biological degradation during storage, with mold and fungal growth potentially compromising the structural integrity of the briquettes and reducing their energy content. During combustion, moisture must be evaporated before the fuel can ignite and burn, consuming energy that would otherwise contribute to useful heat output and reducing the effective calorific value of the fuel. For every percentage point of moisture above the optimal range, the available heat from combustion is reduced proportionally.
Conversely, fuels with excessively low moisture content can be problematic for different reasons. Very dry fuels may produce excessive dust during handling, creating health and safety hazards and contributing to material losses. They may also be prone to spontaneous combustion during storage if not properly managed, particularly when stored in large piles where heat can accumulate. The moderate moisture content of ten percent achieved in these briquettes represents an excellent balance between these competing considerations, providing good storage stability, acceptable ignition characteristics, and minimal energy penalty during combustion.
The consistency of moisture content across the three samples, with a range of only two percentage points, demonstrates the effectiveness of the drying protocols employed in this study. The combination of sun drying and oven drying, followed by storage in airtight containers, successfully produced a uniform feedstock with the low and consistent moisture content required for optimal briquetting. This consistency is essential for producing briquettes with uniform properties and predictable combustion behavior.

3.2 Volatile Matter Content

The volatile matter content of the briquettes, determined by heating samples in covered crucibles to drive off gaseous components, showed remarkably high values as presented in Table 2. The individual measurements yielded volatile matter contents of seventy, seventy-two, and seventy-four percent respectively, with an average of seventy-two percent.

Table 2. Volatile Matter Content of Produced Briquettes

Sample Number	Weight of Sample Taken (g)	Loss in Weight (g)	Volatile Matter Percentage (%)
1	100	70	70
2	120	86.4	72
3	150	111	74
Average			**72**

The exceptionally high volatile matter content of these briquettes, averaging seventy-two percent, is one of their most distinctive characteristics and has profound implications for their combustion behavior. Volatile matter consists of the gases and vapors released when the fuel is heated, including hydrocarbons, carbon monoxide, hydrogen, and various organic compounds. These gases ignite readily when mixed with air, producing the characteristic flame associated with burning biomass.
High volatile matter content confers several advantages for domestic cooking and heating applications. Fuels with high volatile matter ignite easily, requiring less energy input to start the combustion process. They produce vigorous, luminous flames that provide intense radiant heat, which is desirable for many cooking tasks. The flames also provide visual feedback to the user about the state of combustion, allowing intuitive adjustment of air supply and fuel feeding.
However, high volatile matter content also presents certain challenges that must be managed through appropriate combustion system design. Fuels with very high volatile matter can produce smoke and incomplete combustion products if adequate air is not supplied to the flame zone. The rapid release of volatile gases can also lead to flame instability if the combustion system is not designed to handle the high gas evolution rates. For the domestic cooking applications for which these briquettes are primarily intended, these challenges are manageable through proper stove design and user practices.
The volatile matter content of these briquettes is substantially higher than that of typical coal briquettes, which generally range from thirty to forty-five percent volatile matter, and dramatically higher than that of charcoal, which has very low volatile matter due to the carbonization process. This characteristic positions the briquettes as a complementary fuel to coal and charcoal, offering rapid ignition and intense flame where these properties are desired, while other fuels may be preferred for applications requiring long, steady burns without frequent refueling.

3.3 Ash Content

The ash content of the briquettes, representing the non-combustible mineral residue remaining after complete combustion, was determined through muffle furnace combustion and is presented in Table 3. The individual measurements showed ash contents of five, six, and seven percent respectively, with an average of six percent.

Table 3. Ash Content of Produced Briquettes

Sample Number	Weight of Sample Taken (g)	Weight of Ash Left (g)	Ash Content Percentage (%)
1	100	5	5
2	120	7.2	6
3	150	10.5	7
Average			**6**

Ash content is an important parameter affecting both the combustion performance and the operational convenience of solid fuels. High ash content reduces the calorific value of the fuel because the ash represents material that does not contribute to heat release. Ash also accumulates in the combustion chamber during burning, requiring periodic removal and potentially interfering with air flow and heat transfer if allowed to build up excessively. Certain types of ash can also cause operational problems such as slagging and fouling, where ash melts and forms hard deposits on grates and heat exchange surfaces.

