Nature-Positive Solutions

Training Manual

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Biomass Briquetting: A Training Module for Trainers and Practitioners

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About the CGIAR Initiative on Nature-Positive Solutions

The CGIAR Initiative on Nature-Positive Solutions aims to re-imagine, co-create, and implement nature-positive solutions-based agrifood systems that equitably support food and livelihoods while ensuring that agriculture is a net positive contributor to biodiversity and nature. https://on.cgiar.org/3rHjbRO

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About the Manual

This training manual was primarily designed to support the training of small-scale farmers and entrepreneurs on how to produce biomass briquettes from agricultural wastes and residues. Part 1 introduces key concepts in biomass briquette production and the benefits that may be realised. Further information on process parameters is also provided e.g., how operating conditions affect the quality and performance of biomass briquettes; what waste types, binders, and technologies are appropriate for biomass briquetting and the key safety considerations to be put in place to ensure a safe and sustainable enterprise. Part 2 provides step-by-step guidance on 'how-to processes e.g., how to produce briquettes from different biomass or waste streams using carbonisation and non-carbonisation methods and how to use briquettes for fuel and other energy purposes safely. The manual was made available by CGIAR initiative on Nature-Positive Solutions (NATURE+). The training manual can be adapted as an operational or train-the-trainer manual for training community groups, enterprises, individuals, and organizations working or interested in waste management, circular economy, or renewable energy, particularly women and youth. No prior understanding is necessary although a basic background in natural sciences may be useful. Technical training may be facilitated with practical demonstrations.

Learning Objectives

At the end of the training, the participants are expected to be able to:

1. Explain the key concepts behind biomass briquette production.
2. Explain how process parameters affect the quality and performance of biomass briquette production.
3. Identify best practices for sustainable production and health and safety risks and actions to mitigate them.
4. Demonstrate how to produce briquettes from biowaste streams.

About CGIAR Initiative on Nature-Positive Solutions (NATURE+)

NATURE+ is part of CGIAR's research portfolio that focuses on bringing environmentally friendly strategies to farmers in Burkina Faso, Colombia, Kenya, India, and Vietnam. Actions include increasing agricultural biodiversity on farmland (including more native crops and trees), improving water and soil management, and transforming rural waste into fertilizer and energy, among others. The initiative aims to reverse natural resource depletion, enhance biodiversity, mitigate climate change impacts on farms, and augment food and nutrition security. Collaborating directly with farmers and communities is key to the NATURE+ initiative. By working closely with policymakers and influential stakeholders, the initiative aims to establish a comprehensive framework of incentives that not only encourages the widespread adoption of nature-positive practices but also facilitates the development of necessary skills and knowledge among individuals and communities. This approach empowers farmers and communities to actively participate in and contribute to the long-term success of sustainable practices.

Contents

Part 1

Introduction to Biomass Briquetting

1. Background

Around two billion people, or 40% of the world's population, rely on traditional fuels like charcoal and firewood, as their primary or only source of energy for heating and cooking (IEA/WHO, 2022). This contributes to deforestation and other environmental issues such as biodiversity loss. Renewable biomass feedstocks such as wood, switchgrass, and forest residues are a much better way to generate energy; however, when used in inefficient stoves and burned traditionally, in the form of logs and branches, they cause damage to humans and the environment. As traditional fuels, they are inefficient because of large considerable inputs of domestic labour for their collection, processing, and use. In stoves, fuels are not appropriately shaped, and they burn uncontrollably, releasing dangerous greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrogen oxide (NO), and harmful air pollutants. For example, short-term exposure to dangerous air pollutants such as soot (black carbon), carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$), can cause coughing, sneezing, and irritation of the eyes, nose, and throat. Long-term exposure to polycyclic aromatic hydrocarbons can severely affect the lungs and increase the risk of cancer and heart diseases. Poor energy efficiency leads to incomplete combustion and the release of GHGs can warm the planet and increase climate change. The need to produce fuels sustainably is therefore urgent and one proven way of producing this is through biomass briquetting.

Photo credit: Good Neighbors

1.1. Biomass Briquetting

Biomass briquettes can be used as fuels, as a direct replacement to coal or firewood. They can be burned in stoves, boilers, and furnaces to produce heat, steam, and electricity, at household to industrial scale. They are considered a low-carbon alternative because fuels are derived from biogenic sources (that is animals, plants, microorganisms, and humans); and the CO_2 released during their combustion is renewable during plant growth. They are amongst the most efficient energy sources with three distinct properties: high-energy density, high carbon purity, and homogeneous uniform composition.

The higher energy density makes the fuel burn longer and uniformly, often smokeless when carbonised and compared to traditional charcoal. A diversity of biomass materials can be used to manufacture briquettes, including sawdust and other agricultural residues such as corncobs, rice husks, shredded paper, coffee husks, and citrus peel. Biomass briquettes are easy to transport, store, and use because of their compact form. This makes it feasible to burn directly as a fuel, in a similar manner to firewood, in domestic stoves and industrial ovens (with or without retrofitting). The quality and performance of the briquette depend on the material source and manufacturing method, whether manually hand-pressed or mechanically compacted. Table 1-1 summarises the benefits of biomass briquettes over traditional fuelwood or firewood.

Table 1-1: Advantages of biomass briquette over raw biomass (Waheed et al. 2022)

Raw Biomass	Biomass Briquettes	Advantages of Briquetting
Heterogeneous size, shape & composition Lower bulk density: approximately 40 – 200 kg/m^3	Uniform size, shape & composition Higher high bulk density: approximately 450 – 800 kg/m^3	▪ Reduces feedstock volume. ▪ Reduces requirements for handling, storage, and transportation (and associated costs). ▪ Saves time and staff time required.
Lower heating value: approximately 9 – 12 MJ/kg Lower volumetric energy density: approximately 2 – 3 GJ/m^3	Higher heating value: approximately 15 – 24 MJ/kg Higher volumetric energy density: approximately 15 – 19 GJ/m^3	▪ Increases energy per unit mass. ▪ Improves energy efficiency; clean, efficient, smokeless burn can be achieved. ▪ Reduces adverse health impacts associated with firewood burn including particulate matter and exposure to toxic gases.
Low-value fuel and high labour costs	Higher value fuel and low labour requirements	▪ Reduces landfilling and associated GHGs. ▪ Reduces deforestation and fuel consumption. ▪ Opportunities for revenue and rural development

1.1.1. Benefits of Biomass Briquettes

There are a wide range of benefits which can be realised through production and use of charcoal briquettes. Some economic, social, environmental or health benefits are listed in Table 1-2.

Photo credit: Good Neighbors

Table 1-2: Benefits of biomass briquettes

Economic Benefits	**Social Benefits**
☑ Cost-effective than traditional fuels like coal or fuelwood.	☑ Reduces time and energy spent collecting firewood and compatible with daily chores.
☑ New jobs and revenue opportunities are crated which can benefit rural development.	☑ Improves living conditions with positive impact on education and energy security.
☑ Versatile fuel for heating, cooking and electricity needs, at small and large scale.	☑ Reduces unemployment and promotes social cohesion and cooperation for those involved.
Environmental Benefits	**Health and Safety Benefits**
☑ Reduced reliance on traditional fuels like firewood and coal.	☑ Less smoke is produced – reduces risk of eye irritation and other health issues.
☑ Contributes to conservation of forests, biodiversity, and ecological balance.	☑ Reduces health risks associated to harmful indoor air pollutants such as CO and $PM_{2.5}$.
☑ Climate change mitigation through emission reduction and reduced reliance on fossil fuel energy sources.	☑ Controlled burning, as opposed to open fires, and reduced cooking time reduces the risk of burns and injuries during use.

1.2. Types of Biomass Briquettes

There are two types of fuel briquettes (as shown in Figure 1-1):

a) non-carbonised biomass briquettes, where materials retain more of the original composition of the biomass, including some moisture and volatile compounds. They are generally lighter in colour and may have a lower energy density compared to carbonised briquettes. These briquettes are made by compacting biomass materials under high pressure but without the carbonisation step.

b) carbonised biomass briquettes, where the biomass materials are heated in a low-oxygen environment. The finished briquettes are dark in colour and have a higher carbon content, making them burn better with less smoke when used as fuel.

Figure 1-1: Sample of non-carbonised briquettes made with a briquetting machine (left) and carbonised briquettes moulded by hand (right). Photo Credits: James K Gitau (right); Dzifa Agbefu, IWMI (left)

The choice to carbonise or non-carbonise depends on the type of biomass, facilities available and the prevailing or potential market environment. Both carbonised and non-carbonised briquettes have a definite size and shape. They can both be used as fuel sources e.g., for cooking and heating water in domestic households and productive heating purposes, firing ceramics, and generating steam and/or electricity in industrial applications but their burning characteristics differ. Empirical evidence has shown that non-carbonised briquettes can produce high emissions as much as or even higher than firewood when used in traditional stoves. As such, non-carbonised briquettes are better suited for industrial settings where tailpipe emissions can be controlled or cleaned. If non-carbonised briquettes are to be used for domestic cooking or heating, improved stoves must be used and in a well-ventilated area.

Furthermore, there are also two ways that briquettes can be produced: with and without a binder. The first is preferred, because binders hold up loose particles together and prevent the crumbling of the solid briquette. Common binders include starches, clay soil (with sticky properties), wastepaper (with no ink or lamination), molasses, and other natural materials. These binders improve the briquette's durability, during bagging and transportation. Briquettes may also be produced without binders. This is because some biomass materials, when subjected to high pressure, can naturally bind together due to their inherent properties, such as lignin content. For example, many agricultural residues have inherent plasticity and can often form solid briquettes without the need for additional binders, particularly under high temperatures and/or pressures. These types of briquettes rely on the natural bonding properties within the biomass particles.

1.3. Process Description

One way of circumventing copious quantities of smoke that are associated with raw biomass is to carbonise before densifying the material. Carbonisation as illustrated in Figure 1-2 involves heating biomass in the absence of air or a low-oxygen environment at controlled temperature conditions. The process starts with drying, followed by devolatilization (release of volatile gases), and ultimately ends with charring (a partial burn and darkening of the biomass). The volatiles released may contain water, condensable light hydrocarbons, and non-condensable gases such as CO, CO_2, and CH_4 and hydrogen gas (H_2). The charring causes the biomass to darken, and pure carbon is left behind. The solid residue (also known as biochar or carbon dust) can then be used to make briquette fuels. These fuels burn at higher temperatures with less smoke and can achieve smokeless combustion (Box 1).

