Waste Biomass Densification for Thermochemical Conversion

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for the degree of Doctor of Philosophy

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DEDICATION

Dedicated to

My daughters, Aisha and Ameerah Isa,

My husband, Isa Mohammed,

and the loving memory of my father, Alhaji Ibrahim Katsina

ACKNOWLEDGEMENTS

I would like to start by thanking God for being my strength from the start to completion of this project.

My enormous appreciation goes to my supervisor Professor Julia Stegemann, for her immeasurable support and guidance throughout this project. For dedicating much time in reading my drafts and offering valuable corrections and suggestions. For teaching me to be more rigorous and efficient in my research and writing, Thank you very much. I wish to express my profound gratitude to my second supervisor Dr Aiduan Borrion, for providing constructive comments, expert advice and support on my research work.

I am grateful to all the people of the Department of Civil, Environmental and Geomatic Engineering (CEGE) at University College London (UCL). In particular, Ian Sturtevant, Dr Judith Zhou, Catherine Unsworth, Warren Gaynor, Ian Seaton and the workshop staffs, Leslie Irwin and all the staff of CEGE environmental, concrete and structures laboratories, for their support throughout the experimental work. I would like to thank Dr Anna Bogush for her useful suggestions on my research work, Dr Marco Lizzul for providing microalgae for the experiments, Dr Monica for providing the biosolids, and Dr Andy Chow for his help with statistics.

Special thanks to my daughter Aisha Ikram and my husband Isa Mohammed, for their patience, support and understanding throughout the period of this project.

I would like express my gratitude to my entire family, especially my mum Hajiya Hauwa Kulu Wushishi, for her moral support and prayers, and to all my siblings.

I am indebted to my cousin Umar M. Lawal, for his help with sourcing of my research materials from Nigeria, to Christie Anyebe, for helping to purchase the funding application card, to Sa’adu Gambo, and my close friends especially Susan, who have been with me all the way through.

My sincere thanks also go to my friends and colleagues at UCL, especially Konstantina Koutita (my Konstantina), for being a great friend all the way, to Mansoor Adepoju, Hadiza Auta, Lawrence Edomwonye-Otu, Sneha Krishna, Oriana Landa Consiangna and all the GM16 members.

My unquantified gratitude goes to the Federal Government of Nigeria through the Petroleum Technology Development Fund (PTDF), for funding this research project.

Finally, I would like to thank in advance the examiners for reading through my thesis.

DECLARATION

I, Rukayya Ibrahim Muazu, hereby declare that the work contained within this thesis is entirely my own. Unless otherwise acknowledged, this thesis contains no material previously published or written by another person.

Signed: Rukayya Ibrahim Muazu
University College London
Date: 08/03/2017

ABSTRACT

Waste biomass densification into briquettes and pellets improves the characteristics of loose biomass residue for efficient transport, storage and thermochemical conversion into advanced fuels (e.g., syngas, for electricity, liquid fuels and chemicals).

Briquettes of good and consistent quality are required but often difficult to achieve as more work is still required to understand how the chemical and physical properties of different biomass types, along with process variables, affect their quality. Also, the additional energy and cost associated with biomass briquetting has raised the issue of the sustainability of briquetting loose biomass before its conversion.

This research focuses on the use of novel approaches to improve the quality of fuel briquettes for thermal applications, and further evaluates the sustainability of fuel briquetting, using life cycle assessment (LCA).

Experiments were conducted to investigate the potential benefits of blending waste rice husks, corn cobs and bagasse, and with novel binders including enhanced treated biosolids, and microalgae (*Chlorella sorokiniana*), on fuel briquette properties, using factorial design methods. The new binders were also compared with existing starch binder.

The range of briquettes produced in this study had unit densities of up to 3.3 times the loose biomass bulk density, and were stronger than briquettes from the individual biomass materials. Considering average values from two biomass sources, an unconfined compressive strength of 176 kPa was achieved at a compaction pressure of 31 MPa for a 3:7 blend of rice husks to corn cobs with 10% binder (starch + water). These briquettes were durable, with only 4% mass loss during abrasion, and 10% mass loss during shattering, tests. They absorbed 36% less water than loose corn cobs. An unconfined compressive strength of 175 kPa was also achieved for a 2:4:1 blend of rice husks, corn cobs and bagasse with 17% binder (microalgae), also at a compaction pressure of 31 MPa.

The statistical analysis of the above results showed that the source of the biomass had a significant effect on densification, which emphasises the need to understand factors underlying biomass variability. Of all the briquettes produced with the three binders, those containing the microalgae binder were found to be most durable, with a higher energy density, slower mass loss during briquette combustion, and a higher afterglow time. Since microalgae may be grown using CO_2 from biomass combustion, discovery of their advantages as a binder in briquetting is particularly welcome.

To evaluate the sustainability of fuel briquetting, a detailed review of the existing LCA studies on fuel briquetting was carried out. These were found to provide insufficient and inconsistent information, due to different choices in system boundary, data sources, functional unit, allocation procedure, briquetting technology and biomass/briquette properties.

An LCA model of biomass briquetting was therefore developed to enable transparent comparison of life cycle environmental impacts of briquetting with individual or blends of biomass feeds with a variety of technological options. The main model components include materials and process inventory databases derived from standard sources, main process calculations, user inputs and results sections. The model is open-access in a user accessible format (Microsoft Excel).

A representative case study with mixed rice husks and corn cobs showed that the briquetting unit itself made the largest contribution, 42%, to the total life cycle operational energy of the briquetting system. For all the blends of rice husks and corn cobs explored in this study, the total life cycle energy of briquetting was in the range 0.2 to 0.3 MJ per MJ of fuel briquette energy content. Variation of the LCA input parameters in a sensitivity test for the same blend ratios, gave a range of total life cycle energy of briquetting from 0.2 to 1.7 MJ per MJ of fuel briquette energy content. This indicates that energy use in briquetting is not necessarily recovered, highlighting the need for continuous process optimisation and high quality LCA data.

An increase in rice husks content of the blend increased the environmental impact of briquetting including the global warming potential (kg CO_2-eq), acidification potential (kg SO_2-eq), human toxicity (kg 1,4-DB-eq), ozone layer depletion (kg CFC-11-eq), and terrestrial ecotoxicity (kg 1,4-DB-eq) per MJ briquette energy content, as it was associated with a lower briquette density, which increased the energy required for handling.

Keywords: densification; fuel; energy; LCA; modelling; biomass

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NOMENCLATURE

η_e = Thermal efficiency

M_i = target product mass (kg/h)

F_i = unit mass feed rate (kg/h)

M_e = design equipment capacity (kg/h)

R_i = product moisture content (%)

r_i = moisture loss during processing (%)

r_j = solid mass loss during processing (%)

E_i = total calculated unit energy consumption

E_e = design equipment energy consumption

V_i = maximum allowable volume (m^3) of equipment (mold in briquetting machine)

ρ_b = equipment manufacturer quoted residue density (kg/m^3)

ρ_r = density ratio (kg/m^3)

ρ_{bd} = density of biomass blend (e.g., x + y)

ρ_d = final calculated density used (kg/m^3)

N_i = calculated number of equipment

W_e = weight of equipment (kg)

E_{ee} = equipment embodied energy (MJ/kg)

T_r = total briquette curing time (h)

T_{op} = total operating time (h)

T_s = total storage time required (h)

H_s = height of storage building (m)

k_x = proportion biomass material x in blend of x and y

k_y = proportion biomass material y in blend of x and y

ρ_x = density of biomass material x (kg/m^3)

ρ_y = density of biomass material y (kg/m^3)

C_p = specific heat capacity (J/kgk)

T_c = product temperature (^oC)

LHV = lower heating value of biomass (MJ/kg)

HV_i = product heating value (MJ/kg)

Xi = fraction of various material of construction (e.g., steel, plastic) (%)

Yi = specific embodied energy factor (MJ/kg)

s = spacing between equipment and building wall

x = Base length of individual equipment

y = width of individual equipment

d_1 = vehicle allowance at building entry

d_2 = rear allowance for access/maintenance

t = building wall thickness

n = number of equipment within building

ABBREVIATIONS

kg/m^3	kilogram per cubic meter
kPa	kilopascal
MPa	Megapascal
RH	Rice husks
CC	Corn cobs
M	Material ratio
P	Pressure
B	Binder
S	Sample batch
SEM	Scanning electron microscopy
LCIA	Life cycle impact assessment
LCA	Life cycle assessment
LC	Life cycle
TER	Total energy ratio
NER	Net energy production ratio
NEB	Net energy balance
EROI	Energy return on investment
GWP	Global warming potential
AP	Acidification potential
HT	Human toxicity
ET	Eco toxicity
GHG	Greenhouse gases

1 INTRODUCTION

1.1 Bioenergy an alternative energy source

The global demand for energy is increasing with increasing population and industrialisation. The common source of energy in most parts of the world is fossil fuel, but the process of sourcing, exploration, processing and transportation of this fuel into a usable product, and its use, has resulted in various environmental problems [e.g., Pieprzyk, 2009; UNEP, 2006 & 2014]. In particular, air emissions from fossil fuel combustion increase the concentration of "greenhouse gases" in the atmosphere. Notable among the greenhouse gases are CO_2 and CH_4. Their presence in the atmosphere is resulting in an increase in the atmospheric temperature generally referred to as "global warming", the consequences of which include rising sea levels, caused by melting of glaciers, and extreme weather conditions around the world [UNEP, 2012]. As a result, the interest in energy efficiency and alternative energy sources, such as biofuels, has increased significantly in recent years. Figure 1 shows the expansion of the biofuel industry with prospect for strong continued future growth.

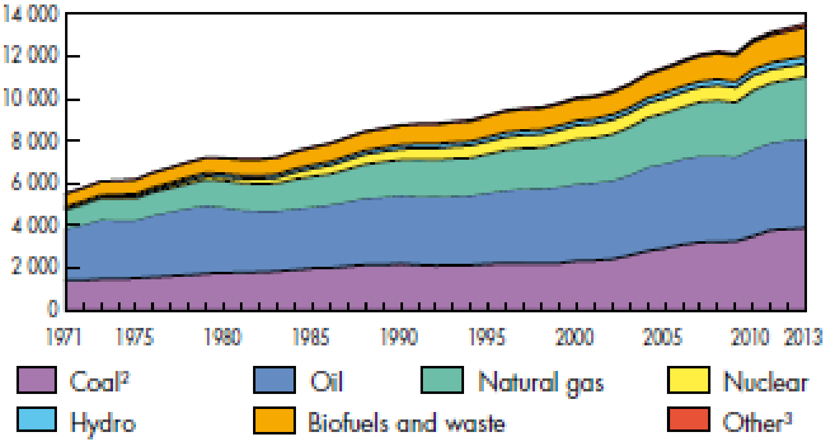


Figure 1: World primary energy supply indicating increase in energy demand across the years including the contribution of biofuels [IEA, 2015]

Lignocellullosic biomass has been identified in the literature as a reliable and promising biofuel source [FAO, 1994; Zhang et al, 2013]. Its major drawback is the competition for cultivable land between energy and food crops [e.g., Ottinger, 2007; Kocar & Civas, 2013]. However, lignocellulosic biomass can also be derived as a by-product from food crops e.g., agricultural residue, and grasses. Agricultural residues are generated in many parts of the world particularly in developing countries such as Nigeria, where farming activity is high and generation of large amount of agricultural residue is on the increase. At present, these residues are combusted directly without optimisation of energy efficiency or control of air emissions, or they are left on farm land/processing sites to decay as shown in Figure 2.

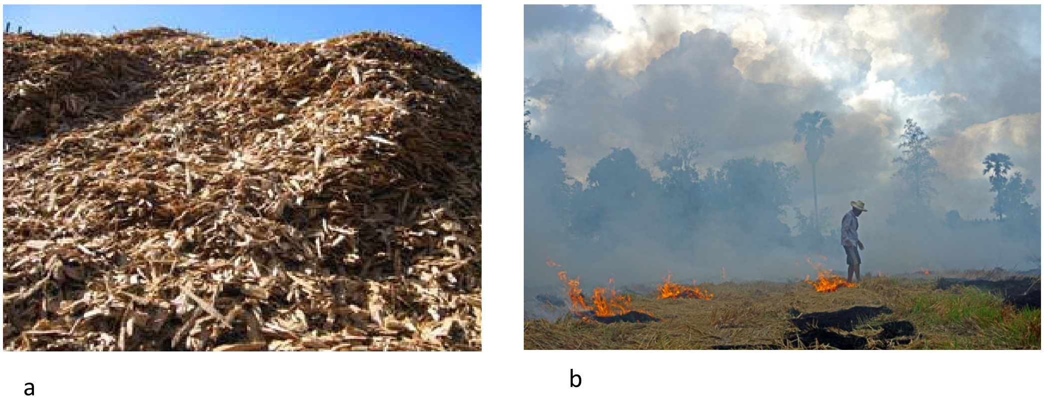


Figure 2: (a) Agricultural residue occupying large space on farm land (b) direct open burning of agricultural residues [Jacobson, 2014; Zafar, 2015]

Agricultural residues generally have a low bulk density, which makes it inefficient to transport these residues to conversion sites, hinders their uniform feeding into conversion equipment, creates a need for large storage spaces, and affects the conversion process of these residues. A study by Kumar et al [2003] examined the cost to produce biomass power from direct combustion in western Canada, and found that, of all the factors considered, transportation had the second highest cost. Similarly, Shie et al [2011], found the transportation energy as the largest (~ 46%) input energy requirement for energy generation from four potential gasification technologies. Nguyen et al [2014] also highlighted the importance of loose biomass transportation cost and handling in the bioethanol production system. Furthermore, increased ash fusion associated with fine biomass in a downdraft gasifier was observed by Sridhar et al [2006].

Densification of loose residues into solid fuels such as briquettes and pellets has been identified as a way of resolving these problems with low bulk density [e.g., Bhattacharya et al, 1996; Tumuluru et al, 2011; Chen et al, 2015]. The produced briquettes or pellets can be further converted into gas and liquid fuels and other useful chemicals, through thermochemical conversion processes including combustion, pyrolysis, gasification, and liquefaction.

The solid fuel briquette's quality is of great importance in biomass densification as a poorly produced briquette may disintegrate and crumble back to its parent material when handled, processed or stored [BEC, 2001]. This may cause emission of fines (dust particles) during transportation and processing and affects the conversion rate during thermochemical processing, which translates to an increase in cost and environmental pollution and may negate the advantages of loose biomass briquetting.

The search by producers and researchers for ways to produce consistently high quality briquettes has significantly increased in recent years [e.g., Kaliyan & Morey, 2010; Tumuluru et al, 2011; Mitchual et al, 2013; Yank et al., 2016]. Although a large amount of work concerning fuel briquetting has been carried out, the science of briquetting is still to be established. This is because more work is required to understand how the chemical composition and physical properties, along with process variables, affect the quality of fuel briquettes made from a variety of biomass materials. The provision of data relevant to briquetting of various biomass types will facilitate design of more efficient technologies for production of high quality briquettes, thus improving the use of biomass energy sources, and reduction in greenhouse gases (GHG's) emissions.

Despite the listed advantages of biomass briquetting, the additional energy and cost associated with biomass briquetting has raised the issue of the sustainability of briquetting loose biomass prior to advanced energy generation. One way to examine the overall sustainability of fuel briquetting, is by the use of life cycle assessment [LCA]. Although LCA in the field of bioenergy has rapidly increased in recent years [e.g., Hu et al, 2008; Cherubini & Stromman, 2011; Borrion et al, 2012], the LCA of fuel briquetting is still relatively rare.

This indicates an urgent need to address the underlying issues associated with biomass briquetting, and critically evaluate the sustainability of fuel briquetting, before its large scale use.

1.2 Problem statement

Achievement of good quality fuel briquettes for efficient handling and conversion of biomass into advance fuels remains a challenge to the biomass energy system. With increasing environmental concerns, the issue does not only lie in energy generation, but rather a balance between increased efficiency and reduced environmental impacts with low costs. The use of biomass in the form of briquette will have to compete successfully with direct use of loose biomass, and/or fossil energy sources (e.g., coal), on the basis of energy, emissions and cost of the overall energy system.

1.3 Motivation

The basis and key motivations to carry out this research include the following;

1. Each year, large amounts of waste biomass are produced in Nigeria, however, their contribution towards meeting national energy demand has remained rather low due to inefficient use of these residues such as in direct burning and abandonment on farm land and processing sites [e.g., Grover & Mishra, 1996; Oladeji, 2010; Emerhi, 2011]. Efficient utilisation of these wastes will reduce energy shortages and undesirable emissions, and improve waste management.
2. Variations in the properties of lignocellulosic biomass materials and briquetting variables have resulted in inconsistent quality of biomass briquettes and briquetting process efficiency. Development of ways of producing briquettes that are of better and consistent quality for efficient thermal applications is therefore necessary.
3. As environmental concerns become increasingly important, interest has shifted towards establishing a balance between increased efficiency, and reduced environmental impacts and cost of the energy generation. This has prompted the use of LCA to evaluate the environmental impacts of briquetting loose biomass before advanced energy generation. However, due to the variability of most lignocellulosic biomass residue and variations in briquetting technologies, outcomes of briquetting LCAs have also varied. A robust solution to this problem is only feasible by first understanding the fundamental differences in the LCA outcomes of various biomass feed and briquetting technologies, and how the key factors associated with the feed biomass and/or briquetting technology, impact on the LCA outcome. A clear sustainability indication of fuel briquetting, will help in harnessing the full potential and maximising the benefits of the fuel briquetting technology.

1.4 Research aim and objectives

The aim of this research was to establish novel approaches for improving the quality of biomass fuel briquettes, for thermochemical application, and evaluate the environmental impact of fuel briquetting, using LCA.

The specific objectives of this research include the following;

Objective 1: To investigate the effect of blending multiple biomass residues and briquetting variables, on durability related properties of biomass fuel briquettes.

Objective 2: To explore the use of novel binding agents with multiple biomass residues for improved physical and combustion properties of fuel briquettes.

Objective 3: To review the existing studies on LCA of fuel briquetting, identify gaps in research and understanding, and suggest possible future approaches for LCA of fuel briquetting.

Objective 4: To develop a user accessible LCA model of fuel briquetting that addresses key issues associated with the fuel briquetting system.

Objective 5: To use the LCA model developed as Objective 4 to assess the environmental impact of briquetting blends of rice husks and corn cobs.

1.5 Structure of the thesis

The thesis covers Eight (8) main chapters as shown below:

Chapter One consists of an introduction to and brief background of the overall research carried out, the research rationale, aim and objectives.

Chapter Two contains discussion of relevant literatures on biomass energy sources, the process of biomass thermal conversion and its associated challenges, a review of biomass densification into briquettes, background on LCA, and briquette application in thermal conversion process.

Chapter Three presents the overall research approach and steps used in solving the outlined research problems, showing the link from raw biomass collection to briquette production work and LCA of biomass briquetting. It presents methods adopted and used to carry out each of the research tasks, including research materials sourcing and collection, data sourcing and collection, methods used for raw materials and briquette characterisation.

Chapters Four, Five, Six and Seven describe the work achieved towards the research objectives and the specific methods used for each task including experimental design for briquette production, and briquetting LCA methodology. Chapters 4 and 5 contain experimental work carried out to investigate the production of briquettes from a variety of biomass materials and binders, whereas chapters 5 and 7 contain work on LCA of the briquette production process. These chapters include published papers and manuscripts in review as well as extended work in relevant appendices.

- The published papers include 1) Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs, Journal Fuel Processing Technology 133 (2015) 137-145, and 2) Biosolids and Microalgae as alternative binders for biomass fuel briquetting, Journal Fuel 194 (2017) 339–347.
- The manuscripts in review include 1) Life cycle assessment of biomass densification systems, submitted to Journal Biomass and Bioenergy (JBB-D-17-00111) on 01/02/2017, and 2) Life cycle assessment model for biomass fuel briquetting.

Chapter Eight summarises the overall research findings and demonstrates an original research contribution to knowledge. It also presents recommendations for further work.

2 LITERATURE

2.1 Introduction

This chapter provides background on biomass energy source, the recovery of energy from biomass via thermal conversion process, the problems associated with thermal conversion of raw biomass, biomass densification into briquette as a way of mitigating such problems, the mechanism of densification, briquetting and quality attribute of fuel briquette, the types and sources of biomass used in briquette production, properties of biomass affecting its use in briquette production, specific process variables that influence briquette quality and process efficiency, energy associated with briquette production and the need for sustainability assessment of the briquetting process, background on LCA, and finally briquette application in thermal conversion process.

2.2 Biomass energy

Biomass is any material that is sourced from plants or animals including their waste. It consists of all materials that were directly or indirectly derived from photosynthesis reactions [Van loo & Koppejan, 2008]. It is an available, cheap carbon-based material that can be burnt and used for fuel, as it reacts with oxygen in a combustion reaction and natural metabolic processes to release heat that can be utilised for electricity generation [Twidell & Weir, 2006].

Fossil fuel is thought to derive from the remains of aquatic animals and plants that lived and died hundreds or millions of years ago [Speight & Ozum, 2002]. Despite fossil fuel being derived from biomass materials, it still has a high degree of negative impact on the atmospheric carbon cycle; this is because the carbon present in the fossil has been out of the carbon cycle for over millions of years. Its combustion results in the release of millions of tonnes of carbon that has accumulated for millions of years, over a short period of time (decades). On the other hand, biomass is regarded as a carbon neutral energy source, as the carbon emitted during biomass combustion will be absorbed back by new plants during photosynthesis [Twidell & Weir, 2006], but the activities of harvesting, transportation and processing of biomass into finished useful products may be associated with carbon emissions.

Biomass is described as the only renewable source of carbon that can be converted into various types of fuel. According to Twidell [1998] and Demirbas [2001], the available net energy from combustion of biomass ranges from 8 MJ/kg for green wood to 20 MJ/kg for dry plant matter and 55 MJ/kg for methane; these values can be compared with coal, which has a net energy of 27 MJ/kg when combusted.

2.3 Thermal conversion

Biomass application for energy includes, combustion, gasification, pyrolysis in both domestic and industrial equipment such as boiler, local stoves and gasifiers [Purohit et al, 2006], biomass combustion mainly provides heat energy [Zhang et al, 2010], while pyrolysis and gasification provides both heat and intermediary products for advance biofuel production. These processes are classified as more energy efficient (75-80%) [Mckendar, 2002], and environmentally friendly compared with direct combustion [Zhang et al, 2010].

Gasification has the best fuel flexibility among the many advanced technologies for power generation [Liu, 2010], it is regarded as an efficient and advanced technology for extracting the energy from biomass. As a result, the use of biomass in gasification technologies has attracted attention in recent years [e.g., Tasma et al, 2012; Malatji et al, 2011]. The gasification process converts the intrinsic chemical energy of the carbon in the biomass into a combustible gas that can be standardised in its quality and is easier and more versatile to use than the original biomass [Liu, 2010].

The gasification process generally starts with 1) drying to evaporate moisture from biomass feed, followed by 2) pyrolysis or devolatilisation, and 3) gasification [Bridgewater, 2003]. When biomass materials are heated to 300 – 500°C in the absence of an oxidising agent, they pyrolyse to solid char, condensable hydrocarbons, and gases. The relative yields of these products depend mostly on the rate of heating and final temperature. The gas, liquid and solid products of pyrolysis further react with the oxidising agent (e.g., air) [Han & Kim, 2008; Basu, 2010].

The product gas from gasification is a mixture of CO and H_2 known as synthetic gas (syngas). This “syngas” has various applications such as heat and electricity generation in gas turbine or generator engines, hydrogen production, Fischer Tropsch diesel, liquid synthesis and chemicals [e.g.., Basu, 2010].

Different gasification medium, including air, oxygen, steam, CO_2 and hydrogen, have been employed to gasify different types of feedstocks. Air gasification has been identified as the cheapest [McKendry, 2002], but results in high contaminant formation when compared with the other gasification medium. The use of gasification in coal conversion has been well established, while the use of gasification for biomass conversion is still under development, except for some wood biomass and MSW [e.g., Erlich et al, 2006].

Due to the low bulk density of unprocessed (raw) biomass materials, its direct use can lead to problems during storage, transportation, handling and the thermal conversion [Van Loo & Koppejan, 2008], resulting in increased cost of energy generation from biomass. This has contributed to the current economic and technical barriers facing the commercialisation of biomass gasification technologies. Therefore, numerous strategies have been developed to convert various types of biomass into secondary fuels that have better characteristics compared to the parent material(s). These strategies include biomass densification.

2.4 Biomass densification

2.4.1 Introduction

Biomass densification involves its compaction into a pellet or briquette of up to ten times higher density than the parent material(s) [Bhattacharya, 1996; Tumuluru et al, 2011]. Such processing increases biomass bulk and energy density per unit volume, leading to lower storage requirements, more efficient transportation, reduced particulate emissions per unit volume of material transported or combusted, and uniform feeding into industrial equipment such as boilers and gasifiers [Grover & Mishra, 1996; Demirbas & Demirbas, 2009].

The two methods generally employed in particulate materials size improvement include, Tumble and pressure agglomeration [Pietsch, 2002]. In tumble agglomeration, equipment such as balling discs, cones and drums are used to pelletise loose materials containing binder, while pressure agglomeration uses pressure within a confined volume to bring smaller particles together [e.g., Kaliyan & Morey, 2009; Tumuluru et al, 2011].

Densification is classified under the pressure agglomeration, and has found application in various industries such as food, pharmaceutical and bioenergy. Densification may be achieved using a pellet mill, briquette press, cuber, screw extruder or tabletizer [Tumuluru et al, 2011]. The conventional densification processes commonly used in bioenergy production are, (i) pelleting (pellet mill), and (ii) briquetting (briquette press) [Li & Liu, 2000]. The difference between briquetting and pelleting technologies can be associated with mainly the solid fuel particle size. Pelleting employs smaller die (hole) to produce small solid fuel or feed called pellet [Eriksson & Prior, 1990], while briquettes are larger in solid fuel size, and can be made with loose biomass of larger particle size through mechanical interlocking [Tumuluru et al, 2011], which may not be applicable in pelleting.

The study of biomass densification has been carried out for many years by a number of researchers [e.g., Bhattacharya et al, 1996; Li & Liu, 2000; Kaliyan & Morey, 2009; Tumuluru et al, 2011; Mitchual, 2013]. Although, more work was focused on pelleting for its specific application in industrial processes (e.g., co-firing with coal) and animal feed production, the use of briquettes in industrial boilers and domestic applications have also been carried out [e.g., Grover & Mishra, 1996; Demirbas & Demirbas, 2009; Chen et al, 2016], and in recent years, briquettes are even utilised in gasification processes.

2.4.2 Mechanism of densification and particle binding

The high pressure during densification allows biomass material to release its natural moisture in the form of steam thereby reducing its basic tissues (hemicellulose and lignin) into lower molecular carbohydrates, sugar polymers and other derivatives, these resulting products enhance binding of particles together with further pressure application, and even better compaction with further addition of heat (to softens the structure of the material) [Grover & Mishra, 1996].

Particle bonding in biomass densification has been studied and reported by others [e.g., Mani et al, 2002; Kaliyan & Morey, 2009]. Pietsch [2002] classified binding forces that act between particles into five precise groups; solid bridges, attraction forces between solid particles, mechanical interlocking bonds, adhesion and cohesion forces and interfacial forces and capillary pressure. These forces have been studied and observed during densification of biomass fuel [e.g., Lindley & Vassoughi, 1989; Tabil & Sokhanji, 1996; Guo et al, 2016], animal feed [e.g., Briggs et al, 1999] and pharmaceutical powders [e.g., Ghebre-Sellassie, 1989].

Solid bridges emerge as a result of chemical reaction between particles, which results in the solidification of melted substances and hardening of binder. The interfacial forces and capillary pressure act as a result of liquid or moisture presence in the biomass material, and, as pressure increases, particles get closer, reducing the void spaces. Intermolecular forces (van der waals) act between the particles and mechanical interlocking between particles occurs. Finally, the material becomes compacted with a reduced volume. Mechanical interlocking of biomass particles may vary with feed biomass morphology. For example, rough surfaces and less round particles are expected to interlock more compared with smooth and round particles.

2.4.3 Biomass briquetting

Briquette presses include hydraulic or mechanical piston and screw presses, using either an oscillating piston or tapered screw to compact and then release, or extrude, briquettes, respectively [e.g., Grover & Mishra, 1996; Tumuluru et al, 2011]. In a briquette press, feed materials pass through an initial densification phase where air is removed from low bulk density materials by compressing it with a tapered auger [Kaliyan & Morey, 2010a]. This is followed by application of high pressure to compact the material flowing between two rollers. Briquettes of desired shape and size can be form through pockets available on the surface of the roll [Kaliyan & Morey, 2009; Kaliyan & Morey, 2010a]. The extrusion stage involves releasing or forcing of the compacted material out of the mold, after the desired load has been reached. Immediately after extrusion, the fuel briquette enters a relaxation stage leading to increase in volume and decrease in density of briquette until a stable relaxed density of briquette is reached [e.g., Guo et al, 2016]. The relaxation rate of briquette varies significantly with the type of material used in briquette production as well as the type of briquetting technology employed [Ndiema et al, 2002].

The temperature of the briquettes leaving the densification equipment is generally higher than the raw or conditioned feed due to frictional heat developed in the pressing systems. Therefore, briquettes are cooled using ambient air or standard curing equipment such as a box dryer and/or counter-flow cooler, before storage and packaging [Thomas et al, 1998; Megalli et al, 2009]

The typical size of briquettes produced with screw press has 40 mm diameter by 40 mm length, and can have unit densities between 800-1000 kg/m^3 [Song et al, 2010], while those produced using a piston press can have unit densities of over 1000 kg/m^3 [Nielson, 2011].

The key attributes of a fuel briquette include: moisture content, density (unit and bulk), calorific value, durability (shattering and abrasion index) and percent fines.

2.4.4 Quality of biomass briquettes

Since standard criteria for solid fuel quality are still under development, some researchers [e.g., Waelti & Dolbie, 1973] have suggested standard measures for some densified fuel attributes, which vary from one geographical region to another. Other standards are also available for testing the quality solid fuels (particularly pellets, but also briquettes). For example, international standards have been established in the U.S by the Pellet Fuel Institute (PFI) and in Europe by CEN. These are shown in Table 1.

Table 1: Standards recommended for measuring densified biomass quality [Tumuluru et al, 2011]

Pellet Quality	**Common European standards (CEN)**	**Pellet Fuel Institute (PFI)**
Moisture Content	CEN/TS 15414-1:2010	ASTM E 871 Standard Test Method for Moisture Analysis of Particulate Wood Fuels
Bulk Density	CEN/TS 15401:2010	ASTM E 873 Standard Test Method for Bulk Density of Densified Particulate Biomass Fuels.
Calorific Value	EN 15400:2011	ASTM E 711 Standard Test Method for Gross Calorific Value of Refuse- Derived Fuel by the Bomb Calorimeter
Durability	CEN/TS 15639:2010	Kansas State University Mechanical Durability of Feed Pellets, Call Number: LD2668.T4 1962 Y68, for assessing the durability of residential/commercial densified fuel products, with the exception that the screen size used in determining durability has been modified to be a 1/8-inch (3.17mm) wire screen sieve.
Percent Fines	3.15 mm screen	1/8-inch (3.17 mm) wire screen sieve

Note: *Unit density is not a standard followed by PFI and CEN, but the American Society of Agricultural and Biological Engineers (ASABE) has a standard procedure (ASAE S269.4) for measuring unit density of pellets and briquettes. Source: CEN/TC 343 - Published standard PFI Standard Specification for Residential/Commercial Densified Fuel, October 25, 2010.*

The bulk density of biomass briquette is important as it helps to estimate the transportation and storage space requirement of the briquettes, it is also useful in the design stage of transport and storage facilities. Measurement of bulk density can be carried out experimentally, using available standards (Table 1). Like the unit density of individual briquettes, the bulk density of briquettes is influenced by the porosity within the bulk sample of briquettes. Porosity can be described as the fraction of volume of space between solid particles of the fuel briquette to the total volume [e.g., Karunanithy et al, 2012; Glover, 2015]. Karunanithy et al, [2012] used Equation 1 to determine the porosity of briquettes using the bulk and true densities. The porosity of a bulk solid may vary with type of materials, solid packing, solid shape and distribution [Glover, 2015].

$$Porosity = \left(1 - \frac{Bulk\ density}{True\ density}\right)$$

Equation 1

In terms of solid fuel briquettes, the reported densities are mostly the unit densities of briquettes [e.g., Grover & Mishra, 1996; Kaliyan & Morey, 2010], while the bulk density reported are relatively rare. A range of briquette bulk densities was reported by Karunanithy et al, [2012] to be 285–964 kg/m^3, for different biomass briquettes including corn stover, switchgrass, prairie cord grass, sawdust, pigeon pea grass, and cotton stalk, and with true densities in the range of 1340 and 2190 kg/m^3. Others reported bulk densities in the range of 450 to 700 kg/m^3 [e.g., Sokhansanj & Turhollow, 2004] and 674 to 816 kg/m^3 [Wakchaure & Sharma, 2007].

A number of standards are available for evaluating the quality performance of fuel briquettes including bulk density, example of these standards includes CTI - R 04/5, and the UK code of good practice, however, the two most recognised are DIN 51731 and the Ö-Norm M7135, and both provide a basic quality standard for solid briquettes. The latter did not specify minimum recommended bulk density requirement of the solid briquettes [Hahn, 2004] but other standards recommended a range between >500 to >750.

The reported range of bulk densities in the literature [e.g., Sokhansanj & Turhollow, 2004, Wakchaure & Sharma, 2007], fall within the standard recommended bulk densities of >600 kg/m^3 by the UK code of good practice except for the lower range of 450 kg/m^3. The correlation between porosity and bulk density, can be used to provide an estimate of possible bulk density of briquettes based on the packing and shape of the produced briquettes. For example, the upper range of briquette true density of 2190 kg/m^3 obtained by Karunanithy et al, [2012] can be theoretically estimated to have bulk density of 1043 kg/m^3, based on a cubic grain packing arrangement. It is important to highlight that since the relationship of briquette porosity, bulk density and true densities is very close, achieving a high bulk density of briquette is feasible when true density of briquette is reasonably high.

2.4.5 Materials for biomass briquetting

2.4.5.1 Sources of biomass and properties

Different sources of biomass exist which include the following;

- Wood and wood wastes are the most common type of biomass in existence and have been used as a source of heat and energy since mankind needed fire for warmth and cooking. It still serves as a source of energy for many developing countries. It can be used in different forms e.g. sawdust, large blocks, wood chips and scraps [Vassilev et al, 2010].
- Agricultural biomass includes all crops such as corn, sorghum, sugarcane etc. and residues from agricultural harvesting and processing, e.g. straws, husks, broken branches and fallen leaves amongst others [Vassilev et al, 2010].
- Waste paper from our offices, schools, homes, packaging etc. are made from plant materials (usually wood) and therefore can be regarded as biomass.
- Municipal solid waste (MSW) contains a mixture of biomass in the form of food scraps, waste paper, leaves from trees and other solid waste.
- Human and animal wastes can be used to generate methane gas, a constituent of natural gas.
- Aquatic plants include algae, water weed, water hyacinth, reed and rushes.