The average ash content of six percent for these briquettes is moderate and compares favorably with many other solid fuels. Fuel wood typically contains around five percent ash, while the coal briquettes used for comparison in this study showed ash contents of six point one eight and seven point two one percent for sixty and eighty mesh sizes respectively. The slightly higher ash content in the eighty mesh coal briquettes likely results from the concentration of mineral matter during fine grinding.

For domestic cooking applications, an ash content of six percent is quite manageable. The amount of ash produced during a typical cooking session is modest and can be easily removed between uses. The ash itself can be beneficially used as a soil amendment in agriculture, returning minerals to the soil and closing nutrient cycles. The moderate ash content also indicates that the briquettes will not produce excessive amounts of particulate emissions during combustion, contributing to their environmental profile.

The variation in ash content across the three samples, from five to seven percent, reflects the natural variability in the composition of agricultural residues and the difficulty of achieving perfectly homogeneous mixtures with diverse feedstocks. Despite this variation, all samples fall within an acceptable range, and the average value provides a reliable basis for characterizing the fuel.

3.4 Fixed Carbon Content

The fixed carbon content of the briquettes, calculated by difference from the moisture, volatile matter, and ash contents, is presented in Table 4. The individual samples showed fixed carbon values of sixteen, twelve, and eight percent respectively, yielding an average of twelve percent.

Table 4. Fixed Carbon Content of Produced Briquettes

Sample Number	Moisture Content (%)	Volatile Matter (%)	Ash Content (%)	Fixed Carbon (%)
1	9	70	5	16
2	10	72	6	12
3	11	74	7	8
Average				**12**

Fixed carbon represents the solid combustible residue that remains after volatile matter has been driven off, and it is the fraction of the fuel that burns in the solid state through heterogeneous combustion with oxygen from the air. The fixed carbon content has a major influence on the burning characteristics of the fuel, particularly the duration of combustion and the stability of the burning bed.

The relatively low fixed carbon content of these briquettes, averaging twelve percent, reflects their high volatile matter content and is characteristic of biomass fuels that have not been subjected to carbonization processes. This low fixed carbon means that the briquettes will burn primarily through flaming combustion of volatile gases, with a relatively short period of char combustion after the flames subside. This burning pattern is well-suited to domestic cooking applications, where rapid heat release during the flaming phase is desired for tasks such as boiling and frying, and the shorter char burn-out time is acceptable given that meals are typically prepared in discrete cooking sessions rather than requiring continuous heat over many hours.

The variation in fixed carbon across the three samples, ranging from eight to sixteen percent, is more pronounced than the variation in other parameters and reflects the compounding effects of variations in the other components. Samples with higher moisture, volatile matter, and ash content necessarily have lower fixed carbon by the subtractive calculation method. Despite this variation, all samples maintain fixed carbon values within the range typical for uncompressed biomass materials.

3.5 Calorific Value

The calorific value of the briquettes, representing their energy content and calculated from the proximate analysis data using the Parikh formula, is presented in Table 5. The individual samples showed calorific values of sixteen point five three, fifteen point four two, and fourteen point three two megajoules per kilogram, equivalent to three thousand nine hundred fifty, three thousand six hundred eighty-five, and three thousand four hundred twenty-two kilocalories per kilogram respectively. The average calorific value was fifteen point four two megajoules per kilogram, or three thousand six hundred eighty-six kilocalories per kilogram.

Table 5. Calorific Value of Produced Briquettes

Sample Number	Fixed Carbon (%)	Volatile Matter (%)	Ash Content (%)	Calorific Value (MJ/kg)	Calorific Value (kcal/kg)
1	16	70	5	16.53	3950
2	12	72	6	15.42	3685
3	8	74	7	14.32	3422
Average				**15.42**	**3686**

The calorific value is the single most important parameter for evaluating the energy potential of a fuel, as it directly quantifies the amount of heat that can be released during combustion. The average calorific value of fifteen point four two megajoules per kilogram obtained for these briquettes falls well within the typical range for biomass briquettes, which generally ranges from fourteen to twenty megajoules per kilogram depending on the feedstock composition and processing conditions.