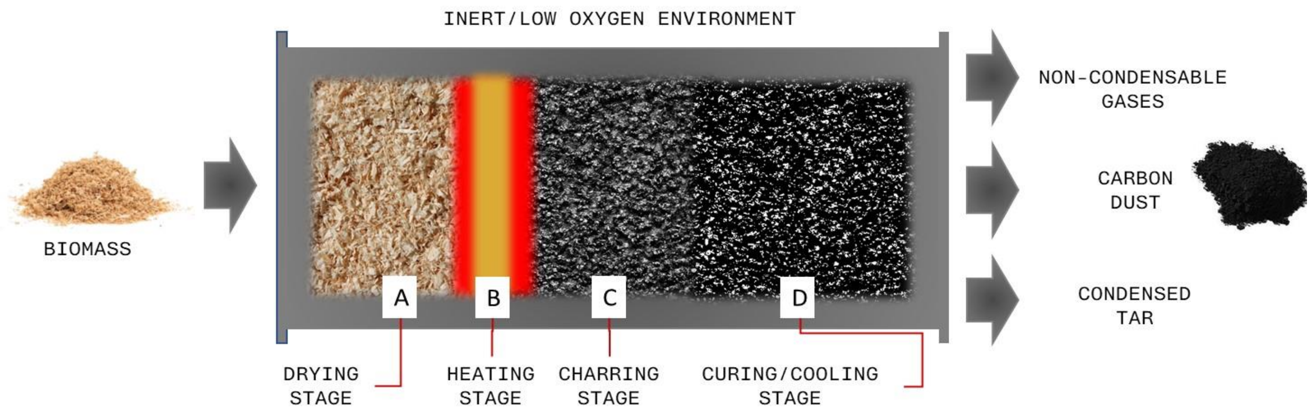


Figure 1-2: Illustration of the process of carbonisation in biomass briquette production.

The key factors influencing the yield of products in a carbonisation process, and the quality and performance of biomass briquettes include a) The composition and the properties of the biomass at the time of carbonisation. This includes particle size, moisture content, compacting pressure, and temperature, amongst others. b) The type of carbonisation equipment used. c) The process conditions applied to heating the biomass. This includes heating rate, amount of air reacting with the biomass during carbonisation, residence time (that is the amount of time that the biomass is heated), and the final temperature reached by the biomass. Some of the parameters relate to the feedstock properties while others relate to briquetting technology and its operating conditions.

Box 1: Benefits of Carbonisation

Heating the biomass in the absence of air increases the briquettes' properties.

- ☑ Reduces moisture content, making it less susceptible to decay and mold growth.
- ☑ Reduces volatile matter content, enabling clean and efficient combustion.
- ☑ Increases fixed carbon content, a form of carbon sequestration if applied to soil.
- ☑ It can be applied to a variety of biomass feedstocks, including agricultural residues and other forestry wastes.
- ☑ Increases carbon content which makes the fuel burn evenly and the flame last longer.

1.3.1. Carbonised Briquette Production

A typical carbonised briquette-making process (as shown in Figure 1-3) involves: i) collection and storage of biomass feedstocks, ii) pre-treatment processes such as size reduction and drying, iii) carbonisation, iv) mixing with a binder (where required), v) compaction, and vi) drying and packaging. For highly moist materials, drying is required before carbonisation to remove moisture. This can be done in open-air or under controlled heating conditions e.g., using a solar dryer/heater.

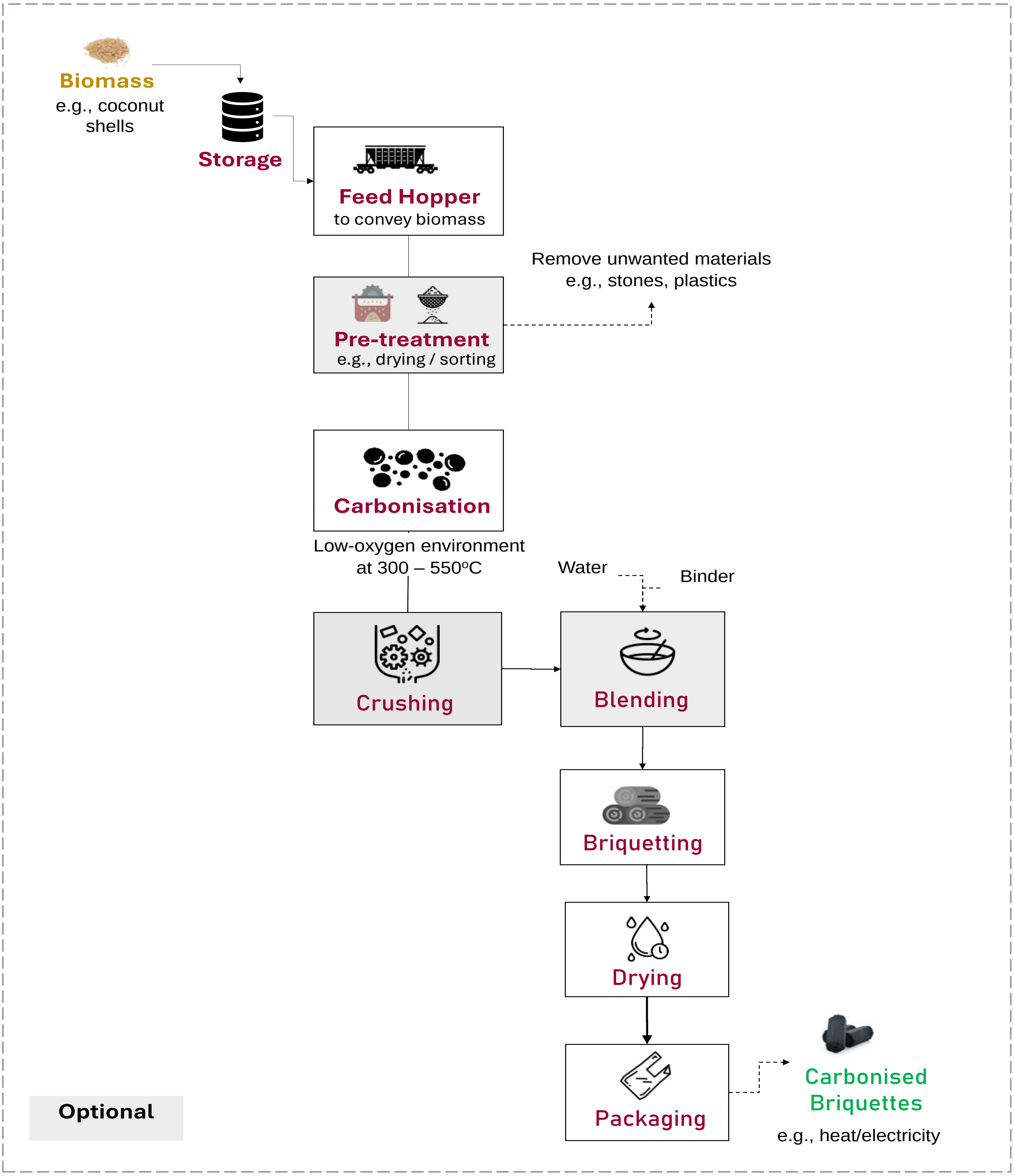


Figure 1-3: Carbonised briquette-making process and workflows.

Briquetting uses compaction or densification to convert loose biomass or agricultural residues, to high-density, low-moisture, high-energy solid fuels. The process is illustrated in Figure 1-4 where loose biomass materials are compressed until equal-sized chunks are formed, known as briquettes. The benefits of briquetting are listed in Box 2. There are various ways of compacting biomass, some relying on hand-operated equipment and others on automation. Manual briquetting can be done using a manual press or mould (suitable for small-scale operations). Mechanised equipment such as piston press, screw extruder, hydraulic press etc can be used for large-scale briquette production.

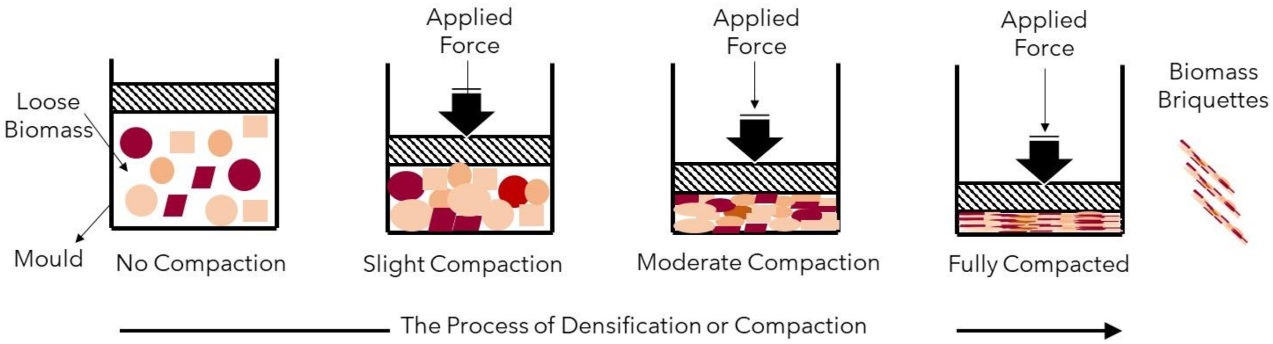


Figure 1-4: Illustration of the process of densification in biomass briquette production

Piston press machines are one of the most used equipment for producing high-quality briquettes and are applicable for medium-to larger-scale operations, but often carbonisation is not feasible in the process. It uses reciprocating pistons, which apply high pressure on crushed biomass to produce dense and uniform briquettes. This method is versatile and can handle various biomass materials, but moisture should be less than 12% for optimum results. A screw extruder can also be used, and this compresses biomass materials through continuous rotation and extrusion through a heated screw, but the power consumption is higher. The final product is carbonised directly, and the briquette quality is higher and uniform with a concentric hole in the middle which facilitates burning. The hydraulic piston press differs from the mechanical press as it relies on a hydraulic ram powered by an electric motor (and in some cases, hand-operated levers). It is compact and light and can tolerate higher moisture content fuel but produces lower bulk density fuel. Table 1-3 compares two major compaction technologies – screw extruder and piston press.

Box 2: Benefits of Briquetting

Biomass in its raw form has relatively high moisture content, low energy density, and low bulk density. Densification makes the briquette more compact and increases energy per unit mass.

- ☑ Reduces moisture content, which makes briquette less susceptible to decay and mold growth.
- ☑ Increases energy density which makes fuel burn longer and improves burners energy efficiency.
- ☑ Increases bulk density which reduces requirements for handling, storage, and transportation.
- ☑ Reduces moisture content and improves combustion efficiency – less energy is wasted drying the biomass.
- ☑ Increases bulk density and makes fuel fit the burner better; reduces emissions thereby averting health risks.
- ☑ Reduces fuel consumption – saves time, and costs collecting firewood.

Table 1-3: Comparison of a screw extruder and piston press (Grover and Mishra, 1996; Kpalo et al. 2020)

Characteristics	Piston Press	Screw Extruder
Optimum moisture content	10-15%	4-8%
Wear of contact parts	Low for ram & die	High for screw
Power Consumption	50 kWh/ton	60 kWh/ton
Briquette Bulk Density	1-1.2 gm/cm^3	1-1.4 gm/cm^3
Maintenance Req.	High	Low
Carbonisation	Not possible	Feasible
Briquette Homogeneity	Non-homogenous	Homogenous
Features	High-pressure press via pistons	Continuous high-pressure extrusion
Binder Requirement	Binder is not mandatory	Binder is not mandatory
Merits	Low noise; wear & tear; power consumption, fuel has moderate combustion performance	Low noise and maintenance requirements; fuel has good combustion performance

1.3.2. Non - Carbonised Briquette Production

A typical non-carbonised briquette-making process is illustrated in Figure 1-5, which involves: i) collection and storage of biomass feedstocks, ii) pre-treatment processes where required, iii) mixing with binder, where required, iv) compaction, and v) drying and packaging. These processes are often mechanised due to the high pressure and temperature required to make the material bind together. Similarly, drying might be required if a significant amount of moisture is present.