Biomass materials that can be used in densification process include; wood scraps from forest, waste from wood industries, loose agricultural residues and other combustible wastes materials. These materials have been utilised in many densification studies, for example; straw and grasses [e.g., Demirbas, 1999; Ndiema et al, 2002; Adapa et al, 2009], olive cake/waste [e.g., Yaman et al, 2001] wood and wood waste [Chin & Siddiqui, 2000; Demirbas et al, 2004], sorghum residue [e.g., Bamgboye & Boluwafi, 2009] and palm fibre [e.g., Bin Hassan, 2009].

Furthermore, charcoal produced from biomass materials have also been utilised in both briquette and pellet production [e.g., Bhattacharya et al, 1996]. In addition to the listed biomass materials, briquettes have also been produced from fossil fuels such as coal, coke, and ash from power plant [e.g., Beker & Küçükbayrak, 1996; Diez et al, 2013; Mollah et al, 2016].

Figure 3 shows sample of briquettes produced from wood biomass (different parts of Oak tree including; sawdust, mulch, bark mulch and chips) at 138 MPa.

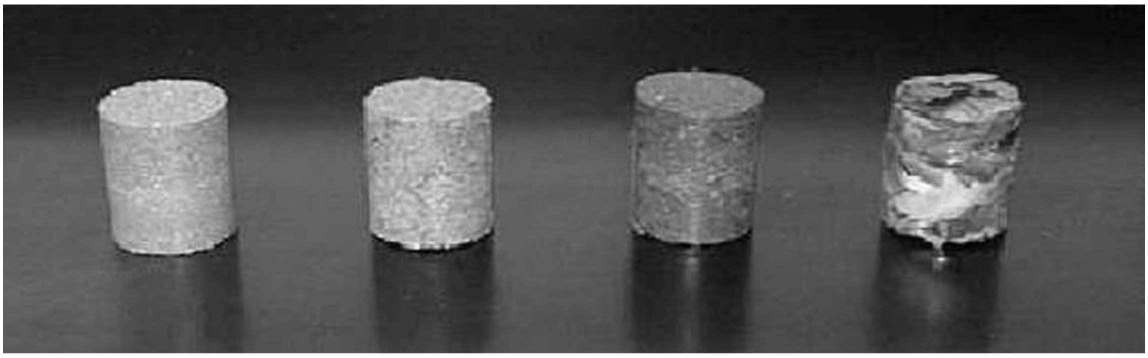


Figure 3: Sample of briquettes produced from different parts of Oak tree [Li & Liu, 2000]

Although most of the work carried out so far on briquetting has been with woody biomass such as sawdust, a relatively large work on briquetting with agricultural residue has also been reported [e.g., Grover & Mishra, 1996; Grover & Mishra, 1996; Bhattacharya, 2003; Demirbas & Demirbas, 2009; Tumuluru et al, 2011].

2.4.5.2 Agricultural residues

The main bioenergy sources are crops and wastes biomass. Agricultural residues are one of the largest sources of waste biomass [e.g., Nonhebel, 2007; Kallis, 2012].

Although large amounts of agricultural residues are generated in many parts of the world, their utilisation for energy is low compared to wood biomass and fossil sources. For example, the use of wood energy in various forms in Nigeria, especially in the rural areas accounts for about 51% of total annual energy consumption in the country [Olorunnisola, 2007; Bello & Adegbulugba, 2010]. The environmental problems caused by deforestation and the abundance of underutilised crop residues is shifting interest towards the use of agricultural residues for energy purposes.

Agricultural biomass such as rice, corn and sugarcane is cultivated in large quantities in Nigeria. For example, Nigeria was identified as one of the largest rice and corn producing countries in the West African region, with estimated annual production of 3 and 7 Mt of rice and corn respectively [Ezedinma, 2008; Suberu et al, 2012], while sugarcane production potential was estimated at about 3 Mt [Sulaiman et al, 2015]. This translates to generation of large amount of wastes from these crops, which are currently underutilised (1.3) and the source of undesirable environmental impacts. Therefore, agricultural residues including rice husks, corn cobs and bagasse are the focus of this research.

2.4.5.3 Rice husks, corn cobs and bagasse

Rice, corn and sugarcane (Figure 4a to c) are examples of major crops that result in generation of huge amounts of waste from their cultivation and processing. In the year 2012, around 148 Mt of rice husks were generated from 740 Mt of global rice production [FAO, 2012]; in the same year, approximately 173 Mt of corn cobs were produced from 1018 Mt of corn production [FAO, 2012]; while 549 Mt of bagasse were produced from 1830 Mt of sugarcane [FAO, 2015]. The high quantity of sugarcane and bagasse production in comparison to rice and corn, and rice husks and corn cobs, can be attributed to the world's high demand for sugar, and high ratio of waste to crop for sugarcane, respectively. Although most sugar refineries utilise the bagasse in combustion to support the energy demand of the plant, excess amounts of this high calorific residue still remain unutilised.

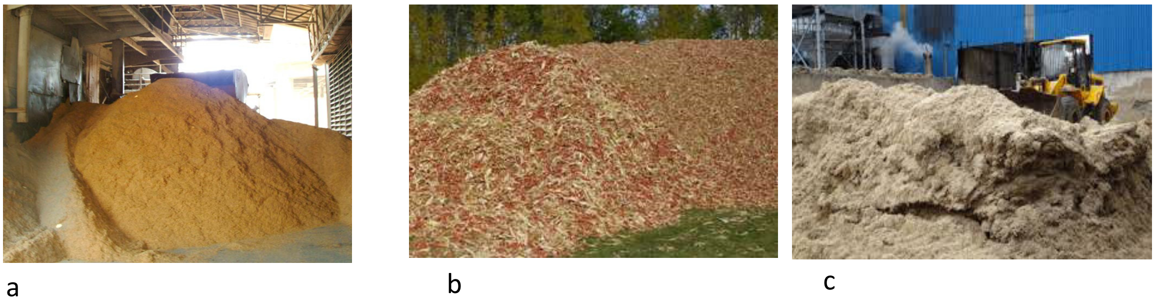


Figure 4: Low bulk density Loose (a) RH, (b) CC, and (c) BG residues [Apollo, 2013; Gustafson, 2013; RKB, 2016]

Table 2 compares energy, ash, moisture contents, bulk density and porosity of rice husks, corn cobs and bagasse, as gathered from sources in the literature [Merill, 1973; Nour, 1987; Perotti & Molina, 1988; Grover & Mishra, 1996; Jorapur& Rajvanshi, 1997; Williams & Nugranad, 2000; Demirbas, 2003; Thakur & Gupta, 2006; Vadiveloo et al, 2009; RKB, 2009; Kaliyan & Morey, 2009; Vassilev, 2010; Shackley et al, 2011; Bazzana, 2011; Pinto et al, 2012; Steffans, 2012; Zhang et al, 2012; Jansen, 2012; Sulzbacher,2014; Oyelaran & Tudunwada, 2015]. It can be estimated that the total annual generation of rice husks, corn cobs and bagasse has an estimated energy content of 16 EJ, which represents about 2.9% of the world total primary energy consumption [EIA, 2013].

Table 2: Comparison of basic properties of rice husks, corn cobs and bagasse

Properties	Rice husks	Corn cobs	Bagasse	Reference
Calorific value (kJ/kg dry mass)	16,000	18,000	19,259	[Grover and Mishra, 1996; RKB, 2009; Demirbas, 2003; Vassilev, 2010; Shackley,2011]
Ash content (% dry mass)	20	<2	2-10	[Grover and Mishra, 1996; RKB, 2009; Vassilev, 2010; Zhang et al, 2012a; Zhang et al, 2012b]
Moisture content (% undried mass)	8-12	20-55	45-55	[Grover and Mishra, 1996; RKB, 2009; Kaliyan and Morey, 2009; Shackley,2011; Zhang et al, 2012a; Zhang et al, 2012b]
Bulk density (unprocessed) (kg/m^3 dry mass)	100-150	160-210	100-200	[RKB, 2009; Kaliyan and Morey, 2009; Zhang et al, 2012a; Zhang et al, 2012b; Pinto et al, 2012]
Bulk density (ground to <0.85 mm) (kg/m^3 dry mass)	331-380	282	NA	[Grover and Mishra, 1996; Zhang et al, 2012a; Zhang et al, 2012b]
Porosity (% dry volume)	63-73*	68	NA	[Zhang et al, 2012a; Zhang et al, 2012b]
Water absorption (% dried mass)	105	327**	186	[Basu, 2010; Thakur and Gupta, 2006; Pinto et al, 2012]
Lignin (% dry mass)	19.2	15.3	18-24	[Williams and Nugrand, 2000; Bazzana, 2011]
Protein (% dry mass)	1.8	2.7	3.0	[Garg and Neelakantan, 1982; Vadiveloo et al, 2009; Perroti and Molina, 1988; Nour, 1987]
Starch (% dry mass)	<1	1.61	NA	[Vadiveloo et al, 2009; Steffens, 2012]
Volatile matter (% dry mass)	62 - 66	76.3	85.5	[Vassilev, 2010; Shackley,2011; Oyelaran & Tudunwada, 2015]
Nitrogen (%dry mass)	0.8	0.4	0.19	[Demirbas, 2003; Vassilev, 2010; Jorapur& Rajvanshi, 1997]
Sulphur (% dry mass)	0.04 -0.08	0.01-0.72	0.06	[Vassilev, 2010; Shackley,2011; Jansen, 2012]
Chlorine (% dry mass)	0.12	0.17 -0.26	0.03	[Vassilev, 2010; Sulzbacher,2014]

NA = not available

*range of 4 different types including long and short grain rice

**average water absorption of whole small cobs

Due to variations in properties of biomass materials, some feedstocks are more easily densified than others. Biomass materials with a higher lignin, starch or protein content exhibit better compaction than those with higher cellulosic content [Hedon, 2009]. This has prompted addition of biomass containing higher amounts of these components to other biomass. For example, blending sawdust from Scots pine with wheat straw resulted in more durable pellets compared to wheat straw alone (Table 3) [Wamukonya & Jenkins, 1999], rice bran was used as a binder in briquetting rice straw [Chou et al, 2009] and olive refuse blended with fibrous paper mill waste [Yaman et al, 2001], for reportedly improved briquette durability, sawdust from different species of hard wood [Mitchual et al, 2013].

Table 3: Effect of mixed biomass densification on solid fuel durability [Wamukonya & Jenkins, 1999]

Feed biomass	Briquettes/Pellets Durability Rating (%)
Wheat Straw	46.5
Sawdust	82.6
50% Wheat Straw:50% Sawdust	51.5
25% Wheat Straw:75% Sawdust	67.6

Furthermore, problems have been encountered with the use of briquettes produced from some individual biomass materials. Briquettes produced from rice husks have been reported to cause clogging of industrial boilers and domestic stoves due to their high ash content [Hedon, 2009], which is also abrasive and wears equipment quickly due to the high silica content of the rice husk ash [RKB, 2009]. Briquettes produced from corn cobs have a tendency for water absorption due to the high porosity of corn cob particles. High moisture contents are undesirable in thermochemical processes such as pyrolysis and gasification due to the energy requirement for drying of biomass and the reduced heating value of the product gas [Rajvanshi, 1986; Demirbas, 2005].

Blending of rice husks and corn cobs and/or bagasse, will result in fuel briquettes with a lower ash content compared to briquettes produced from rice husks alone. On the other hand, briquettes containing rice husks are expected to absorb less water than briquettes from corn cobs alone, due to the lower water absorbency of the thick outer walls of rice husks [Thakur & Gupta, 2006].

It is apparent that the variability of biomass materials has resulted in inconsistency in the characteristics of fuel briquettes produced from different types of residues [Tumuluru et al, 2011; Mitchual et, 2013], this may even apply to the same type of residues grown at different season or different locations. Therefore, it becomes necessary to understand how the variability in biomass materials and other briquette production variables, affect the characteristics of fuel briquette and densification process.

Factors that affect briquette production can be classified into feed properties and process variables.

2.4.6 Feed biomass properties

The properties of feed biomass are of high importance in its direct and indirect use, these properties affect their suitability for both densification and thermal conversion [e.g., Quaak et al, 1999; Vassilev et al, 2010].

Feed biomass properties that have potential effect on briquetting process include, moisture content, ash content, particle size, particle shape, flow characteristics and chemical composition.

2.4.6.1 Moisture content

The moisture content of feed biomass to be densified determines the extent of drying required before densification and affects the characteristics of fuel briquette. A suitable moisture content for densification, in the range of 8 to 15 % was suggested by other authors [e.g., Grover & Mishra, 1996; Mani et al, 2006; Kaliyan & Morey, 2009], while a standard moisture content between 5 and 8 % is recommended by DIN 51731 [Bin Hassan, 2009]. High moisture content in excess of 15 % in feed biomass was reported to reduce briquette density [Mani et al, 2006].

A suitable moisture content in feed biomass can improve gelatinization of starch and softening of biomass fibre which facilitates particle binding [e.g., Thomas et al, 1999], and may also increase the contact area of particles by van der Waal's forces, and promotes formation of solid bridges.

2.4.6.2 Ash content and composition

The quantity of ash and its composition affects most bioenergy products and processes. In the case of briquetting, the ash content mainly affects the thermal conversion stage of the briquette. For example, briquettes containing high ash content feedstock have tendency to cause slagging (formation of molten or soften ash particles on furnace walls) and fouling on equipment surfaces. Agricultural residue such as rice husks are associated with high ash content of up to 20 % wt [e.g., RKB, 2009; Vassilev et al, 2010] (Table 2). The ash content of agricultural biomass consists of mainly alkaline minerals such as potassium and silicon [Grover & Mishra, 1996; RKB, 2009]. These mineral constituents are entrained or volatilised during combustion and condenses on heat exchanger tubes. The minerals also lower the ash sintering temperature and causes deposition on equipment surfaces, leading to equipment fouling [Grover & Mishra, 1996].

2.4.6.3 Particle size and shape

For pellet production, smaller or finer biomass materials (0.25-3.0 mm) are preferable [Payne, 1978; Kallis, 2012] as this increases the surface area for moisture or binder absorption during pre-treatment operation such as steam conditioning and improved particle binding [Payne, 1978; MacBain, 1996], also resulting in increase in bulk density [e.g., Kallis, 2012].

Briquettes can be produced from both small and large particle size biomass, for example, a particle size greater than 6 mm resulted in better particle interlocking and promoted durability for briquette production in one study [Tumuluru et al, 2011], while another [Chou et al 2009] produced denser briquettes by reducing the biomass particle size from 10 to 2 mm. The effect of biomass particle on densification is greatly influence by the type, shape and texture of the biomass (2.4.2).

2.4.6.4 Flow characteristics

The ability of biomass material to flow easily during handling and storage indicates its suitability for biofuel production. Most agricultural residues have poor flow characteristics compared with wood biomass such as saw dust. However, poor flow characteristics of biomass material have less impact on actual densification process, but affect the handling and storage, as well as process scale up potential.

2.4.6.5 Biomass composition

The basic tissues of biomass consist of cellulose, hemicellulose and lignin; resins, fats and other material may be present [e.g., Zonglin et al, 1994; Yank et al, 2016]. The largest fraction of biomass at 38-50% by weight is, a polymer consisting of linear chains of 1,4-D-glucopyranose units with an average molecular weight of 100,000 [Duku et al, 2011]. Roewell [1984] described cellulose as the most abundant form of carbon in the biosphere and a good biochemical feedstock. Hermicellulose is a polymer of 5-carbon consisting mainly of xylose and 6-carbon monosaccharides [e.g., Duku et al, 2011; Chen et al, 2015]. It represents 20-40% by weight of the total biomass and rated as a marginal biochemical feedstock. Lignin is described as a chemical compound with an amorphous nature and high molecular weight. The building blocks of lignin are three carbon chain attached to rings of six carbon atoms called phenyl–propane. It constitutes about 15–25% of the composition of lignocellulosic biomass and has a very high energy content, but with a resistance to biochemical conversion [Roewell, 1984; Duku et al, 2011; Chen et al, 2015].

Cellulose, hemicellulose, lignin, and chemical components including starch content, protein, fibre, sugar, water and fat content of biomass material, affects its behaviour during densification [Thomas et al, 1999].

Cellulose

Cellulose is an organic polymer ($C_6H_{10}O_5$) consisting of linear chains of (1,4)-D-glucopyranose units and has an average molecular weight of 100,000 [Updegraff, 1969; Duku et al, 2011;]. It is described to form crystalline microfibrils that are surrounded by amorphous cellulose inside plant cells [Chen et al, 2004]. It is the source of carbon in biomass materials and due to the crystalline nature and type of bond present (hydrogen bonding) in cellulose molecule, it reduces the binding characteristics of the biomass [Nelson & Cox, 2005] during densification. However, this negative effect can be reduced by softening of the structure through heat treatment.

Hemicellulose

The structure of hemicellulose is described as random, amorphous with little strength, it is found in most plant cell walls and can be hydrolyzed using chemicals (acid or base) and hemicellulase enzymes [Tumuluru et al, 2011]. Degradation of hemicellulose molecules could result in production of a natural binding agent which is suitable in the densification process.

Lignin

Lignin is amorphous in nature with high molecular weight. It constitutes about 15-25% of the composition of lignocellulosic biomass, and yields higher energy during biomass combustion, compared with cellulose [Roewell, 1984; Duku et al, 2011]. It is usually found in wood and parts of the secondary cell wall of plants and some algae [Lebo et al, 2001; Martone et al, 2009]. In wood biomass, lignin molecules enhance bonding, creating the rigid structure of most wood materials. A high lignin content in biomass is anticipated to improve densification and durability of fuel briquette as a result of its natural binding properties.

Furthermore, lignin exhibits thermosetting properties at temperature above 40^{o} C, acting as natural resin to produce more durable solid fuel [Van Dam et al, 2004]. It facilitates the formation of solid bridges at elevated temperatures [Tumuluru et al, 2011]. However, Wilson [2010] stated that no consistent relationship exists between lignin content and durability of solid fuel (the case of hard wood and soft wood samples). An additional benefit of lignin is its hydrophobic nature, which has the potential to make briquettes water resistant [Angles et al, 2001]. Table 4 shows example of other agricultural biomass materials and their compositions.

Table 4: Material composition of some biomass [Adapa et al, 2009; Mohan et al, 2006]

Component	Wheat straw (% dry matter)	Oat straw (% dry matter)	Rice straw (% dry matter)
Cellulose	34.20	37.60	34.0
Hemicellulose	23.68	23.34	27.2
Lignin	23.88	12.85	14.2
Starch	2.58	0.12	NA
Protein	2.33	5.34	NA
Fat	1.59	1.65	NA

Note: wheat and oat straws data from Adapa et al [2009] and rice straw from Mohan et al [2006]

NA: not available from reported literature

Starch

At elevated temperatures and in the presence of moisture, the starch content of biomass gelatinizes and form bonds between particles [e.g., Thomas et al, 1999]. Additional starch is therefore utilised in most densification processes as binding agent.

Protein

Protein in biomass materials are denatured when subjected to heat, thereby forming new bonds with other proteins and starch molecules [Thomas et al, 1998]. The use of natural protein was found to improve the physical quality of pellets `compared with denatured protein [Tumuluru et al, 2011].

Other biomass components that may affect densification include, fat and fibre content of feed biomass [e.g., Briggs et al, 1999]. Fat content in biomass acts as a lubricant during densification, which reduces densification pressure, while fibre reduces the binding characteristics of biomass during densification.

2.4.7 Briquetting process variables

Some process variables that affects briquetting process include, pressure, temperature, binder addition, hold time and die geometry [e.g., MacBain, 1996; Tumuluru et al, 2011].

2.4.7.1 Pressure

During biomass densification into briquettes, an increase in pressure results in increase in the mechanical strength of the briquettes as a result of plastic and elastic deformation, molecule diffusion and closing up of void spaces between particles to form a compacted solid. This is achieved with the help of attractive forces such as van der Waal's (2.4.2). However, as pressure increases, an optimum level is expected to be reached, and beyond that, sudden dilatation may take place resulting in fractures and splits on fuel briquette [Yaman et al, 2000. This behaviour was related to the reversible nature of the plastic deformation above an optimum briquetting pressure [Yaman et al, 2000]. In addition to this, very high compaction pressure could also result insufficient trapped air in the pore spaces for combustion. Kaliyan & Morey [2009] in their review, reported a range of obtainable pressures for pellet mills and roll presses: 100-150 MPa and 100-200 MPa, respectively.

A number of studies have been carried out to investigate effect of densification pressure on briquette and pellet quality [e.g., Srivastava et al, 1981; Li & Liu, 2000; Chin & Siddiqui, 2000; Kaliyan & Morey, 2010b]. Chin & Siddiqui [2000] found that increasing the densification pressure from 1 to 10 MPa (10-100 bar) increased the shear strength of briquettes from 27.5 to 95.7 N, from 1.2 to 4.6 N, from 1.3 to 6.7 N, from 10 to 73.3 N, and from 10 to 36.2 N for sawdust, rice husk, peanut shell, coconut fiber, and palm fiber, respectively. Additionally, briquettes manufactured at lower pressures of 30 to 60 MPa crumble easily, while those produced at higher pressures of 150 to 250 MPa remain compacted and durable [Mitchual et al, 2013], for example, increasing the compaction pressure from 1 to 10 MPa increased the shear strength of briquettes from 2.8 x 10^{-2} kPa to 9.6 x 10^{-2} kPa [Chin & Siddiqui, 2000].

Currently, efforts are directed towards improving the quality of fuel briquettes produced at lower compaction pressures.

2.4.7.2 Temperature

Elevated temperature promotes particle deformation and facilitates the release of natural binders from feed materials as well as additional binders during densification. This improves the binding of the material, and may reduce the amount of compaction pressure required to densify it. The use of increased temperature during briquetting may also reduce the relaxation rate of fuel briquettes when they are extruded from the mold.

Research has been carried out to investigate the effect of temperature in densification of different biomass materials [e.g., Smith et al, 1977; Rhen et al, 2005; Kaliyan & Morey, 2010b]. Kaliyan & Morey [2010b] observed that increasing the densification temperature from 25 to 85°C increased briquette relaxed density from 604 & 971 kg/m^3 to 1100 & 1120 kg/m^3, and improved briquette durability from 0 to 88 & 92% respectively. There was also an increase in compaction rate and dimensional stability as temperature increased from 60 to 140°C during briquetting of wheat straw [Smith et al, 1977].

2.4.7.3 Hold time

Research has shown that, during high-pressure compaction, removal of material from the die results in relaxation of product which continues until a final relaxed density is reached [Shaw, 2008]. The relaxation rate of briquettes after extrusion from the mold is influenced by the hold time, which is the additional time the compacted biomass material spends in the die after the desired load or pressure is reached. Chin & Siddiqui [2000] observed a decrease in relaxation rate of briquettes as the hold time increased, and for the same briquettes, an increased in briquette shear strength was also observed with increase in hold time. However, when a hold time of 40s was exceeded, there was no observable change in briquette relaxation. Li & Liu [2000] also found that hold time had more effect at lower compaction pressure, for oak sawdust densification.

2.4.7.4 Die geometry

The die is the hole of the mold in which the biomass material is loaded and densified. The die geometry can be expressed as the ratio of length (L) to diameter (D) of the die, L/D. According to Tumuluru et al [2011], increasing the length of die increases compaction pressure (for pelleting) while increasing the diameter reduces compaction pressure, because biomass compaction mainly takes place in the vertical direction, hence more compaction pressure is required with higher L/D ratio.

The Die geometry also influences product properties like moisture content, bulk density, and durability, for example, Hill & Pulkinen [1998] found that increasing the L/D ratio results in increase product durability by 30 to 35 %. This can be attributed to increase pressure, and load distribution over the biomass material that is being compacted in the mold, in other words, the less biomass material per unit area in the mold, the lesser the load distribution.

2.4.7.5 Binder addition

Many biomass feedstocks possessed natural binding agents [Shaw, 2008]. However, additional binders are often added for better binding in densification. Various binders have been employed to improve the binding characteristics, compressive strength, and general quality of fuel briquettes. They can also reduce the energy cost of producing such briquettes by reducing the amount of compaction pressure or temperature required for conditioning. The use of binders during biomass densification also reduces the wear on production equipment and production costs [e.g., Kaliyan & Morey, 2010b; Tumuluru et al, 2011], for example, by reducing the compaction pressure, energy, and time required to densify a specific quantity of biomass material.

Binders commonly used in briquetting include starch, molasses, lignosulphonates (in animal feed processing) or sulfonate salts made from lignin in pulp [Thomas et al, 1998; Williams & Nugrand, 2000; Tabil & Sokhansanj, 1996], or biomass wastes that are rich in natural binders, e.g., rice bran and sawdust [Chou et al, 2009]. Recent research has focused on developing new, cheaper and more sustainable binders, as well as optimising the ratio of binder to feed biomass. A variety of effects of binders on briquette quality have been reported:

Chin & Siddiqui [2000] reported a decrease in the relaxed density of briquettes with an increase in binder ratio for sawdust and coconut fiber, yet an increase in relaxed density of briquettes with an increase of binder ratio for peanut shell and palm fiber. Singh & Singh [1982] reported an increase in briquette strength with increased addition of a molasses and sodium silicate binder in briquettes from rice straw. Kaliyan & Morey [2009] discovered that solid bridges were made by natural binders such as lignin and protein, in binderless briquetting with corn stover and switch grass. They also found that temperatures in the range of glass transition (75 - 100°C) is important for efficient particle bonding.

Oladeji & Enwerenmadu [2012] also showed a reduction of corn cob briquette density with increased addition of a starch binder.

Emerhi [2011] used three different organic binders including cow dung, wood ash and starch in briquetting of sawdust, to assess the effect on calorific value of the produced briquettes. Results showed that starch-bound briquettes produced the highest calorific value while ash bound briquettes had the least calorific value. Sivakumar et al [2012] showed that briquetting sawdust with a cow dung binder could be optimized to increase the thermal efficiency and methane content of the product gas in a downdraft gasifier.

Despite the advantages of using binders in biomass briquetting, problems have been encountered with some types of binders when fuel briquettes are converted to energy, including air emissions from pollutants in untreated materials, deposit formation and corrosion of equipment [Obernbergera & Theka, 2004]. Other binders may have resource problems, e.g., starch, which is also a food product. There is therefore a need to explore better and more environmentally friendly binders for biomass briquetting, and evaluate these with existing binders. The main binders investigated in this research include, starch, biosolids and microalgae.

Figure 5a to c shows examples of starch, biosolids and microalgae as binders for briquetting. Table 5 compares the physical and chemical properties of starch, biosolids and micro-algae binders used in this study as gathered from sources in literature [Paine & Vadas, 1969; Merrill &Watt, 1973; Logan & Harrison, 1994: Stain, 1998; Andreoli et al, 2001; Dweck et al, 2006; Xiong et al, 2008; Barz, 2009; Phuphuakrat et al, 2010; Silva et al, 2012; Vardon et al, 2012; Egun and Abah, 2013; Bi & He, 2013; Jiang et al, 2014; Sudjito et al, 2014].

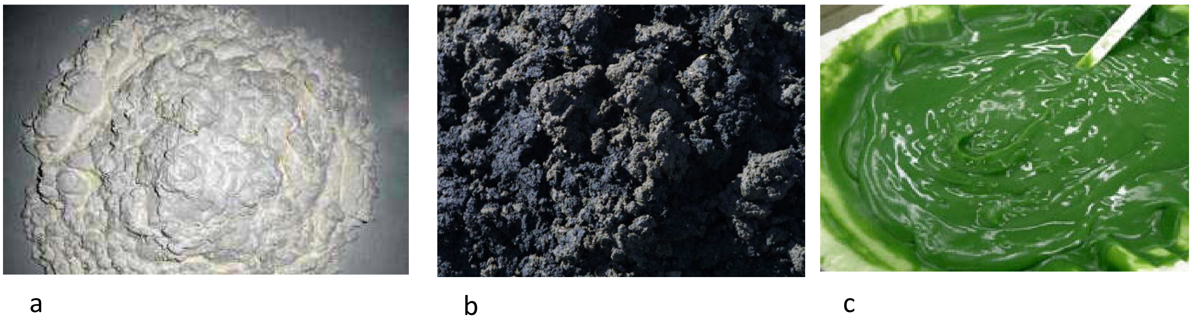


Figure 5: Binders for briquetting (a) starch, (b) biosolids, and (c) harvested concentrated microalgae [UFP, 2013; OSE, 2015; PJC, 2013]

Starch

Starch in its pure form is a tasteless and odourless white powder which can be sourced from various kinds of crops such as rice, wheat, cassava, yam, and potato. It has two major components: amylose and amylopectin [Satin, 1998]. These polymers are very different structurally, amylose being linear and amylopectin highly branched. The ratio of these two components influences its viscosity, shear resistance, gelatinization, textures, solubility, tackiness, gel stability, cold swelling and retrogradation of the starch [Satin, 1998; Oladeji & Enweremadu, 2012]. These components of starch are also regarded as one of the natural binding compounds present among protein and lignin part of various types of biomass.

Table 5: Comparison of basic properties of starch, biosolid and micro-algae

Properties	Starch	Biosolid	Micro-algae	Reference
Calorific value (MJ/kg dry mass)	18	6-19	15-23	[Silva et al, 2012; Andreoli et al, 2001; Dweck et al, 2006; Merrill and Watt, 1973]
Ash content (% dry mass)	0.08	31	10	[Jiang et al, 2014; Xiong et al, 2008; Phuphuakrat et al, 2010; Vardon et al, 2011]
Moisture content (% undried mass)	4-11	5-11	7	[Jiang et al; 2014; Egun and Abah, 2013; Xiong et al, 2008]
Volatile matter ((% dry mass)	-	39-57	67	[Jiang et al, 2014; Phuphuakrat, 2010; Sudjito et al, 2014]
Bulk density (kg/m^3 dry mass)	617	400-800	370-435	[Egun and Abah, 2013; Logan and Harrison, 1994]
Amylopectin (%)	0-70*	N/A	N/A	[Satin, 1998]
Cellulose	-	1	7.1	[Ververis et al, 2006; Hattori and Mukai, 1986]
Lignin (% dry mass)	-	10-10.3	2	[Ververis et al, 2006; Vardon et al, 2011; Hattori and Mukai, 1986]
Hemicellulose (%dry mass)	-	-	16.3	[Ververis et al, 2006; Hattori and Mukai, 1986]
Protein (% dry mass)	0.23	15-35	64**	[Xiong et al, 2008; Vardon et al, 2006; Sudjito et al, 2014]
Fat (% dry mass)	0.075	13	2-10	[Silva et al, 2012; Andreoli et al, 2001; Dweck et al, 2006; Merrill and Watt, 1973]
Nitrogen (% dry mass)	NA	3.3 -3.7	1.6 -6.8***	[Bi & He, 2013; Barz, 2009]
Sulphur (% dry mass)	NA	0.18 -3.6	0.4 -1.0***	[Bi & He, 2013; Khan,1991]

Properties	Starch	Biosolid	Micro-algae	Reference
Chlorine (% dry mass)	NA	0.02	1.97	[Sudjito et al, 2014; Barz, 2009]
Calorific value (MJ/kg)	17.5	10.1 -16.2	18.59	[Silva et al, 2012; Bi & He, 2013; Barz, 2009]
Lipid (%)	NA	NA	21.3 -30.8	[Bi & He, 2013]

NA = not available

* The remainder of the starch is assumed to be amylose

**Value obtained from different strains of microalgae

***Range is for green and mixed green algae of different strains

Starch has various applications as a binder in non-food industries such as textiles, cosmetics and pharmaceuticals, explosives, paper, construction, etc. Its high energy content, and chemical and structural properties make it a promising binding agent for fuel briquetting. Addition of water and heat to starch granules causes swelling, which results in the formation of intermolecular hydrogen bonds between the amylose and amylopectin components of starch, followed by loss of the individual crystalline structure of the two components [Tako & Hizikuri, 2002]. This leads to formation of a viscous solution that undergoes retrogradation, i.e., gelling, during cooling or storage. The viscosity of hydrated starch increases its shear and tensile strengths. The fluidity and viscoelasticity of the produced solution [Tako & Hizikuri, 2002] gives it the ability to occupy the void spaces present within and between biomass particles, forming solid bridges that become stronger upon air-drying.

Biosolids

Biosolids are the residue from anaerobic digestion of waste activated sludge from municipal wastewater treatment. Biosolids contain valuable organic matter and high content of natural binding compounds such as lignin and protein (Table 5), which are useful in solid compaction processes [Silva et al, 2012] (2.4.6.5).

In its untreated state, biosolids contains pathogenic organisms present in municipal wastewater [EC, 2012]. Therefore, it has become a requirement to treat biosolids before disposal, application on farm land or other applications [ADAS, 2001]. Conventional treatment destroys at least 99% of the pathogens; this has been superseded by enhanced treatment which ensures that 99.99% of pathogens are destroyed [ADAS, 2001]. The binding ability of a particular biosolid is highly influenced by the type of waste and treatment method it undergoes.

Microalgae

Algae consist of large group photosynthetic, heterotrophic organisms from different phylogenetic groups, representing many taxonomic divisions. They are distributed worldwide, inhabiting pre-dominantly fresh and sea water ecosystem [Guschina & Harwood, 2013].

The use of microalgae as a source of renewable oils for biofuel production has gained significant attention in the recent years; this is attributed to the potential benefits presented by microalgae biomass, for example, easy to cultivate, ability to capture carbon during growth, waste management potential (waste water), high lipid content etc. Under the right conditions, some algae strains can produce 50% of their dry weight in the form of lipids suitable for fuel production. However, the remaining 50% contains large amount of fixed carbon and energy. The efficient recovery of the energy and carbon entrained in this residue is important for improved environmental and economic sustainability of algal biofuels [Jarvis, 2011].

Algal residue has a potential application in material binding due to its high quantity of protein and other biomass tissue including cellulose, hermicellulose and lignin. In the presence of moisture, algae residue releases a binding substance that act as glue between loose material particles, this facilitates the formation of solid bridges and closing of void spaces between biomass particles [Ververis et al, 2006]. For example, fresh water micro algal biomass was found to increase the mechanical strength of paper pulp [Ververis et al, 2006].