The variation in calorific value across the three samples, from fourteen point three two to sixteen point five three megajoules per kilogram, correlates with the variation in fixed carbon and ash content, with higher fixed carbon and lower ash content producing higher calorific values. Sample one, with the highest fixed carbon and lowest ash, achieved the highest calorific value, while sample three, with the lowest fixed carbon and highest ash, showed the lowest calorific value. This relationship is expected, as fixed carbon represents the primary energy-containing component of the solid fuel, while ash contributes no energy and dilutes the combustible material. For practical applications, a calorific value of fifteen point four two megajoules per kilogram means that one kilogram of these briquettes, when completely combusted, releases approximately fifteen point four two megajoules of heat energy. This is sufficient to bring about thirty-seven liters of water from room temperature to boiling, or to maintain a moderate cooking fire for one to two hours depending on stove efficiency and cooking practices. The energy density of the briquettes, combined with their favorable combustion characteristics, makes them suitable for a wide range of domestic and small-scale industrial heating applications.

3.6 Comparative Analysis with Conventional Fuels

To place the properties of the produced bio-briquettes in context and to assess their potential as alternatives to conventional fuels, a comparative analysis was conducted with fuel wood and with coal briquettes of sixty and eighty mesh sizes. The comparative data are presented in Table 6 and illustrated graphically in Figure 1.

Table 6. Comparative Analysis of Various Bio-Fuels

Proximate Analysis	Fuel Wood	Produced Briquette	60 Mesh Coal Briquette	80 Mesh Coal Briquette
Moisture Content (%)	7	10	9.16	8.66
Ash Content (%)	5	6	6.18	7.21
Volatile Matter (%)	15	72	37.04	43.86
Fixed Carbon (%)	85	12	47.62	20.78

Figure 5. Comparative Analysis of Various Briquettes

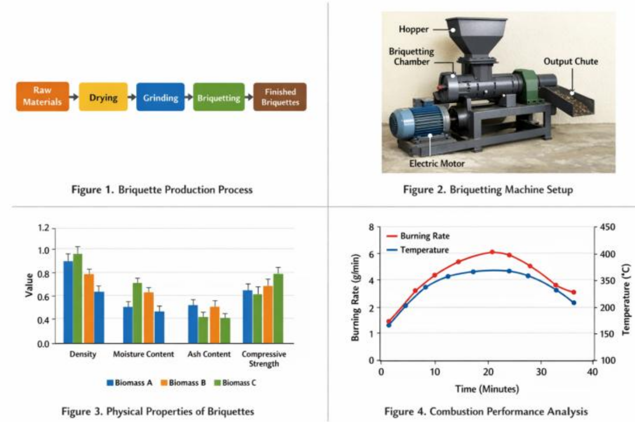

Figure 1. Briquette Production Process
Figure 2. Briquetting Machine Setup
Figure 3. Physical Properties of Briquettes
Figure 4. Combustion Performance Analysis

The comparison with fuel wood reveals several interesting patterns. Fuel wood typically contains lower moisture than the produced briquettes, which would contribute to easier ignition and higher flame temperatures. The ash content of fuel wood is slightly lower, meaning slightly less residue to manage during combustion. However, the most dramatic difference is in volatile matter and fixed carbon. Fuel wood, having been subjected to natural drying but no other processing, retains the characteristic biomass composition with moderate volatile matter and high fixed carbon. The produced briquettes, by contrast, show dramatically higher volatile matter and correspondingly lower fixed carbon, a difference that reflects both the specific composition of the feedstocks used and the effects of the briquetting process on the material properties.

The comparison with coal briquettes is particularly instructive, as coal represents the dominant solid fuel for many industrial and domestic applications. The sixty and eighty mesh coal briquettes, which differ in the fineness of grinding before compaction, show moisture contents slightly lower than the produced briquettes, ash contents comparable or slightly higher, volatile matter substantially lower, and fixed carbon substantially higher. These differences reflect the fundamentally different origins of coal and biomass, with coal representing ancient biomass that has been subjected to geological processes that have driven off volatile matter and concentrated fixed carbon over millions of years.