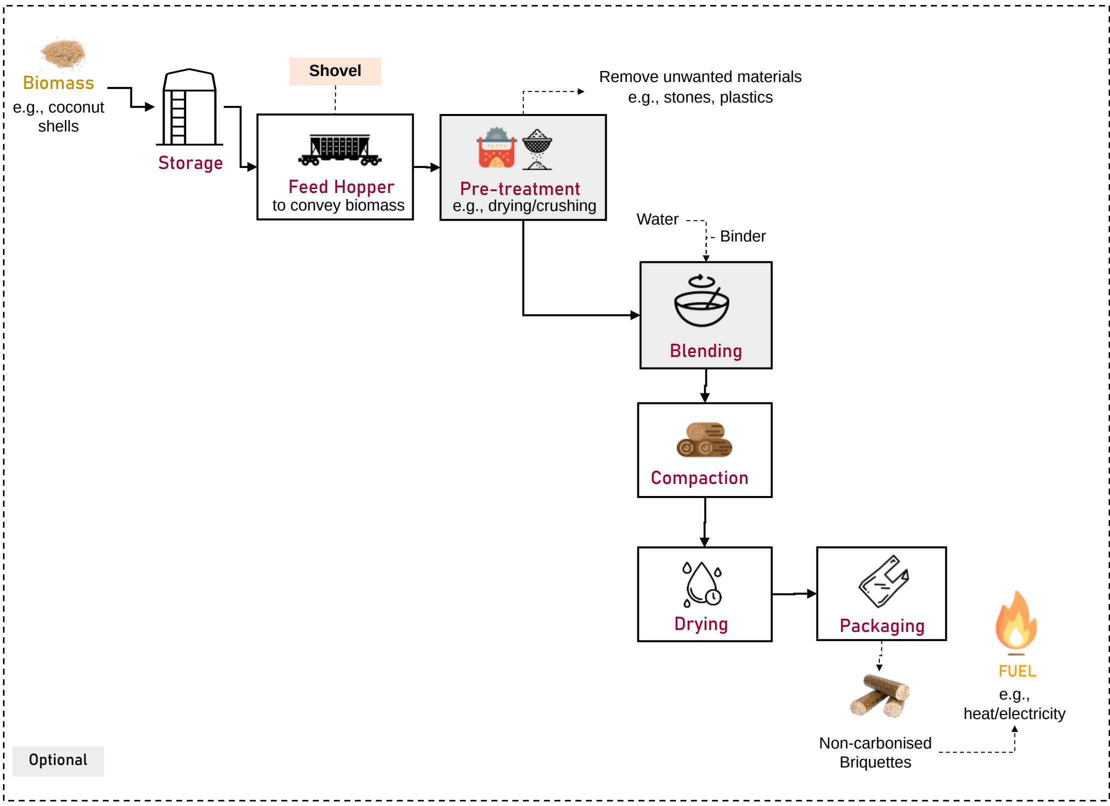


Figure 1-5: Non-carbonised briquette-making process and workflows

1.4. Process Parameters

Waste Types & Composition: Biomass materials can be sourced from a variety of origins, both natural and cultivated (Figure 1-6). Some common sources include: i) *wood and forestry residues* – working with forestry and logging industries to obtain wood shavings, branches, sawdust, wood chips, bark, and other by-products, ii) *agricultural residues* – working with farmers and cooperatives to obtain residues such as straw, husks, stalks, cobs, and shells from crops like rice, wheat, corn, sugarcane, and others, iii) *dedicated cultivation* - specifically cultivating crops for briquette production such as miscanthus, switchgrass, willow, and other fast-growing plants with high energy content, provided these are economical and do not compete with food or result in significant land use changes, iv) *animal manure* – obtaining organic manure with low moisture content e.g., cow dung from livestock farmers. v) *aquatic biomass* – harvesting suffocating seaweeds, water hyacinth, and other environmentally challenging aquatic plants for biomass, vi) agro-industrial residues and by-products from food processing industries.

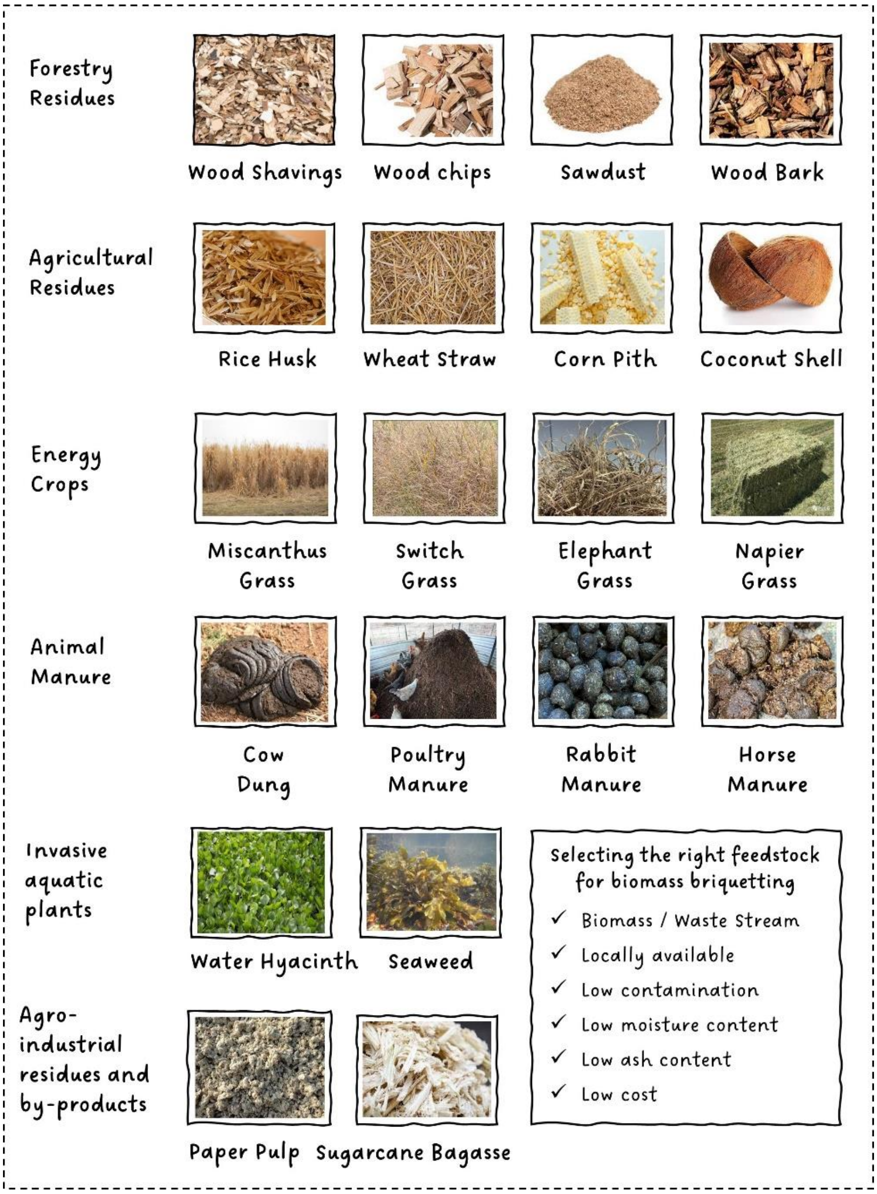


Figure 1-6: Common biomass feedstocks for briquette production

Any of the above can be mixed to increase the security of supply, but ultimately the final composition affects briquette's quality and performance (as shown in Table 1-4). The key characteristics that make biomass suitable for briquette are outlined in Tables 1-5.

Table 1-4: Typical biomass compositions and briquette characteristics

	Minimum Biomass Composition Requirements *	Typical Biomass Briquette Characteristics**
Ash Content	6 - 14%	0.5 – 6%
Moisture Content	<4%	5 - 12%
Volatile Matter Content	50 – 90%	50 – 75%
Fixed Carbon Content	9 – 25%	15 – 30%
Gross Calorific Value	10 – 35 MJ/kg	15 – 20 MJ/kg
Size of Briquettes	-	70 – 90 mm
Length of Briquettes	-	50 – 300 mm
Particle Size	1 – 10 mm with 10 – 20% powdery	-
Bulk Density	> 50 kg/m^3	240 – 750 kg/m^3
Carbon	40 – 55%	43 - 46%
Hydrogen	5 – 8%	5 - 6%
Oxygen	35 – 48%	37 – 48%
Nitrogen	0 – 1%	0 – 1%
Sulfur	0 – 2%	<0.1%
Chlorine	0 – 1%	<0.1%

* Asamoah et al. 2016
** Asamoah et al. 2016; Ivanova et al. 2018

Table 1-5: Biomass properties and influence on briquette quality

Properties	Description	Influence on Biomass Properties on Briquette Quality	Examples of Biomass Feedstocks
Fixed Carbon	The carbon left after carbonisation	High fixed carbon content will help the fuel to burn longer and have higher mechanical strength.	High fibre materials like walnut shells, coconut shells, cassava stem, maize cob and wood residues have high fixed carbon content.
Ash Content	The mineral constituents left after carbonisation	Most biomass materials have low ash content but may contain major minerals like K, Na, Ca, and S, and trace amounts of Fe, Zn, and Cu. Compound minerals like SiO_2, Na_2O, and K_2O may also be present in ash, absorbed from the soil during plant growth. These minerals are not beneficial for briquette fuels as they do not readily participate in combustion reactions and may result in fouling of equipment.	Materials such as rice husks, rice straw and paddy straw have high ash content, at least more than 10 wt.%. Woody biomass such as sawdust, soyabean stalk, spent ground coffee and sugarcane bagasse, flax straw has low ash content (at most 1 wt.% dry basis (db)).
Volatile Matter	The chemical molecules released on heating the biomass	Volatile matter increases the calorific value of the fuel but may release a significant amount of emissions during burning.	Most agro wastes including rape stalk, corn (cob, stalk, stover) and sugarcane straw have high volatile matter, in excess of 70 wt.% db.
Moisture Content	The moisture that is present in the biomass	High moisture can adversely affect the briquetting process by making it difficult to burn the briquettes, but extremely low moisture content may cause flakiness in the raw materials. Low moisture should be preferred to reduce the need for drying.	Food, vegetable, kitchen, and market wastes e.g., orange pulp, and onion peel have high moisture; hence not ideal. Agro wastes e.g. coffee husks, corn cob have low moisture.
Bulk Density	The weight of biomass per unit volume.	High bulk density means denser and more compact materials. Low bulk density may increase handling, storage, and transportation costs.	-
Particle Size	The average size of biomass particles	An appropriate particle size distribution ensures uniform particle size. It affects the density and strength of the briquettes. Smaller particles ensure better compaction and binding during briquette production.	-
Calorific Value	The energy contained in the biomass	Ash, moisture, fixed carbon, and volatile matter content affect the calorific value of briquette products. A high calorific value means high energy per unit mass.	Rice husks/straws have lower calorific values (13-16 MJ/kg) while groundnut shell, sugarcane bagasse, jute waste, sunflower stalk, and wood chips have higher values of more than 17 MJ/kg.