2.4.8 Energy consumption in biomass briquetting

Energy consumption during briquetting depends on factors including material type, briquetting technology, and the feed pre-treatment method. The briquetting process consists mainly of compression and extrusion, each of which has specific energy requirement [Tumuluru et al, 2011]. According to Mewes [1959], it is only about 37– 40% of total input energy that is required for compression, the remaining energy is required to overcome friction during extrusion. Studies on energy consumption in biomass densification have been carried out by other authors [e.g., Reed et al, 1980; Miles et al, 1980]. A summary of these works was compiled by [Mani et al, 2006] (Table 6).

Table 6: Densification energy consumption of some biomass materials [adapted from Mani et al, 2006]

Biomass Materials	Densification Equipment	Specific Energy Consumption (kWh/t)	Source
Grass	Pellet mill	33-61	[Shepperson & Marchant, 1978]
Sawdust	Pellet mill	36.8	[Reed & Bryant,

Biomass Materials	Densification Equipment	Specific Energy Consumption (kWh/t)	Source
			1978]
Straws with binder	Pellet mill	37-64	[Miles et al, 1980]
Straws with binders	Cubing Machine	75	[Miles et al, 1980]
Sawdust	Piston press	37.4	[Reed et al, 1980]
Grass	Piston press	77	[Shepperson & Marchant, 1978]
Straws	Screw press	150-220	[Carre et al, 1987]

From Table 6, the energy consumption for densification of straw with binders in a pellet mill is less than that for cubing machine. Densification of grass consumed almost twice the energy (77 kWh/t) needed to compress sawdust (37.4 kWh/t), using the same equipment (piston press). This can be attributed to differences in material properties, and indicates that sawdust may contain a higher amount of natural binding agents compared to grass. The screw press had the highest energy consumption; this may be associated with the biomass material processing technique in the screw press, which includes shearing and mixing before extrusion.

There is significant additional energy associated with densification of biomass into briquettes, which appears to vary with changes in the briquetting variables, and shows a need to critically review, and evaluate the sustainability of briquetting for a variety of biomass materials. Quantitative assessment of life cycle impacts on energy and emissions can be accomplished using LCA.

2.4.9 Life Cycle Assessment

The densification of loose biomass materials into briquettes increases their energy density, resulting in several benefits, such as reduced transportation costs and storage space requirements, as well as more uniform feeding into conversion equipment [Tumuluru et al, 2011] (2.4). However, the sustainability of biomass densification also depends on the energy consumption, emissions and cost associated with briquetting itself, and application of the briquettes, e.g., in combustion or gasification [Caputo et al, 2005]. One way to examine the overall sustainability of briquetting is by life cycle assessment.

LCA is an environmental management tool that examines the environmental impact of a product, process or service over its entire life cycle, “from cradle to grave” [Finnveden, 1999; ISO14044, 2006]. It systematically analyses a system to account for all the inputs and outputs within a defined system boundary. The useful output is termed the functional unit, which must be of a defined quantity and quality, for example, 1kg of fuel briquette. During the LCA, all inputs are traced back to primary resources, for example electricity is generated from primary fuels like oil and coal. Equipment require steel, plastic, and other materials for their manufacture, all of which incur energy costs, in addition to their operational use of fuel (e.g., diesel). The minerals, their extraction, energy and other natural resources used are all included in an LCA. The plant buildings, and transportation energy costs, also form a major part of the LCA.

The main steps involve in an LCA include Goal and scope definition, Life cycle inventory (LCI) analysis, Life cycle impact assessment (LCIA) and interpretation [ISO 14044, 2006; ILCD, 2010] (Figure 6).

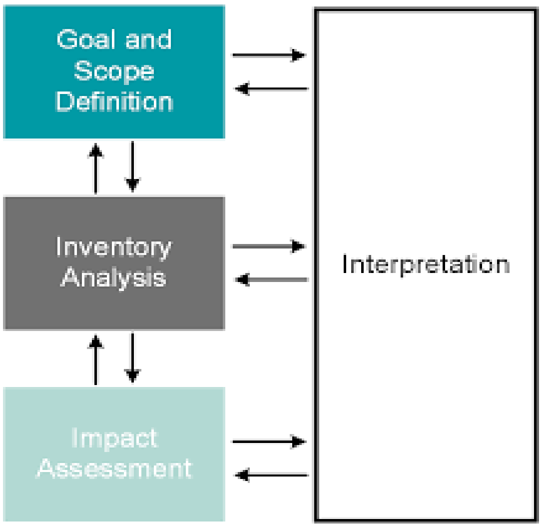


Figure 6: LCA framework according to ISO 14044, [2006]

The Goal and scope definition phase of the LCA is where the purpose of carrying out the LCA is established, the function of the system (functional unit) and specific system boundary (life cycle stages of the product, location and time) for the LCA are defined, and data quality required for the LCA is determined.

The Life cycle inventory analysis phase involves creating a flow chart that classifies events in the product's life cycle, defining all mass and energy inputs and outputs related to the product system, collection of data (including assumption for unavailable data) required, and calculation of mass and energy balances for each stage and event within the defined system boundary (example shown in Figure 7) [Bras & Roman, 2006].

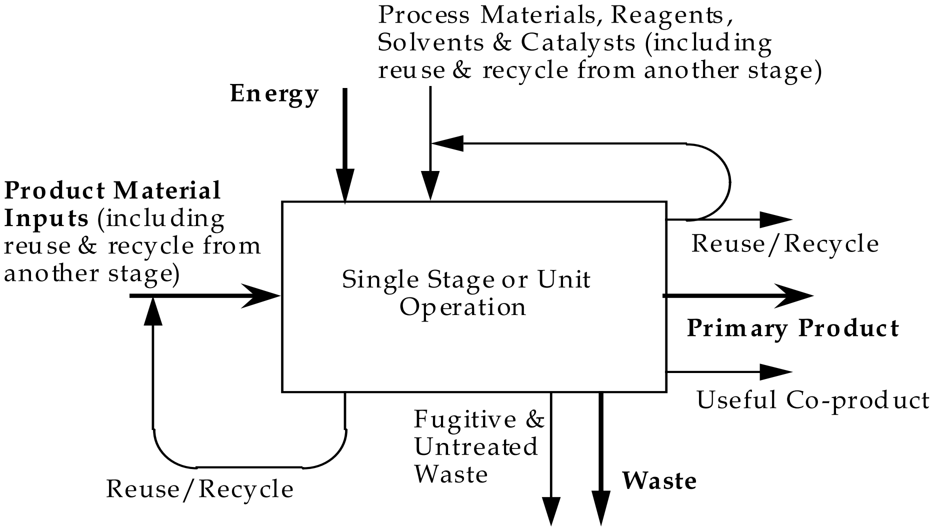


Figure 7: Input/output diagram for single stage or unit operation [Bras & Roman, 2006]

The Life cycle impact assessment phase include 1) selection of impact categories and classification (environmental impacts relevant to the study are defined) which is a mandatory stage, 2) characterisation (the impact of each emission or resource consumption is modelled quantitatively, according to the environmental mechanism), also a mandatory stage, 3) normalisation (characterised impact scores are associated with a common reference, such as the impacts caused by one person during one year in a specific location), an optional stage, and 4) weighting (ranking of the different environmental impact categories according to their relative importance), also an optional stage [ILCD, 2010].

The use of LCA in the field of bioenergy has rapidly increased in recent years due to concerns about environmental impacts associated with bioenergy systems, e.g., biodiesel, bioethanol and bio-oil [e.g., IEA, 2011].

Most existing LCA studies of bioenergy systems have different specific goals and have therefore adopted different approaches, leading to different results even for studies with similar goals, and input and output flows [Quek & Balasubramanian, 2014; Hennecke et al 2013]. Variations in LCA outcomes may be observed and are attributed to factors such as: data source [Borrion et al, 2012], data age [Audsley et al, 2015], and methodological issues including definition of the functional unit and system boundary [Borrion et al, 2012; Suh et al, 2004], and allocation or expansion procedures [Quek & Balasubramanian, 2014; Wiloso et al, 2012].

Unlike other bioenergy products such as bioethanol [e.g., Cherubini & Stromman, 2014; Borrion et al, 2012; Wiloso et al, 2012] and biodiesel [Cherubini & Stromman, 2014; Coniglio et al, 2014], assessment of life cycle environmental impacts associated with biomass fuel briquettes is still relatively rare. It indicates limited data for complete LCA of biomass fuel briquetting, and poor understanding of associated uncertainties.

2.4.10 Briquette application in the bioenergy system

Briquette application for bioenergy is mainly via thermal conversion processes including: combustion, gasification, and pyrolysis, in both domestic and industrial equipment such as boilers, local stoves and gasifiers [Purohit et al, 2006]. Since the thermochemical conversions (gasification and pyrolysis) are classified as more energy efficient and environmentally friendly compared with direct combustion [McKendry, 2002; Zhang et al, 2010] (2.3), the focus for briquette use in this study is gasification process.

Briquette gasification

Gasification is currently one of the most promising thermochemical conversion techniques for efficient briquette use but most of the work carried out so far on briquettes gasification has been focused on fixed bed gasifiers such as updraft and down draft gasifiers [e.g., Sivakumar et al, 2012; Tasma et al, 2012]. Unlike fixed bed gasifiers, fluidised bed gasifiers have the potential to be effectively sized to medium or large scale [Zhang et al, 2010; Anis &

Zainal, 2011]. They also offer better heat transfer between feed particles as a result of intensive mixing in the bed, and can use a variety of feed particle sizes.

In fluidised bed gasifiers, feed briquettes in a bed material such as sand/silica are fluidised with a gasifying medium (e.g., air). Fluidized bed gasifiers can further be classified into two types: bubbling and circulating. Circulating fluidized bed has additional feature to bubbling bed in which the solid particles that get trapped in the gas phase are collected and recirculated back to the gasification bed [Basu, 2010]. Figure 8 illustrates the concept of fluidised bed gasification in a bubbling and circulating fluidised bed gasifiers.

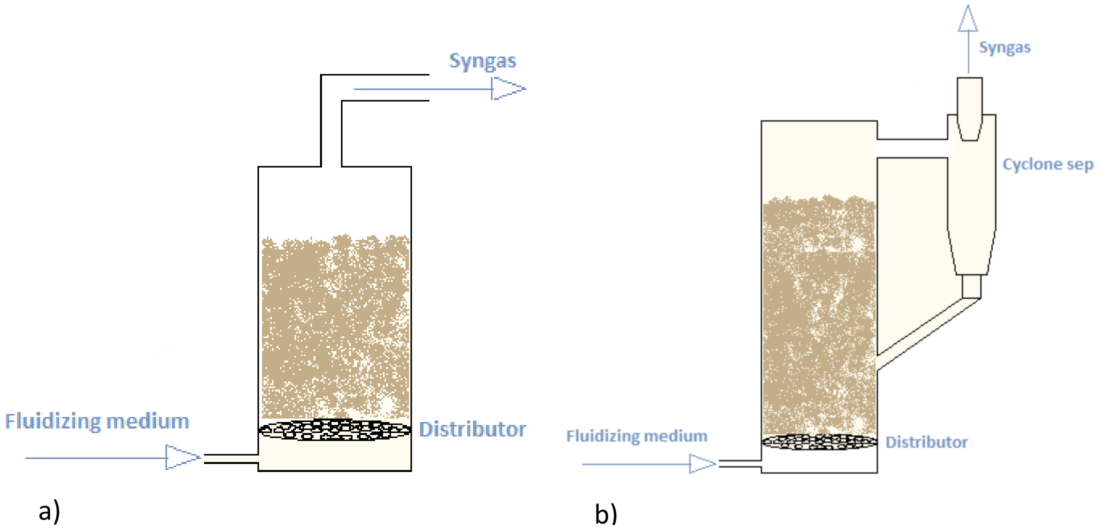


Figure 8: a) bubbling fluidised bed and b) circulating fluidised bed [Gautam, 2010]

Generally, gasification process and products are affected by feed particle size used in the gasification process, as biomass with different sizes have different gasification rates [Erlich et al, 2006]. This is important in briquette gasification as densification of loose biomass into briquette is associated with increase particle size of the feed biomass.

A fixed bed gasification of peach prunings with feed particle sizes between 1 and 80 mm was carried out by Yin et al [2012], where an increase in product gas yield, decrease in tars formation and dust with increase biomass particle size was observed. Tars are major impurities associated with biomass gasification syngas, which hinder the efficient utilization of syngas [Han & Kim, 2002].

In fluidised bed gasification, the region in which the thermal conversion of the feed particle takes place, is determine by the feed particle size [Wilk & Hofbauer, 2013]. Feed particle size in the range of 6 to 25 mm was used in a fluidised bed gasification of white oak [Gaston et al, 2011] where the increase in particle size was found to aid formation of tars and polycyclic aromatic hydrocarbons (PAHs). In contrast, the study by Wilk & Hofbauer [2013] showed that the concentration of smaller particle size in the mixture of feed (sawdust and pellets) during gasification reduced product gas yield and increased tar formation. This was attributed to the rapid devolatilization of the smaller particles in the freeboard of the gasifier thus limiting contact with bed materials, and further reformation of these volatiles. One study suggests that pellets with different sizes have different gasification rates but not different pyrolysis rates; the larger the pellet is, the slower the gasification would be [Erlich, 2006].

Since briquetting is associated with increase particles size of biomass materials, a major drawback that may be encountered in fluidised bed gasification of biomass briquettes is the formation tars and CO_2 in the product gas [Ruoppoloa, 2013; Gaston et al, 2011]. Further research is needed to established an optimum range of briquette particle size suitable for use in fluidised bed gasification process.

2.5 Summary

Several studies in the literature have established the importance of biomass densification into briquettes as a way of mitigating the challenges associated with direct use of loose biomass for energy purposes. It has been demonstrated that the composition of biomass and process variables play an important role in briquette production as well as briquette thermal conversion. The key research gaps identified from existing literature on biomass densification systems are summarised further.

There is need for continuous optimisation of the briquetting process. This requires more work to develop in-depth understanding of the behaviour of various biomass properties, process variables and other related factors during the briquetting process, and their effect on the quality of fuel briquette. Furthermore, development of new ways of producing briquettes that are of better and consistent quality for efficient thermal applications, is urgently required.

Although briquetting of loose biomass offers numerous advantages in the recovery of energy from biomass, its sustainability within the bioenergy system remains unclear due to additional energy cost required for the briquetting process. Therefore, it becomes imperative to assess the sustainability of briquetting loose biomass prior to thermal conversion.

3 MATERIALS AND METHODS

3.1 Research approach

This chapter explains the steps and procedures followed to achieve the stated research objectives in section 1.4. The overall approach employed in this research include laboratory experiments, literature research, and modelling.

For objectives 1 (To investigate the effect of blending multiple biomass residues and briquetting variables, on durability related properties of biomass fuel briquettes) and 2 (To explore the use of novel binding agents with multiple biomass residues for improved physical and combustion properties of fuel briquettes), different laboratory experiments were carried out including research materials characterisation, briquette production (including optimisation) and briquette characterisation. Since general procedures were used for material characterisation and briquette production in both works carried out for objectives 1 and 2, the combined procedures are described in upcoming sections of this chapter. While the specific experimental design and briquette characterisation methods used for each work in objectives 1 and 2, are further discussed in the chapters 4 and 5 respectively. For these chapters, laboratory experiments were used to obtain data for analysis.

The detailed methodology employed to achieve objectives 3 (To review the existing studies on LCA of fuel briquetting, identify gaps in research and understanding, and suggest possible future approaches for LCA of fuel briquetting), 4 (To develop a user accessible LCA model of fuel briquetting that addresses key issues associated with the fuel briquetting system) and 5 (To use the LCA model developed as Objective 4 to assess the environmental impact of briquetting blends of rice husks and corn cobs), are discussed in chapters 6 and 7 respectively. For objective 3, literature sources were used to obtain data for analysis, while for objectives 4 and 5, a combination of laboratory experiments, standard databases, and the literature, were used to obtained data for analysis.

3.2 Raw materials collection and preparation

Feed materials used in this research included the following;

Rice husks, corn cobs, bagasse, starch, biosolids and microalgae.

Bulk samples of air dried rice husks, corn cobs and bagasse were sourced and collected from local farms and milling sites in Niger state, Nigeria. Corn cobs and bagasse were chopped and milled using a hammer mill to a particle size of 1.6mm and smaller, rice husks were used as received from the milling site, since they have a particle size of 2 mm or smaller, which can readily undergo densification. The mass median diameter ("D50") of the rice husks was 0.7 mm. Corn cobs and bagasse were used with a particle size of <1.6 mm, based on preliminary experiments which found that larger particles (2-10 mm) were less easily compacted. Corn cobs and bagasse particles obtained using a hammer mill fitted with a 1 mm screen were blended with larger particles (1-1.6 mm) that had been manually crushed. The mass median diameter of the resulting blend for both corn cobs and bagasse was 0.8 mm.

Unrefined starch was obtained from a local market in Niger state, Nigeria, in a dry powder form with less than 7% moisture content.

Enhanced treated biosolids collected from a UK municipal wastewater treatment plant as a filter cake with a solids content of 21% wet mass. The specific enhanced treated biosolids used in this study was also free of bad odour.

Whole microalgae (*chlorella sorokiniana*) were grown in our laboratory and centrifuged to obtain a concentrated slurry with a solids content of 25% wet mass. It was expected that the binding characteristics of this slurry would be similar to that of algal residue following lipid extraction, as the lipid content of our algae was relatively low (<10%).

3.3 Raw materials characterisation

Characterisation of rice husks, corn cobs and bagasse included determination of bulk density by BS EN 15103 [2009], moisture content by BS EN 14774-2 [2009], particle size by DD CENT/TS 15149-2 [2006], water absorption by adaptation of BS EN 772-21 [2011] and specific gravity using a Micromeritics helium pycnometer (ACCU Pyc 1330). The porosity of materials was determined using Equation 2.

$$\text{Porosity} = (1 - \frac{\rho}{SG}) X\ 100$$

Equation 2

Where;

ρ = density of material (kg/m^3 dry basis)

SG = specific gravity of material (kg/m^3*)*

The starch, biosolids and microalgae binders were prepared separately by mixing each individual solid binder into a paste with water at a mass ratio of 2:3, for 5 minutes prior to addition to the blends of rice husks, corn cobs and bagasse, in each of the experimental work. The inherent water contents of the biosolids and microalgae were included in this ratio.

3.4 Briquetting experiments

Briquette production in the laboratory was carried out using mainly factorial design experimental methods to design various experimental runs [Box et al, 2005] (4.1; 5.1). Production was carried out using a hand-held stainless steel mold and hydraulic compression machine (controls- 04600/FR). Characterisation of produced briquettes was carried out using scientific standard testing methods and the measured variables included; density, unconfined compressive strength, moisture content, particle size, water absorption, shattering and abrasion resistance (4.3; 5.3).

Figure 9 presents the framework that was adopted during briquetting experiments, the briquetting work was divided into two main parts including (1) investigation of the effects of briquetting variables on briquette's durability related properties, and (2) the feasibility of the use of novel binders for fuel briquette production, and evaluation of the effect of these binders on physical and combustion characteristics of fuel briquettes.

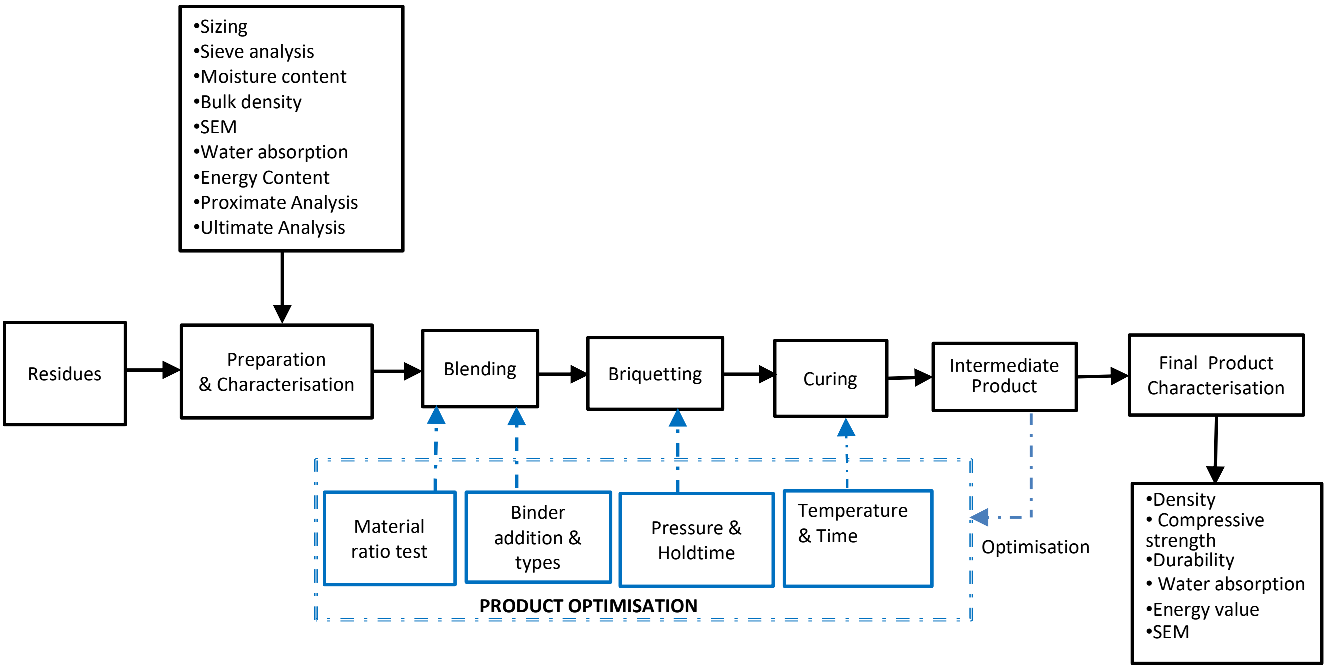


Figure 9: Briquette production framework

For all the briquetting experiments carried out in this study for objectives 1 and 2, biomass and binder blends were weighed out in various proportions, and densified using a simple hand-held laboratory steel mold with an inner diameter of 32 mm, an outer diameter of 51 mm, and length of 100 mm (Figure 10). The proportions of biomass and binder blends used in briquetting experiment carried out to achieve objective 1 and objective 2, are indicated in columns 2 to 5 of Table 9 (chapter 4), and columns 2 to 8 of Table 13 (chapter 5) respectively.

Figure 10: Blend of rice husks and corn cobs loaded into the 32 mm diameter mold

A hydraulic compression testing machine (Controls-04600/FR) was used to compress the blended biomass in the mold to the desired load (column 6 of Table 9, and column 8 of Table 13), at a rate of 200 N/s as shown in Figure 11. Based on previous findings by the author and other researchers [Chin & Siddiqui, 2000; Al-Widyan et al, 2002] that a hold time under compression in the mold in excess of 40 seconds has little effect on briquette characteristics, the compacted briquettes were held at the desired compaction pressures of 19 and 31 MPa for 60 seconds, and then extruded from the mold through the hole shown on the right side of the mold base plate in Figure 10.

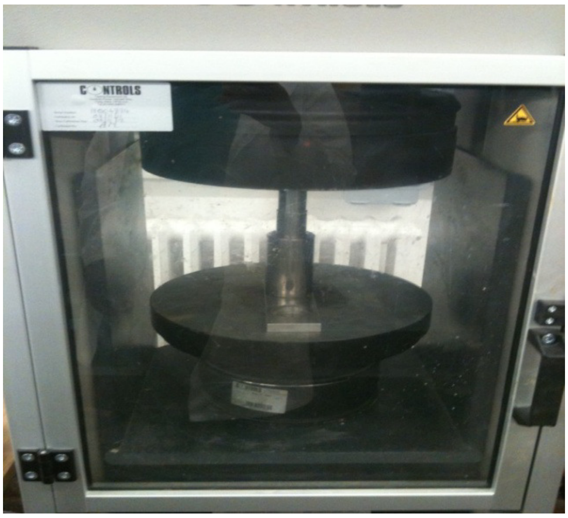


Figure 11: Mold with sample subjected to load in compression machine

4 EFFECTS OF OPERATING VARIABLES ON DURABILITY OF FUEL BRIQUETTE FROM RICE HUSKS AND CORN COBS

4.1 Experimental design and analysis

A factorial experimental design method involving 24 runs was employed for production of briquettes. The variables investigated in this study were chosen based on their expected influence on briquette quality: sample batch (S), i.e, two different samples, A and B, of rice husks and corn cobs obtained for two different seasons and farms sites, material ratio (M), i.e., percentage mass of rice husks in the blend of rice husks and corn cobs, and binder addition (B), i.e. mass of starch and water added as a percentage of the rice husk and corn cob blend, and compaction pressure (P). The response variables measured were green (immediately after extrusion from the mold) and relaxed (after 24 hours curing) unit density, unconfined compressive strength, mass lost in abrasion and shattering tests (i.e., "durability rating") [Thoreson et al, 2012], and water absorption. The methods used to measure these response variables are summarised in Table 7, and further discussed in section 4.3. Unless otherwise specified, each test was repeated for three briquettes.

Table 7: Briquette characterisation methods

Briquette Property	Method Summary	Standard Test Method	Reference
Unit density	Ratio of cylinder mass to volume	DD CEN/TS 15405	[2010]
Moisture content	Mass lost in drying at 105°C ±2	BS EN 14774-2	[2009]
Unconfined compressive strength	Failure loading of axially loaded cylinder	ASTM C39-96 (adapted)	[1998]
Abrasion resistance	Mass lost in tumbling for 24 h	DD CEN/TS 15639	[2010]
Shattering resistance	Mass lost in drop from 1 m		adapted from [Lindley & Vossoughi, 1989; Li & Liu, 2000; Sengar et al, 2012]
Water absorption	Mass gained after soaking in water at room temperature	BS EN 772-21	[2011]

Two levels (low and high) were selected for each of the independent variables; the 2^4 (i.e., 4 variables with 2 levels) factorial design that was used for briquette production is shown in columns 2 to 5 of Table 9, which also shows the measured responses.

Since the effect of water in the binder was confounded with that of the starch in this experiment, additional experimental runs were conducted to assess the effect of water on the response variables, with and without starch. The responses for briquettes containing water only (without starch) are presented in rows 21** to 24** of Table 9, for comparison with the results for otherwise similar briquettes produced with both water and starch mixture in rows 9 to 12. In the statistical analysis, the effect of dry starch on briquette responses was assumed to be the same as when only rice husks and corn cobs residues were used (i.e., with no water or starch in rows 17** to 20** of Table 9).

Statistical effects of variables and their interactions on the responses were calculated based on the individual replicate results shown in columns 7, 9 and 11 of Table 9 [Box et al, 2005]. Effects of the variables and interactions between the variables on a response are estimated as the differences between the averages for the high and low levels of a variable or interaction, and the total mean response. The highest order interactions of variables were assumed to be largely due to random noise [Box et al, 2005]. Normal probability plots of the effects can be used to visualize the significance of the effects of individual variables on the responses [Box et al, 2005]. The estimated effects can be read from the abscissa, against the standard deviation of the normal distribution on the ordinate. The scale of the ordinate has been adjusted such that a normal distribution appears as a straight line, i.e., points that lie on the straight line may be a result of normal random variability, whereas those that deviate from the straight line indicate significant effects of these variables or interactions on the response. Analysis of variance was also used to determine the statistical significance of the observed effects [Box et al, 2005].

The fitted model for the predicted responses is shown as Equation 3 [Box et al, 2005], and Equation 4 was used to calculate the residuals (ε) of the responses.

$$\dot{Y} = \bar{Y} + \left(\frac{j1}{2}\right) * x1 + \left(\frac{j2}{2}\right) * x2 + \cdots \left(\frac{jn}{2}\right) * \mathcal{X}n$$

Equation 3

$$\mathcal{E} = \mathrm{y} - \dot{\mathrm{Y}}$$

Equation 4

Where;

$\bar{\Upsilon}\ is\ thegrand\ mean\ for\ each\ set\ of\ response\ data(eg.green\ density)$

$j1, j2 \ldots .jn\ is\ the\ observed\ main\ or\ interaction\ effect\ of\ the\ variables$

$x1, x2 \ldots xn\ is\ the\ respective\ sign\ of\ the\ observed\ effects\ for\ each\ response\ value$

A normal probability plot of the residuals was used to visualize the normality and check that all effects other than those included in the model are explained by random noise.

4.2 Briquette curing

All briquettes produced in the factorial design experiment were cured for 24 hours at 23 ± 2°C and relative humidity of 50 ± 5 % before testing.

New batches of the briquette formulations with the highest relaxed density and those with the highest unconfined compressive strength were made for further testing after curing as follows:

24 hours + 6 days at 23 ± 2°C

24 hours at 35°C + 6 days at 23 ± 2°C.

The briquettes were cured at 35°C to assess the effect of warm weather conditions, e.g., in the source country of the raw materials, Nigeria.

Figure 12 shows some of the briquettes produced.

Figure 12: Briquettes produced from blends of rice husks and corn cobs

4.3 Briquette characterisation

4.3.1 Density

Briquette density was determined according to the draft European standard DD CEN/TS 15405 [2010]. The mass and dimensions of each briquette were measured immediately after extrusion from the mold to calculate the green densities, and again after 24 hours to calculate the relaxed densities of the briquettes. Measurement of the relaxed densities of briquettes with the same formulations as those with the highest densities and compressive strengths at 24 hours (Table 9) was repeated after an additional 6 days (Table 10).

4.3.2 Moisture content

Briquette moisture content was determined as the percentage mass lost after oven drying to constant mass at 105°C ±2 according to BS EN 14774-2 [2009]. This measured was included in the durability tests carried out on briquettes with the highest density and compressive strength (Table 9), and the results are presented in Table 10.

4.3.3 Unconfined compressive strength

The unconfined compressive strengths of the cured briquettes were determined by adapting ASTM C39-96 [Rajvanshi, 1986], using an Instron 3345 universal testing machine with a maximum load of 5 kN (Figure 13). Each briquette was placed on the base of the machine in a diametric position and subjected to load gradually at 1.7 N/s until it failed. The maximum load at failure was recorded and divided by the briquette cross-sectional area of 8.1×10^{-4} m^2

to calculate the compressive strength. Measurement of the compressive strengths of the briquettes with the same formulation as those with the highest density and compressive strength (Table 9), was repeated after an additional 6 days (Table 10).

Figure 13: Briquette set for compressive strength test

4.3.4 Abrasion resistance

The abrasion resistance of the cured briquettes was measured according to the European standard for determination of mechanical durability of pellets and briquettes, DD CEN/TS 15639 [2010]. For each test, three briquettes were weighed and placed together in a laboratory container of 35 mm internal diameter and 42 mm external diameter by 80 mm height and closed with a lid. The container with the briquettes was then rotated at 25 rpm for 15 minutes in a rotary extractor. The fines were separated from larger pieces of briquette by shaking through two sieves, a larger sieve of 21 mm and smaller sieve with 1 mm diameter apertures for fines collection. The abrasion index of the briquettes was determined as the percentage mass loss during tumbling, relative to the total original briquette mass.

4.3.5 Shattering resistance

There is no standard method for measuring the shattering resistance (also known as impact or drop resistance) of briquettes, but a drop test method has been used for solid fuels by other researchers [Updegraff, 1969; Lindley & Vossoughi, 1989; Li & Liu, 2000; Sengar et al, 2012]. Briquettes were held at 1 m height above the ground and dropped on a concrete floor; each briquette was dropped three times. The largest briquette fragment was weighed and the shatter index was calculated as the percentage mass lost relative to the total original briquette mass.

4.3.6 Water absorption

The resistance of briquettes to wetting was determined as water absorption in adapted method BS EN 772-21 [2011]. All the cured briquettes were individually immersed into 50 mL of water in a laboratory beaker for 60 seconds. The water absorption was calculated as the percentage mass gain relative to the original undried briquette mass.

4.4 Results and discussion

4.4.1 Properties of loose rice husks and corn cobs

Table 8 shows the properties of the rice husks and corn cobs measured in this study.

Table 8: Feed material properties (averages of three measurements)

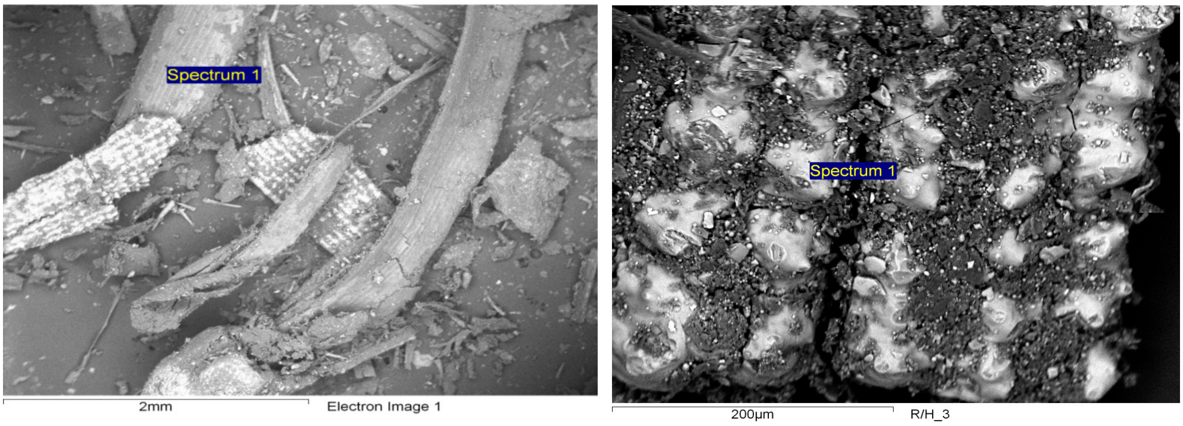
Raw feed sample	Rice husks		Corn cobs	
	Sample A	Sample B	Sample A	Sample B
Ash content (% dry mass)	19.6	ND	4.1	ND
Moisture content (% undried mass)	7.0	7.0	6.9	6.8
Specific gravity	1.50	1.50	1.47	1.46
Bulk density (dried mass, kg/m^3)	363	354	395	278
Porosity (% of uncompacted volume)	75	76	73	81
Water absorption (% dried mass)	112	160	168	289
(% saturation of porosity)	48	109	130	251
(% volume change)	29.4	ND	40	ND
Particle size (mm)	<2	<2	<1.6	<1.6

ND = not determined as the quantity of sample B was limited

The ash content of the rice husks in Table 8 appears to be consistent with the literature value in Table 2, while that of the corn cobs, though almost twice the literature value, is much lower than that of the rice husks. The moisture contents determined for both the rice husks and corn cobs in this study were similar, although moisture content of corn cobs is commonly found to be higher than that of rice husks, and both our measurements are slightly lower than the ranges reported by others [Grover & Mishra, 1996; Kaliyan & Morey, 2010a] (Table 2). This may be due to handling and storage conditions of the materials before the moisture content test, whereby our materials were not fresh, and air drying and hammer milling of the corn cobs is associated with significant moisture loss [Kaliyan & Morey, 2010a].