The higher volatile matter of the biomass briquettes means they will ignite more easily and produce more vigorous flames than coal, which can be advantageous for applications requiring rapid heat release. However, the lower fixed carbon means they will not sustain combustion for as long as coal on a mass basis, requiring more frequent refueling for applications requiring continuous, long-duration heat. The choice between biomass briquettes and coal for any particular application will depend on the specific requirements of that application, the availability and cost of the fuels, and the environmental considerations that increasingly favor renewable, carbon-neutral energy sources.

The eighty mesh coal briquette shows higher volatile matter and lower fixed carbon than the sixty mesh version, indicating that finer grinding may promote more complete devolatilization during the coking process or may allow better integration of the volatile-rich and fixed carbon-rich components of the coal. This difference highlights the importance of particle size in determining the properties of densified fuels, a factor that was carefully controlled in the production of the biomass briquettes through sieving to uniform particle size.

3.7 Interpretation and Implications

The results of this study demonstrate conclusively that agricultural residues, which are often considered waste materials with little or no value, can be transformed through appropriate processing into high-quality solid fuels with properties suitable for domestic cooking and small-scale industrial heating applications. The combination of high volatile matter, moderate ash, acceptable moisture, and satisfactory calorific value positions these briquettes as a viable alternative to conventional fuels in many contexts.

The exceptionally high volatile matter content of the briquettes, averaging seventy-two percent, is perhaps their most distinctive feature. This property gives the briquettes excellent ignition characteristics and produces the vigorous, luminous flames that users associate with good cooking fires. For domestic cooking applications, where rapid heat release and visual feedback on combustion intensity are valued, this characteristic is highly advantageous. The flames provide radiant heat that efficiently transfers energy to cooking vessels, and the visible flame allows users to gauge the intensity of the fire and adjust air supply or fuel feeding accordingly.

The moderate ash content of six percent is operationally manageable and compares favorably with many other solid fuels. During combustion, the ash accumulates in the combustion chamber and must be periodically removed, but the rate of accumulation is low enough that this does not become an onerous task. The ash itself has value as a soil amendment, containing potassium, phosphorus, and other plant nutrients that can be returned to agricultural soils, closing nutrient cycles and reducing the need for synthetic fertilizers.

The calorific value of fifteen point four two megajoules per kilogram provides adequate energy density for most cooking and heating applications. While this is lower than the energy density of coal, it is compensated by the renewable nature of the feedstock and the lower environmental impact of biomass combustion. The carbon dioxide released during biomass combustion is part of the active carbon cycle, having been recently fixed from the atmosphere by photosynthesis, whereas the carbon dioxide from coal combustion represents carbon that has been sequestered for millions of years and whose release contributes to the net increase in atmospheric carbon dioxide concentrations.

The successful utilization of banana peel as a natural binder represents an additional waste utilization opportunity and demonstrates the potential for creating value-added products from multiple waste streams simultaneously. The starch and other carbohydrates in banana peel provide effective binding without the need for synthetic, non-renewable binders, and the incorporation of banana peel into the briquettes adds to their energy content while solving a waste disposal problem.

The production process developed in this study is scalable and adaptable to local conditions. The equipment required—pulverizer, sieve, mixer, hydraulic press, and drying racks—is readily available and can be operated with relatively low skill levels, making the technology accessible to rural entrepreneurs and community-based organizations. The feedstocks are locally available in agricultural areas, eliminating transportation costs and creating local economic opportunities in waste collection and processing.

From an environmental perspective, the production and use of bio-briquettes offers multiple benefits. The diversion of agricultural residues from open burning or uncontrolled decomposition reduces emissions of greenhouse gases and air pollutants. The substitution of renewable biomass for fossil fuels reduces net carbon dioxide emissions and contributes to climate change mitigation. The use of natural binders eliminates the environmental footprint associated with synthetic binder production. And the return of combustion ash to agricultural soils closes nutrient cycles and reduces the need for synthetic fertilizers.

From a socioeconomic perspective, bio-briquette production can create rural employment opportunities in waste collection, feedstock processing, briquette manufacturing, and product marketing. These opportunities can provide income diversification for agricultural households and can be particularly valuable for women and marginalized groups who may have limited access to other economic opportunities. The availability of affordable, locally produced cooking fuel can reduce household energy expenditures and improve energy access for rural populations.