Water and Water Sources: Water acts as a natural binder during briquetting, especially in manual or low-pressure processes. It helps the biomass particles to bind together, facilitating compaction and homogeneity. Water also acts as a lubricant enabling the material to flow through the equipment and moulds, reducing normal wear and tear associated with friction. This moisture can be present naturally in the binder as in the case of molasses. Note: If the feedstock is too dry, the briquettes may not hold their shape, while excessive moisture can lead to difficulty in moulding and lower product quality. To ensure sustainable production, water can be recycled (Box 3) and reclaimed from other sources, provided water is not polluted or can affect the quality of the product.

Box 3: Unconventional Water Sources for Biomass Briquette Production

Exploring unconventional water sources is not only sustainable but can be economical; however, it is worth mentioning that the health and environmental risks should be given due consideration. Some examples of unconventional water sources:

- ☑ Rainwater: Water from rooftops or around the facility can be used.
- ☑ Industrial wastewater: non-portable water from wastewater treatment facilities and organic-rich waste streams can be used as a binder or water source.
- ☑ Stormwater: Water from paved drains or reservoirs that is not suitable for drinking. Treatment may be required.
- ☑ Agricultural drainage water: Recycled water can be used provided they are not polluted with pesticides and pesticides.

Binders and Binder Ratio: Biomass generally contains naturally occurring structural binders or stabilizing agents, such as lignin and proteins that are released and activated when biomass is densified at relatively high levels of temperature and pressure. This improves the structural integrity of the briquette, particularly during handling and transportation. However, in some cases, certain biomasses do not have a significant amount of natural binder, even under densification. For example, failure to hold a form has been reported with sugarcane bagasse and rice husks. Bagasse could not hold a shape with manual compaction, even with 20% w/w cassava binder ratio and higher amount was needed. Briquetting rice husks without a binder or below 6% w/w binder ratio result in a tacky and viscous mixture which could also not hold a form (Lubwama and Yiga. 2017; 2018). In this respect, additional binders are required to achieve the desired hardness and durability.

Briquette binders can be broadly divided into organic and inorganic binders, depending on their composition. Organic binders generally have good binding properties, including high impact and abrasion strength, and high-water resistance. However, at high temperatures, they decompose due to low ignition temperature, losing mechanical strength and thermal stability. Low-cost and readily available organic binders include starch, gelatine, paper pulp, gums, molasses, and lignin. Inorganic binders e.g., clay and bentonite have strong adhesion and thermal stability even at high temperatures. They can retain sulphur and hydrophilic, but their combustion efficiency is lower due to their high ash content. The choice of binder depends on several factors such as desired bonding strength, availability, and cost of raw materials as well as the desired characteristics of the final product. Starch, clay, and molasses are widely used binders for biomass briquettes. Starch can be derived from cereals, legumes, tuber, and root crops e.g., maize, cassava, potato, wheat, rice, etc., or bought directly as a commercial product. Their extraction from food crops requires grinding and separation from other components can be achieved through washing, settling, and drying. Molasses from sugarcane or beets can also be used as a binder and are cost-effective if derived from sugar-producing factories at little or no cost. The challenge with the use of molasses relates to the highly viscous nature of the material which makes processing difficult. Figure 1-7 illustrates how the briquette mixture with binder is prepared (Njenga, 2014 modified).

In briquette production, the binder ratio (weight of biomass to binder) is important: the right ratio ensures that the briquettes have sufficient compressive strength and structural integrity, during handling, transportation, and use; however, too much binder can increase production expenses. To determine the optimal binder ratio, briquette manufacturers typically do trials and experimentation to find the right balance between materials and their performance. Table 1-6 summarizes some good examples of binder ratios for different agricultural residues.

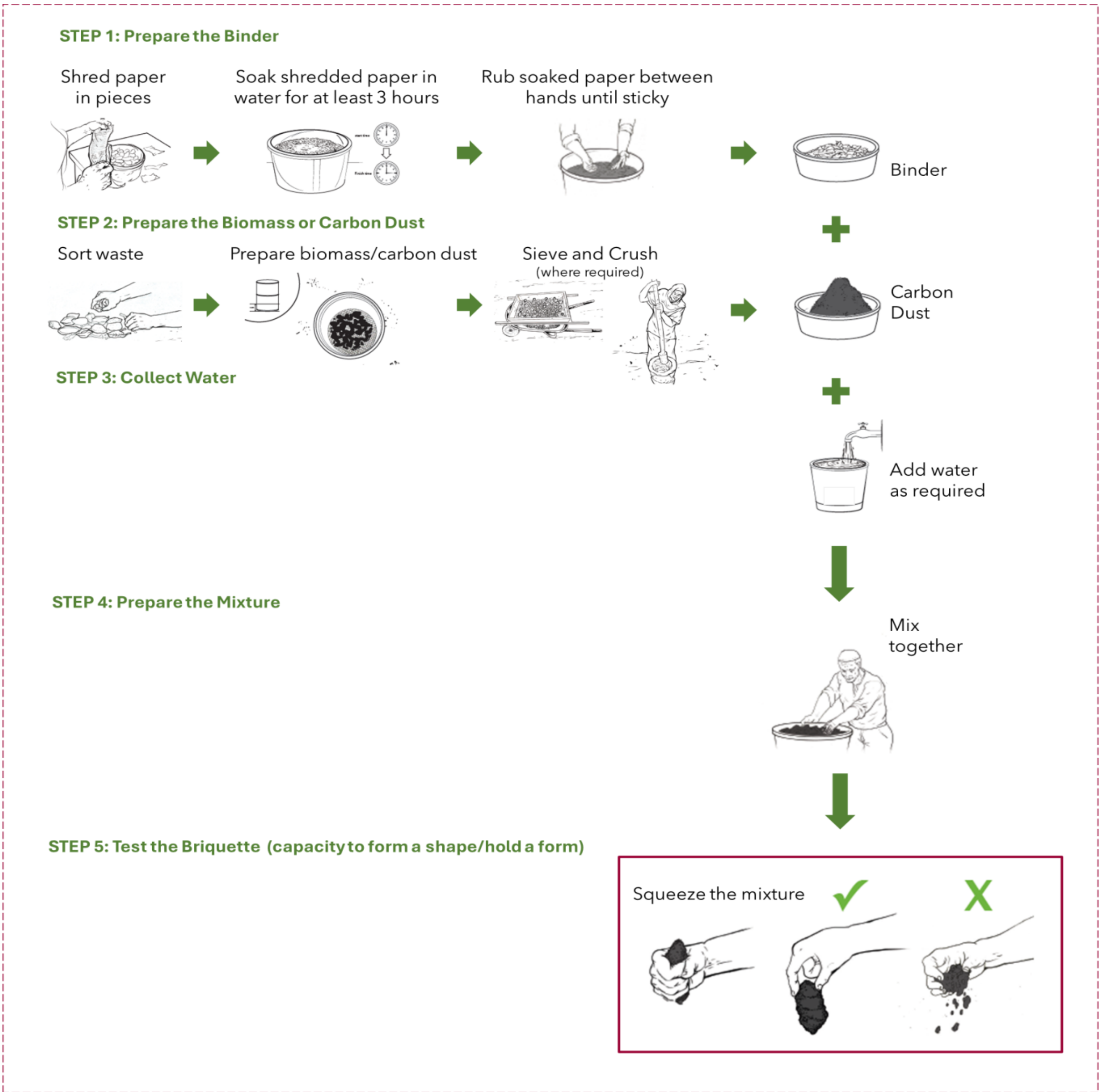


Figure 1-7: Preparing the biomass and binder mixture (Njenga, 201, *modified*)

Table 1-6: Binder ratios for different agricultural residues

Biomass Type	Binder Type	Binder Ratio*	Notes
Recovered Charcoal Dust	Soil/Compost + Water	1:6	Compost must be dried well
	Gum Arabica + Water	1:10-19	Soak in water overnight
	Cassava Flour + Water	1:19-25 L	Boiled in water into a porridge
	Molasses (Liquid form)	1:40	-
	Cow Dung + Water	1:2-3	Cow dung must be sufficiently dried
	Biodegradable Paper + Water	1:3-6	Paper is shredded and soaked in water for 3 hours
Rice Husks + Sugarcane Bagasse in 1:5 ratio	Cassava Flour + Water	1:10	[a]Cassava binders produce briquettes with high density, ignition time and calorific values of 849-980 kg/m3, 62-95 s and 6.3-7.6 kcal/g respectively.
	Clay Binder + Water	1:7	[b]Compact at 108 – 397 kPa for 10 s. Clay binder produces denser briquettes (869-1000 kg/m3) which burns longer but poorly ignited (110-191s) and lower calorific values (5.5 - 6.9 kcal/g).
Non-carbonised Groundnut Shells	Wheat/Cassava Flour + Water	1:5	[c]High-pressure compaction at 230 MPa; no carbonisation. Surface of the non-carbonized groundnut briquettes is smooth and shiny, with no loose particles visible on the circumferential area. HHV is ~16 MJ/kg.
Carbonised Groundnut Shells	Wheat/Cassava Flour + Water	1:10 - 30	[c]Low pressure (<7 MPa) compaction. Carbonisation process inhibited moisture adsorption and increased fixed carbon content; HHV is 21-23 MJ/kg; 99% drop strength.
Carbonised Peanut Shells (about 6 mm)	Corn starch wastewater	1:3-5	[d]Carbonisation at 240 – 270°C for 90 min; 30% Yield; 460 – 499 kg/m^3; HHV of the carbonised briquette is ~ 26 – 27 MJ/kg.
Carbonised/Non-carbonised Coffee Husks	Cassava Starch (liquid form)	1:10-30	[e]High pressure compaction at 230 MPa; HHV of non-carbonised briquette is ~15 MJ/kg. HHV of carbonised briquette is ~22 - 23 MJ/kg. Cassava binder increased drop strength better than clay.
Carbonised Coffee Husks	Clay soil + Water	1:2-10	[c]High pressure compaction at 230 MPa. HHV is about 16 MJ/kg
	Molasses	1:4-5	[f]HHV is about 22 MJ/kg
	Cassava Starch	1:4-5	[f]HHV is about 24 MJ/kg

*Carbon Dust or Biomass:Binder; a - Arewa et al. 2016; b - Daniel et al. 2020; c - Lubwama and Yiga 2017, d - Mamuad et al. 2022; e - Lubwama and Yiga 2018; f - Tesfaye et al. 2022

1.5. Quality Parameters

Due to transportation, storage, and handling conditions, biomass briquettes are subject to various loads and forces including shearing and compression. Materials also degrade over time due to environmental factors, e.g., ambient temperature and humidity; hence quality is paramount. Whilst there are no universal standards, material properties such as calorific value, compressive strength, abrasion resistance, water penetration resistance, etc., are good quality indicators.