Furthermore, the measured solids specific gravities were consistent between samples of each material, but those of the rice husk solids were slightly higher than those of the corn cob solids. This observation may be attributable to the higher ash content of the rice husks, or other differences in composition between rice husks and corn cobs as shown in Table 2 and Table 8. The loose bulk densities of both the rice husks and corn cobs in this study fall within the ranges determined by other workers (Table 2), except for corn cob Sample A which is about 40% higher than expected. The porosities of the rice husks and corn cobs were similar, but also higher than results by others reported in Table 2, with a notable difference between the porosities measured for the two samples of corn cobs, reflecting the difference in bulk density.

These results indicate a greater variability in the properties of lignocellulosic biomass than has hitherto been reported in the literature, potentially caused by factors including growth conditions, cultivation methods, and post-harvesting handling of the crop.

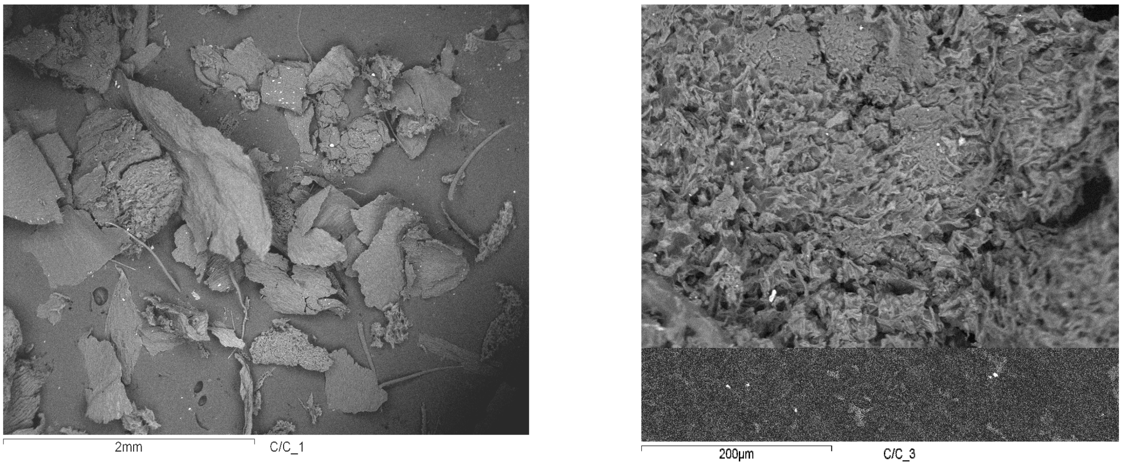


(a)

(b)

Figure 14: Morphology of rice husks under SEM (Sample B)

Based on visual observation, rice husk samples A and B appeared similar. On the other hand, corn cob sample B appeared to have flat, flakey and porous particles while sample A, had round particles with a thick outer layer that appeared less porous. The SEM investigation of the biomass particle morphology confirmed a difference in the texture between the rice husks (Figure 14) and corn cobs (Figure 15), and between the two samples of corn cobs. Corn cobs consist of softer, porous particles (Figure 15b), which can aid water penetration, while rice husks have thicker cell walls and fewer openings on particle surfaces, which resist rapid water penetration. The microstructure of corn cob particles implies existence of a capillary network and an associated tendency to absorb water [Pinto et al, 2012].



(b)

(a)

Figure 15: Morphology of corn cobs under SEM (Sample B)

Consistent with the literature [Thakur & Gupta, 2006; Pinto et al, 2012] (Table 2), the water absorption of the corn cobs was found to be higher than that of the rice husks. For all four biomass samples, the available pore spaces within the biomass residue were oversaturated. The oversaturation of the porosity is observed as swelling (% volume change in Table 8), which is typical of most lignocellulosic materials when immersed in fluids such as oil [Ragunathan et al, 2011] and water.

4.4.2 Briquette density and compressive strength

Columns 7, 9 and 11 of Table 9 show the mean unit densities and compressive strengths of briquettes obtained for each run of the factorial design experiment; the standard deviations for the three replicates of each test are shown in columns 8, 10 and 12.

Results showed that blending rice husks and corn cobs produced briquettes with a unit density of up to 1.9 times the average bulk density of the loose biomass, and of better strength than briquettes made from the individual materials. The bulk densities of the fuel briquettes in this study were estimated to range from 366 to 570 kg/m^3; the higher value compares well with the ≥ 500 recommended value for standard solid biofuels under the UK code of good practice [CEN/TS 14961:2004].

For various blends of rice husks and corn cobs, the compressive strengths and relaxed densities obtained were in the range of 25 to 237 kPa and 490 to 712 kg/m^3 respectively.

Considering average values from both biomass sources investigated, an unconfined compressive strength of 176 kPa was achieved at a compaction pressure of 31 MPa for a 3:7 blend of rice husks to corn cobs with 10% binder (starch/water = 2:3). These briquettes were found to be durable with only 4% mass loss during abrasion and 10% mass loss during shattering tests. They absorbed 36% less water than the loose corn cobs. The durability properties of briquettes obtained in this study compare well with those obtained by other researchers [e.g., Kaliyan & Morey, 2010a; Oladeji & Enwerenmadu, 2012; Chin & Siddiqui, 2000] for individual agricultural biomass and [e.g., Wamukonya & Jenkins, 1999; 98], for mixed woody biomass, The durability properties fall within the specification of ≤12% moisture content and <10% mass loss during shattering and abrasion tests for CEN/TS 14961, the European standard for solid fuel quality [2004].

Table 9: Briquette density and strength measured in a factorial design with sample batch, material ratio, binder content and compaction pressure

Run 1	VARIABLES					RESPONSES*					
	Sample batch (S) 2	Material ratio (M) (% mass of rice husks in rice husk/corn cob blend) 3	Binder (B)		Pressure (P) (MPa) 6	Unit Green Density (kg/m^3)		Unit Relaxed Density (kg/m^3)		Compressive Strength (kPa)	
			(% mass of starch in rice husk/corn cob blend) 4	(% mass of added water in rice husk/corn cob blend) 5		Mean 7	SD 8	Mean 9	SD 10	Mean 11	SD 12
1	A	50	4	6	19	815	15	616	18	70	4
2	A	30	4	6	19	867	14	671	41	152	7
3	A	50	4	6	31	896	17	673	19	158	1
3+	A	50	4	6	31	830	19	664	8	148	1
4	A	30	4	6	31	874	17	631	11	183	7
4+	A	30	4	6	31	870	11	660	10	179	3
5	A	50	6	11	19	767	40	556	13	151	19
6	A	30	6	11	19	808	26	592	9	155	4
7	A	50	6	11	31	815	36	583	16	171	9
8	A	30	6	11	31	846	25	596	22	175	14
9	B	50	4	6	19	698	23	593	22	25	7
10	B	30	4	6	19	766	10	612	33	64	9
11	B	50	4	6	31	761	21	586	39	59	8
12	B	30	4	6	31	795	9	629	15	189	14
13	B	50	6	11	19	767	4	490	24	168	11
14	B	30	6	11	19	715	20	556	29	191	6
15	B	50	6	11	31	707	27	572	10	237	21
16	B	30	6	11	31	703	15	512	5	177	16
17**	B	50	0	0	19	316	0	316	0	0	0
18**	B	30	0	0	19	607	28	301	0	0	0

Table 9: Briquette density and strength measured in a factorial design with sample batch, material ratio, binder content and compaction pressure

Run 1	VARIABLES					RESPONSES*					
	Sample batch (S) 2	Material ratio (M) (% mass of rice husks in rice husk/corn cob blend) 3	Binder (B)		Pressure (P) (MPa) 6	Unit Green Density (kg/m^3)		Unit Relaxed Density (kg/m^3)		Compressive Strength (kPa)	
			(% mass of starch in rice husk/corn cob blend) 4	(% mass of added water in rice husk/corn cob blend) 5		Mean 7	SD 8	Mean 9	SD 10	Mean 11	SD 12
19**	B	50	0	0	31	659	46	316	0	0	0
20**	B	30	0	0	31	615	37	549	13	0	0
21**	B	50	0	6	19	752	10	623	26	59	4
22**	B	30	0	6	19	791	36	695	14	98	4
23**	B	50	0	6	31	777	16	642	11	48	4
24**	B	30	0	6	31	812	27	712	11	70	4

* Average of three responses; SD is standard deviation

** Experimental runs for effect of water only on briquette responses

4.4.3 Effects of briquetting variables on response variables

The main (individual) and interaction (two-factor and three-factor) effects of the sample batch, material ratio, binder content and compaction pressure, on the green densities, relaxed densities and compressive strengths of the briquettes in the 2^4 factorial design experiment (Runs 1 to 16), are presented in normal probability plots in Figure 16a to c.

The effects that deviate from the straight line in the probability plot are the most significant. The probabilities that the shown effects are attributable to random error, p, were determined based on the F-statistics calculated in the analysis of variance (ANOVA). An effect is generally considered as statistically significant when $p < 0.05$ [Box et al, 2005]. A normal plot of the residuals from Equation 3 showed a straight line, indicating good model fit.

The use of corn cob sample A rather than B had a highly significant positive effect on both green and relaxed densities ($p = 0.0001$ and $p = 0.0001$, respectively), but only a small positive effect on compressive strength ($p = 0.562$). Since densification is the primary motivation for briquetting, this effect emphasises the importance of understanding the variability of biomass properties, and possibly the need for consistent pre-treatment of residues before their application as biofuels. The lower rice husk content had a highly significant positive effect on briquette relaxed density and compressive strength ($p = 0.0001$ and $p = 0.0001$, respectively). The smaller particle size of the corn cobs and their porous nature may have resulted in better compaction. This observation also compares well with findings by other authors [Kaliyan & Morey, 2010a; Oladeji & Enwerenmadu, 2012], where briquettes produced from smaller particles sizes exhibited less relaxation. There is an increased energy cost associated with biomass grinding, but energy is saved in compaction, as smaller particles are more easily densifiable due to their greater surface area [Tumuluru et al, 2011] which increases the effect of short range electrostatic and magnetic forces, and causes particles to adhere to each other [Kaliyan, 2008].

The use of the starch/water binder decreased briquette density ($p = 0.003$), which may be attributable to the low density of the starch/water gel, in comparison with the residues that it replaced, and the possible expansion of briquettes due to heat development during densification. However, the briquettes produced without binder (experimental runs 17** to 20**), were crumbly and with negligible compressive strength, and the use of the binder was thus critical to achieve a useful compressive strength, as expected (Table 9). It was postulated that the effect of the binder on the briquette responses may be due to the natural presence of binders in most biomass materials, which are activated using moisture or temperature [Kaliyan & Morey, 2010a]. Therefore, to assess the effect of water separately from that of starch, an ANOVA was conducted for experimental runs 9 to 12 (including starch and water) and 21** to 24** (including water only), in Table 9. The results compared well with those for the 2^4 factorial design experiment, and showed that starch had an effect of 16 kPa ($p = 0.0001$) on strength, on top of the effect of water alone. There was also an interaction between sample batch and binder content, which significantly reduced the green density of the briquettes made with corn cob sample B containing the starch binder ($p = 0.0040$). This interaction effect was not apparent for the relaxed density ($p = 0.135$), but had a strong negative effect on the compressive strength ($p = 0.0001$). The use of the higher pressure of 31 MPa yielded a significant positive effect on briquette relaxed density ($p = 0.001$), which is consistent with rational expectations and the literature [Chin & Siddiqui, 2000].

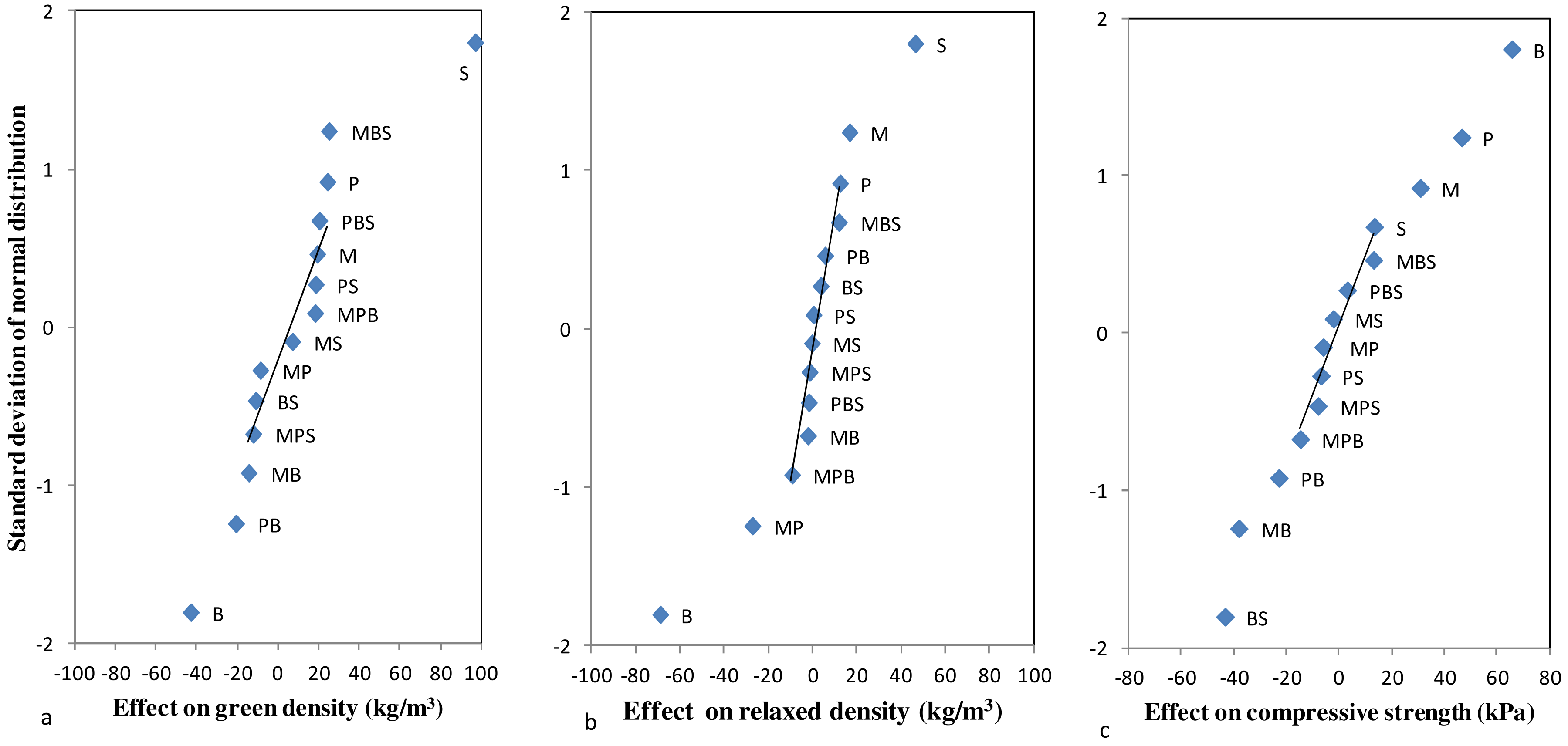


Figure 16: Normal probability plots of the effects of sample batch (S), material ratio (M), binder addition (B), compaction pressure (P), and their interactions (MS, BS, PS, MB, MP, PB, MBS, MPS, PBS, MPB, on briquette a) green density, b) relaxed density and c) compressive strength

Table 10 summarises the durability properties of the briquettes with the highest density and compressive strength from Table 9.

Despite the addition of the binder containing water to the blends of rice husks and corn cobs, briquette moisture contents in Table 10 appear within range for good quality briquettes (≤ 12%) recommended by the European standards for solid fuels CEN/TS 14961 [2004]. The briquette moisture contents in this study can also be compared with the range of 9 to 14 % achieved for binderless corn cob briquettes by Kaliyan & Morey [2010a]. Curing at 35°C significantly reduced the moisture content of briquettes, as a result of increase moisture loss due to elevated temperature. Briquette expansion was mainly due to longitudinal with an average of 15 % longitudinal expansion compared with 4 % diametrical. An average reduction in density of briquettes sample A and B was found to be 22 % (Table 10).

Water absorption of briquettes produced at 3:7 rice husks to corn cobs (repeats of runs 4+,12) is almost twice that of 1:1 rice husks to corn cobs (repeats of runs 3+,15). This may be due to the high ratio of porous corn cobs (Figure 15) in the 3:7 blend of rice husks to corn cobs. The over-saturation observed in briquettes can also be related to the swelling nature of lignocellulosic residues that was observed in the raw feed samples (4.4.1).

Shattering and abrasion resistance of briquettes produced from 3:7 blend of rice husks to corn cobs conform with the <10% mass loss required by standards for quality assurance of solid biofuels CEN/TS 14961[2004]. This compares well with 8 to 12% mass loss for corn cob briquettes produced at 150 MPa and 85°C [Kaliyan & Morey, 2010a]. The difference in porosity of the briquettes and their individual parent materials was relatively small at 8 to 22%. Whereas relatively low compaction pressures were investigated in this work to reduce energy and equipment costs, preliminary results for the 3:7 blend of the B samples of rice husks and corn cobs, without use of a binder, suggest that a relaxed density of 774 kg/m^3 could be achieved at an increased compaction pressure of 80 MPa. The blend ratio may also affect the briquetting process energy consumption; for example, there was a decrease in energy consumption when the blend ratio changed from 30/70 to 50/50 (manuscript in preparation).

Table 10: Durability properties of briquettes at different curing conditions

Briquette properties	Run from Table 9	Curing temperature (°C±2° C)	Curing time (d)	Response (sample A)	Response (sample B)
Unit relaxed density (kg/m^3)	3+	23	1	664	ND**
	15	23	1	ND*	572
	3 (repeat)	23	7	645	ND**
	15 (repeat)	23	7	ND*	616
	15 (repeat)	35	1	ND*	586
	3 (repeat)	35	1	586	ND**
	3 (repeat)	35	7	531	ND**
	4+, 12	23	1	660	629
	4, 12 (repeat)	23	7	644	669
	4 (repeat)	35	1	660	ND**
	4 (repeat)	35	7	600	ND**
Reduction in unit density (after storage) (% of green density)	3+	23	1	20	ND**
	15	23	1	ND*	19
	3 (repeat)	23	7	28	ND**
	15 (repeat)	23	7	ND*	13
	15 (repeat)	35	1	ND*	17
	3 (repeat)	35	1	35	ND**
	3 (repeat)	35	7	40	ND**
	4+, 12	23	1	24	21
	4, 12 (repeat)	23	7	26	16
	4 (repeat)	35	1	24	ND**
	4 (repeat)	35	7	30	ND**
Densification (proportion of average loose biomass density of 348 kg/m^3)	3+	23	1	1.9	ND**
	15	23	1	ND*	1.6
	3 (repeat)	23	7	1.9	ND**
	15 (repeat)	23	7	ND*	1.8
	15 (repeat)	35	1	ND*	1.7
	3 (repeat)	35	1	1.7	ND**
	3 (repeat)	35	7	1.5	ND**
	4+, 12	23	1	1.9	1.8
	4, 12 (repeat)	23	7	1.9	1.9
	4 (repeat)	35	1	1.9	ND**
	4 (repeat)	35	7	1.7	ND**
Moisture content (% undried mass)	3+	23	1	9	ND**
	15	23	1	ND*	12
	15	35	1	ND*	6
	4+, 12	23	1	10	10
Porosity (% volume)	3+	23	1	59	ND**
	15	23	1	ND**	65
	4+,12	23	1	60	60
Water absorption (% dried mass)	3+	23	1	70	ND**
	15	23	1	ND*	66
	4+,12	23	1	142	151
(% saturation of porosity)	3+	23	1	118	ND**
	15	23	1	ND*	100
	4+,12	23	1	237	245
Compressive strength (kPa)	3+	23	1	148	ND**
	15	23	1	ND*	237

Briquette properties	Run from Table 9	Curing temperature (°C±2° C)	Curing time (d)	Response (sample A)	Response (sample B)
	3 (repeat)	23	7	98	ND**
	15 (repeat)	23	7	ND*	180
	3 (repeat)	35	1	73	ND**
	3 (repeat)	35	7	60	ND**
	4+, 12	23	1	179	189
	4, 12 (repeat)	23	7	167	167
	4 (repeat)	35	1	135	ND**
	4 (repeat)	35	7	130	ND**
Shattering resistance (% undried mass loss)	3+	23	1	14	ND**
	15	23	1	ND*	4
	4+,12	23	1	9	11
Abrasion resistance (% undried mass loss)	3+	23	1	20	ND**
	15	23	1	ND*	3
	4+,12	23	1	3	4

ND* = not determined for sample A, see initial run in **Table 9**

ND** = not determined for sample B, see initial run in **Table 9**

4.5 Summary

The research presented in this chapter has demonstrated that briquettes of good and consistent quality, which conform to CEN/TS 14961[2004], can be produced by blending of rice husks and corn cobs.

Briquettes had a unit density of up to 1.9 times the loose biomass bulk density, and were stronger than briquettes from the individual materials. Considering average values from two biomass sources, an unconfined compressive strength of 176 kPa was achieved at a compaction pressure of 31 MPa for a 3:7 blend of rice husks to corn cobs with 10% binder. These briquettes were durable, with only 4% mass loss during abrasion and 10% mass loss during shattering tests. They absorbed 36% less water than loose corn cobs.

Statistical analysis of the results showed that starch and water addition was required for adequate briquette strength, but significantly reduced green and relaxed densities. The source of the biomass had a significant effect on densification, which emphasises the need to understand factors underlying biomass variability.

Further study of the causes and effects of biomass variability is recommended. The negative effect of starch binder on briquette density also indicates the need to explore other sources of binder that do not result in swelling during biomass densification (investigated in chapter 5 of this research). Further research into the impact of blend ratio on the briquetting process energy consumption is also required (Investigated in Chapter 7 of this research). Since the maximum storage period for briquettes used in this chapter was 7 days, it is important to consider the effect of longer storage periods on briquette quality (recommended for future work on this research).

5 BIOSOLIDS AND MICROALGAE AS ALTERNATIVE BINDERS FOR BIOMASS FUEL BRIQUETTING

5.1 Experimental design and analysis

Experiments in this chapter explored the use of alternatives to starch for binding the biomass residues used in Chapter 4, corn cobs and rice husks, also with bagasse. Biosolids and microalgae were considered as binders because: 1) they are natural waste materials that do not compete with food crops, unlike starch, which is also a food source, or contain anthropogenic chemical contaminants; 2) they have a high energy content, and 3) they possess other properties that have a potentially positive effect on densification (2.4.7.5).

A factorial experimental design method involving 16 runs was employed for production of briquettes. The variables investigated in this study were chosen based on their influence on briquette properties from previous work by the authors [Muazu & Stegemann, 2015]; these included material ratio (M), i.e., percentage masses of rice husks, corn cobs and bagasse in the blends, binder addition (B), i.e., mass of starch (ST) or biosolids (BS) or microalgae (AL) binder and water (W) added as a percentage of the rice husks, corn cobs and bagasse blend, and compaction pressure (P). The response variables measured were green (immediately after extrusion from the mold) and relaxed (after 24h curing) density, unconfined compressive strength, calculated energy density, and the combustion profile of the briquettes.

The $2^2 3^1$ (i.e., 2 variables with 2 levels, and 1 variable with 3 levels) multilevel level factorial design that was used for briquette production is shown in columns 2 to 6 and 8 of Table 13, which also shows the measured responses. Two levels were selected for material ratio (40% rice husks: 40% corn cobs: 20% bagasse, or 25% rice husks: 65% corn cobs: 10% bagasse; columns 2 and 3 of Table 13). Thus, the effects of rice husks and bagasse are confounded, as both were higher when the corn cob content was lower, and vice versa. Two levels were also selected for the compaction pressure (19 or 31 MPa; column 8 of Table 13), while three levels were selected for the binder (17% starch, biosolids or microalgae; columns 4, 5 and 6 of Table 13). The quantity of water in the binder paste for each experimental run is shown in column 7 of Table 13. The effect of water was confounded with that of the starch, biosolids or microalgae used in the experiments, however, the effect of water separately with and without binder, was evaluated in our previous work with starch binder [Muazu & Stegemann, 2015]. Table 13 shows that Runs 1 to 4 were repeated, whereby the first replicate was run together with the runs for the biosolids, and the second replicate was run together with those for the microalgae.

Statistical effects of variables and their interactions on the responses were calculated based on the individual replicates, corresponding to the averaged results shown in columns 9, 11 and 13 of Table 13 [Box et al, 2005]. Effects of the variables and interactions between the variables on a response are estimated as the differences between the averages for each level of a variable or interaction, and the total average response. Normal probability plots of the effects can be used to visualize the significance of the effects of individual variables on the responses [Box et al, 2005]. The estimated effects can be read from the abscissa, against the standard deviation of the normal distribution on the ordinate. The scale of the ordinate has been adjusted such that a normal distribution appears as a straight line, i.e., points that lie on the straight line may be a result of normal random variability, whereas those that deviate from the straight line indicate significant effects of these variables or interactions on the response. Analysis of variance was also used to determine the statistical significance of the observed effects [Box et al, 2005].

5.2 Briquette curing

Biomass and binder blends were weighed out in the proportions indicated in columns 2 to 7 of Table 13 and densified using hydraulic compression, as previously described [Muazu & Stegemann, 2015]. The briquette diameter was 32 mm, and the green lengths ranged from 25 to 33 mm before relaxation, while the relaxed lengths ranged 33 to 43 mm. The briquette masses ranged from 16 to 19 g. The briquettes were cured for 24 hours at 23 ± 2^{o}C and relative humidity of 50 ± 5 % before testing. Figure 17 shows sample briquettes produced from the blends of rice husks, corn cobs and bagasse with different binders.

Figure 17: Briquettes produced from blends of rice husks, corn cobs and bagasse with different binders

5.3 Briquette characterisation

The methods used to measure the response variables are summarized in Table 7 (density and unconfined compressive strength), and Table 11 with the exception of the combustion test, which is further described below. All tests were repeated for three briquettes.

Table 11: Briquette characterisation methods

Briquette Property	Method Summary	Standard Test Method	Reference
Energy density	Proportionally weighted sum of average component energy density from the literature multiplied by the relaxed density		adapted from Table 5, [68]

An atmospheric combustion test (from [Chaney et al, 2010; Musa, 2007]) was carried out in the laboratory by placing a single briquette in the centre of a steel wire mesh grid resting on fire retardant bricks, allowing the free flow of air through the briquette. The combustion rig was positioned on top of a digital mass balance to record the briquette mass throughout the combustion process. Smoke was allowed out through an extraction hood.

Figure 18: Briquette atmospheric combustion test

Individual briquettes were ignited using a laboratory ignition blow torch powered by propane gas (Calor gas 340) as shown in Figure 18. The blow torch was left in until the briquette was well ignited and had entered into its steady state burn phase [Chaney et al, 2010]. The briquette mass was recorded every 3 minutes until less than 10% of the briquette remained. The afterglow time was recorded as the amount of time within which a red glow was observed after the ignition flame disappeared, i.e., the period in which useful heat is evolved.

The remaining residue from briquette combustion was further heated in a Carbolite laboratory muffle furnace at 600ºC for 4h, to obtain the residual combustible fraction and total non-combustible (ash) portions in a complete combustion.

Figure 19: Determination of ash content of briquettes produced with starch, biosolids and microalgae binders in a muffle furnace

5.4 Results and discussion

5.4.1 Properties of loose rice husks, corn cobs and bagasse

Table 12 shows the properties of the rice husks, corn cobs and bagasse measured in this study.

The properties of rice husks and corn cobs have been discussed in previous work by the authors [Muazu & Stegemann, 2015]. The moisture content of the bagasse appears to be very low compared with that reported in the literature (Table 2). This may be attributed to air drying at source and during hammer milling [Kaliyan & Morey, 2009]. The specific gravity of bagasse is slightly lower than that of rice husks and corn cobs, corresponding to the lower ash content. The high ash content of corn cobs can be attributed to the type of biomass species and possible contamination from soil during cultivation and handling of residue [e.g., Hoffman, 2005]. The loose bulk density falls within the range reported in Table 2 but is lower than that of rice husks and corn cobs, corresponding to a higher inter-particle porosity. In contrast, the water absorption and percentage saturation of available pore space were far less than for the rice husks and corn cobs, and the reported values in the literature. During the water absorption test, water was observed to rapidly penetrate between the particles of bagasse, but quickly separated from the residue at the filter stage of the absorption test. The slight oversaturation of the porosity observed in bagasse is associated with swelling (% volume change in Table 12) that occurs in most lignocellulosic materials when immersed in fluids such as oil [Ragunathan et al, 2011] and water, including also the rice husks and corn cobs.

These results again indicate significant variability in the properties of lignocellulosic biomass, which is potentially caused by factors including growth conditions, cultivation methods, and post-harvesting handling of the crop. Our results suggest that the post-harvest handling of the crop is particularly significant.

Table 12: Feed material properties (averages of three measurements)

Raw feed sample	Rice husks	Corn cobs	Bagasse
Ash content (% dry mass)	19.6	4.1	ND
Moisture content (% undried mass)	7.0	6.8	8.1
Specific gravity	1.50	1.46	1.38
Bulk density (undried mass, kg/m^3)	354	278	173
Porosity (% of uncompacted volume)	76	81	87
Water absorption (% dried mass)	160	289	90
(% saturation of porosity)	109	251	4
(% volume change)	29	40	20
Particle size (mm)	<2	<1.6	<1.6

ND = not determined

5.4.2 Briquette density and compressive strength

Columns 9, 11 and 13 of Table 13 show the average green and relaxed densities and compressive strengths of briquettes obtained for each run of the multilevel factorial design experiment; the standard deviations for the three replicates of each test are shown in columns 10, 12 and 14. The green and relaxed densities refer to the specific unit density of an individual briquette.

The relaxed densities obtained for the twelve runs with different proportions of the three raw materials and three binders ranged from 463 to 577 kg/m^3. These relaxed densities were up to 1.9 times the average bulk density of the loose rice husks and corn cobs and up to 3.3 times the bulk density of loose bagasse.

The compressive strengths obtained for the twelve runs with different proportions of the three raw materials and three binders ranged from 70 to 175 kPa. Briquette moisture contents ranged from 10 to 12% mass. These values comply with the recommended moisture specification of ≤12% by CEN/TS 14961, the European standard for solid fuel quality [2004].

5.4.3 Energy density of starch, biosolids and algal bonded briquettes

Column 15 of Table 13, shows the estimated energy densities of briquettes produced using starch, biosolids and microalgae binders, with the blend ratio of rice husks, corn cobs and bagasse.

From Table 13, the use of a higher proportion of corn cobs, which have a higher calorific value, yielded briquettes with higher calculated energy densities for all three binders (Table 2). The influence of the bagasse calorific value was relatively minor, because of the relatively small difference in the mass proportion of bagasse residue in the 40/40/20 and 25/65/10 blends of rice husks, corn cobs and bagasse.

Briquettes produced with starch binder had the lowest energy densities while briquettes produced with the algae binder had the highest energy densities for both blends of rice husks, corn cobs and bagasse. Although untreated biosolids have a high calorific value [Jiang et al, 2014; Silva et al, 2012], enhanced treated biosolids were used in this study to avoid health hazards [2.4.7.5, ADAS, 2001]. Enhanced treatment of biosolids may be associated with a reduction in energy density.

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Table 13: Briquette densities and strengths measured in a factorial design experiment to study effects of material ratio, binder content and compaction pressure

Run 1	VARIABLES							RESPONSES*							
	Material ratio (M) (% dry mass in blend**)		Binder (B) (% dry mass added to blend**)				Pressure (P) (MPa) 8	Unit Green Density (kg/m³) 9		Unit Relaxed Density (kg/m³) 10		Compressive Strength (kPa) 11		Energy Density (kJ/m³) 12	
	rice husks 2	corn cobs 3	starch 4	biosolids 5	algae 6	water 7									
								Average	SD	Average	SD	Average	SD	Average	SD
1-1	40%	40%	6%	0%	0%	11%	19	752	24	470	14	125	12	1175	7
2-1	25%	65%	6%	0%	0%	11%	19	714	37	489	30	119	10	1164	9
3-1	40%	40%	6%	0%	0%	11%	31	782	12	465	25	102	6	1175	7
4-1	25%	65%	6%	0%	0%	11%	31	858	6	515	20	155	13	1164	9
1-2	40%	40%	6%	0%	0%	11%	19	722	16	463	8	118	14	1169	4
2-2	25%	65%	6%	0%	0%	11%	19	698	23	491	10	104	17	1162	9
3-2	40%	40%	6%	0%	0%	11%	31	779	11	470	21	121	6	1169	4
4-2	25%	65%	6%	0%	0%	11%	31	840	4	503	19	159	23	1162	9
5	40%	40%	0%	6%	0%	11%	19	759	19	520	20	94	7	1196	5
6	25%	65%	0%	6%	0%	11%	19	796	29	500	30	101	8	1185	12
7	40%	40%	0%	6%	0%	11%	31	759	29	463	27	70	15	1196	5
8	25%	65%	0%	6%	0%	11%	31	859	21	577	20	146	27	1185	12
9	40%	40%	0%	0%	6%	11%	19	822	17	473	21	124	21	1247	5
10	25%	65%	0%	0%	6%	11%	19	809	36	544	40	150	13	1237	6
11	40%	40%	0%	0%	6%	11%	31	836	13	502	32	137	15	1247	5
12	25%	65%	0%	0%	6%	11%	31	826	46	571	37	175	31	1237	6

* Average of three responses; SD is standard deviation

** Blend is rice husks/corn cobs/bagasse without binder; % of bagasse in blend can be obtained by subtraction of the sum of the % masses of rice husks and corn cobs from 100%.

5.4.4 Effects of briquetting variables on response variables

Figure 20a to c presents the normal probability plots of the main (individual) and interaction (two-factor and three-factor) effects of the material ratio, binder content/type and compaction pressure, on the green densities, relaxed densities and compressive strengths of the briquettes produced in the multilevel $2^2 3^1$ factorial design experiment (Table 13). The effects that deviate from the straight lines in the probability plots are the most significant. The magnitudes of the effects, and the probabilities that they are attributable to random error, p, determined based on the F-statistics calculated in the analysis of variance (ANOVA), are shown in Table 14. An effect is generally considered as statistically significant when $p < 0.05$ [Box et al, 2005].