4. CONCLUSION

This comprehensive study on the production of bio-briquettes from agricultural waste has successfully demonstrated the technical feasibility, environmental benefits, and practical applicability of converting locally available residues into valuable solid fuels. The research encompassed eight different agricultural waste materials collected from diverse sources across the Namakkal and Tiruchirapalli districts of Tamil Nadu, including rice husk, sawdust, sugarcane bagasse, groundnut shell, coconut shell, cotton stalk, banana peel, and corn cobs. Through a systematic production process involving drying, size reduction, mixing with natural binders, compaction, and final drying, these waste materials were transformed into dense, durable briquettes with favorable fuel properties.

The proximate analysis of the produced briquettes revealed a combination of characteristics that make them well-suited for domestic cooking and small-scale industrial heating applications. The average moisture content of ten percent falls within the optimal range for solid fuels, ensuring good storage stability and minimal energy penalty during combustion. The volatile matter content of seventy-two percent, remarkably high compared to conventional fuels, provides excellent ignition properties and produces the vigorous, luminous flames that users associate with effective cooking fires. The ash content of six percent is moderate and operationally manageable, with the additional benefit that the ash can be returned to agricultural soils as a nutrient-rich amendment. The fixed carbon content of twelve percent, while lower than that of coal, is appropriate for the intended applications where rapid heat release is valued over extended burn duration. The calorific value of fifteen point four two megajoules per kilogram, equivalent to three thousand six hundred eighty-six kilocalories per kilogram, provides adequate energy density for cooking and heating needs, with individual samples ranging from fourteen point three two to sixteen point five three megajoules per kilogram.

The comparative analysis with conventional fuels, including fuel wood and coal briquettes of different mesh sizes, positioned the produced bio-briquettes as a competitive alternative with distinct advantages. Relative to fuel wood, the briquettes offer higher energy density, more consistent properties, and easier handling and storage. Relative to coal, the briquettes offer renewable sourcing, carbon neutrality, and the environmental benefits of waste utilization. The combination of favorable fuel properties, environmental benefits, and socioeconomic opportunities positions bio-briquettes as a compelling technology for sustainable energy development in rural areas.

The successful use of banana peel as a natural binder represents an additional innovation, demonstrating the potential for creating synergies between different waste streams and eliminating the need for synthetic, non-renewable binders. The starch and lignin in the banana peel provide effective binding through gelatinization and thermosetting mechanisms, producing briquettes with good mechanical strength and durability.

This project makes several important contributions to the field of biomass energy and sustainable development. It provides a practical demonstration of the technical feasibility of producing high-quality briquettes from locally available agricultural residues using relatively simple equipment and processes. It generates quantitative data on the fuel properties of briquettes produced from a diverse range of feedstocks, contributing to the knowledge base needed for process optimization and quality control. It demonstrates the potential for utilizing multiple waste streams synergistically, with banana peel serving as both a feedstock and a binder. And it provides a basis for economic analysis and technology transfer to rural communities and entrepreneurs.

The broader implications of this work extend beyond the immediate technical results. By demonstrating that agricultural wastes can be transformed into valuable energy products, this research supports the transition toward a circular bioeconomy in which waste streams are viewed as resources rather than disposal problems. By providing a renewable alternative to fossil fuels, it contributes to climate change mitigation and energy security. By creating opportunities for rural employment and enterprise development, it supports sustainable livelihoods and inclusive economic growth. And by improving access to clean, affordable cooking fuel, it contributes to improved health outcomes, particularly for women and children who are most exposed to indoor air pollution from traditional cooking methods.

Future research directions building on this work could include optimization of the production process for different feedstock combinations, investigation of the combustion characteristics and emissions from briquettes in different stove types, development of quality standards and certification systems for bio-briquettes, economic analysis of commercial-scale production and marketing, and assessment of the social and environmental impacts of bio-briquette adoption in rural communities. Continued research and development in this area can help realize the full potential of agricultural waste as a resource for sustainable energy production and contribute to the broader transition toward a more sustainable and equitable energy future.

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