Calorific Value

This indicates the amount of energy contained in the briquettes and released during combustion. It is measured in megajoules per kilogram (MJ/kg). A higher calorific value signifies a more energy-dense briquette. This value can be deduced from the percentages of volatile matter, fixed carbon, moisture, and ash content.

Water Penetration Resistance

This parameter is important for the storage of briquettes in highly humid environments or when exposed to rain. It is a measure of the water resistance ability and sensitivity of biomass briquettes to moisture/water which can decrease their quality. This can be measured by immersing a biomass briquette in water at about 25°C for one minute and comparing the before and after dimensions of the briquette. The lower the swelling, the higher the water penetration resistance.

Shattering Resistance/Drop Strength Test

The effectiveness of compaction can be measured in terms of compressive strength and mechanical durability. These terms describe the internal strength of the briquette that is, the maximum force that the briquette can withstand before it fractures; the capacity of the briquette to remain intact when dropped from a height onto a floor of known material surface, and general resistance to breakage and impact. This quality parameter is important for dust and explosion risk mitigation. Shattering resistance can be measured by dropping a briquette from 1 m height to a concrete surface, about 10 times. The percent loss after the test indicates the shatter resistance of the briquettes. A lower percentage value indicates a better quality with shattering resistance. Figure 1-8 illustrates how the drop strength of a briquette is simply determined.

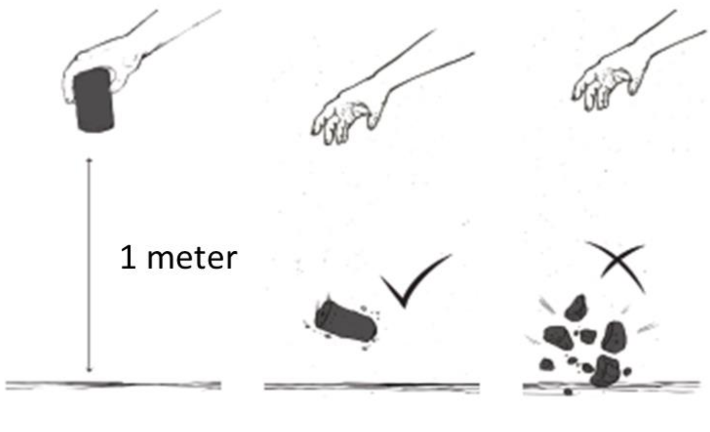


Figure 1-8: Checking the drop strength of a biomass briquette after drying (Njenga, 2014)

Part 2

A Practical Guide to Biomass Briquette Production

2. Practical Guide

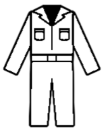
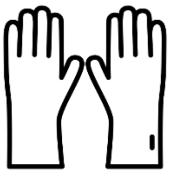
This practical guide complements Part 1 "Introduction to Biomass Briquetting" with step-by-step guidance step on how to produce the two types of biomass briquettes: carbonised and non-carbonised briquettes on a small-scale. Specific case studies are provided for saw dust and rice husks, but biomass briquettes can be produced from a variety of sources.

2.1. Safety Considerations

Organic wastes are biogenic and subject to microbial degradation; hence, materials may contain pathogens or disease-causing organisms. Feedstock may also contain lignin degradation products (e.g., phenolic acids, acetic acid, and furfural) which may be toxic to humans when burned and inhaled. The carbonisation process involves high temperatures and may lead to harmful gases if completed in an unsafe manner. For example, carbonisation releases gases such as carbon monoxide, hydrogen, and light hydrocarbons, which are potentially harmful to humans when inhaled. The risk of fire due to self-heating is not uncommon if biomass briquettes are not handled with care during storage, handling, and transportation. Other additional fire sources include electrical sparks, embers from smouldering materials, vehicle-triggered sparks, friction, and arson (intentional fires). An electrical failure can lead to major fatalities if motorised equipment(s) is/are not properly maintained; hence, strict safety precautions are needed for processing biomass to briquette fuel. Some of the risks associated with biomass briquetting and the role of protective equipment in mitigating these risks are outlined in Table 2-1.

Photo credit: Chris Campbell

Table 2-1: Personal Protective Equipment and key risks mitigated

PPE	Risks Mitigated
 Safety Boots	Scalding/Burns from carbonisation of biomass. Pathogen contamination from contact with organic waste materials. Physical injury from falling objects or due to trip/falls.
 Safety Googles	Eye irritation from exposure to carbon/biomass dust. Eye disease from exposure to contaminated waste. Physical injury from sharp or flying objects
 Safety Helmet	Physical head injury due to sharp and falling objects. Physical head injury from falling due to slip/trip.
 Safety Coverall	Skin irritation from exposure to carbon/biomass dust. Skin irritation/disease from exposure to contaminated waste. Physical head injury from falling due to slip/trip. Skin scalding/burns from carbonisation of biomass.
 Nose Mask	Acute or chronic respiratory problems due to inhalation of dust.
 Gloves	Scalding/Burns from carbonisation of biomass. Skin irritation from exposure to carbon/biomass dust. Skin irritation/disease from exposure to contaminated waste. Cut due to exposure to sharp objects.
 Ear Plugs	When utilizing a mechanical crusher, protect the ear from loud noise. Prevent intrusion of dust or any other foreign material when handing biomass

2.2. Equipment

There are various technologies available for briquette production, ranging from simple manual methods to more advanced, automated processes. The choice of technology depends on several factors including the scale of production, the type of biomass materials being used, available resources, and the desired quality and characteristics of the briquettes. The cost of production, operation, and maintenance as well as market environment can also affect choice of technology used. Some common briquette processing technologies are categorized according to their use and purpose in Table 2-2.

Table 2-2: Tools & Equipment for Biomass Briquette Production

Equipment	Examples	Key Considerations
Material Storage	Storage Bin / Enclosed Structure	Depending on environmental conditions, production scale, feedstock seasonality and material bulk density, storage can be in an enclosed structure (outdoor or indoor) or in storage bins (of various sizes), provided there is sufficient reserve and quality at the point of use. For a small-scale facility, a feedstock store or bin size of 5 -10 m^3 is recommended but sizes up to 100 m^3 might be required for large-scale units. The bin can be manually loaded, and a feeding mechanism can be fitted to an enclosed structure/bin, but vehicular access and a convenient way of transferring feedstock for use should also be considered. Storage bin should be lidded, durable and water resistant to avoid mould and rot.
Feed Mechanism	Manual / Screw Feeder	A screw feeder/conveyor can move the biomass from the storage area into the feedstock hopper for further processing. Inclined screw feeders are common and ideal for moving materials from ground to top level with variable speed motor so that capacity can be matched with equipment. For manual operation, biomass feedstock can be moved using manual tools such as shovel.
Screening Equipment	Screening Trays / Vibratory Screen	Screening is essential for materials like sawdust which may contain wood strips, steel and stones. Screening trays and vibratory equipment take various forms and shapes, manual or motor operated. Various mesh sizes of screens can be used depending upon the type of material. Screen mesh size should be based on particle size and can be enclosed to reduce dust.
Dryer/Drying Trays	Industrial Dryer / Solar Dryer	Drying is not normally required for biomass materials like coffee husk, groundnut shells and rice husk, but moisture removal is necessary for those with moisture content above 15 wt.%. There are various types of dryers: paddle dryer, flash dryers, rotary dryers,

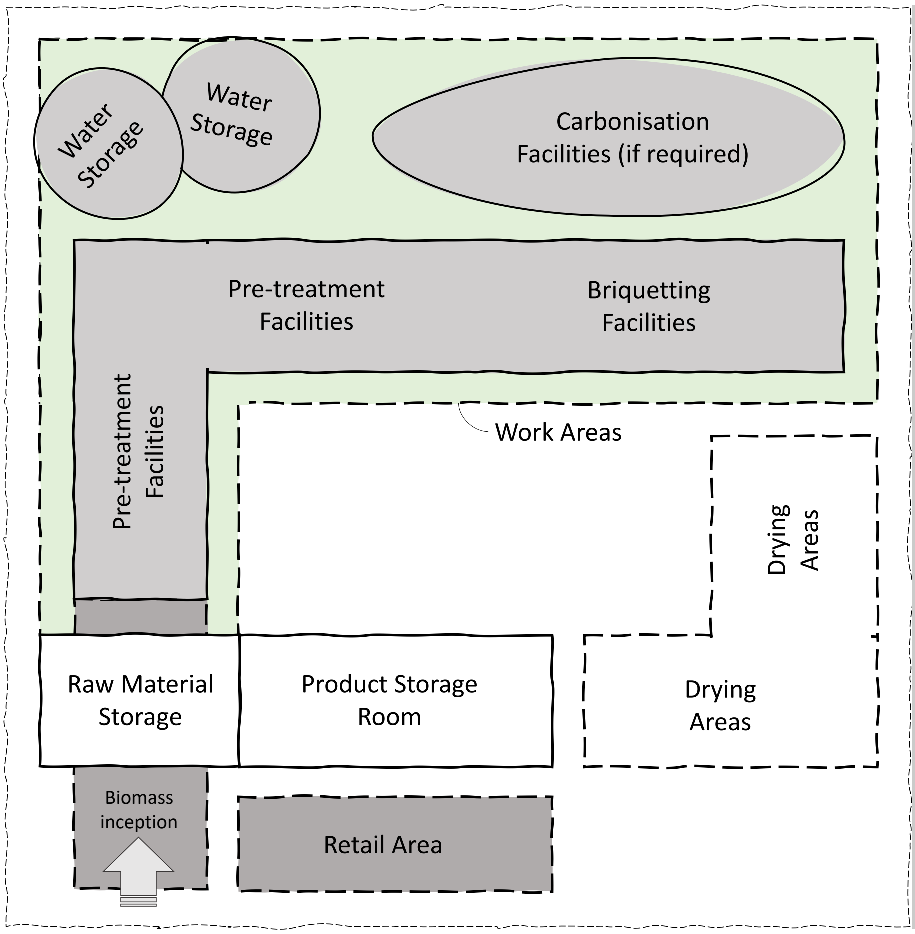
		even tray dryers. Drying can be enhanced using the following methods: a) High moisture content material can be mixed with dry product to improve drying properties. b) Drying trays can be used to pre-dry feedstock or post-dry products in open air or in a solar dryer. c) Metal trays are recommended to facilitate heat transfer. d) Waste heat from industrial facilities can be channeled for drying to minimize energy costs.
Carbonisation Equipment	Carboniser	Carbonisation equipment is necessary to produce carbonised briquettes. In the equipment, the feedstock is heated at temperatures of about 300 to 500°C and in a limited oxygen environment. A drum kiln is common in rural areas and appropriate for low-skilled workers. It is easy to maintain, and suitable for small-scale production. Where the equipment is not available, simple methods
Crushing/Milling	Hammer Mills	There are many types and sizes of crushing and grinding equipment, from a few kg/hr to 10-15 tonne per hour. A milling machine or shredder is valuable for particle size reduction and better processing of feedstocks. Hammer mills are commonly used in mechanised systems; however, other grinding machines can be retrofitted for use, provided feedstock can be cut down into manageable sizes. Materials such as sawdust, which are small, do not require crushing but larger materials can be crushed to 6-8 mm with 10-20% fines. Where crushing equipment is unavailable, simple tools such as mortar and pestle can be used to crush the large, carbonised pieces into dust. They can also be bagged and hit with a stick.
Briquetting Machine (Compactor)	Briquette Machine	Compaction can be manually or mechanically powered. Manual compaction requires melds e.g., metal cups, which hold and shape the briquette, but pressure must be applied to enable compaction. Two major types of high-compaction technologies are used for briquetting: In a piston press, biomass is extruded through a die by a reciprocating ram at a very high pressure. In a screw press, the biomass is extruded continuously by a screw through a heated taper die. If a machine is not available/accessible/affordable, briquettes can be moulded using bare hands, or compacted in empty plastic containers.
Product Drying		Briquettes can be dried in well-constructed drying racks or placed on a bag under the shade to dry.
Miscellaneous	Items can include, shovels, wheelbarrow, containers etc.	