The use of the lower content of rice husks and bagasse (i.e., higher corn cob content) in the biomass blend, had a significant positive effect on briquette relaxed density and compressive strength (p = 0.001 and p = 0.001, respectively). The corn cobs particles were smaller, and findings by other authors [Kaliyan & Morey, 2009; Oladeji & Enwerenmadu, 2012; Muazu & Stegemann, 2015] indicate that briquettes produced from smaller particles sizes exhibited less relaxation; this may be attributable to lower compressible intraparticle porosity. Also, bagasse has a high moisture content and rich natural binders. Therefore, addition of these components was expected to improve the briquette density and strength. However, a mild exothermic reaction, attributed to degradation of residual sugar present in the bagasse [Thomas, 2009], caused immediate drying after densification, which reduced the mass, and therefore the density of the briquettes. Small cracks were also physically observed on the briquettes containing the higher proportions of rice husks and bagasse, which may have reduced their strength. The presence of cracks was also related to greater expansion/relaxation of the briquettes.

In contrast with the negative effect of the starch binder observed in previous work by the authors [e.g., Muazu & Stegemann, 2015; Oladeji & Enwerenmadu, 2012], the use of biosolids and microalgae binders increased briquette green density and relaxed densities (p = 0.02) and (p = 0.035). This may be attributable to the high protein content of microalgae and biosolids (Table 5), which is known to improve binding in densified fuels [Jiang et al, 2014; Kaliyan & Morey, 2010]. Additionally, the use of biosolids and microalgae binders did not result in swelling during densification. This is consistent with findings by Jiang et al [2014] for untreated biosolids binder used in pellet production and Ververis et al [2011] for use of a microalgae binder in paper pulp production. The addition of starch and microalgae had positive effects on briquette compressive strength ($p = 0.001$), but there was apparently no interaction effect of binder and material ratio on compressive strength ($p = 0.38$).

The use of the higher compaction pressure of 31 MPa had a significant positive effect on green density ($p = 0.001$) but this effect was not apparent for compressive strength, while the interaction of compaction pressure with binder and material ratio both had negative effects ($p = 0.05$ and $p = 0.04$) on briquette green and relaxed density respectively. This agrees with findings from previous work by the authors [Muazu & Stegemann, 2015] and the literature [Chin and Siddiqui, 2000].

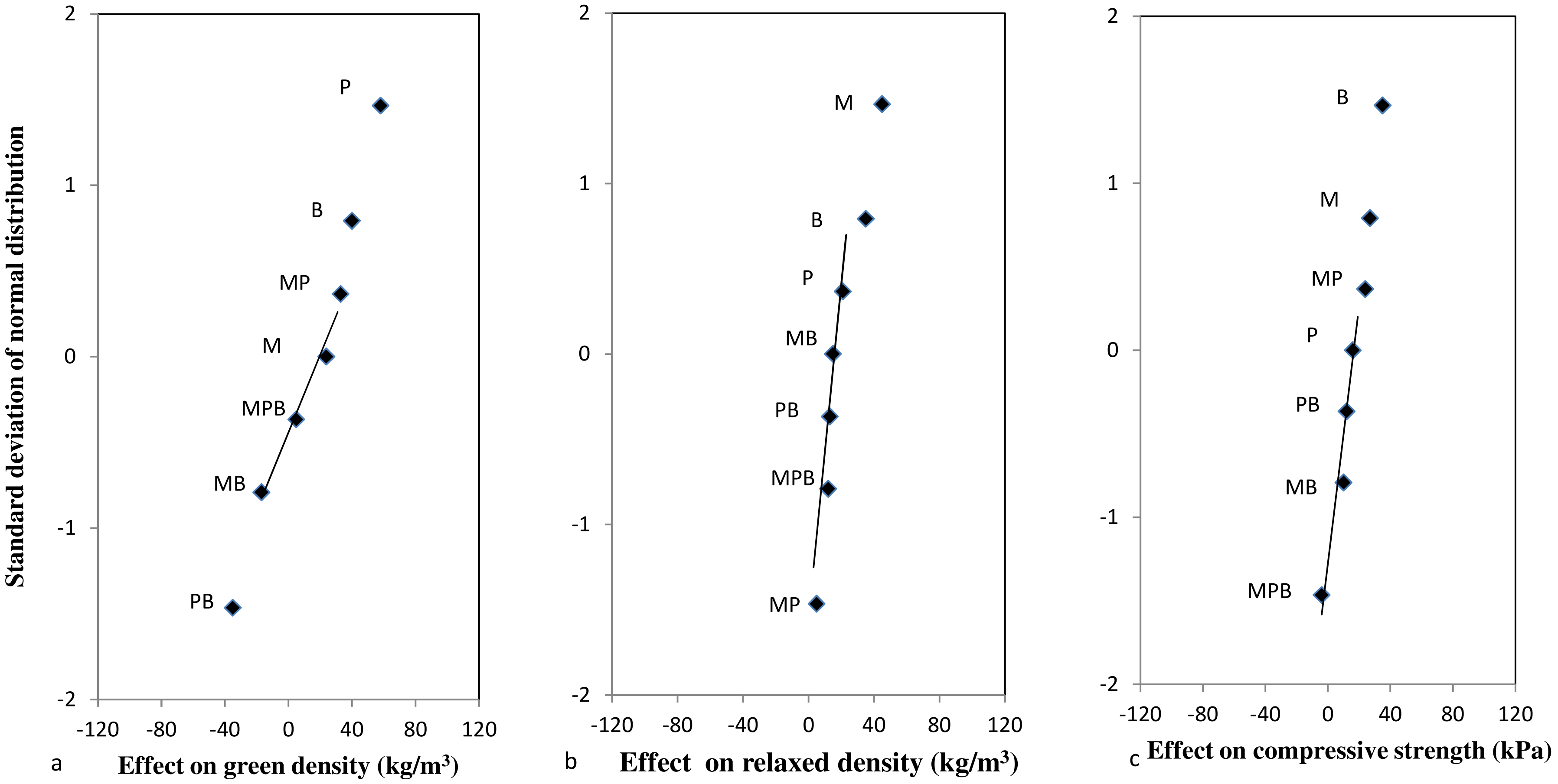


Figure 20: Normal probability plots of the effects of material ratio (M), pressure (P) and binder (B) and their interactions (MP, MB, PB, MPB) on briquette a) green, b) relaxed density, and c) compressive strength

Table 14: Probabilities that effects are attributable to random error based on analysis of variance

Factor	Green density		Relaxed density		Compressive strength	
	Effect (kg/m^3)	Probability, *p*	Effect (kg/m^3)	Probability, *p*	Effect (kPa)	Probability, *p*
M	24	0.07	45	0.001	27	0.001
P	58	0.001	15	0.06	16	0.06
B	40	0.02	35	0.035	35	0.001
M*P	33	0.01	21	0.04	24	0.001
M*B	-17	0.055	13	0.57	10	0.38
P*B	-35	0.05	5	0.21	12	0.66
M*P*B	5	0.19	12	0.056	-4	0.1

M=material ratio, P=compaction pressure, B=binder addition

Overall, the values of relaxed density obtained in this study are slightly less than those obtained in a previous study by the author [Muazu & Stegemann, 2015]. This may be due to the increased quantity of binder present in the blend (17% mass of residues compared with 10%), which increases the overall moisture content and porosity. This agrees with findings by Mani et al [2006] that a lower moisture content of 5-10% results in good quality briquettes, and Kaliyan & Morey [2009] also suggest a moisture content less than 15%.

5.4.5 Combustion characteristics of starch, biosolids and algal bonded briquettes

The combustion profiles of briquettes produced containing the biomass blends with starch, biosolids and microalgae binders, i.e., percentage mass loss over time, can be viewed in Figure 21.

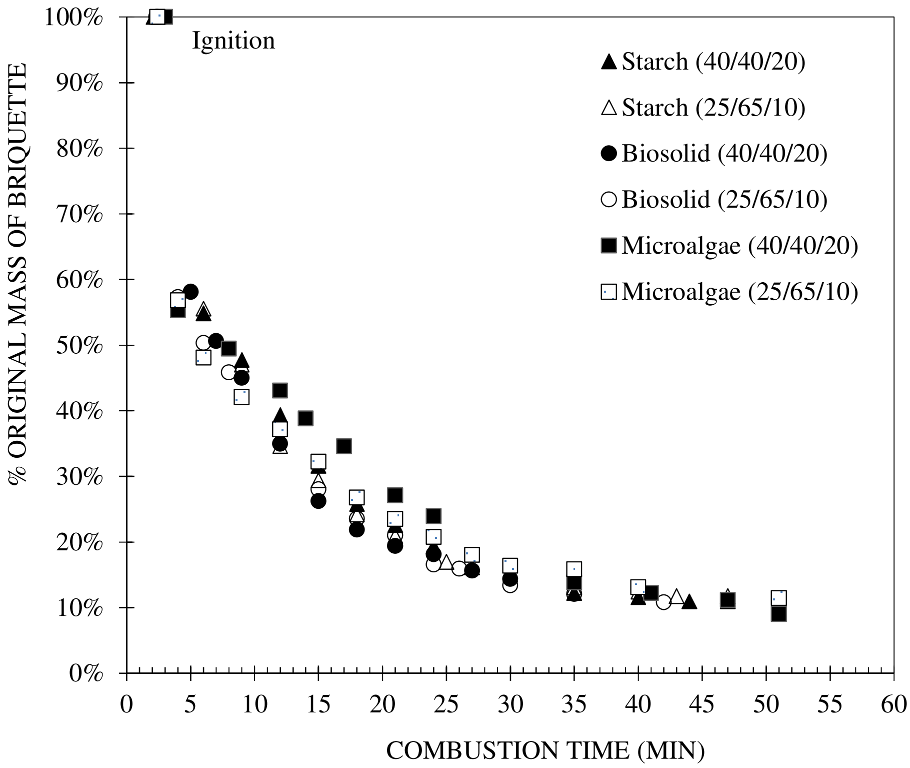


Figure 21: Change in briquette mass with time during atmospheric combustion of briquettes made of rice husks, corn cobs and bagasse, with a starch, biosolids or microalgae binder

Figure 21 shows that briquettes produced with the biosolids binder burned more quickly than briquettes produced with starch, which in turn burned more quickly than those made with microalgae. Figure 22 shows that the afterglow times of the briquettes tend to increase as a function of their relaxed densities, with the highest density and afterglow time associated with the microalgae binder. The error bars indicating the standard error suggest that real differences in both afterglow time and density exist.

It is postulated that the combustion rates of the briquettes are associated with their morphological characteristics (5.4.2), and particularly the presence of air in the void spaces of the briquettes containing biosolids. This agrees well with findings by other authors [e.g., Chaney et al, 2010; Musa, 2007] for waste newspaper briquettes and peanut shells, and indicates the importance of binder type in biomass densification as well as the thermal conversion of densified fuels.

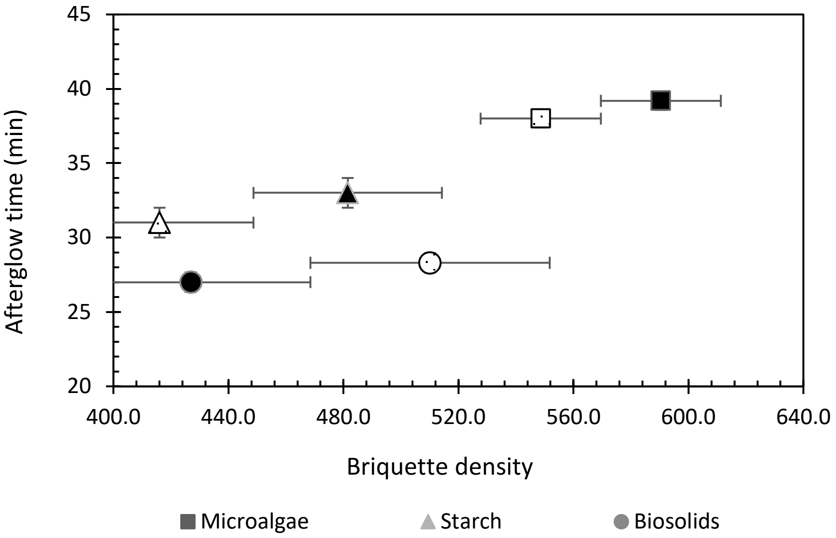


Figure 22: Afterglow time of fuel briquettes made of rice husks, corn cobs and bagasse, with a starch, biosolids or microalgae binder

For efficient combustion, the release of heat must be controlled to keep the fuel burning [EPA, 1999] and for efficient capture of useful energy, and solid fuel must burn as completely as possible. The briquettes made with microalgae have the advantage of a higher energy density, compared with the starch and biosolids binders. The proportions of uncombusted organic matter remaining in the char for briquettes made with starch, biosolids and microalgae indicated comparable completeness of combustion, with 6.5, 7.5 and 6.8 % of the mass of original briquettes remaining, respectively.

5.5 Summary

The research work carried out in this chapter has identified and demonstrated the suitability of using enhanced treated biosolids and microalgae as binders for durable briquette production from blends of rice husks, corn cobs and bagasse. The physical and combustion characteristics of briquettes produced with biosolids, microalgae and starch binders, were evaluated. A range of good quality briquettes that conform to CEN/TS 14961[2004] can be produced with the addition of biosolids, microalgae or starch binder to the blends of rice husks, corn cobs and bagasse.

Briquettes had relaxed unit densities of 1.9 to 3.3 times the loose biomass bulk density, and were stronger than briquettes from the individual materials. An unconfined compressive strength of 175 kPa was achieved for a 2:4:1 blend of rice husks, corn cobs and bagasse with the microalgae binder at a compaction pressure of 31 MPa.

Statistical analysis of the results showed that the addition of biosolids and microalgae binders significantly improved briquette density, while the addition of starch reduced briquette density, and biosolids reduced briquette strength. Of all the briquettes produced with the three binders, those containing the microalgae binder were found to be most durable, with a higher energy value, slower mass loss during briquette combustion, and a higher afterglow time.

The advantages of briquetting and novel approaches for improved fuel briquette quality has been presented in Chapters 4 and 5. The associated energy cost of briquetting has also been highlighted, indicating a need for the assessment of life cycle energy and environmental impacts of briquetting system (2.4.8).

The life cycle assessment for briquetting in chapters 6 and 7 did not include the effect of binder use on the life cycle environmental impacts of the briquetting systems, due to time constraints.

6 LIFE CYCLE ASSESSMENT OF BIOMASS DENSIFICATION SYSTEMS

6.1 Introduction

Several recent LCAs of biomass densification have been carried out. This chapter reviews data from 19 sources with 48 case scenarios to assess the status of LCA of biomass densification. It describes the specific units in a reference "gate-to-gate" LCA in relation to the existing studies, and summarises key differences between them. Finally, it provides a qualitative analysis of the associated sources of uncertainty.

6.2 Life cycle components for biomass densification

6.2.1 Biomass densification system boundary

A full cradle-to-grave LCA of biomass densification starts from biomass cultivation and ends with disposal of waste (ash and plant facilities) from briquette/pellet conversion to energy (Figure 23), including environmental impacts that are embodied in the capital equipment, as well as operational environmental impacts. Since densified biomass is mostly produced from agricultural residues such as straws, husks, stalks, leaves and wood wastes, some LCAs define a system boundary that starts at the farm gate, i.e., omitting the processes that result in residue production [e.g., Hu et al, 2014]. A reference "gate-to-gate" system boundary for the biomass densification by itself can be defined as from the densification plant entry gate (B in Figure 23), through the densification plant, to its shipping gate (C in Figure 23). In some cases, the start gate is defined as the farm or biomass source gate (A) which includes transportation of loose biomass from source to the densification plant entry gate (B), while the end gate can include distribution of densified biomass from the shipping gate (C) to the consumer's or conversion site's gate (D) (Figure 23). Arguably, biomass densification has impacts on conversion of biomass to fuel or energy, which is therefore part of the full life cycle of densified biomass, but the complexities are such that this aspect has not been included in LCA of biomass densification in the literature, and biomass conversion has been simplified as a single box outside the system boundary in Figure 23. The reference "gate-to-gate" biomass densification system (indicated by the red line in Figure 23) thus consists of subsystems including raw biomass storage, drying, size reduction, mixing (in the case of binders or multiple feed biomass), conveying, densification, curing/cooling, screening, packaging, and storage prior to shipping from the briquetting plant gate. The specific components of a biomass densification system affect its life cycle environmental impacts, yet only a few studies provided information on the contributions of specific components to the LCA results. The available information is shown in Table 15, and is discussed in the following sections, including all the components of the reference “gate-to-gate” system as well as transportation.

6.3 Specific units in a gate-to-gate LCA of biomass densification system

6.3.1 Feed biomass and/or densified biomass storage

The loose biomass to be densified and/or the densified biomass may be stored in an open area or buildings (such as silos, warehouses and storage rooms), where the latter prevent losses due to weather and/or animals but are associated with embodied environmental impacts. Some literature studies on LCA of biomass densification showed that the storage unit contributes less than 3% of the total energy and 2% of the GHG emissions (Table 15). However, Rousset et al, [2011] showed that the storage unit contributes 14% of the total GHG emissions of the densification system, as a result of additional energy requirement for onsite storage of starch binder. Densified biomass fuel takes less space than loose biomass, with the improvement in storage efficiency depending on the increase in bulk density achieved.

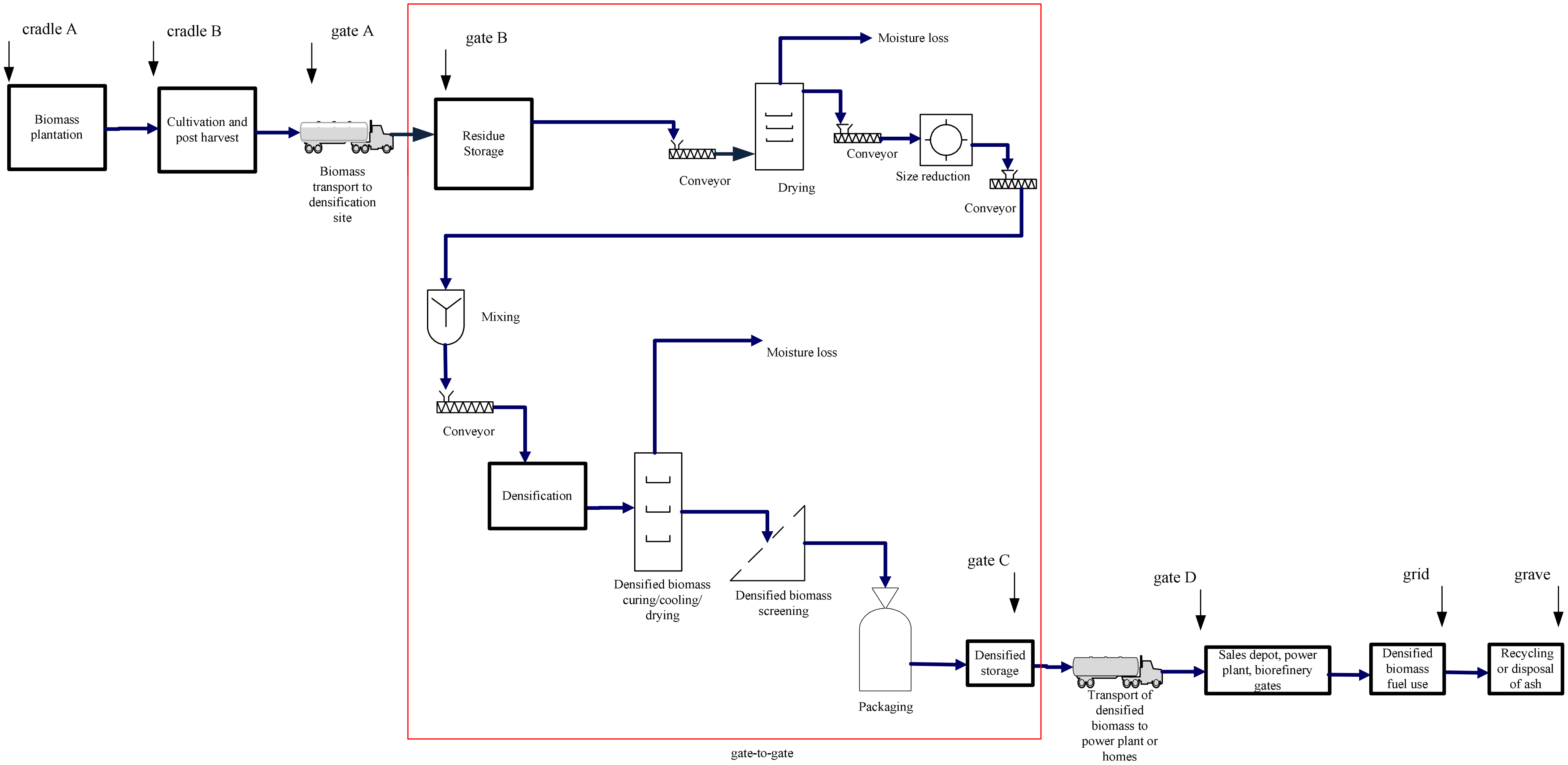


Figure 23: Cradle-to-grave life cycle stages of biomass densification, including biomass production and conversion to energy (red solid line indicates the system boundary for the reference gate-to-gate LCA discussed in the text and used in normalisation of reviewed studies)

Table 15: Proportional contributions of specific biomass densification system components to energy consumption and greenhouse gas emissions (%)

Indicator	Storage	Drying	Conveying	Size reduction	Densification	Blending	Curing/ Cooling	Screening	Packaging	Transport	Reference
Energy	**3**	**24**	NA	**19**	**32**	NA	NA	NA	NA	**22** (5.5 km)[d]	Adams et al [2015][a,b]
	2	**30**	NA	**36**	**9**	NA	NA	NA	NA	**23** (4.6 km)[d]	Adams et al [2015][a,c]
	NA	**6**	NA	**26**	**63**	NA	**5**	NA	NA	NA	Hu et al [2014]
	NA	**26**	NA	NA	**74**	NA	NA	NA	NA	NA	Sultana & Kumar[2011]
	NA	**65**	NA	**11**	**24**	NA	NA	NA	NA	NA	Shie et al [2011]
	1	**29**	**2**	**60**	**7**	NA	**1**	NA	NA	NA	Fantozzi & Buratti [2010][a]
GHG emissions	NA	**33**	NA	**21**	**34**	NA	**2**	NA	NA	**10** (356 km)	Kylili et al [2016][a]
	2	**23**	NA	**20**	**33**	NA	**1**	NA	NA	**21** (5.5 km)[d]	Adams et al [2015][a,b]
	1	**27**	NA	**38**	**11**	NA	**1**	NA	NA	**22** (4.6 km)[d]	Adams et al [2015][a,c]
	14	**24**	NA	NA	NA	**48**	NA	NA	**0.0002**	NA	Rousset et al [2011]
	NA	**8**	NA	NA	**92**	NA	NA	NA	NA	NA	Fantozzi & Buratti [2010]

a: Some values were approximated from plots provided in source
b: Torrefied pellets
c: Wood pellets
d: Distance only covers loose biomass transportation

6.3.2 Drying

Biomass residues can sometimes be collected with a suitable moisture range for densification [Muazu & Stegemann, 2015], as a result of air drying and exposure to sunshine at farm sites. However, some biomass has as high as 70% moisture content on a wet basis [Shie et al, 2011] and must be dried to 8 to 10% for densification [Grover & Mishra, 1996]. Drying is energy intensive and could make a significant contribution to the overall energy use [e.g., Shie et al, 2011; Chiew & Shimada, 2013] and GHG emissions [e.g., Kylili et al, 2016] (Table 15), depending on the amount of moisture to be removed. The type of dryer (e.g., rotary or superheated steam), capacity, temperature and residence time of the biomass will also affect the environmental impacts of drying [e.g., Amos, 1998]. For example, a rapid increase in temperature can result in higher emissions of volatile organic carbon during the drying process [Stahl et al, 2004].

6.3.3 Size reduction

Most densification systems include a size reduction stage where biomass is chopped, crushed, or ground using equipment such as a crusher or hammer mill [e.g., Mani et al, 2006; Kaliyan & Morey, 2014]. Size reduction enables more rapid drying of loose feed biomass to be densified [Kaliyan & Morey, 2009], and improves compaction. The energy and emissions associated with size reduction depend on the extent of size reduction required, which is greatly influenced by the type of feed biomass and its morphology [e.g., Tabata et al, 2011].

6.3.4 Conveying systems

In most biomass fuel densification systems, loose biomass and densified biomass are mainly transported through conveying systems, including screw and belt conveyors. The density, particle size and abrasiveness of the biomass to be conveyed affect the design of the conveyor and the quantity of biomass residues conveyed in a given time, which influences the operational hours required, the number of conveyors needed, and the life cycle environmental impacts [e.g., Thao et al, 2011, Muazu et al, manuscript in review]. However, the environmental impacts of the conveying system on its own are not very well understood, as most LCA studies count the impact of the conveyor unit as part of the unit to which the feed is conveyed. For example, some densification machines have built-in conveyors. As such, only one of the few studies reported in Table 15 showed the impact of conveying systems.

6.3.5 Blending

Most fuel densification systems do not use a separate mixing unit; some [e.g., Rousset et al, 2011] used the screw conveyor for mixing. In multiple biomass densification, or where binders are added, a separate mixer (e.g., tumble, double cone, or screw) may be required for production of a homogenous feed to the densification unit, which will have an additional energy requirement, dependent on the type and proportion of different materials in the feed mixture.

6.3.6 Densification (briquetting/pelleting)

Biomass densification into pellets and briquettes involves the use of equipment such as a pellet mill or briquette press (screw and piston). Pellets, being smaller, are commonly produced by extrusion, whereas larger briquettes are produced by compaction. Pellet mills consist of a perforated die plate with one or two attached rollers. The loose biomass is discharged onto the surface of the plate and forced through the perforations by rotating the die and rollers, to form densified pellets [e.g., Tumuluru et al, 2011; Kaliyan & Morey, 2009]. Pellet mills are characterised by an ease of operation that permits a high production capacity, but have a high energy requirement. Pellets have a wider industrial application (e.g., co-firing with coal) as a result of their smaller particle size.

Briquette presses include hydraulic or mechanical piston and screw presses, using either an oscillating piston or tapered screw to compact and then release, or extrude, briquettes, respectively [e.g., Grover & Mishra, 1996; Tumuluru et al, 2011]. The screw press was found to consume more energy than the piston press [Grover & Mishra, 1996], which can be attributed to the high energy required for extrusion compared with only compaction [e.g., Tumuluru et al, 2011].

In addition to the use of conventional equipment in densification, manual operations, including hand-moulding and shaping are sometimes employed to make briquettes, such as charcoal dust mixed with binder [Njenga et al, 2014], as well as low pressure densification machines.

In most cases, the composition of biomass and its morphological characteristics determine the level of pressure required in densification processes.

6.3.7 Curing/Cooling

The densified biomass leaving the densification unit is usually hot due to incidental or deliberate heating during densification, so a curing unit may be required to cool and dry it before packaging and storage. Densified biomass curing may take place at room temperature, or using equipment such as a box dryer and/or counter-flow cooler, which blows air through the fresh briquettes/pellets. Operational energy is required to supply air for drying or cooling, and curing at room temperature requires space with embodied energy [Muazu et al, manuscript in review].

6.3.8 Screening

The produced briquettes/pellets may be screened to remove fines and shattered briquettes/pellets before packaging or storage [Hu et al, 2014]. However, the specific impact of densified biomass screening is not available in the literature.

6.3.9 Packaging

Densified biomass may be packaged to make it easier to load, transport and distribute, as well as protecting it from weathering. Packaging is mostly important when the densified biomass is being distributed for domestic applications or small-scale thermal sites, whereas packaging is usually avoided for large-scale thermal conversion sites, which may use specialised transport. Packaging can be carried out manually or using equipment such as thermal shrink packaging [Agico, 2014]. The packaging unit can be considered as a moderate energy consumption unit relative to high energy units such as drying, and low energy units such as storage.

6.3.10 Feed biomass/ densified biomass transportation

The transportation requirement of loose biomass from source to densification site varies with the type of biomass residue to be densified, particularly its density, and the distance between the biomass production and densification sites [e.g., Kylili et al, 2016; Hu et al, 2014; Feng et al, 2013]. The associated environmental impacts also depend on the type of vehicle used in both cases. Transportation is excluded from the reference “gate-to-gate” system boundary, but in a typical “A-to-D” gate-to-gate LCA of biomass densification systems found in the literature, the transportation stage consumed up to 23% of the total energy of densified biomass production [e.g., Adams et al, 2011] (Table 15). Nguyen et al [2014] found that greenhouse gas (GHG) emissions associated with the biomass logistics in a bioethanol production chain, are most sensitive to the transportation of densified biomass with emissions of 0.2 to 13 g CO_2-eq/MJ ethanol. One of the possible ways to reduce the impact of transportation is densification of the loose biomass at source (onsite) [e.g., Chiew & Shimada, 2013; Shie et al, 2011].

6.4 Previous work on LCA of biomass densification systems

Studies selected for this study were found by searching scientific and technical databases including, Web of Science, Science Direct, FAO, and Google Scholar. Combining keywords such as “biomass”, densification”, “briquetting” and “LCA”, the authors found a total of 87 publications. 19 out of these studies reported environmental impacts specifically for biomass densification, while other studies embedded densification within the energy production system, which made it difficult to extract quantitative information specific to the densification unit from those studies.

The 19 LCA studies with accessible information about biomass densification are summarised in Table 16, including the types of biomass densified, the densification technologies, the system boundaries, and the environmental impacts. Environmental impacts are summarised as reported, and also normalised to uniform units (including a uniform functional unit in the denominator), to enable comparison of the results from different studies.

Figure 24 and Figure 25 show the information in Table 16, after conversion to the reference densification plant entry gate-to- exit gate (B to C in Figure 23) system boundary, i.e., including all capital and operating components of the densification system, again with normalisation of the units.

For the 19 reviewed studies, five different system boundaries were used, and none reported a complete "cradle-to-grave" LCA of the densification process (Figure 23). Three [Kylili et al, 2016; Chiew & Shimada, 2013; Mani et al, 2006] already had the reference “B-to-C” gate–to-gate system boundary. Four other studies [Hu et al, 2014; Waewsak et al, 2013; Tabata et al, 2011; Shie et al, 2011] used a “gate-to-grid” system boundary. Eight studies [Adams et al, 2015; Bergman et al, 2015; Tsalidis et al, 2014; Nguyen et al, 2014; Li et al, 2012; Reed et al, 2012; Rousset et al, 2011; Magelli et al, 2009] considered a "cradle–to-gate" system boundary. Njenga et al. [2014], Kabir & Kumar [2012], Sultana & Kumar [2011], Fantozzi & Buratti [2010] considered a "cradle–to-grid" system boundary, whereby the definition of cradle, gate and grid varied for the different studies, as indicated in Table 16. These studies also used different functional units, for example, the functional unit was defined as the annual mass of fuel pellets by Bergman et al [2015], whereas Chiew & Shimada [2013] defined the functional unit in terms of the mass of processed feed biomass residues.

The indicators used to assess the environmental impacts of the fuel densification varied across the studies, and included energy consumed in briquette production per unit of energy produced by the densified biomass, GHG emissions, as well as a variety of others.