2.3. Selecting a Site for Biomass Briquette Production

To ensure effectiveness, sustainability, and profitability, there is a need for careful consideration of where a briquetting facility is located and how it is operated. Several factors need to be carefully considered including availability of water and energy and access to the market and labour. An example of a site layout for a small-scale biomass briquette facility is illustrated in Figure 2-1.

An ideal site should:

- ☑ Be closely located to biomass supply to minimize costs and environmental impacts.
- ☑ Have access to water but not sited close to a water source to reduce pollution risks.
- ☑ Have sufficient space to accommodate process equipment and any drying and storage requirements. A small-scale facility will require about 15 m^2 but a large production facility might take up to 100 m^2 depending on the scale and type of equipment used.
- ☑ Be well laid out: encourage first-in, first-out biomass storage, organized production of biomass briquettes, safe operation, maintenance, and operation of facilities.
- ☑ Be accessible to the public to reduce the logistical challenges associated with the delivery of biomass feedstocks and collection of products.
- ☑ Be secure, that is safeguarded from theft and vandalism and from extreme weather conditions.



Tips

Optimize layout based on plant's processing stages, in a way that:

- Feedstock and product losses are minimized.
- There is minimized risk of fires, from vehicle sparks/fumes and carbonisation equipment.
- There is reduced occupational health hazards due to manual labour, slips, trips and falls.
- There is direct access to solar energy for open drying areas/racks.
- There is access to vehicles for delivery of feedstock delivery and product collection.

Figure 2-1: An example of a site layout for a biomass briquette facility (not drawn to scale)

2.4. Sourcing of Biomass Feedstocks

As outlined in Part 1, biomass can be sourced from a variety of sources, ranging from forestry wastes, agricultural residues to animal manure. Section 2.4.1 outlines how to select the right feedstock for biomass briquettes considering seasonal availability, environmental sustainability, and alternative use of the feedstock. Additionally, safe handling, storage, and processing should be put in place for high-quality briquette production, as described in section 2.4.2.

2.4.1. How to select the right feedstock for biomass briquette production

Biomass materials can be sourced from a variety of sources. Selecting the right feedstock is a critical step for producing high-quality briquettes. Some important considerations include:

- ☑ Local Availability: Ensure the biomass feedstock is readily available in your area to reduce costs, transportation requirements, and environmental impact.
- ☑ Costs: Consider costs and alternative use of the feedstock before selection. What types of wastes are being processed, at what distances, and at what cost? Are there competing uses for waste streams in target areas? Any supply limitations concerning the periodicity or seasonality of the feedstock? Who delivers the waste and at what costs?
- ☑ Environmental Sustainability: Consider the environmental impact and sustainability of the process and products. Is the feedstock from a renewable source and in proximity to the production site? What are the known occupational health hazards associated with feedstock, if any? For example, is feedstock polluted with contaminants and will it result in environmental pollution if burnt? Will the feedstock compete with food or result in significant land use changes? Are there any environmental benefits for humans and nature?
- ☑ Biomass Composition & Size: Prioritise biomass with low moisture and ash content such as agricultural residues for high-quality briquettes. High calorific value and carbon materials can be identified in Table 1-5 (Part 1), those with high energy per unit mass. This will help the fuel to burn longer and can increase its mechanical strength.

2.4.2. How to safely handle and store biomass feedstocks and briquettes

Safeguarding biomass feedstock through appropriate handling and storage is indispensable in preserving its quality. The method you choose depends on the type of biomass feedstock and your specific needs e.g., environmental conditions, production scale, feedstock seasonality, and material bulk density. Storage can be in an enclosed structure (outdoor or indoor) or in storage bins (of various sizes), provided there is sufficient reserve and quality at the point of use. Some guidelines for handling and storing biomass feedstock for briquette production are listed below.

- Biomass feedstocks and briquettes must be kept in a dry, cool area away from heat and ignition sources and stored in small piles or thin layers, rather than large piles to allow maximum cooling effect and prevent self-heating/ignition.

- Materials can be stored outdoors provided they are shielded from rain and extreme wet conditions e.g., in a shed or roofed structures (Figure 2-2); however, large volumes should be avoided due to fire risks.
- Materials should be separated from other waste streams and soils to prevent contamination.
- The temperature distribution of the storage compartments should be measured and monitored, and storage time-limited based on first-in, first-out principles.
- To prevent fire risks, monitor and control all heated and electrical equipment in the area of storage and remove any heat source.
- The carbonisation process must not be completed indoors, within an enclosed space, and without the monitoring of harmful gases. Adequate ventilation must be ensured in all production areas to prevent the accumulation of dust and inhalation of toxic fumes.
- It is recommended that personnel wear CO detectors when carbonizing biomass to minimize health risks. Ensure maximum ventilation in handling areas to reduce health risks.
- Incomplete combustion of biomass briquettes can release toxic gases; hence stoves, heaters, or combustion systems should be properly maintained and functioning.
- As biomass is often derived from waste, safety precautions must be taken to ensure that handwashing is completed after handling materials and before eating. No eating or drink consumption within and around briquette production facilities.

Storage and handling practices need to be adjusted to environmental conditions due to seasonal variations in moisture content and temperature. Extra precautions might be required to keep feedstocks and products dry; hence regular visual inspection and monitoring will be important.

Figure 2-2: Sawdust is passively dried in a solar dryer at Somanya Biomass Briquetting Plant in Accra Ghana. Photo Credit: Dzifa Agbefu, IWMI

2.4.3. How to pretreat biomass feedstocks

Pretreatment is often essential because of the variability of biomass feedstocks. For example, different fractions of the same plant e.g., the leaves, stems and husk differ in their moisture content, size, and composition. In this regard, pretreatment helps to make the different parameters consistent or uniform. Some of the ways to pretreat biomass feedstocks include sorting, screening, and crushing to reduce size (Refer to Table 2-3).

Table 2-3: Common pretreatment methods and their application

Pre-treatment Method	Manual Operation*	Recommendations
Sorting - to separate waste streams and cluster based on size or types.	 Sorting by hand	☑ Optional – useful for classifying different materials based on fractions, sizes, shapes and densities e.g., fine, light materials from coarse, heavier materials. ☑ Can simply be done by hand
Screening - to remove unwanted materials such as stones, plastics, glass etc.	 Use of tray sieves	☑ Essential for wood, agricultural residues and mixed waste streams - materials like sawdust which are small and may contain wood strips, steel and stones. ☑ Can simply be achieved with tray sieves
Crushing – to cut down biomass into manageable sizes	 Use of mortar and pestle	☑ Materials such as sawdust, which are small, do not require crushing. ☑ Larger materials can be crushed to 6-8 mm with 10-20% fines to optimise results. ☑ Crushing can be done manually using mortar and pestle or mechanised using a hammermill or similar equipment.
Drying – to remove/reduce unwanted moisture	 Sun dry materials	☑ For highly moist fuel, drying is mandatory. ☑ Drying is not normally required for materials like groundnut shells and rice husk, but moisture levels must be < 15 wt.%. ☑ Drying trays can be used to pre-dry
Mixing – to enable even distribution or make uniform	 Mixing by hand	☑ Essential for mixed waste streams and when separate batches are received. ☑ This can be achieved manually.
Wetting – to adjust moisture or improve mixing	 Wet with water	☑ If materials are too dry and dusty, it might be necessary to wet them slightly with water. ☑ High moisture material can be mixed with dry product or binder used to wet materials

* Photo Credits: Njenga, 2014

2.5. Carbonising Biomass Feedstocks

Carbonisation (also described as slow pyrolysis) involves heating biomass in the absence of air or in a low-oxygen environment where airflow is very limited. The process breaks down complex biomass materials into volatile gases, charcoal (carbon) and tar. If the biomass is wet, the material must first be dried before carbonisation begins and a lot of tar is produced which can be avoided. The extent of carbonisation depends on the type of biomass, carbonisation temperature, and the environmental conditions e.g., the amount of air taking place in the reaction. This might take a few hours to days depending on the type of facilities used and the quantities produced. A simple method for carbonising biomass in a manual operation is described in Table 2-4. You will require a burn kiln but if not available, this can be made from a used oil barrel (See Figure 2-3).

Figure 2-3: Carbonisation equipment made from used oil barrel. Photo Credit: James K. Gitau

Table 2-4 - How to carbonise biomass for briquette production.

Step 1: Prepare the biomass feedstocks	☑	Ensure any unwanted impurities such as stones, and plastics are removed and required pretreatment is done.
Step 2: Prepare the burn kiln or metal drum	☑	Ensure that the container has a tight-fitting lid and an appropriate vent to safely remove any volatile gases produced.
	☑	Ideally, the burn kiln should have a chimney on top of it to move gases away from the producer and others around the facility. The smoke passing through the chimney should be harvested as wood vinegar.
	☑	Ensure that the container is clean e.g., from oil and greases.
Step 3: Load the Burn Kiln	☑	Use a shovel or similar tool to convey the biomass into the burning kiln. Pack the dry biomass into the drum until it is fully loaded.
	☑	A hole can be left in the middle of the drum while compacting materials.
	☑	Fill the container to the top, leaving the space for gases to expand.
Step 4: Seal and make air-tight	☑	Ensure that the container is airtight, and a limited amount of air is allowed into the process.
Step 5: Heat the biomass	☑	High temperatures are required for a quality process. Temperatures of ~700°C can reduce dangerous pollutants such as Polycyclic Aromatic Hydrocarbons. If you have a thermometer, the temperature can be monitored ensuring that heating is taking place and temperatures between 300 and 600°C are achieved.
	☑	Heating can be done in two ways: directly heating by igniting the biomass at the top or indirectly heating the metal drum at the base. You might need a kindling material such as paper or wood, but petrol/kerosene, plastics should be avoided.
Step 6: Allow carbonisation	☑	Limit the amount of time that the container is opened and allow the process to be completed. As heating takes place, gases are released and over time the material changes color.
	☑	Keep an eye on how the smoke changes from a deep, dense white smoke (during carbonisation) to a light, blue smoke (when carbonisation is done).
Step 7: Cool gradually to room temperature	☑	Avoid opening the container while the metal drum is still hot to prevent char burnout or scalding.
	☑	Once carbonisation is complete, seal all inlets to starve the process of oxygen and remove char-like (black and brittle) material when the burn kiln is cool.
	☑	Store the product in a cool dry well-ventilated space.

2.5.1. How to select a carbonisation equipment

There are various types of burn kilns, all differing in shape, capacity and performance – traditionally made with mud and bricks but in varying modern contexts, metal containers are used. The kind of feedstock, production volume, need for temperature control, and desired products and byproducts are just a few of the variables that influence the type of kiln used for carbonisation. A description of key technologies used for biomass carbonisation is provided below.

Earth Kiln: They look like brick or earthen mounds (Figure 2-4a) with a central chimney - traditionally used in the production of conventional charcoal. To use: Logs of wood are placed on the ground with space between them to allow air passage. The pile is built to a meter high and covered with leafy vegetation 30 cm deep and soil or clay. The materials are then set on fire and allowed to burn vigorously. They are low technologies, and useful in situations where capital is scarce but inefficient. Materials required include space for earth kiln, spade, ax and biomass feedstock.

Oil Barrel Kiln: Oil drums with a volume of 200 – 250 L are modified as drum kilns (Figure 2.4b) with a small opening for kiln lighting, a lid to cover the kiln, and a chimney to let out the smoke. At the base, 2 – 5 cm wide holes are drilled to allow a small amount of air, but this can be channeled to a plug fitting so that air can be controlled if needed. It is estimated that a kiln can produce 1 ton of charred biomass monthly and the recovery rate is about 30%. The inexpensive oil drums make this cost-effective, but they do have a limited lifespan, except if fabricated from steel sheets. Smoke is cooled and harvested as wood vinegar through the chimney.

Metal Retort Kilns: They are more effective than traditional earth kilns. They are metal cylinders, frequently with an external heating source applied to the retort after the biomass has been loaded (Figure 2c). Better temperature control and gas collection capabilities of these kilns enable them to be used for large-scale production. A tar condenser may be fitted, and by-products like wood vinegar can be collected. Tar may also be collected and used for road construction or other uses.

Figure 2-4: Examples of different carbonisation equipment. a) wood charcoal production with a traditional earth mound kiln near Pondicherry, India, b) a burn kiln made from used oil barrels in Kenya, c) Retort kiln design based on two-chamber, the inner cylinder filled with wood (as cited in Uwase et al. 2022). Photo credits: Adam, 2004 as cited in Biocoal.org (Left), James K Gitau (Middle), Uwase et al. 2022 (Right)

2.6. Crushing Biomass Feedstocks

When using raw materials that do not have consistent shape or size for briquette production, crushing is a critical step. Crushing ensures that the carbonised material is consistent in size and can bind together during briquetting. To prepare charcoal fines that can be mixed with a binder, small particles should be distinguished from large chucks using screens or sieves and any lump carbonised particle can be crushed to 6-8 mm. There are many types and sizes of crushing and grinding equipment, from a few kg to 10-15 tonne per hour. These machines often use hammers or other grinding or rolling mechanisms for size reduction. Alternatively carbonised particles can be grinded to fines using a mortar and pestle for small-scale production (as shown in Figure 2-5); however, motorised equipment will be required for medium- to- large scale production.

Figure 2-5: A mechanical crusher in Somanya Plant used for wood chips. Photo credit: Dzifa Agbefu, IWMI

Tips

- ☑ Large chunks of biomass should be crushed to about 6-8 mm, retaining about 10-20% fines for optimum results.
- ☑ Moisture content is a critical factor when crushing. Excessive moisture in the carbonised biomass will cause the material to become a sticky paste but if too dry, a high amount of dust will be generated.
- ☑ Work outdoors if possible and in a well-ventilated area, wearing the necessary protective gear, such as gloves, safety glasses, and nose mask.

2.7. Mixing and Blending with Binder

When using multiple materials, of different or inconsistent composition, mixing is a critical step. For instance, biomass materials with high ash content and biomass materials with low ash content can be combined. Rice husk is a good example of a biomass with low energy content, and this can be mixed with cow dung to achieve high energy content. This ensures that the carbonised material is not only consistent in size but also in composition before briquetting. Blending is also necessary to coat the charcoal particles with a film of binder. To achieve this, an appropriate binder e.g., starch or clay should be added and mixed thoroughly with the fine carbonised biomass (as shown in Figure 2-6). This can be done manually for a small mixture or in a kneader-type, double shaft mixer, stirring continuously, a binding paste is formed which is not sticky to touch. Water can be added to the mixture if the binder is not in a liquid form or materials remain dry upon mixing.

Figure 2-6: Women mixing carbon dust and binder using a manual mixer. Photo Credit: James K. Gitau

Tips

- ☑ Mix raw materials thoroughly until is uniformly mixed.
- ☑ Mould one briquette and shake it between the thumb and index finger to test if it holds together. If holds make the rest of the briquettes and if it doesn't, add more binder/charcoal dust.
- ☑ Test the mixture to confirm it is ready for making briquettes. If crumbly, add more binder. If briquette mixture does not hold a form, add more charcoal dust and/or binder as necessary. If too dry, add more water or binder in liquid form.
- ☑ Work outdoors if possible and in a well-ventilated area, wearing the necessary protective gear, such as gloves, safety glasses, and nose mask.

2.8. Briquetting (Compaction)

The process of manually briquetting loose biomass materials into solid fuel is a simple and low-technology process; however, the compressive strength of the product is not as high as those machined. Figure 2-7 shows an example of a briquetting process completed with a metal briquetting machine, but this can be formed by hand with using molds of diverse shapes and sizes. To form briquettes by hand, shape a handful of the mixture into the shape of a briquette e.g., cylinders and rectangular blocks, ensuring it is tightly packed. The act of manually producing briquettes requires a great deal of physical effort and is commonly practiced on a small scale, particularly in remote areas with limited access to equipment. Though not as efficient as mechanical briquetting machines, this method can still be a viable and eco-friendly solution for those with limited resources to produce their own fuel.

Figure 2-7: Women compacting briquette using a manual briquetting machine. Photo Credit: James K. Gitau

Tips

- ☑ Choose a mold shape and size that is suitable for the application. Cylindrical molds are popular.
- ☑ Mold should be durable to withstand frequent use. Metals like steel and aluminum are common.
- ☑ To prevent the briquette mixture from adhering to the mold, coat the inside of the mold with a non-stick substance. You can apply either cooking oil or a release agent for this purpose
- ☑ Fill the mold evenly, press down firmly on the mixture as you fill the moulds. Remove air pockets.
- ☑ If pressing by hand, take a handful of the mixture and shape it into a tightly packed briquette. To keep the briquette from disintegrating, make sure it is tightly compacted – a hammer might help to compact it in stages. Gentle set on drying racks to avoid breakage.

2.9. Drying, Storage & Packaging

Set the freshly formed briquettes on a mesh/sheet in a well-ventilated area to dry. The briquettes can be dried in a warm area under a shade or plastic sheet to prevent cracking. This can also be dried in an open area under supervision as shown in Figure 2-7. Drying may last a few days to weeks, depending on climatic conditions, materials used to make briquettes and size of the briquettes. To ensure even drying, briquettes can be turned from time to time. When the briquettes are dry, store them in a cool dry place, preferably packing them in a tight-seal bag or container until its ready for use.

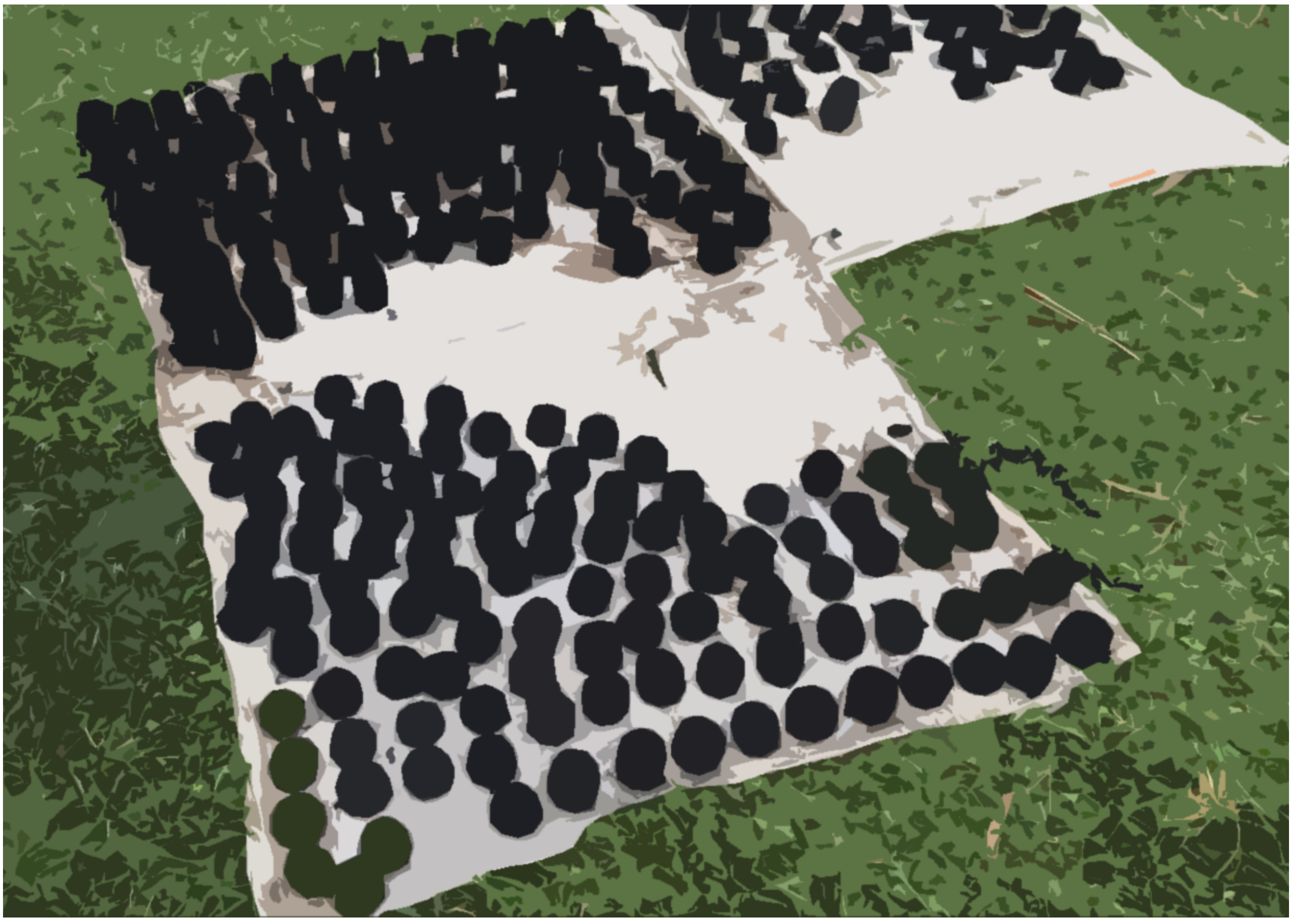


Figure 2-7: Biomass briquettes dried in open space. Photo Credit: James K. Gitau

Tips

- ☑ Place the hand-molded briquettes in a single layer on the drying surface, spacing them evenly for optimal air circulation. Stack if necessary, with spaces for air to circulate.
- ☑ Opt for a ventilated and sheltered area for drying. Sufficient air circulation promotes faster and more effective drying. Sheltering prevents wet and direct sunlight.
- ☑ Avoid prolonged exposure to strong sunlight as it can lead to cracking on the surface. Use shaded or partially shaded area or solar dryer with drying racks.
- ☑ Rotate the briquettes frequently to achieve uniform drying on all surfaces and maintain consistent hardness. Adjust drying conditions to ambient humidity and allow sufficient time.
- ☑ Store the briquettes in a dry and covered area to prevent them from absorbing more moisture.