Table 16: Summary of previous work on life cycle assessment of biomass densification (listed in reverse order of publication date)

Code in Figures 2 & 3	Type of biomass	Technology	Annual Densified biomass output (t/y)	System boundary (gates as shown in Figure 1)	Results for different environmental impact indicators						Reference
						Energy consumption		GHG emissions			
					Scenario	Reported (per functional unit)	Normalised (MJ/t densified biomass)	Reported (per functional unit)	Normalised (kg CO_2-eq / MJ densified biomass energy content) [h]	Others	
1A	Olive husks	Pelletizer	NA	gate A -to-gate D	Centralised management	4.8 MJ/kg pellet	4800	240 kg CO_2-eq/t pellets	0.011	NA	[Kylili et al, 2016]
1B					Decentralised management	3.4 MJ/kg pellet	3400	167 kg CO_2-eq/t pellets	0.0075		
1C					Centralised management/ renewable energy	9.4 MJ/kg pellet	9400	35 kg CO_2-eq/t pellet	0.0016		
1D					Decentralised management/ renewable energy	6.6 MJ/kg pellet	6600	16 kg CO_2-eq/t pellet	0.00072		
2A	Wood chips	Pelletizer	60,000 t	cradle A -to-gate C	3.0 MJ/kg water removed	5.7 g oil-eq/MJ TP	5300[a,e]	17.50 g CO_2-eq/MJ TP	0.018	47.1 km^2/y land use	[Adams et al, 2015]
2B						9.8 g oil-eq/MJ WP	6400[a,e]	27.60 g CO_2-eq/MJ WP	0.028	45.9 km^2/y land use	
2C					6.0 MJ/kg water removed	9.5 g oil-eq/MJ TP	8800[a,e]	28 g CO_2-eq/MJ TP	0.028	47.1 km^2/y land use	
2D						12 g oil-eq/MJ WP	7800[a,e]	34 g CO_2-eq/MJ WP	0.034	45.9 km^2/y land use	
2E					9.0 MJ/kg water removed	14.3 g oil-eq/MJ TP	13200[a,e]	40.02 g CO_2-eq/MJ TP	0.040	47.1 km^2/y land use	
2F						14.7 g oil-eq/MJ WP	9560[a,e]	41.05 g CO_2-eq/MJ WP	0.041	45.9 km^2/y land use	
3	Switchgrass	Pelletizer	NA	cradle A -to-gate C	NA	4.1 GJ/t	4100	0.012 kg CO2-eq/MJ	0.012	NA	[Bergman et al, 2015]
4A	Wood waste	Pelletizer	60,000 t	cradle B -to-gate C	Torrefied pellets	NA	NA	0.814 kg CO_2-eq/kWh pellets	0.23	NA	[Tsalidis et al, 2014]
4B			70,000 t		Wood pellets			0.811 kg CO_2-eq/kWh pellets	0.23		
5	Corn stalks	Flat die briquette machine	20,000 t	gate A -to-grid	NA	15325.9 GJ/y	770[h]	323.00 t CO_2-eq/yr	0.0016	0.0016 g SO_2-eq/MJ pellets 0.0150 g PM10/MJ pellets	[Hu et al, 2014]
6A	Corn stover	Pelletizer	900,000 t	cradle B -to-gate D	Pelleting plants located near source	NA	NA	41[f] g CO_2-eq/MJ ethanol	0.041[e,g]	NA	[Nguyen et al, 2014]
6B					Pelleting plants located near biorefinery			33[f] g CO_2-eq/MJ ethanol	0.033[e,g]		
7	Charcoal dust	Manual operation	4.6 t[b]	cradle A -to-grid	NA	NA	NA	1.6 kg of CO_2-eq /1000 g meal	0.065	NA	[Njenga et al, 2014]

Code in Figures 2 & 3	Type of biomass	Technology	Annual Densified biomass output (t/y)	System boundary (gates as shown in Figure 1)	Results for different environmental impact indicators						Reference
						Energy consumption		GHG emissions			
					Scenario	Reported (per functional unit)	Normalised (MJ/t densified biomass)	Reported (per functional unit)	Normalised (kg CO_2-eq / MJ densified biomass energy content) [h]	Others	
8A	Empty fruit bunch (EFB)	NA	5940	gate B-to-gate C	Without allocation of avoided products	166 MJ/t EFB	503[i]	43.7 kg CO_{2}-eq/t EFB	0.0074[i]	0.17 kg SO_{2}-eq/t EFB	[Chiew & Shimada, 2013]
8B					With allocation of avoided products			25 kg CO_{2}-eq/t EFB	0.0042[i]	0.1 kg SO_{2}-eq/t EFB	
9A	Rice husks & glycerol	NA	700	gate B-to-grid	biomass transportation excluded	NA	NA	0.28 kg CO_2- eq/kWh briquettes	0.080	NA	[Waewsak et al, 2013]
9B				gate A -to-grid	biomass transportation included			4.95 kg CO_2- eq/kWh briquettes	1.4		
10A	Forest residue	Pelletizer	150,000	cradle A -to-grid	Torrefied pellets	2.2 GJ/MWh pellets	13000[e]	169 kg CO_2-eq/MWh pellets	0.047[e]	NA	[Kabir & Kumar, 2012]
10B					pellets	3.4 GJ/MWh pellets	15000[e]	244 kg CO_2-eq/MWh pellets	0.068[e]		
10C	Unspecified agricultural residue pellets				Torrefied pellets	1.5 GJ/MWh pellets	9200[e]	137 kg CO_2-eq/MWh pellets	0.038[e]		
10D					pellets	1.9 GJ/MWh pellets	8200[e]	165 kg CO_2-eq/MWh pellets	0.046[e]		
10E	Whole tree				Torrefied pellets	2.7 GJ/MWh pellets	16000[e]	215 kg CO_2-eq/MWh pellets	0.051[e]		
10F					pellets	4.1 GJ/MWh pellets	18000[e]	302 kg CO_2-eq/MWh pellets	0.084[e]		
11A	Wheat straw	Pelletizer	31,000 – 62,000[b]	cradle A -to-gate C	Mass-based allocation	NA	NA	326.30 g CO2-eq/kg pellets	0.020[e]	NA	[Li et al, 2012]
11B					Value-based allocation			299.02 g CO2-eq/kg pellets	0.018[e]		
12A	Hardwood flooring residue	Pelletizer	6,000 – 125,000[b]	cradle B -to-gate C	Mass-based allocation	13.4 GJ/t pellets	13400	0.0198 kg CO_2-eq/MJ	0.020	NA	[Reed et al, 2012]
12B					Value-based allocation	3.0 GJ/t pellets	3000	-0.0183 kg CO_2-eq/MJ	-0.018		
13A	Rice straw	Pelletizer	64,000	gate B -to-grid	Radio frequency plasma gasification system	1800 MJ/t rice straw	1400[i]	NA	NA	NA	[Shie et al, 2011]
13B					Microwave induced gasification system	1770 MJ/t rice straw	1420[i]				
13C					Downdraft gasifier system	1790 MJ/t rice straw	1430[i]				
13D					Plasma touch gasification system	1800 MJ/t rice straw	1400[i]				

Code in Figures 2 & 3	Type of biomass	Technology	Annual Densified biomass output (t/y)	System boundary (gates as shown in Figure 1)	Results for different environmental impact indicators						Reference
					Scenario	Energy consumption		GHG emissions		Others	
						Reported (per functional unit)	Normalised (MJ/t densified biomass)	Reported (per functional unit)	Normalised (kg CO_2-eq / MJ densified biomass energy content) ^{h}		
14	Charcoal fines	Screw press	1000^{b}	cradle A -to-gate D	NA	NA	NA	4 kg CO_2-eq / kg briquettes	0.2^{e}	NA	[Rousset et al, 2011]
15	Wood chips	NA	NA	gate B -to-grid	NA	5000 MJ/t briquettes	5000	35.7 kg CO_2-eq/t briquettes	0.0013	NA	[Tabata et al, 2011]
16A	Wheat straw	Pelletizer	150,000	cradle A -to-grid	Mass-based allocation (base case)	0.29 MJ/MJ pellets	4700^{e}	0.031 kg CO_2-eq/MJ pellets	0.031^{e}	NA	[Sultana & Kumar, 2011]
16B					no allocation of upstream farming activities to straw	0.15 MJ/MJ pellets	2500^{e}	0.02 kg CO_2-eq/MJ pellets	0.02^{e}		
16C					Use of organic fertilizer	0.12 MJ/MJ pellets	1900^{e}	0.01 kg CO_2-eq/MJ pellets	0.01^{e}		
16D					Zero tillage system	0.27 MJ/MJ pellets	4400^{e}	0.027 kg CO_2-eq/MJ pellets	0.027^{e}		
16E					Drying with biomass energy	0.284 MJ/MJ pellets	4660^{e}	0.028 kg CO_2-eq/MJ pellets	0.028^{e}		
16F					Drying with natural gas	NA	NA	0.028 kg CO_2-eq/MJ pellets	0.028^{e}		
16G					No drying	0.281 MJ/MJ pellets	4610^{e}	0.027 kg CO_2-eq/MJ pellets	0.027^{e}		
16H					100% truck transportation	0.29 MJ/MJ pellets	4700^{e}	0.027 kg CO_2-eq/MJ	0.027^{e}		
16I					Mixed truck and rail transportation	0.283 MJ/MJ pellets	4640^{e}	0.027 kg CO_2-eq/MJ pellets	0.027^{e}		
17A	Wood	Pelletizer	12,400^{b}	cradle A -to-grid	EDIP	NA	NA	2.42 µPt/MJ pellets	0.00030^{c,e}	3.78 µPt AP	[Fantozzi & Buratti, 2010]
17B					Eco-indicator 99			64.4 µPt/MJ pellets	0.0057^{c,e}	209.9 µPt AP and EP	
18A	Sawdust	Pelletizer	670, 000^{d}	cradle B -to-gate D	Drying with sawdust	7.2 GJ/t pellets	7200^{e}	532 kg CO_2-eq/t pellets	0.028^{g}	NA	[Magelli et al, 2009]
18B					Drying with natural gas	6.4 GJ/t pellets	6400^{e}	723 kg CO_2-eq/t pellets	0.039^{g}	NA	
19A	Sawdust	Pelletizer	31,000^{b}	gate B-to-gate C	Drying with wood pellet	3382.8 MJ/t pellets	3400^{e,h}	50 kg CO_2-eq/t pellets	0.0026	NA	[Mani et al, 2005]
19B					Drying with wet sawdust	3777.5 MJ/t pellets	3800^{e,h}	45 kg CO_2-eq/t pellets	0.0024		
19C					Drying with dry sawdust	3689.2 MJ/t pellets	3700^{e,h}	43 kg CO_2-eq/t pellets	0.0023		
19D					Drying with coal	3422.5 MJ/t pellets	3400^{e,h}	300 kg CO_2-eq/t pellets	0.02		
19E					Drying with natural gas	2973.3 MJ/t	2900^{e,h}	230 kg CO_2-eq/t	0.012		

Code in Figures 2 & 3	Type of biomass	Technology	Annual Densified biomass output (t/y)	System boundary (gates as shown in Figure 1)	Results for different environmental impact indicators						Reference
						Energy consumption		GHG emissions			
					Scenario	Reported (per functional unit)	Normalised (MJ/t densified biomass)	Reported (per functional unit)	Normalised (kg CO_2-eq / MJ densified biomass energy content) [h]	Others	
						pellets		pellets			

NA: Not available/applicable
AP: Acidification potential
EP: Eutrophication potential
a: 1 kg of oil equivalent = 42 MJ [PRé, 2015] was used in conversion.
b: 20h/d operating time and 85% plant availability were used to convert hourly/daily to annual densified biomass production.
c: Eco scores (µPt) were converted to kg CO_2-eq using normalisation values of 1.29 E-4 and 8.9 E-5 for the EDIP and Eco-indicator respectively [PRé, 2015].
d: Densified biomass output was calculated assuming that the Canadian West Coast production capacity is ~ 2/3 of the 1,000,000 t total annual Canadian pellet production [38].
e: Heating values of densified biomass from reviewed studies were used in normalisation; where data were not available, equivalent values for densified or loose biomass were adapted from the literature [e.g., 41-44].
f: Upper boundary values provided in the study were used, lower boundary values resulted from the assumption of extreme low values for process components employed in model.
g: Recovery of 100 % densified biomass energy content following thermal conversion was assumed.
h: Values were rounded to 2 significant figures.
i: 1 t of EFB = 0.33 t briquettes, and 1 t of rice straw residue = 0.8 t briquettes

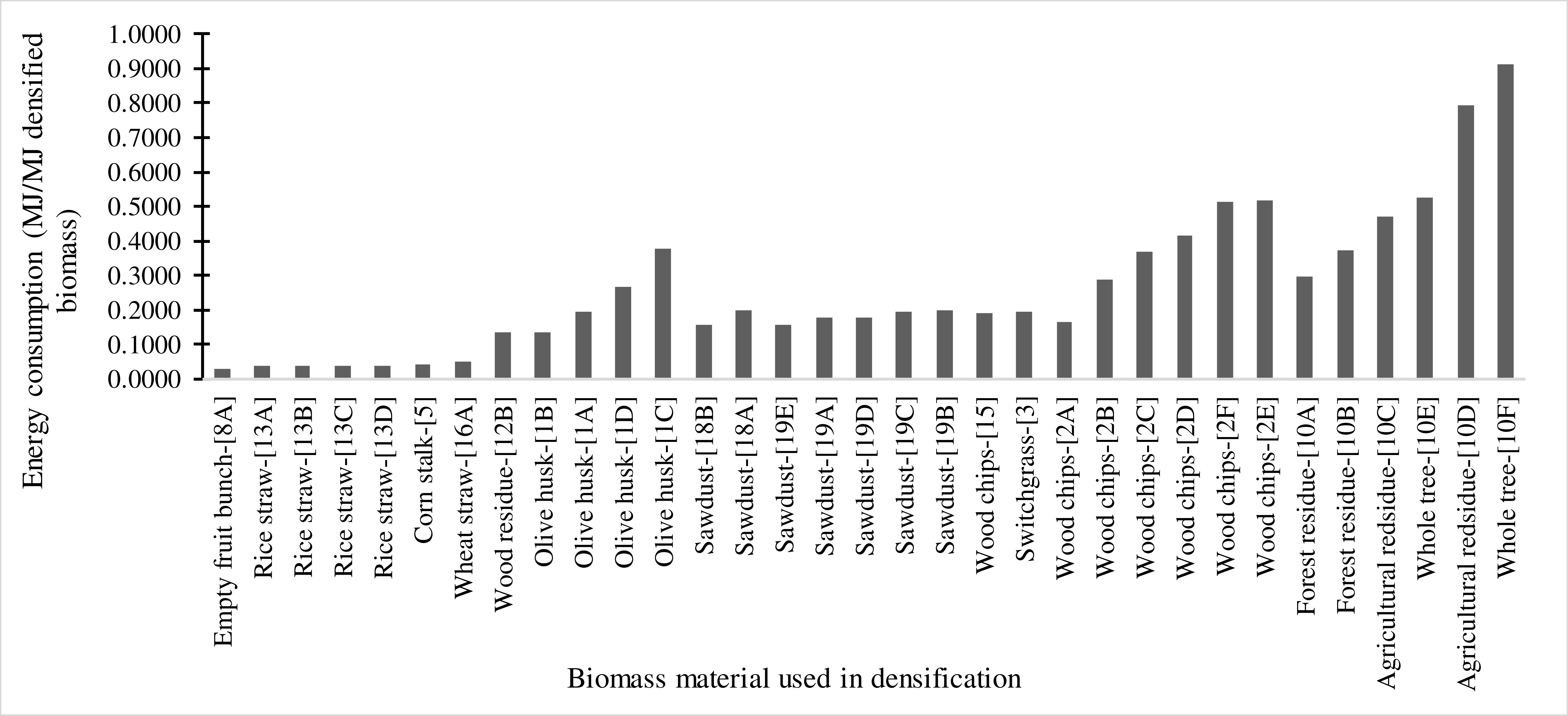


Figure 24: Comparison of literature values (see column 1 of Table 1 for codes) of life cycle energy consumption per MJ densified biomass energy content for a reference gate-to-gate biomass densification system

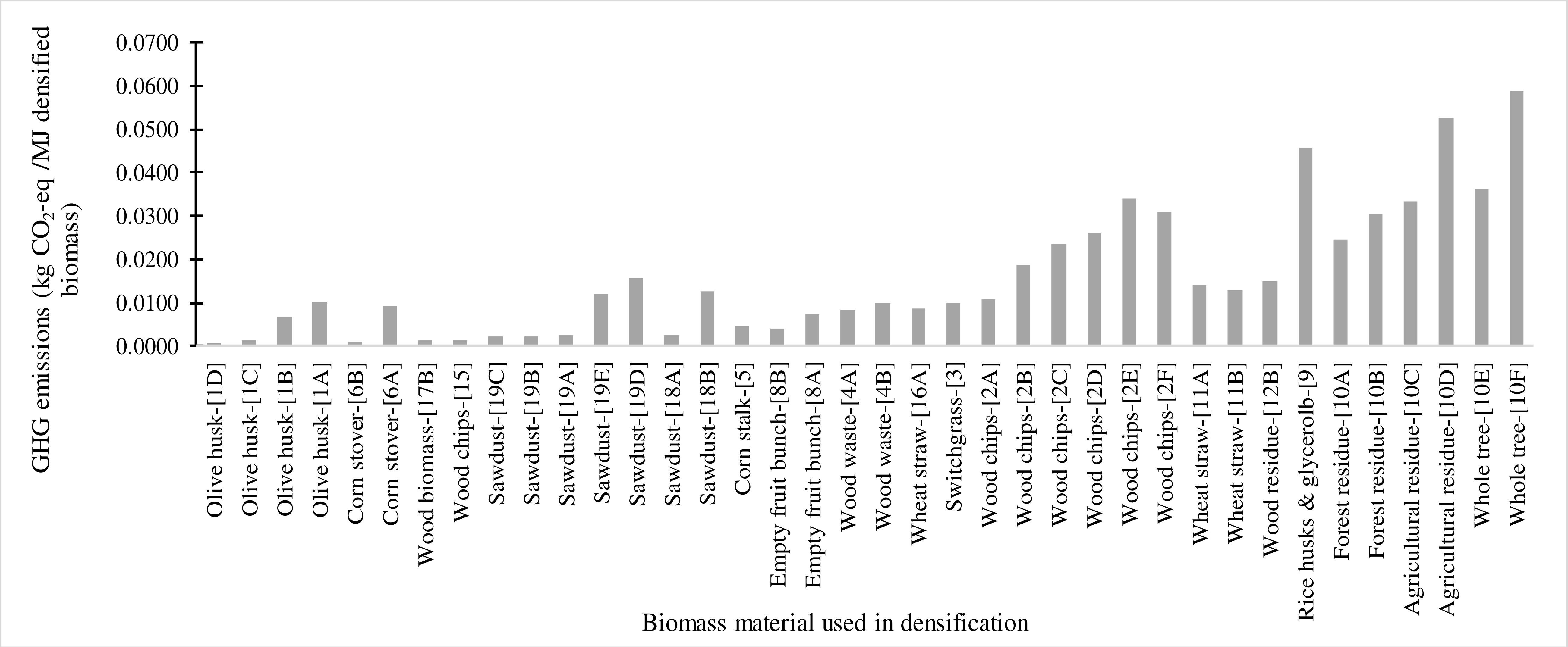


Figure 25: Comparison of literature values (see column 1 of Table 1 for codes) of life cycle GHG emissions in kg CO_2-eq per MJ densified biomass energy content for a reference gate-to-gate biomass densification system

A detailed LCA of biomass densification, with reporting of a variety of impacts, was conducted in 13 of the reviewed studies [Kylili et al, 2016; Adams et al, 2015; Bergman et al, 2015; Tsalidis et al, 2014; Chiew & Shimada, 2013; Waewsak et al, 2013; Li et al, 2012; Reed et al, 2012; Kabir & Kumar, 2012; Sultana & Kumar, 2011; Fantozzi & Buratti, 2010; Magelli et al, 2009; Mani et al, 2006] using impact assessment methodologies such as CML 2 baseline 2000, EDIP 2003, Eco-indicator 99, and Recipe methodologies. The remaining 6 studies used energy and greenhouse gas (GHG) emissions to assess the sustainability of the biomass densification systems.

As is the case with other LCA studies of bioenergy systems, variations can be observed among and within different scenarios of the reported outcomes of the LCAs (Table 16, Figure 24 and Figure 25). For all the reviewed studies, the life cycle energy consumption of the gate-to-gate densification systems ranged between 0.02 to 0.9 MJ/MJ of densified biomass energy content. The lower the total energy consumption, the more sustainable the biofuel. For example, Kabir & Kumar [2012] showed that a densification energy of 0.29 MJ/MJ densified biomass and above is unsustainable.

The GHG emissions of the gate-to-gate densification systems from the reviewed studies ranged from 0.0006 to 0.05 kg CO_2-eq/MJ of densified biomass energy content, while a range of 0.19 to 0.23 kg CO_2-eq/MJ of electricity generation with densified biomass was estimated on a cradle-to-grid basis. To give an indication of the sustainability of this range of GHG emission it can be compared, for example, to the total CO_2 emissions of 0.23 kg CO_2-eq/MJ of biomass energy content from electricity generation with loose biomass (rice straw) [Shafie et al, 2014], or 0.35 kg CO_2-eq/MJ of coal energy content, for a cradle-to-grid system boundary [Shafie et al, 2014].

The most obvious impacts of densification are on energy consumption and GHG emissions associated with transportation, where we might roughly assume that any increase in bulk density is associated with proportional reductions in fuel use and transport emissions reduction. Given that the bulk density increase factors reported in 5 of the reviewed studies ranged from 2.3 to 5.5 [Hu et al, 2014; Adam et al, 2015; Sultana & Kumar, 2011; Bergman et al, 2015; Kabir & Kumar, 2012], and assuming transport energy use of 2.57 MJ/t/km and transport emissions of 0.126 kg CO_2-eq/t-km [Weidema et al, 2013], this suggests that densification reduces net energy consumption in these studies by 0.2 to 1 MJ/MJ biomass/briquette energy, and GHG emissions by 0.009 to 0.05 kg CO_2-eq/MJ biomass/briquette energy for a hypothetical maximum transport distance of 500 km and target transport load of 20,000 kg/day.

The compiled LCA outcomes varied over a wide range and normal probability plots (not shown) of the LCA outcomes in Figure 24 and Figure 25 suggest that the variations are not attributable to random error, which further indicates the significant effects of the various methodological choices employed on the LCA outcome. More extreme outlier values were also observed, e.g., outlier values of 0, 0.00001, and 0.7 were excluded from the summary of GHG emissions in Figure 25. The studies by Njenga et al [2014] and Rousset et al [2011] were not included in the plot but are further discussed below. The reliability of the outlier case reported by Fantozzi & Buratti [2010] was very low due to high weight allocated to equipment during characterisation and weighting phases of the LCA, and was thus excluded from the analysis.

Wide variations in LCA outcomes are also common in the literature. Most existing LCA studies of bioenergy (and other) systems have different specific goals and have therefore adopted different approaches, leading to different results. Even for studies with similar goals and input and output flows, variations in LCA outcomes may be observed, e.g., with a range of 0.0044 to 0.1 kg CO_2-eq/MJ of fuel in a review of hundreds of LCA studies on biopower technologies carried out between 1980 to 2010 [Chum et al, 2011], -1.3 to 0.08 kg CO_2-eq/km travelled in a review of 53 LCA studies using bioethanol E100 [Borrion et al, 2012], and 0.0003 to 0.193 kg CO_2-eq/MJ electricity, and 0.0016 to 0.021 kg CO_2-eq/MJ heat generated, in a review of 58 LCA studies of various biomass fuels [Muench & Guenther, 2013]. For the latter review, outlier GHG emission values widened the range to -0.113 to 0.301 kg CO_2-eq/MJ electricity and 0.0016 to 0.067 kg CO_2-eq/MJ heat generated. Such wide variations have been attributed to factors such as: data source [Borrion et al, 2012], data age [Audsley et al, 2009], methodological issues including definition of the functional unit and system boundary [Suh et al, 2004], and allocation procedures [Quek & Balasubramanian, 2014; Wiloso et al, 2012]. For example, in the present review, the reporting of results on the basis of biomass energy content implies that the variations in heating values of different types of densified biomass (15 to 26 MJ/kg) among the reviewed studies influence the LCA results. The GHG emissions and overall LCA results can be sensitive to the scale of production [e.g., Nguyen et al, 2014; Tabata et al, 2011], but a clear correlation between scale of production and life cycle energy or GHG emissions was not observed for the reviewed studies.

The common sources of variation between the LCAs are discussed further in the following sections. However, it should be noted that the literature sources do not report all of the details of their analyses, which makes the cause of the very wide variation in results from different studies difficult to determine.

6.5 Sources of uncertainty in LCA of biomass densification systems

6.5.1 System boundary

Definition of different system boundaries is a significant source of variation in LCA results among the reviewed studies. For example, a study by Rousset et al [2011] showed that for each kg of briquettes produced from wood charcoal fines and starch, an estimated 0.1 kg of CO_2-eq was sequestered per MJ of briquette energy content in a cradle-to-gate system boundary, while emission of 0.7 kg CO_2-eq/MJ densified biomass was associated with the gate-to-gate system boundary. The inclusion of the agricultural stage in the cradle-to-gate system boundary, reduced the net GHG emission of the densification system. However, it seems more appropriate to use CO_2 capture in the agricultural stage to offset the dependent CO_2 emissions in biomass conversion, rather than to include them in the biomass densification subsystem, which is independent of the agricultural stage.

This source of variation was eliminated by separating out the components of the reference "gate-to-gate" boundary system for each of the literature sources in Figure 24 and Figure 25. However, significant variations can still be observed between some of the studies, especially for the GHG emissions. For example, a study by Reed et al, [2012] showed that a gate-to-gate LCA of wood residue pelleting emitted 0.01 kg CO_2-eq/MJ of pellet energy, while, for the same gate-to-gate system boundary, 0.002 and 0.007 kg CO_2-eq were associated with corn stalk briquetting by Hu et al, [2014] and EFB briquetting by Chiew & Shimada [2013] respectively. Hu et al [2014] used an integrated briquetting system and did not include the burden of conveying and packaging unit. The conveying and packaging units can respectively contribute up to 22% and 7% of the total life cycle GHG emissions of the gate-to-gate densification system (Table 15). Likewise, the EFB briquetting had only four production stages including conveying, size reduction, drying and briquetting (pressing of the EFB into cylindrical moulds) [Chiew & Shimada, 2013], whereas pelleting of the wood residue by Reed et al, [2012] included all the other units of the densification system (including conveying, size reduction, drying and densification) and additional energy used for pellet lubrication.

This indicates that even for the same nominal system boundary, the LCA outcome is highly dependent on the specific components and activities included in the system.

6.5.2 Densification variables

The type of densification technology employed in the production of briquettes or pellets can influence the properties of densified fuels [e.g., Tumuluru et al, 2011; Grover & Mishra, 1996] as well as the results of an LCA. For example, the use of manual operations in briquetting of charcoal dust resulted in total GHG emissions of 0 kg CO_2-eq/MJ of briquette energy content [Njenga et al, 2014], while use of conventional densification equipment (e.g., briquette press and pellet mill) resulted in GHG emissions of 0.0006 to 0.05 kg CO_2-eq/MJ briquette energy from charcoal fines. The manual collection of binding agent as spoil gathered from pit digging by roadsides and riversides, and the transportation of these materials by foot from sources to the briquetting point, and the use of water from natural shallow wells, in the study by Njenga et al, [2014], avoided the net energy input into the system that would be required by electrical machinery. However, other work has shown that the durability and energy density of manually densified biomass may be less than that of densified biomass produced using high pressure compaction equipment [e.g., Muazu & Stegemann, 2015]. Therefore, a balance between lower environmental impacts and quality of densified biomass should be considered. It is also important to look into the social impact of employing manual operations in biomass densification.

The high outlier values for GHG emissions were associated with charcoal briquetting. Charcoal biomass has poor plasticity and normally requires high energy for densification using conventional equipment, as well as the need for a binder, which further increases the storage space requirement for raw binder (Table 15) and energy requirement of curing the densified biomass. However, the charcoal dust used by Njenga et al [2014] and charcoal fines used by Rousset et al [2011] had different characteristics (e.g., particles size and source of charcoal), which also influence the densification processes and LCA results.

In another example, the life cycle energy of densification with a pellet mill by Kabir & Kumar [2012] was 22 times higher than the life cycle energy of densification with an integrated flat die briquette machine by Hu et al [2014].

In addition to the densification technology, the biomass material properties such as moisture, particle size, species and density, affect the energy requirement of the densification system [e.g., Sultana & Kumar, 2011]. From Figure 24, densification of biomass from whole trees had the highest life cycle energy consumption, while agricultural residues such as wheat straw had lower life cycle energy consumptions. This can be attributed to less energy required for drying and size reduction of wheat straw compared with wood biomass, as these two units contribute significantly to the total densification life cycle energy and GHG emissions (Table 15).

6.5.3 Functional unit

The functional unit is critical in LCA as it forms the basis for comparison between different systems [e.g., Muench & Guenther, 2013; Borrion et al, 2012].

The functional unit definition was inconsistent among the reviewed studies, which makes it difficult to compare and evaluate results between these studies. The functional unit may be defined in terms of system input (e.g., t of biomass residues), output (e.g., t of densified biomass, MJ of energy, or kWh of electricity), production time (e.g., year), or unit of agricultural land (e.g., ha). The great majority of biomass densification LCAs used an output-related functional unit [e.g., Njenga et al, 2014; Kabir & Kumar, 2012]. Cherubini & Stromman [2011] also reported that 73% of 90 LCAs of different bioenergy technologies defined an output-related functional unit. Normalising the functional unit of the LCA studies to a uniform unit of 1 MJ densified biomass energy (Table 16, Figure 24 and Figure 25) eliminated this source of variation.

6.5.4 Data source and age

LCA requires data on material and energy flows, and processes/infrastructure such as equipment and buildings. The quality of data used in the LCA strongly affects the reliability of the LCA results.

Availability of full-scale data for LCA of biomass densification systems is limited, as highlighted by Fantozzi & Buratti [2010]. This can be attributed to the fact that biomass densification is still gaining popularity in the bioenergy system, and some of the equipment currently in the market is either made locally from local materials, or by a few established manufacturers who do not report detailed information. This often results in the use of numerous assumptions and/or use of mixed data in LCA studies [e.g., Adams et al, 2015; Mani et al, 2005], which limits the reliability of the outcome [Fantozzi & Buratti, 2010] and increases variations among existing studies [e.g., Johnson et al, 2011].

The results of an LCA based on data from the literature can be expected to be different from LCA results based on data collected directly from an existing briquetting plant. For example, for the reference gate-to-gate system, the GHG emissions of 0.0013 kg CO_2-eq/t briquettes determined by Tabata et al. [2011; 15 in Figure 24] based on literature data differed from the 0.0048 kg CO_2-eq/t briquettes determined by Hu et al, [2014; 5 in Figure 24] with real data for an existing plant; both differed substantially from the 0.046 kg CO_2-eq/t briquettes determined by Waewsak et al [2013; 9 in Figure 24] which had a mixture of data sources (i.e., reports and an existing plant). On the other hand, Fantozzi & Buratti [2010] reported a relatively minor difference (a factor of 1.3) between LCA results based on an existing plant as compared with literature data. Some of the studies provided limited information on the data and sources used in the LCA studies, and it is difficult to be certain of the reasons for the very wide variation in results.

6.5.5 Allocation

In LCA, the environmental impacts may be allocated to different products in a system based on their share of mass, energy, economic market price; in some cases, allocation is avoided [Ekvall & Finnveden, 2001], for example, through system expansion [ISO 14044, 2006]. According to Ekvall & Finnveden [2001], a methodological allocation problem arises when a multifunctional process fulfils one or more functions for the product life cycle that is investigated, and a different function, or set of functions for other products.

The effect of allocation and expansion methodologies on LCA results of bioenergy systems (e.g., heat, electricity and liquid fuels) has been discussed by a number of authors [e.g., Cherubini & Stromman, 2011; Heller et al, 2004] indicating the strong need for standard allocation procedures between different products in multifunctional bioenergy systems.

However, only a few authors [e.g., Muench & Guenther, 2013] have developed and suggested a robust approach for dealing with allocation in LCAs. Some recognised standards including EU [2009] and PAS 2050 [2008] also recommend specific procedures for handling allocation problems in LCA.

Unlike other bioenergy systems, or a cradle-to-grave LCA of biomass densification, gate-to-gate biomass densification is associated with a single product (the fuel briquette/pellet), which implies that all energy use and emissions are allocated to the product "densified biomass". The need for allocation is avoided as it arises only in the case of a multi- input densification process [e.g., Wawsaek et al, 2013; Rousset et al, 2011].

For the pre-gate activities, some of the reviewed studies used economic market price, and energy to allocate environmental burden to co-products [e.g., Hu et al, 2014; Chiew & Shimada, 2013], while some studies used allocation on a mass basis [e.g., Li et al, 2012; Sultana & Kumar, 2011] and some did not clearly indicate the allocation approach used in the study [e.g., Tabata et al, 2011]. The impact of allocation methodology on LCA results was demonstrated by Reed et al, [2012], where the environmental impact of wood residue production reduced by 97.5% when economic rather than mass allocation was employed between the wood residue and a wood flooring product. Some key points on the principles of different allocation methodologies, their applications and limitations, were reported by Borrion et al [2012].

6.6 Uncertainty analysis in LCA of biomass densification systems

Nearly all LCA studies are associated with uncertainties which can result in over- or under-estimation of the environmental impacts [Salway & Shaddick, 2011], thereby affecting the quality and usefulness of the LCA outcome. Uncertainty analysis aims to provide additional information for decision-making on the basis of a presented LCA outcome. Some LCA studies [e.g., Lloyd & Ries, 2007; Huijbregts, 1998] include a quantitative analysis of uncertainty, which is usually expressed as a probability distribution of the resulting outcome, while other studies adopt a qualitative approach to express uncertainties [Chen et al, 2007].

In treating uncertainties in LCA, appropriate classification of the various sources of uncertainties is useful. Different typologies have been used to classify uncertainty in LCA, for example; Lloyd & Ries [2007] and Huijbregts et al, [2003] described uncertainty in input data as “*parameter uncertainty*”, in normative choices as “*scenario uncertainty*” and uncertainty associated with mathematical relationships as “*model uncertainty*”. In many biomass densification LCAs, uncertainty mainly comes from the input parameters (inaccurate data, lack of knowledge), and sometimes from various assumptions and simplifications of the densification system structure (6.3.4 and 6.5.4), also referred to as methodological choices /case scenarios. Loucks [2005] classified uncertainty into “*knowledge uncertainty*”, “*decision uncertainty*” and “*natural variability*”. Arguably the latter includes “*Temporal variability” and “Spatial variability”* [Huijbregts, 1998].

Classification and ranking of the possible sources of uncertainties in LCA of biomass densification would provide better understanding for future LCAs, as well as information for interpretation of LCA results in decision-making.

Therefore, the possible sources of uncertainty within the reference gate-to-gate biomass densification LCA (including transportation) have been summarised and classified into parameter, methodological and embodied impact uncertainties in Figure 26 and Figure 27, where:

- Parameter uncertainty (as also defined by Huijbregts, 2003) in biomass densification LCA can arise from errors in densification process inputs, various characteristics of densification technologies, and their specific emission factors, such as discussed above in 6.5.2 and 6.5.4. It includes knowledge uncertainty and natural variability (as defined by Loucks, 2005).
- Methodological uncertainty concerns the procedures and assumptions employed to assess the densification process, including scenario and modelling uncertainties (Huijbregts, 2003, and decision uncertainty [Loucks, 2005], e.g., data collection procedures and the aspects discussed above in 6.5.1, 6.5.3 and 6.5.5.
- Embodied impact uncertainty is associated with embodied environmental impacts in the biomass densification system, such as steel production and electricity generation.

The listed sources of uncertainty were qualitatively categorized as high, medium or low depending on effect of the uncertainty source on reliability of the LCA outcome. These categories of uncertainty were also reported by Salway & Shaddick [2010], which also describes these categories as context specific, i.e., the categorization might be different for processes other than biomass densification.

Figure 26 and Figure 27 showed that limited, highly variable and inconsistent data results in more high parametric and methodological uncertainties, compared with the embodied impact uncertainty. These are further described in the following section.