2.10. Use of Biomass Briquettes

The burning quality of charcoal briquettes depends on the type and amount of binder used in briquette making as illustrated in Table 2-5 below. As described in Part 1, biomass briquettes can be used as fuels for: i) cooking and heating in households, using stoves or heating appliances designed to burn solid fuels efficiently. ii) heating, using boilers or biomass power plants, iii) in smelting and diverse industrial processes. Figure 2-8 provides examples of use of biomass briquettes in cookstoves and institutional stoves in Kenya.

Figure 2-8: Cooking with carbonized briquettes in a domestic cookstove (a-c) and institutional stove (d-f)
Photo credits: James K. Gitau

Tips

- ☑ Arrange the briquettes in a cookstove and light using a paper (not contaminated, laminated, heavy ink-based paper). Kindle and match just like ordinary charcoal
- ☑ Don't use plastics to light briquettes due to health and safety hazards from poisonous smoke.
- ☑ Light the cookstove outdoor but can safely be returned to the kitchen when stove is well lit.
- ☑ Once the food is ready, remove any unburned briquettes from the stove and cover them with an old pot to cut off oxygen and allow them to cool for another use.

Table 2-5: Performance of briquettes made with carbon dust and various binders

Briquette Type	Heat	Burning Period	Lighting	Ash	Smoke	Smell
Carbon Dust + Soil/Compost	Low	Very long over 4hrs. Good for heating space and foods that take long to cook	Delayed	Very high	Very low	Very low
Carbon Dust + Gum Arabica	Very high	Long about 2.5hours	Fast	Very low	Very low	Very low
Carbon Dust + Cassava	Very high	Long about 2.5hours	Moderate	Low	Moderate	Moderate
Carbon Dust + Molasses	High	Long about 2.5hours	Moderate	High	High	High
Carbon Dust + Cow Dung	Moderate	Long about 2.5hours	Moderate	High	High	High
Carbon Dust + Biodegradable paper	High	Long about 2.5hours	Fast	Very low	Low	Very low

2.11. Troubleshooting

Addressing common issues that are likely to emerge in the biomass briquetting process can help ensure successful and efficient briquette production. Some of the common problems and recommended solutions are summarized in Table 2-6. To obtain the optimum briquette quality, modifications are necessary and continuous improvement is essential.

Table 2-6: Some of the common problems in biomass briquetting and recommended solutions

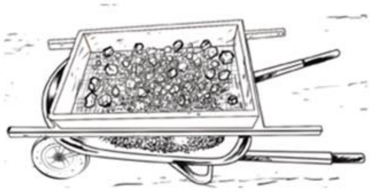
Potential Problem(s)	Potential Solution(s)
The briquettes easily crumble and do not maintain their shape.	☑ If using a binder, increase the binder-to-biomass ratio. ☑ If the mixture is too dry, you can add moisture in the form of water or water-based binder. ☑ The feedstock is not small enough to compact - reduce size. ☑ When molding the briquettes, firmly compact the mixture.
The briquettes are taking too long to dry or remain wet.	☑ If material is naturally wet, consider mixing with another biomass with low moisture content or pretreating the feedstock by drying. ☑ Ensure briquettes are not packed too tightly, enough airflow can pass through them in a well-ventilated space. ☑ Check that there is adequate ventilation and materials are not exposed to weather conditions such as rain. ☑ Ensure that the materials are above ground and absorbing water from the floor
The biomass mixture is difficult to form or doesn't hold a shape.	☑ The material may not stick together if it is too fine and dry. Ensure fine particles (<5 mm). ☑ To increase cohesion, add some water or binder. ☑ Ensure uniform composition by mixing.
When burned, the briquettes emit a lot of thick white smoke.	☑ Before using, make sure the briquettes are completely dry. ☑ Ensure carbonisation is complete before removing feedstock from the burn kiln. ☑ Do not mix raw and carbonised feedstocks. ☑ Explore other feedstocks/binder – feedstock is not suitable and may contain more volatile matter than fixed carbon.
When burned, the briquettes don't produce enough heat.	☑ Explore other feedstocks – the sample might contain more ash content than fixed carbon. ☑ If the product looks whitish, the feedstock is burnt during carbonisation stage, thereby losing some of its energy content. Check that there is limited air during carbonisation. ☑ Briquettes that have been properly compacted typically burn more quickly. Make sure the material is tightly compacted.

Appendix

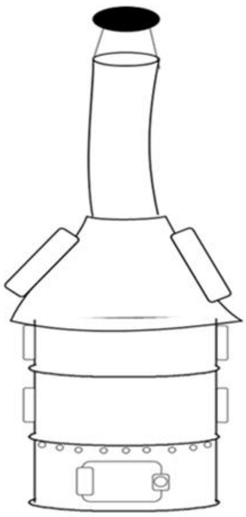
Case Study 1: Carbonised Briquette from Coffee Husks (**Household**)

Step 1: Gather Coffee Husks e.g., from farmers or co-operatives

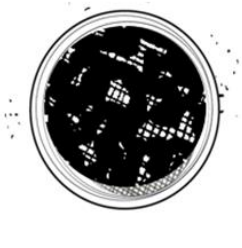
Step 2: Remove unwanted materials like stones, and plastics.



Step 3: Sun dry in a solar dryer or open air for 6 – 24 hours if needed.



Step 4: Load the Burn Kiln with dry coffee husks.



Step 5: Allow to carbonise and cool off

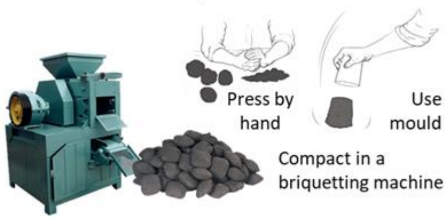
Step 6: Crush the dry carbonise coffee husks to 6 – 8 mm.

Sieve if needed

Step 7: Mix 4 parts coffee carbon dust + 1 part cassava starch binder in liquid form.

Step 8: Blend the mixture until smooth consistency.

Step 9: Mould by hand, use a mould to compact the solid.

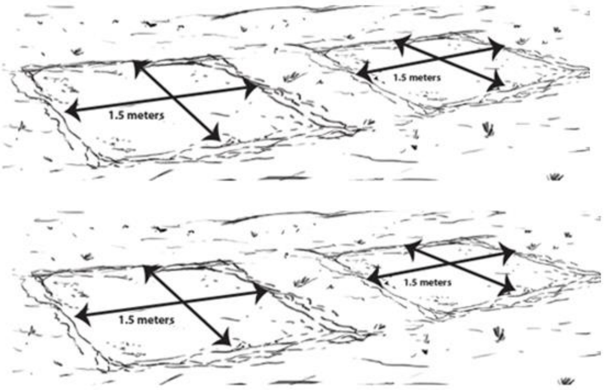


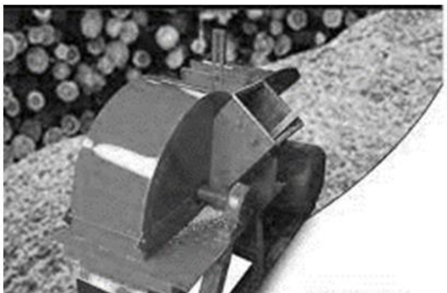
Case Study 2: Non-carbonised Briquette using wood shavings (**Industrial**)

Step 1: Collect wood shavings e.g., from wood processing industries/sawmill

Step 2: Spot remove any unwanted materials like stones, and plastics (if present).

Step 3: Sun dry in a solar dryer until needed





Step 4: Crush the dry wood chips to 6 – 8 mm.

Step 5: Add cassava starch binder (if needed)

Step 6: Blend the mixture until smooth consistency (if needed).

Step 7: Compress in a briquetting machine at high pressure

Step 8: Store in a cool, dry and well-ventilated space.

1. Supervisors are to provide PPE and ensure all workers adhere to safety rules.
2. All workers must wear appropriate personal protective equipment including gloves, safety goggles, and coveralls, onsite and around production facilities.
3. The carbonisation process must not be completed indoors, within an enclosed space, and without the monitoring of harmful gases. Adequate ventilation must be ensured in all production areas to prevent the accumulation of dust and inhalation of toxic fumes.
4. All personnel involved in carbonisation and the vicinity of the production area are recommended to wear personal CO detectors to alert them in the case of toxic gases.
5. All motorized equipment must be operated by an authorised person. The personnel must be trained on the use of equipment and adhere strictly to safety procedures.
6. All machinery and equipment are to be periodically maintained and monitored for defects or malfunctions, including electrical failures. Safety guards must be installed on machines to automatically shut down and prevent contact with moving parts.
7. There are significant fire risks when handling biomass materials and in briquette production facilities; hence fire extinguishers and fire-fighting equipment must be accessible and in good working condition. Production areas must be free from fire hazards.
8. Biomass briquette production involves lifting and moving heavy feedstocks which pose health risks. Workers must be trained in manual handling to avoid strains and injuries.
9. Materials should be stored appropriately and organized to avoid trips and falls.
10. As biomass is often derived from waste, safety precautions must be taken to ensure that handwashing is completed after handling materials and before eating. No eating or drink consumption within and around briquette production facilities.
11. All hot surfaces e.g., drum kilns should be covered, and safety precautions must be followed to avoid scalding or physical injury.
12. Personnel should be aware of potential risks and how to mitigate them.
13. All safety instructions must be understood by every employee and followed precisely to prevent unneeded accidents and damage.
14. Provide a first aid kit at the production site.

Figure 1: Biomass Briquette Facility Safety Guidelines and Protocols

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