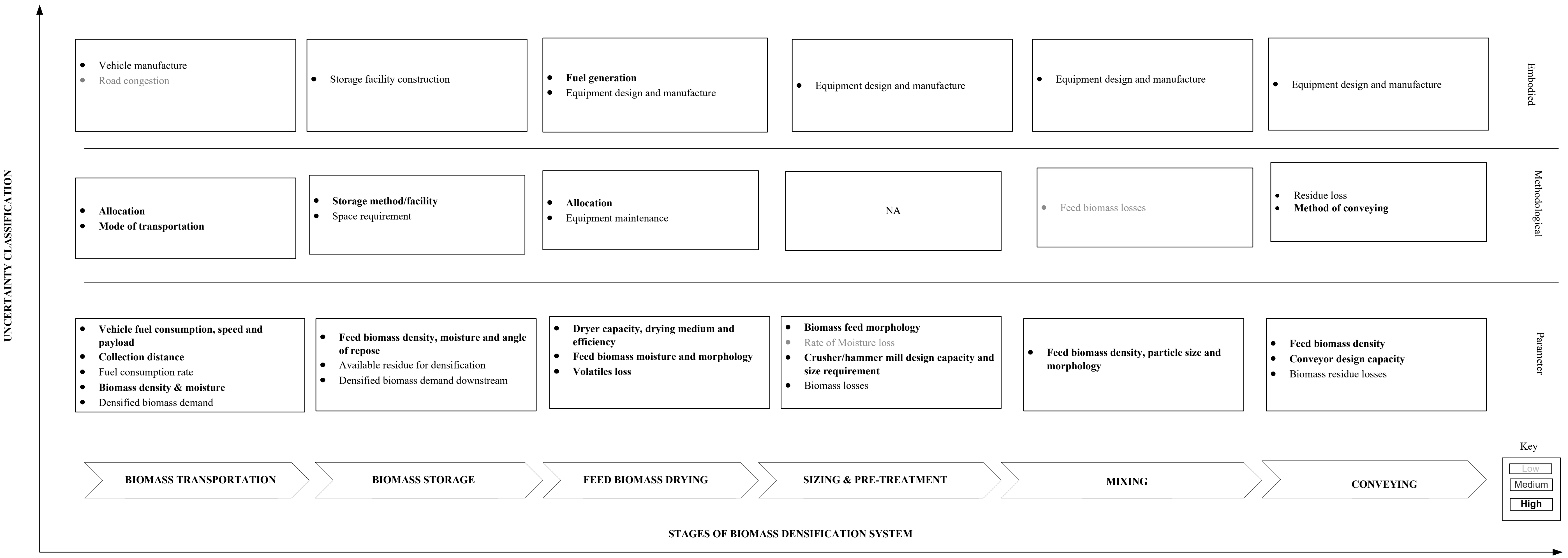
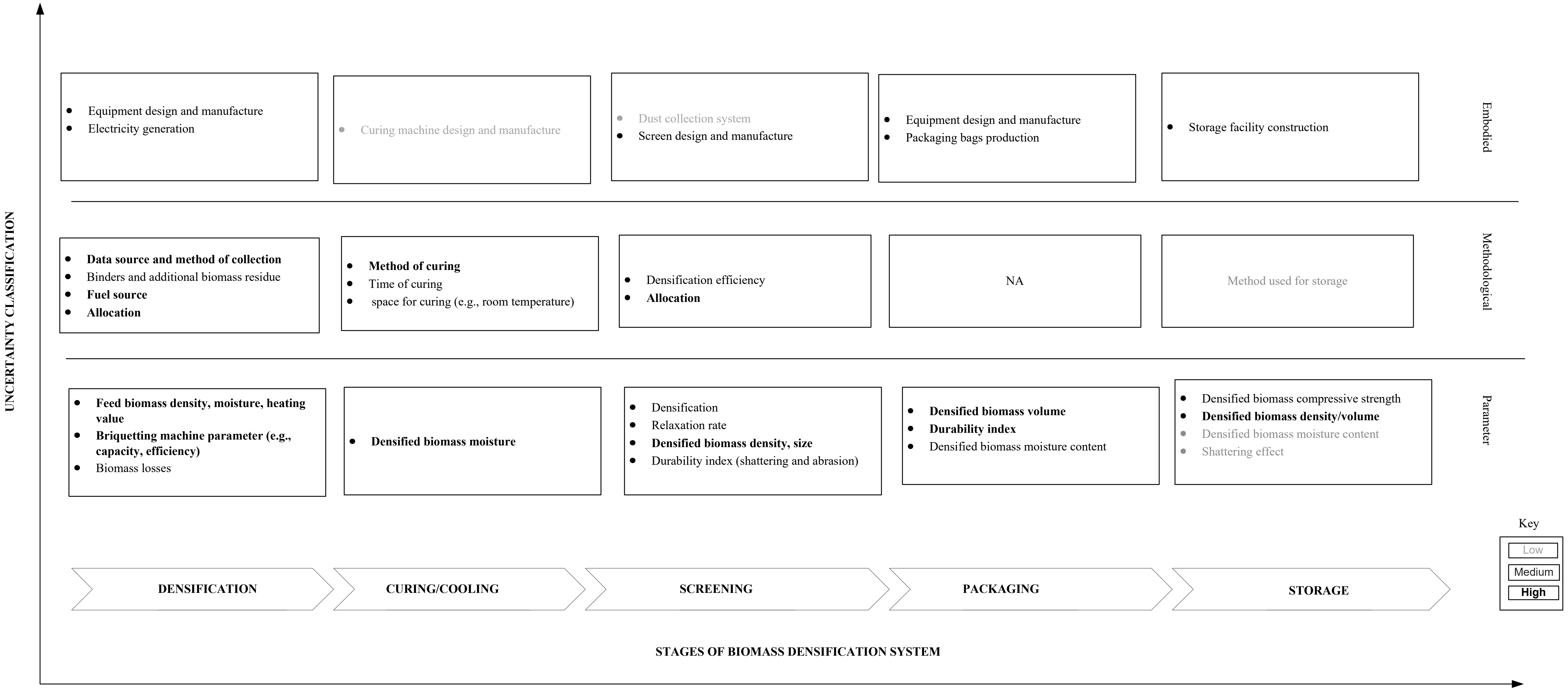


Figure 26: Possible sources of uncertainty in fuel densification LCA (Pre-densification)



	DENSIFICATION	CURING/COOLING	SCREENING	PACKAGING	STORAGE
Embodied	Equipment design and manufacture Electricity generation	Curing machine design and manufacture	Dust collection system Screen design and manufacture	Equipment design and manufacture Packaging bags production	Storage facility construction
Methodological	**Data source and method of collection** Binders and additional biomass residue **Fuel source** **Allocation**	**Method of curing** Time of curing space for curing (e.g., room temperature)	Densification efficiency **Allocation**	NA	Method used for storage
Parameter	**Feed biomass density, moisture, heating value** **Briquetting machine parameter (e.g., capacity, efficiency)** Biomass losses	**Densified biomass moisture**	Densification Relaxation rate **Densified biomass density, size** Durability index (shattering and abrasion)	**Densified biomass volume** **Durability index** Densified biomass moisture content	Densified biomass compressive strength **Densified biomass density/volume** Densified biomass moisture content Shattering effect

Figure 27: Possible sources of uncertainty in fuel densification LCA (Post-densification)

Parameter uncertainty is often ignored in LCA of biomass densification. Some studies did include an analysis of the sensitivity of LCA outcomes to variations in selected LCA parameters, though without further analysis of uncertainty in the LCA studies [e.g., Adams et al, 2015; Kabir & Kumar, 2012]. In dealing with uncertainty in process inputs, Adams et al, [2015] accounted for variance associated with the energy required for biomass drying, by using low, medium and high values to evaluate the sensitivity of the LCA outcomes to possible changes in the drying energy. Kabir and Kumar [2012] explored 4 case scenarios to evaluate the sensitivity of the LCA outcomes to possible changes in LCA components including farming operations (case 1), silviculture and road construction (case 2), impact of grid emissions (case 3), and variable transportation distance (case 4). Nguyen et al [2014] also reported uncertainties in advanced biomass feedstock logistics supply chains. However, more than 80% of the reviewed studies did not provide information about uncertainties in the LCA parameters, which suggests a limited appreciation of their effects on the reliability of the LCA outcome.

Methodological choices employed in LCA studies are also associated with uncertainties, which can be associated with insufficient standard methods [e.g., Cherubini & Stromman, 2011] (6.5.5). This often results in different assumptions in different LCA studies, which increases the uncertainty in the LCA outcome. For example, data collection methods and impact allocation procedures in transportation of biomass/briquettes are inconsistent between some LCA studies of biomass densification [e.g., Kylili et al, 2016; Li et al, 2012].

In the case of embodied impact uncertainty, standard databases, such as ecoinvent, provide embodied impact data for most product life cycle components such as materials, energy, and transport, which has reduced the level of uncertainty arising from this source. As such, the embodied impact sources of uncertainty had only a medium potential effect on the reliability of the LCA outcome (Figure 26 and Figure 27).

6.7 Summary

This chapter has reviewed previous work on LCA of biomass densification into briquettes and pellets. It has assessed the current status and identified gaps in understanding in the LCA of biomass densification.

The existing LCA studies of biomass densification were found to provide insufficient and inconsistent information for full transparency and comparability, due to different choices in system boundary, functional unit, allocation procedure, densification technology and biomass residues. Most of the reviewed studies attributed most of the energy use and greenhouse gas (GHG) emissions to transportation, drying and densification. The energy and GHG emissions of the gate-to-gate densification system were highly sensitive to the technology, feed material used in densification and scale of production.

Apart from one study with zero energy consumption as a result of the use of manual operations, the normalised values of energy consumption for the reviewed studies ranged from 0.02 to 0.9 MJ/MJ densified biomass energy content. Neglecting three outlier values, GHG emissions for the reviewed studies ranged from 0.0006 to 0.05 kg CO_2-eq/MJ densified biomass energy content. Similar variations in result and outlier cases have been reported for other bioenergy processes, by other authors. Assuming that the biggest impact of densification processes is on transport fuel use, and based on 5 studies that reported densification ratios, the net energy and GHG emissions savings resulting from densification ranged from 0.2 to 1 MJ/MJ biomass energy content and 0.009 to 0.05 kg CO_2-eq/MJ biomass energy content, respectively. On this basis, it can be concluded that biomass densification is a worthwhile addition to the biomass energy conversion system. There is a need for more transparent reporting and analysis of uncertainty in the modelling, to better understand the wide variation in outcomes.

The following recommendations can be adopted in future LCA studies of biomass densification, to improve consistency and reliability of LCA studies.

- Studies should expand their analysis to cover a detailed and wider range of potential environmental impacts of biomass densification.
- Since lignocellulosic biomass properties are highly variable, an understanding of how these properties affect the environmental impacts of biomass densification systems needs to be developed.
- Studies would benefit from a database specific to biomass densification systems, to provide more flexibility during LCA and reduce inconsistency in LCA studies as well as uncertainty in the LCA outcome.

- LCA results should be reported with the associated uncertainties to improve clarity and usefulness of the resulting outcomes.
- Since biomass densification has been identified as a worthwhile addition to the biomass energy system, it is important to extend LCA work to include the use stage of fuel briquettes (downstream of the briquetting process). This would provide more complete analysis of the system, and support the decision-making process on development of the briquetting technology.

7 LIFE CYCLE ASSESSMENT MODEL FOR BIOMASS FUEL BRIQUETTING

7.1 Introduction

This chapter addresses some of the issues identified in chapter 6 by developing a LCA model that provides understanding of the relationship between briquetting process variables and the life cycle environmental impacts.

In recent years, LCA models have been developed for various systems [e.g., construction: Bilec et al, 2010, waste management: Kulczycka et al, 2015], to address LCA methodological issues and improve speed and flexibility of assessment, as well as understanding of the outcome. However, in the bioenergy sector, these models have been focused on other processes such as: 1) the Agrifood LCA model [Williams et al, 2006], which focuses on the biomass cultivation stage, 2) the Greenhouse gases Regulated Emissions and Energy use in Transportation (GREET) software [Wang, 2012], which focuses on transportation fuels, 3) the CAMPUBIO [Aresta, 2005], which focuses on LCA of various types of algal biomass and technologies, and 4) the Biofuel Energy Systems Simulator (BESS), which focuses on assessing the life cycle energy and greenhouse gases (GHG) emissions of corn to bioethanol system [Liska et al, 2009].

These models and more general LCA software such as Simapro [Goedkoop et al, 2013], GaBi [PE International, 2012] and openLCA [Winter, 2015] have limited applicability for briquetting processes due to their emphasis on process variables and data unrelated to briquetting, resulting in increased time for data gathering, slower assessment, and limited flexibility to model specific briquetting process features. Some also attract high financial costs.

The LCA model presented here utilises data specific to the context of briquetting to develop a life cycle inventory (LCI), and enable quicker assessment and greater flexibility to change, modify and optimise specific briquetting process features (depth and breadth of assessment), as well as reduce reliance on high cost software.

The specific objectives were;

1. To develop key mathematical equations for calculating life cycle energy for different units and technological options of the briquetting system, using basic engineering principles.
2. To use the developed equations and impact assessment methods to create an open-access user accessible format (Microsoft Excel) of the model.
3. To generate inventory specific to the briquetting process and integrate into the user model for further use.
4. To carry out a representative LCA case study with mixed rice husks and corn cob biomass.

7.2 Methodology

7.2.1 Model development

The LCA model was developed in accordance with the basic principles described by ISO 14044 [2006]. A gate-to-gate system boundary was considered, and key units include loose biomass storage onsite, drying, crushing, conveying, blending/mixing, briquetting (densification), curing/cooling, packaging and briquette storage.

Figure 28 illustrates the overall approach used in developing the LCA model; it shows a set of integrated excel worksheets that describe process flows of material, energy and emissions across the different units of the briquetting process, and other components of the model. For each briquetting unit, mass and energy balance equations were developed using engineering principles and by applying the law of conservation of mass [Coulson & Richardson, 1999] to account for all materials within the system boundary (including losses).

Figure 29 shows the approach used in modelling the life cycle operational and embodied energies of the system, including primary production of machinery and building components, their transportation, fuel production, and fuel use in the briquetting plant (Figure 29).

Both operational and embodied energies are dependent on selected equipment duty (e.g., capacity, volume and mass restrictions), number of equipment units required and energy rating. The expected variations in feed biomass properties and briquette characteristics on equipment duty [e.g, Tumuluru et al, 2011; Muazu & Stegemann, 2015] were accounted for by developing mathematical relationships that incorporate density, mass and volume.

The model adopts a comparative approach and allows assessment of up to ten cases of biomass blends with different technological options. It consists of four main sections including; inventory, main calculations, user input and results (Figure 28). The main calculation section of the model uses the programmed mathematical equations in combination with user input and information collected from the inventory to estimate the number of equipment units required, the life cycle operational and embodied energies, and carbon emissions. The model calculates the environmental impacts and display the results by impact categories.

7.2.2 Allocation of burdens

Allocation in LCA deals with the attribution of an appropriate share of the environmental burden to different co-products in a system. A functional approach (the use of specific allocation factor such as mass, volume, energy content and energy input associated with various co-products in a multifunctional system), was used in the burden allocation to the biomass briquette as well as wastes (loose biomass and shattered briquette), and this was based on specific energy density of material. There is possibility of recycling the waste loose biomass and shattered briquettes but this depends on the briquetting process and properties of the wastes, as some of the waste materials may lose the original biomass properties and become less densifiable (e.g., in high temperature densification or addition of chemical binders).

The environmental burdens of various briquetting equipment components were calculated over the life time of the briquetting plant. In terms of the burden allocation, the energy used in equipment manufacture and maintenance (embodied impact) was separated from energy required to operate the equipment (operational impact).

The burdens of the briquetting plant building structure were based on the masses of the steel and concrete [e.g., Cole & Kernan, 1996; Johnson, 2006] components.

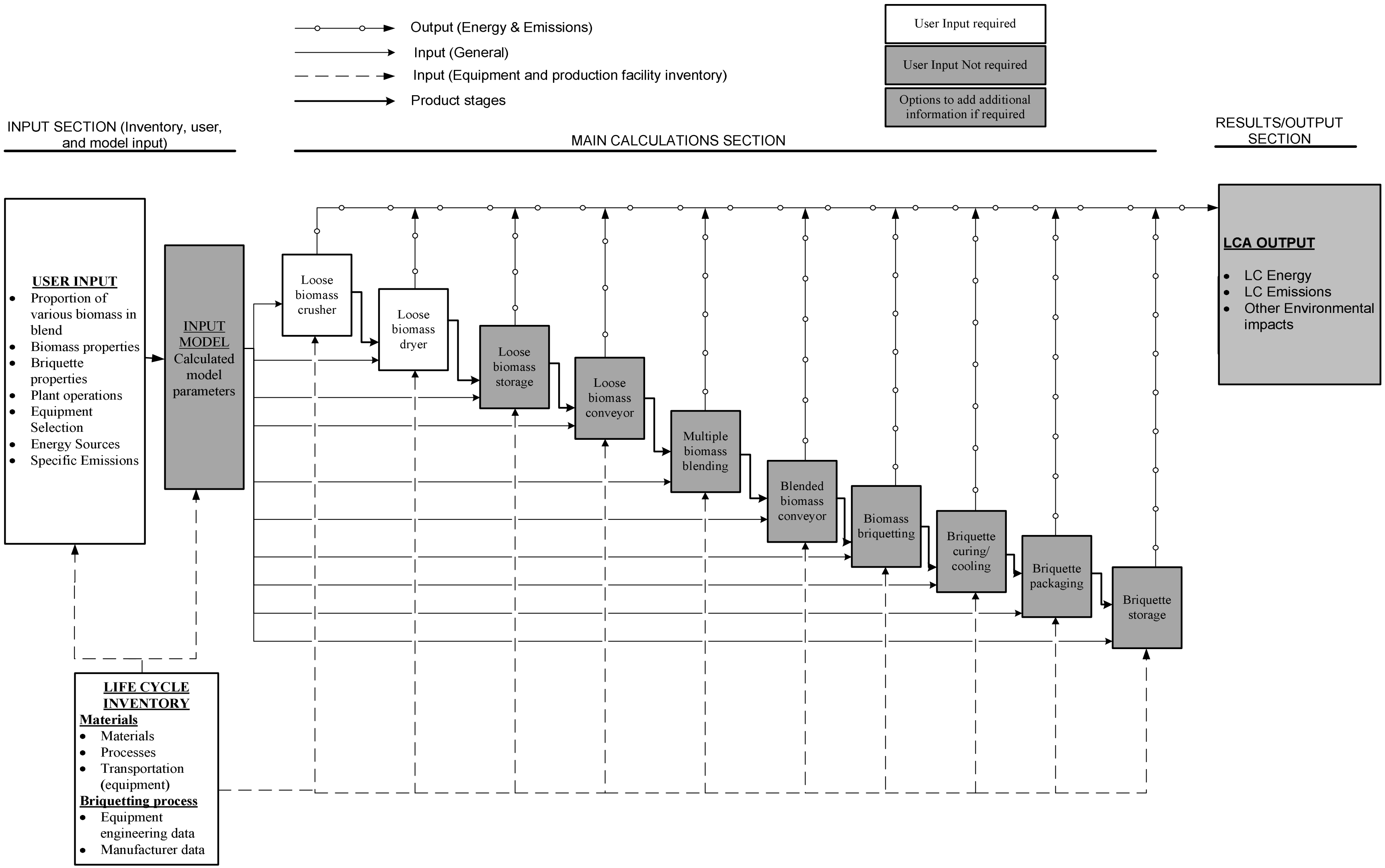


Figure 28: The LCA model framework for mixed biomass briquetting

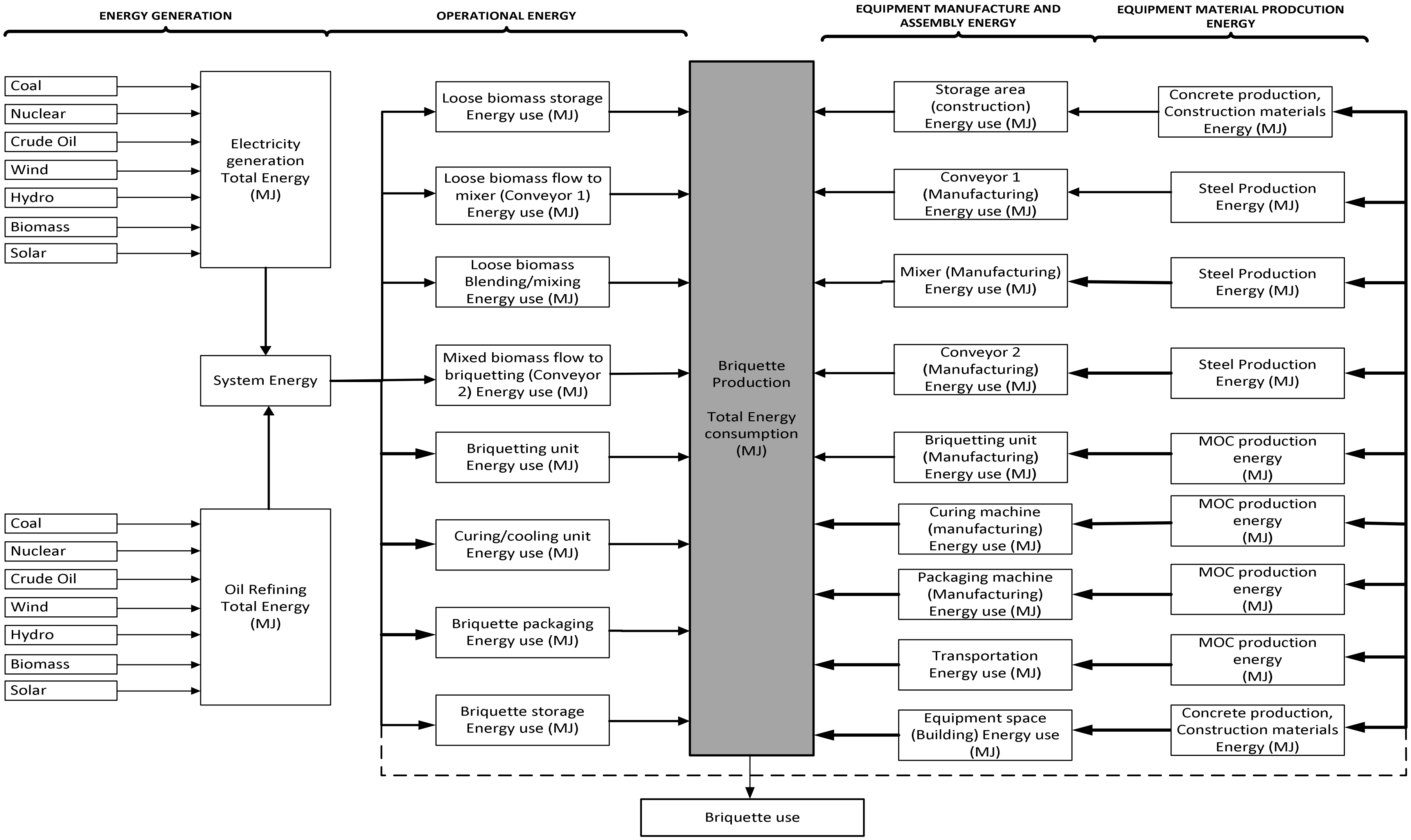


Figure 29: Energy analysis framework for biomass briquetting (MOC = equipment materials of construction)

7.2.3 Life cycle inventory (database)

The life cycle inventory was built in the form of a database within the integrated worksheets (Figure 28), to allow the user to select from a range of equipment (up to 30 options), materials and associated energy and emissions of processes related to the briquetting system. Two main data tabs describe: 1) the briquetting machinery database (engineering data), and 2) materials for this machinery, buildings, fuels and transport systems.

Foreground data on the briquetting process, such as equipment design and operational data, and their materials of construction (database 1), were collected from equipment manufacturers such as AGICO group [2014] and Gongyi Lantian [2014], and published process equipment compendia [e.g., ESI, 2006]. These sources were among the few established manufacturers of the briquetting process equipment.

Background data on materials, fuels and transport processes were collected from Ecoinvent v3 [2013, via the Simapro platform], which is one of the most recognised standard LCI databases, with general process data and emission factors that are applicable for different geographical regions. In addition to the Ecoinvent data, construction materials inventory data were also collected from ICE [2014] and the literature [e.g., Johnson, 2006; Cole & Kernan, 1996].

7.2.4 Briquetting system mass balance equations

7.2.4.1 General approach

A simple mass balance across each unit of the briquetting process (Figure 3) was carried out using the product mass (M_i in Figure 30) as the basis. Since mixed biomass streams were considered in developing the model equations, subscripts x and y were used to denote two types of biomass materials used in the briquetting process, and b denotes the blend. The % proportion and density of biomass material x in mixture of x and y, was denoted with k_x and ρ_x respectively. The proportion of biomass material y (k_y) and density of biomass blend can be calculated as:

$$Proportion\ of\ biomass\ material\ y\ (k_y) = 1 - k_x$$

Equation 5

$$Density\ of\ biomass\ blend\ (\rho_{bd}) = k_x \cdot \rho_x + k_y \cdot \rho_y$$

Equation 6

The mass of biomass processed in each unit is controlled by density of biomass material, equipment volume and maximum allowable mass quoted by manufacturer. Since some of the equipment are designed to process specific feed biomass with density (ρ_b), a conditional criterion for selecting the density of new biomass material to be processed using the same equipment, is shown in Equation 7.

$$Actual\ density\ of\ biomass\ processed\ (\rho_d) = \begin{cases} \rho_{bd}\ if\ \rho_{bd} \leq \rho_b \\ \rho_b\ otherwise \end{cases}$$

Equation 7

The lower heating values (LHV) of biomass materials x and y, are used in Equation 8:

$$Heating\ value\ of\ biomass\ blend\ (LHV_b) = k_x \cdot LHV_x + k_y \cdot LHV_y$$

Equation 8

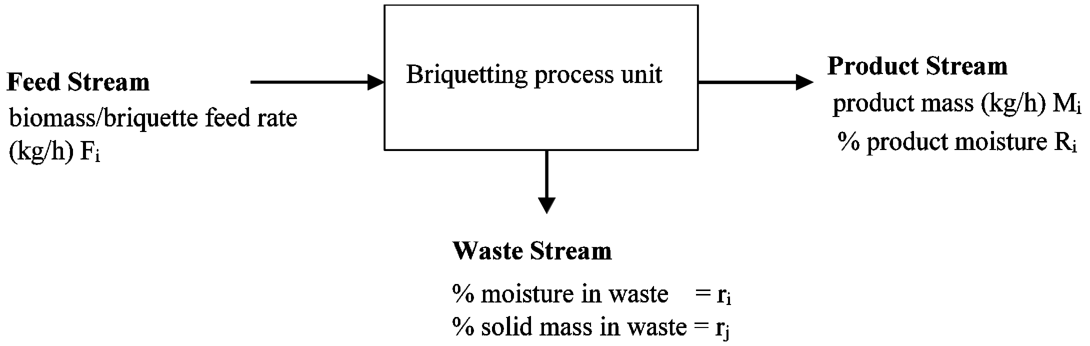


Figure 30: Mass balance representation for specific unit in briquetting system

Note: *Please refer to mass balance diagram for definition of main symbols used in mass balance equations and other subsequent sections.*

Product stream

The mass of moisture in the product can be calculated from Equation 9, while the solid mass can be calculated by substituting R_i with $(1 - R_i)$.

$$Moisture\ mass\ (\frac{kg}{h}) = R_i \cdot M_i$$

Equation 9

Waste stream

The moisture mass flow rate in the waste stream can be calculated using Equation 10, while R_i can also be substituted as $(1 - R_i)$ to calculate the solid mass in the waste stream.

$$Waste\ stream\ (Moisture\ mass) = \frac{r_i \cdot R_i \cdot M_i}{1 - r_i}$$

Equation 10

Feed stream

For the feed stream, Equation 9 and Equation 10 were used in developing Equation 11 for calculating the mass of moisture in the feed stream (Figure 30), and the mass of solid biomass can be calculated by replacing R_i with $(1 - R_i)$.

$$Feed\ stream\ (Moisture\ mass) = \frac{100\% \cdot R_i \cdot M_i}{1 - r_i}$$

Equation 11

Combining equations for moisture and solid mass in the feed stream gives Equation 12:

$$Total\ Feed\ (F_i) = M_i \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 12

Note: The subscript "i" in the total feed (F_i) is denoted differently for each unit of the briquetting system, e.g., for storage unit, F_i is denoted as F_s.

The general assumptions employed in developing the life cycle energy equations for the various briquetting process units are shown below;

Model assumptions

- A simple warehouse building was assumed to house both the onsite storage of loose biomass and briquette.
- Equipment are operated in batch mode.
- Storage unit operational energy is limited to electric bulbs and extractor fans.
- The model is valid for storage of 100% of each material storage and subsequent material blending ratios can be calculated from the derived equations.
- Equipment data were obtained from manufacturer and used in developing subsequent equations.

- Number of batches per hour is a controlling criterion, and manufacturer equipment production rate was used.
- The time for feeding of biomass to and out of the equipment is included in the manufacturer equipment hourly production rate.
- The manufacturer equipment capacity shown excludes allowance for any losses.
- A batch mixer with a volume (V_m) is constraint by a maximum allowable mass (M_{lm}), therefore, the number of batches mixed per hour is dictated by either volume of the mixer or the maximum allowable mass of residue that can be loaded to mixer at a given time.
- Blended residue are mixed continuously for a given time (t_m), which includes the time for loading, mixing and emptying of the mixer.
- Equipment maintenance and repairs were accounted for, by allocation of additional percentage mass of each equipment weight.
- Equipment installation energy at briquetting site was not included.

The total operational energy in each unit was denoted as E_i (the subscript "i" also changes for each unit, e.g., the subscript "i" is substituted by "s" for storage unit), the equipment power rating (e.g., kWh) was denoted with E_e, and equipment production capacity with M_e.

For all the briquetting process units, all equipment data obtained from the manufacturers were referred to as BASE or VENDOR data.

Mixed streams of biomass were considered in developing the life cycle model equations for all units apart from biomass drying and crushing, where separate streams of each biomass were considered. A detailed model calculation for these units was not provided, however, a space within the model has been created for users to input their own values of energy and emissions specific to these units, for integration into the overall model results page.

7.2.4.2 Loose biomass/briquette storage

Total storage feed can be calculated from Equation 13 substituting F_i from Equation 12.

$$Total\ storage\ feed\ (F_{st}) = M_s \cdot T_s \cdot T_{sd} \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 13

T_s and T_{sd} represents daily operating time (h/d) and buffer storage duration (d) respectively. The total area required for storage can be calculated using Equation 14.

$$Total\ storage\ unit\ area\ (A_{st}) = \frac{V_{st}}{H_s}$$

Equation 14

where H_s is the height of storage facility, and V_{st} the total volume of storage required by various biomass materials in the blend, based on their densities (ρ_i) and % proportion, as shown in Equation 15.

$$Total\ storage\ volume\ (V_{st}) = \sum_{i=A}^{n} \frac{M_i}{\rho_i}$$

Equation 15

Given $M_i = K_i \cdot F_{ts}$, the total energy required for biomass or briquette storage from biomass materials x and y, can be calculated using Equation 16.

$$Storage\ unit\ energy\ (E_{st}) = E_e \cdot \frac{V_{st}}{H_s} = \frac{E_e}{H_s} \cdot F_{ts} \cdot \left[\frac{K_A}{\rho_A} + \frac{K_B}{\rho_B}\right]$$

Equation 16

Where E_e is the equipment power rating (kW)

7.2.4.3 Conveyor

The total number of batches per given time (e.g., 1h) can be calculated from Equation 17, and Equation 18 can be used to calculate the number of conveyors required for a given mass of biomass or briquette per time.

$$Number\ of\ batches\ (N_{lc}) = \frac{F_c}{M_{ld}}$$

Equation 17

$$Total\ number\ of\ conveyors\ required\ (N_c) = \frac{N_{lc}}{N_L}$$

Equation 18

Where F_c is the total feed mass and M_{ld} is the maximum mass that can be loaded on the conveyor per time. N_L is the maximum number of batches that can be conveyed per time (h) based on equipment design, which can be calculated using equipment capacity, volume, and biomass material or briquette density. Therefore, the total energy required to convey a given mass of biomass/briquette can be calculated using Equation 19.

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot \frac{F_c}{M_e} \cdot \frac{\rho_b}{\rho_{bd}}$$

Equation 19

Me is the vendor-quoted equipment capacity (kg/h).

Substituting F_c (Equation 12, 7.2.4.1) into Equation 19 and applying a density and mass constraint within the conveyor specification will give Equation 20 and Equation 21.

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 20

M_r is the ratio of design equipment capacity (M_e) and production target (M_t), and ρ_r is the ratio of vendor quoted biomass density (ρ_b) and calculated biomass density (ρ_{bd}).

$$\boldsymbol{M_r = \frac{M_i}{M_e}} \qquad \boldsymbol{\rho_r = \frac{\rho_b}{\rho_{bd}}}$$

$$Conveyor\ unit\ energy\ (E_c) = E_e \cdot M_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 21

Note:

Equations 20, 24b, 28b, 31a, 34b: applicable when feed biomass density equals to or less than vendor quoted biomass density.

Equations 21, 24c, 28c, 31b, 34c: applicable when biomass density equals to or greater than vendor quoted biomass density.

7.2.4.4 Blending/mixing

The number of batches mixed per given time, can be determined using Equation 22.

$$Number\ of\ batch\ mixed\ (N_{lm}) = \frac{F_m}{M_{lm}}$$

Equation 22

M_{lm} is the calculated mass of biomass that will fit in a mixer, based on mixer volume (V_m) and density of biomass blend (ρ_d), and F_m is the total feed mass for mixer.

This can be further used to calculate the equipment required for blending of the total feed biomass (F_m) (Equation 23).

$$Number\ of\ mixers\ required\ (N_m) = \frac{N_{lm}}{N_{bm}}$$

Equation 23

Where N_{bm} is the number of batches per hour per mixer, this means that for a specific time (t_m) given to mix the total feed biomass (F_m), the number of batches that was calculated based on biomass properties and volume of mixer (V_m), is also constrained by the maximum allowable volume and mass of mixer for a given time (t_m). Therefore, the energy required for blending of multiple briquetting feed, can be calculated using Equation 24a.

$$Blending\ energy\ (E_m) = E_e \cdot N_m$$

Equation 24a

and by substituting N_m, equation 24a becomes 24b.

$$Blending\ energy\ (E_m) = \frac{E_e \cdot t_m}{V_m \cdot \rho_d} \cdot F_m$$

Equation 24b

By substituting F_m, Equation 24b will become 24c, depending on the ratio of vendor quoted biomass density (ρ_b) and the calculated density of biomass blend (ρ_{bd}), (see Note in 7.2.4.3).

$$Blending\ energy\ (E_m) = M_i \cdot \left[\frac{E_e \cdot t_m}{V_m \cdot \rho_d} \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]\right]$$

Equation 24c

7.2.4.5 Briquetting

In a typical briquetting machine, the mold is filled with specific mass of biomass material (M_{die}) before compaction. This can be calculated using Equation 25, and the total number of times a mold can be loaded per time (1h), can then be calculated using Equation 26.

$$Mass\ of\ biomass\ to\ fill\ briquetting\ mold/die\ (M_{die}) = V_{die} \cdot \rho_d$$

Equation 25

$$Total\ number\ of\ mold\ loading\ (N_{ldie}) = \frac{F_{bq}}{M_{die}}$$

Equation 26

V_{die} is the volume of mold, and F_{bq} is the total briquetting feed biomass.

Therefore, the number of units of equipment required to densify a given mass of biomass per hour, can be determined using Equation 27.

$$Total\ number\ of\ briquetting\ machine\ required\ (N_{bq}) = \frac{N_{ldie}}{N_{ld}}$$

Equation 27

N_{ld} is the number of time the briquette compaction mold can be loaded per per time (h) based on manufacturer equipment design, and N_{ldie} is the calculated (new) number times the mold can be loaded based on individual biomass properties.

Equation **28**a can be used to calculate the total energy required for briquetting.

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot \frac{F_{bq}}{M_e} \cdot \rho_d$$

Equation 28a

By further expansion of F_{bq}, we have Equations 28b and 28c (see Note in 7.2.4.3).

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 28b

$$Briquetting\ energy\ (E_{bq}) = E_e \cdot M_r \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right]$$

Equation 28c

see Equation 20 for M_r and ρ_r.

7.2.4.6 Briquette curing/cooling

The number of curing cycles for green briquettes per equipment per time (e.g., day) can be calculated using Equation **29**, while Equation 30 can be used to determine the units of equipment required.

$$Number\ of\ briquette\ curing\ cycles\ (N_{rc}) = \frac{F_r}{M_{lr}}$$

Equation 29

$$Number\ of\ briquette\ curing\ machine\ required\ (\,N_r\,) = N_e \cdot T_r$$

Equation 30

Where M_{lr} is mass of loading per curing equipment, T_r is the vendor quoted residence time for briquettes in curing machine, while N_e is the ratio of calculated number of curing cycles N_{rc} to the vendor quoted curing cycles per equipment per time N_{rd} ,F_r is the total curing unit feed.

Thus, the total energy required to cure fresh briquette can be calculated using Equation 31.

$$Briquette\ curing\ energy\ (E_r) = \frac{E_e}{(V_r \cdot \rho_d)} \cdot M_i \cdot \left[\frac{R_i}{1-r_i} + \frac{(1-R_i)}{1-r_j}\right] \cdot \frac{T_r^2}{T_{op}}$$

Equation 31

Where V_r and T_{op} represents volume of curing space in equipment and daily operating hours respectively.

See Equation 7 for ρ_d (briquette density in this case).

7.2.4.7 Briquette packaging

The total number of packaged briquette bags required per hour can be calculated using Equation 32. Therefore, based on the calculated number of bags, the equipment required to package a given mass of cured/cooled briquettes can be calculated from Equation 33.

$$Number\ of\ packaged\ briquette\ bags\ (N_{pb}) = \frac{F_p}{M_{lp}}$$

Equation 32

Where M_{lp} is the calculated mass of briquettes per bag and F_p is the total packaging unit feed of briquettes.

$$Number\ of\ packaging\ machines\ required\ (N_p) = \frac{N_{pb}}{N_{lp}}$$

Equation 33

Where N_{lp} is the vendor quoted packaging machine capacity (e.g., bags per hour).

The total energy required for briquette packaging can be calculated using Equation 34a.

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot \frac{F_p}{M_e} \cdot \rho_d$$

Equation 34a

see Equation 7 for ρ_d (briquette density in this case).

Equation 34a was further expanded and modified (using density variation and change in production target) to give 34b and 34c (see Note in 7.2.4.3).

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot M_r \cdot \rho_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 34b

$$Briquette\ packaging\ energy\ (E_p) = E_e \cdot M_r \cdot \left[\frac{R_i}{1 - r_i} + \frac{(1 - R_i)}{1 - r_j}\right]$$

Equation 34c

7.2.4.8 Embodied energy

Machinery

A generic Equation 35 can be used to calculate embodied energy of machinery used in all units of the gate-to-gate briquetting system.

$$Equipment\ embodied\ energy\ (E_{ei}) = N_e \cdot W_e \sum_{i=1}^{n} X_i \cdot Y_i$$

Equation 35

N_e which stands for actual number of equipment required/used in a specific unit, varies for the different units of the briquetting system. For example, briquetting equipment embodied energy (E_{eb}) was determined from Equation 36.

W_e is the net weight of equipment, X_i is the fraction of each material of construction of the equipment e.g., steel (%), and Y_i is the unit embodied energy of each material (MJ/kg).

$$Briquetting\ equipment\ embodied\ energy\ (E_{eb}) = \frac{N_{ldie}}{N_{ld}} \cdot W_e \sum_{i=1}^{n} X_i \cdot Y_i$$

Equation 36

Buildings

The building space requirement of each equipment was calculated from the base dimensions of the individual equipment, allowing space for vehicle access, maintenance and allowance at rear, all in metres (m) as shown in Figure 31. In writing the equation for calculating the specific burden of the briquetting plant building, the building technical specification (including type of structure and specific features) and material inventory (e.g., steel, concrete, wood) were used, while some careful assumptions were employed where necessary (e.g., use of length, height and width in building).

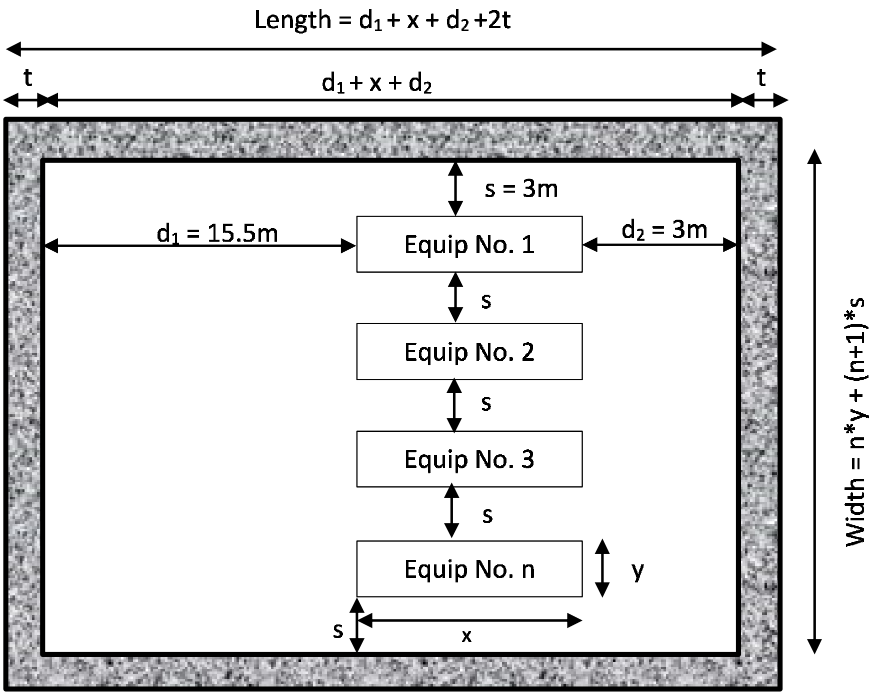


Figure 31: Approach used in calculating building space requirement of individual equipment in the briquetting plant

7.2.4.9 Fuel briquette energy content

The product (e.g., briquette) heating value (HV_i) can be determined using Equation 37, which can also be utilised in calculating the life cycle energy per MJ of briquette energy.

$$Briquette\ heating\ value\ (HV_{bq}) = M_i \cdot (1 - R_i) \cdot LHV_b + M_i \cdot R_i \cdot C_p \cdot T_p$$

Equation 37

Where C_p is the specific heat capacity (MJ/kgK) of water, T_p is the product temperature.

7.2.5 Life cycle impact assessment modelling

7.2.5.1 Energy indicators

The parameters calculated by the model to indicate the energy performance of the briquetting system, include: 1) Net energy production ratio (NER) which shows how much energy is produced as marketable products in comparison to the external, non-feed, energy input, 2) Energy return on investment (EROI) which represents the ratio of the energy delivered to energy used directly and indirectly in the process, and 3) the overall thermal efficiency (η_E) which is the ratio of energy provided by a system to that supplied to it during thermal conversion [Shie et al, 2011]. The higher the EROI, the more commercially viable a biofuel is [e.g., Pradhan et al, 2008]. The EROI has also been used to examine the energy efficiency of some biofuels including bioethanol [e.g., Farrell et al, 2006], and various fossil fuels [e.g., Cleveland, 2005]. The NER and EROI values greater than 1 are considered sustainable, thus 1 indicates a breakeven point.

Other energy indicators included in the model are; Total energy ratio (TER), Net energy production ratio (NER), and Net energy balance (NEB) [Shie et al, 2011].

7.2.5.2 Characterisation

The use of resources and emissions to the environment are collectively termed environmental burdens [e.g., Williams et al, 2006; De Benedetto, 2009]. Environmental impacts are a consequence of particular burdens. For example, SO_2 emission to the atmosphere is a burden, while the consequent Acidification is an impact. Different impact assessment methods can be used to calculate the LCA results, the main difference is between the midpoint and endpoint which look at the different stages in the cause-effect chain to calculate the impact. The midpoint impact category (problem-oriented approach), translates impacts into environmental themes such as climate change and acidification, while the endpoint impact category (damage-oriented approach), translates environmental impacts into issues of concern such as human health, and natural resources. Endpoint results have a higher level of uncertainty compared to midpoint [Goedkoop et al, 2013]. Therefore, a midpoint approach was employed in modelling the environmental impact of the briquetting system.

Environmental impact assessment initially starts by quantifying the burdens to the environment associated with emission of individual chemical species. These chemical species are further aggregated into environmentally functional groups referred to as Impact categories [Williams et al, 2006]. A generic equation for calculation of indicators for each impact category, using inventory data and generic characterisation factors, is shown in Equation 38 [Pennington et al, 2004; De Benedetto, 2009].

$$\text{Category Indicator} = \sum_{s} (\text{Characterisation Factor(s)}\ X\ EmissionInventory(s))$$

Equation 38

Where *s* represents the chemical species, and the respective characterisation factors (specific contribution to the impact category) are available in the literature and databases.

The main impact categories used in this study included Global warming potential (GWP) (kg CO_2-eq), Acidification potential (AP) (kg SO_2-eq), Ozone layer depletion (ODP) (kg CFC-11-eq), Human toxicity (HT) (kg 1,4-DB-eq) and Ecotoxicity (ET) (kg 1,4-DB-eq), obtained from the Recipe midpoint (H) methodology via the Simapro platform. These categories were considered based on their relevance on the briquetting unit [De Benedetto, 2009], location of the briquetting plant, and previous work reported on LCA of biomass briquetting [Chiew & Shimada, 2013; Waewsak et al, 2013]. For all the impact categories, key pollutants considered in the model, were based on a 1% cut off (The level of environmental significance associated with unit processes or product system that were excluded from the study) [Weidema et al, 2013; ISO 14040].

7.2.6 User inputs

The first section of the user model includes a specific menu page which allows user to navigate easily within the model (Figure 32).

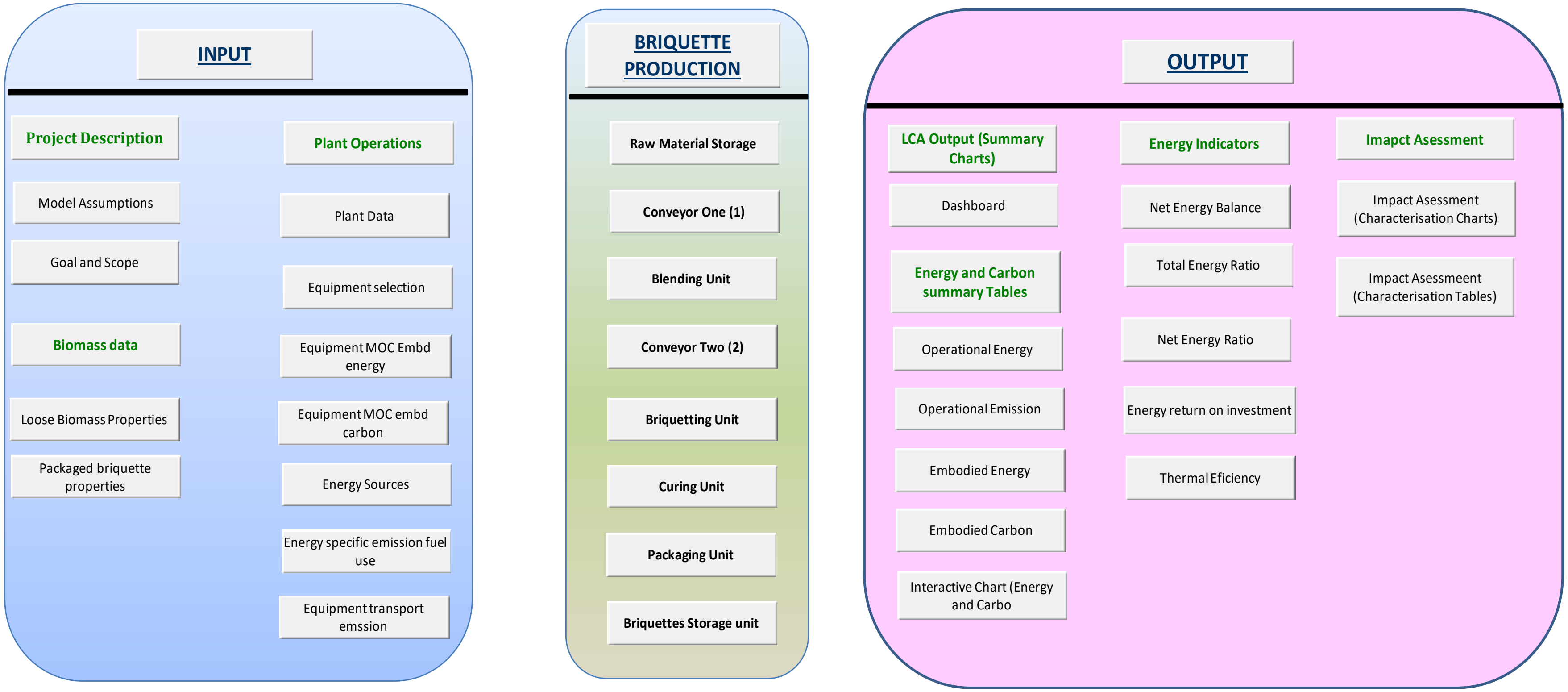
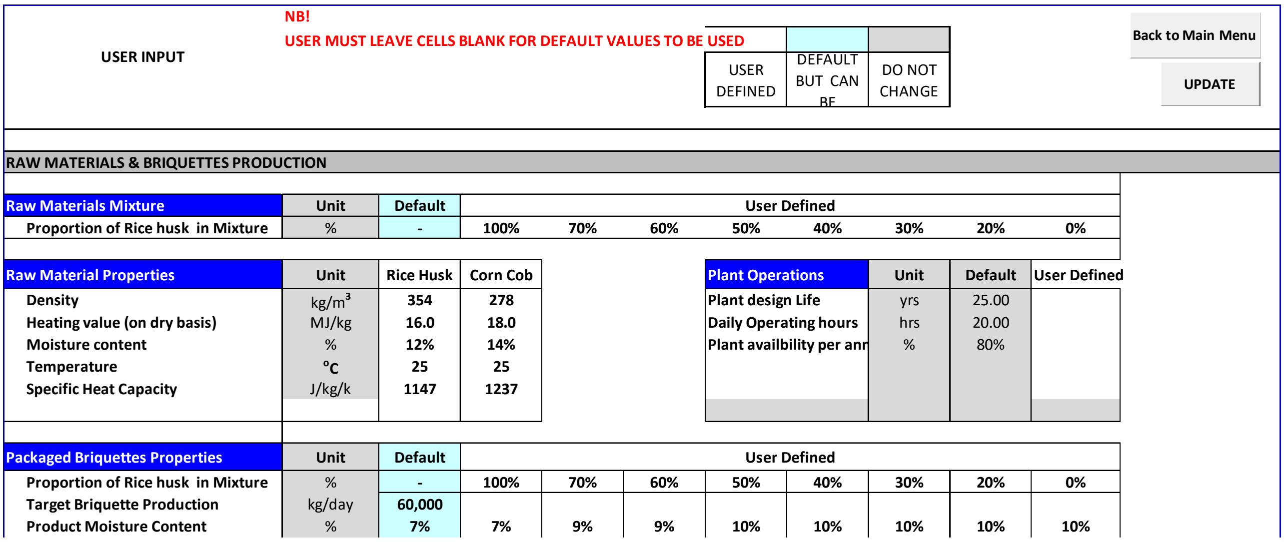


Figure 32: User navigation page in LCA model of briquetting system

The user input section allows the user to enter key briquetting process variables such as loose biomass density and moisture, scale of production, expected briquettes characteristics (e.g., density, moisture, shattering and abrasion index), and equipment selection, for up to ten scenarios. Figure 33 shows a screenshot of the user input tab. Other authors [e.g., Bilec et al, 2010; Williams et al, 2006] have used a similar approach in LCA modelling.



USER INPUT

NB!
USER MUST LEAVE CELLS BLANK FOR DEFAULT VALUES TO BE USED

RAW MATERIALS & BRIQUETTES PRODUCTION

Raw Materials Mixture	Unit	Default	User Defined							
Proportion of Rice husk in Mixture	%	-	100%	70%	60%	50%	40%	30%	20%	0%

Raw Material Properties	Unit	Rice Husk	Corn Cob
Density	kg/m^3	354	278
Heating value (on dry basis)	MJ/kg	16.0	18.0
Moisture content	%	12%	14%
Temperature	°C	25	25
Specific Heat Capacity	J/kg/k	1147	1237

Plant Operations	Unit	Default	User Defined
Plant design Life	yrs	25.00	
Daily Operating hours	hrs	20.00	
Plant availbility per ann	%	80%	

Packaged Briquettes Properties	Unit	Default	User Defined							
Proportion of Rice husk in Mixture	%	-	100%	70%	60%	50%	40%	30%	20%	0%
Target Briquette Production	kg/day	60,000								
Product Moisture Content	%	7%	7%	9%	9%	10%	10%	10%	10%	10%

Figure 33: User Input page for LCA model of briquetting system

An "input model" tab is provided to also serve as an interface between the user input and main calculations. Based on user input, the input model searches the inventory for relevant equipment or material information required for subsequent calculations. However, the user has the option to override these pre-selected inventory values (also called default values).

7.2.7 Results section

The result section includes a series of chart and tables of various LCA output including energy and environmental impact (Figure 28, 7.2.1). Charts representing a summary of the LCA results can be viewed from the "*Dashboard*" of the excel model (Figure 34), while other charts and tables can be accessed via the menu page. A screenshot of an interactive chart that allows the user to compare different LCA outputs is shown in Figure 35.

DASHBOARD

Back to Main Menu

KEY DEFINITIONS

1) NET ENERGY RATIO (NER)

NER indicates how much energy is produced as salable products in relation to the external, non-feed, and energy input.

2) ENERGY RETURN ON INVESTMENT (EROI)

The EROI is defined by the ratio of gaining useful energy, and the higher the EROI, the more renewable the fuel.

3) TOTAL ENERGY RATIO (TER)

The TER is the ratio of the total input energy to the total output energy.

4) NET ENERGY BALANCE (NEB)

The NEB is the life cycle energy balance, a positive NEB indicates energy of fuel output (biofuel), is greater than input

5) THERMAL EFFICIENCY (ῃe)

The ῃe 'indicates how much useful energy is produced over and above the energy consumed by the system, and this value is

MODEL ERROR SUMMARY

Input Page 0 Errors

Figure 34: Dashboard for LCA model of briquetting system

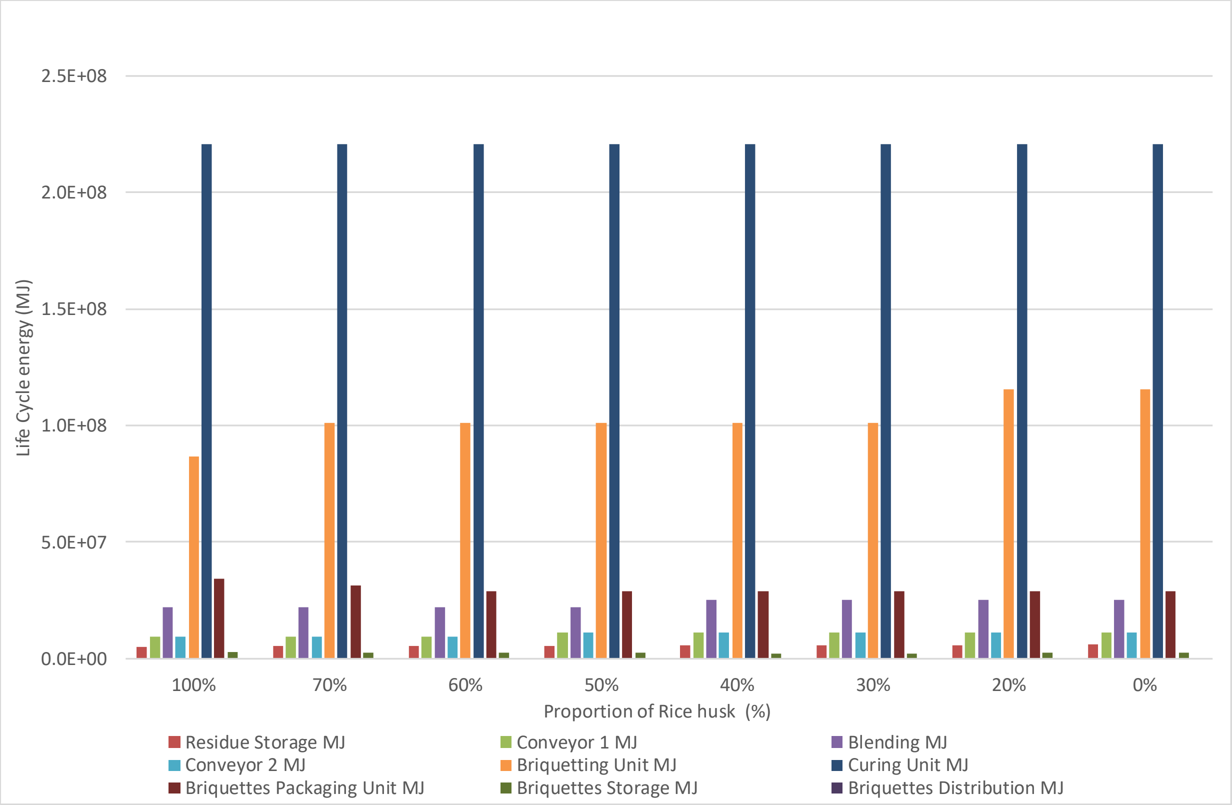


Figure 35: User Interactive chart in LCA model of briquetting system

7.3 Case study

7.3.1 Description

For the representative case study of briquetting of rice husks and corn cobs, a functional unit of 1 MJ briquette energy content at the briquetting plant gate was defined.

The life cycle scenario assumed the case of a fully operating briquette production plant located in the north central part of Nigeria with a packaged briquette production capacity of 20,000 t/year [e.g., Hu et al, 2014]. Briquette production was assumed to occur at 25 ± 2^{o} C with a mass loss of 7% during briquette packaging i.e., average of shattering and abrasion resistance of fuel briquettes [Muazu & Stegemann, 2015] and a 100% moisture loss (no solid) in curing unit. The shattering and abrasion resistance value excludes losses during briquette transport, but includes losses during the briquette packaging within the briquetting plant (from handling of packaged briquette, which was assumed to remain in the sealed bags through to conversion site).

A system boundary of gate-to-gate was used excluding the dryer and crusher (Figure 28) for the specific case study, because the case study focuses on where the two biomass materials are processed collectively, to identify the effect of differences in their properties, on the environmental impact. Furthermore, it was assumed that both feed materials were obtained at suitable moisture and rice husks biomass was obtained with suitable particle size for briquetting.

7.3.2 Data source

The properties of loose rice husks and corn cobs biomass were obtained from Muazu & Stegemann, [2015]. Fuel briquettes were produced and characterised for blend ratios from 100% rice husks 100 % corn cobs.

The machinery used in the case study and its specific electricity consumption is shown in Table 17. The materials, energy and transport emissions inventory of the briquetting system is provided in Appendix 1 (10.1).

Table 17: Briquetting system machinery and building inventory (case study)

Briquetting unit machinery	Capacity (kg/h)*	Electricity (kW) consumption	Net weight (kg)	Main material of construction	Equipment code	Reference
Feed Storage	2	0.01	2700	Concrete	NA	[Cole & Kernan, 1996; Johnson, 2006]
Conveyor 1	550	2.0	130	Steel	GC-LXSSJ	[AGICO, 2014]
Blender/mixer	991**	14.9	1000	Steel	SAI-DC10	[Tapasya, 2015]
Conveyor 2	550	2.0	130	Steel	GC-LXSSJ	[AGICO, 2014]
Briquetting machine	550	27.5	2400	Steel	MPP550	[Lancashire fuels, 2014]
Curing/cooling	3000	0.8	630	Steel	SKLN1.5; RBR 34-4	[Azeus, 2015; BLISS, 2016]
Packaging	550	5.0	60	Steel	TSP	[AGICO,2014]
Briquette Storage	2	0.01	2700	Concrete	NA	[Cole & Kernan, 1996; Johnson, 2006]

* storage unit in days
**calculated mass from volume given by manufacturer

7.3.3 Sensitivity analysis methods

As it is with many LCA model, among numerous data and assumptions used in the LCA model, 95 to 99% of the results may be determined by a few of these assumptions and/ data [Goedkoop et al, 2014]. One of the proposed methods of testing the sensitivity of a LCA output to various input variables, is the factorial design [e.g., Loucks et al, 2011; Bjorklund, 2002].

Considering the comparative nature of the LCA model in this study, a sensitivity analysis was carried out within the model first by doing a "*contribution analysis*" of various input variables such as briquetting equipment, biomass/briquette density, moisture, abrasion resistance, and scale of production, used in the case study. A factorial design was employed to test the variable with the most effect to changes in the LCA result [Box et al, 2005]. A high and low points for the input variables were selected based on the point at which significant changes were observed in the LCA output, from initial contribution analysis, variables with numerical input were varied by a factor of 3 (Table 18).

7.3.4 Results and discussion

7.3.4.1 Life cycle energy and carbon dioxide emissions of rice husk and corn cob briquetting

The life cycle energy (operational and capital equipment) associated with the production of 1 MJ of fuel briquette energy content from various blends of rice husks and corn cob biomass, is shown in Figure 37. Since the system boundary for the case study does not include biomass drying and crushing (7.3.1), the briquetting and blending units appear to be the most energy intensive units in the briquetting system. For example, 100% and 50% rice husks resulted in contributions of 39 and 42%, respectively, of the briquetting unit to the total life cycle operational energy. This is consistent with findings reported by other authors [e.g., Hu et al, 2014; 63.2%, and Shie et al, 2011; 43.3%]. The briquette curing unit had the least energy consumption of 0.43%, while fuel briquette storage had 0.5%.

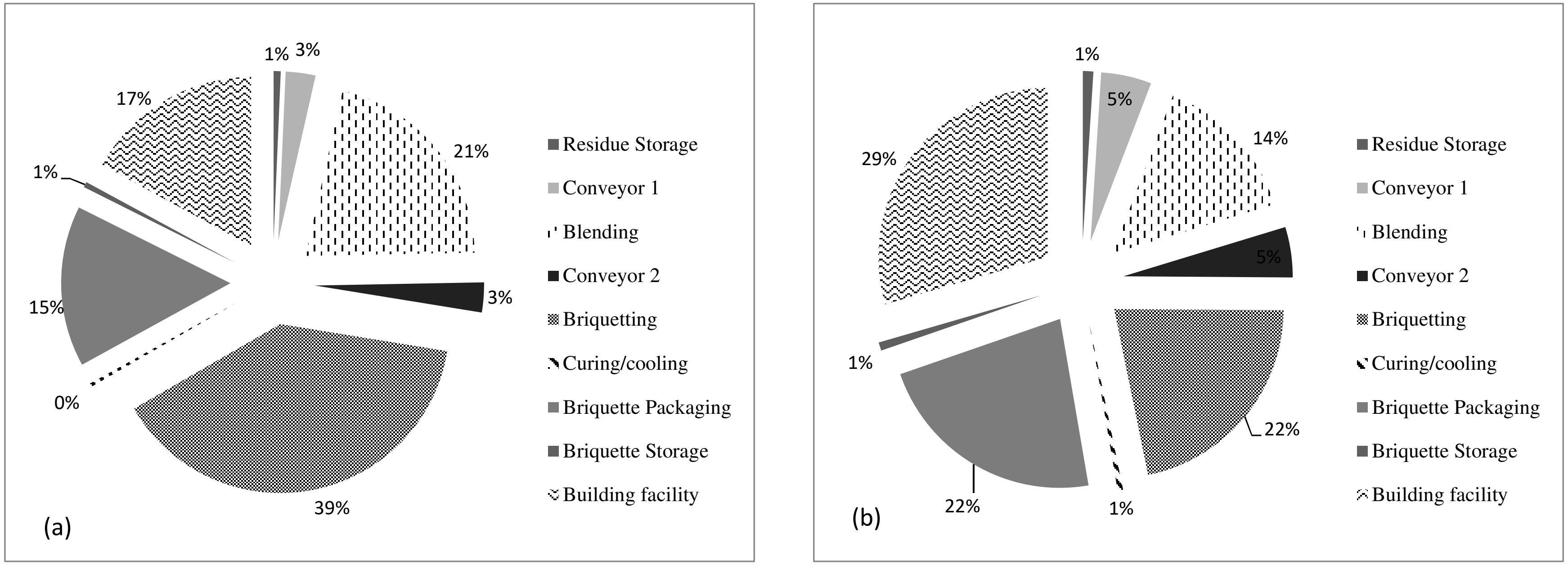


Figure 36: Life cycle operational energy of briquetting 100 % rice husks using briquetting equipment (a) T1 (LancaFuels-MPP550: low capacity, high energy consumption, high net weight) and (b) T2 (Lantian-LTM III: high capacity, high energy consumption, low net weight)

The contribution of each unit of the briquetting system to the life cycle energy, can be highly influenced by the type of equipment employed. For example, Figure 36a and b shows the change in total life cycle energy of the different units of the briquetting system, as a result of change in the briquetting equipment employed. This can be attributed to factors such as the equipment design capacity and efficiency.

The use of higher ratio of corn cobs in the blend with rice husks, increased the overall life cycle energy of the system. This can be attributed to the lower density and morphological characteristics of corn cobs biomass, which increased the number of biomass processing cycles per given time in the pre-densification units (i.e., before biomass compaction).

Figure 38 shows the life cycle carbon dioxide emissions of briquetting rice husks and corn cobs where the briquetting and blending units also had the highest contribution to the total life cycle carbon dioxide emissions. The life cycle energy (Figure 37) and carbon dioxide emissions (Figure 38) associated with production of 1 MJ fuel briquette energy content, were in the range of 0.2 to 0.3 MJ and 0.01 to 0.02 kg CO_2 respectively, which is within the range reported by other authors [Li et al, 2012; Megalli et al, 2009; Mani et al, 2005].

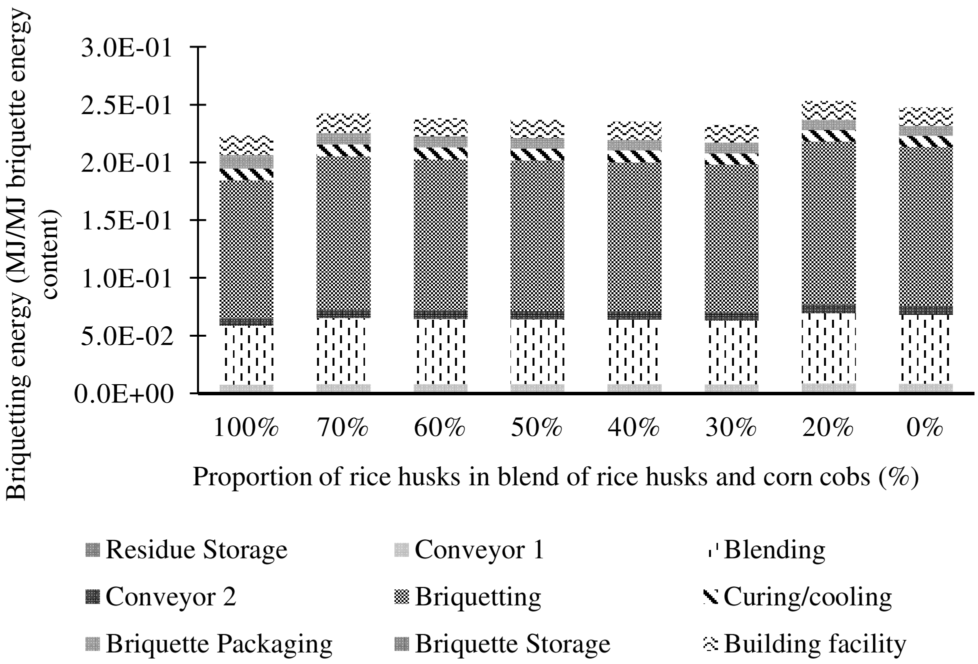


Figure 37: Life cycle energy of fuel briquetting with blends of rice husks and corn cobs

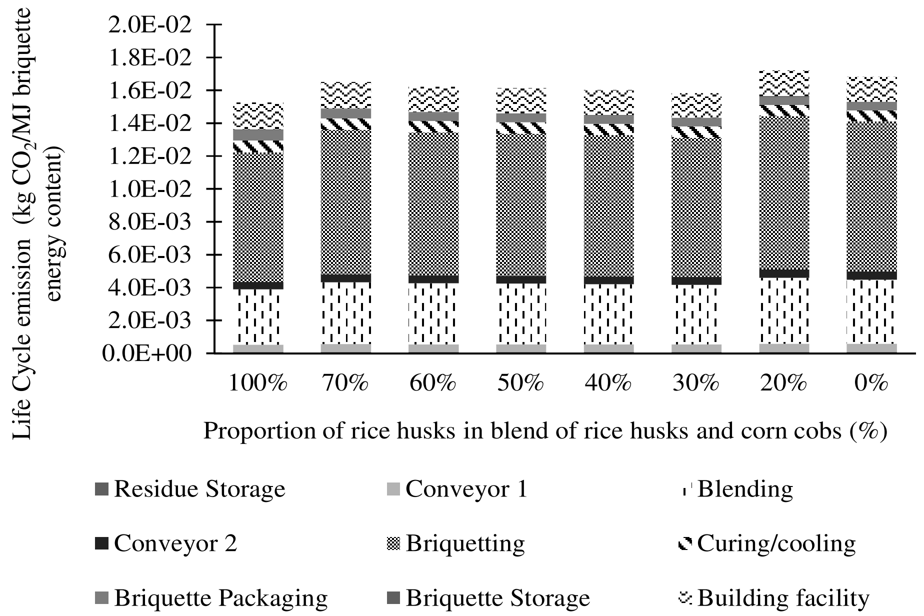


Figure 38: Life cycle carbon dioxide emissions of the fuel briquetting with blends of rice husks and corn cobs

A fair comparison between many LCA studies has been difficult because each assessment is specific to the design scenario. However, a fairly accurate comparison can be made among LCA results of different biomass or briquetting process, with the same functional unit, system boundary, and methodology.

7.3.4.2 Energy indicators for rice husks and corn cobs briquetting

Figure 39 shows the NER and EROI of the briquetting system. From Figure 39, the NER and EROI were both positive, and greater than 1, for all the blends of rice husks and corn cobs.

From Figure 39, the highest NER and EROI of 28 and 29, was obtained at 100% rice husks, this can be attributed to the low energy use for briquette production at 100 % rice husks compared with other blend ratios. However, the energy content of briquette was lowest at 100% rice husks and increased with higher blend of corn cobs, thus higher NER and EROI values of 27 and 28 was also obtained at 30/70 % blend of rice husks to corn cobs.

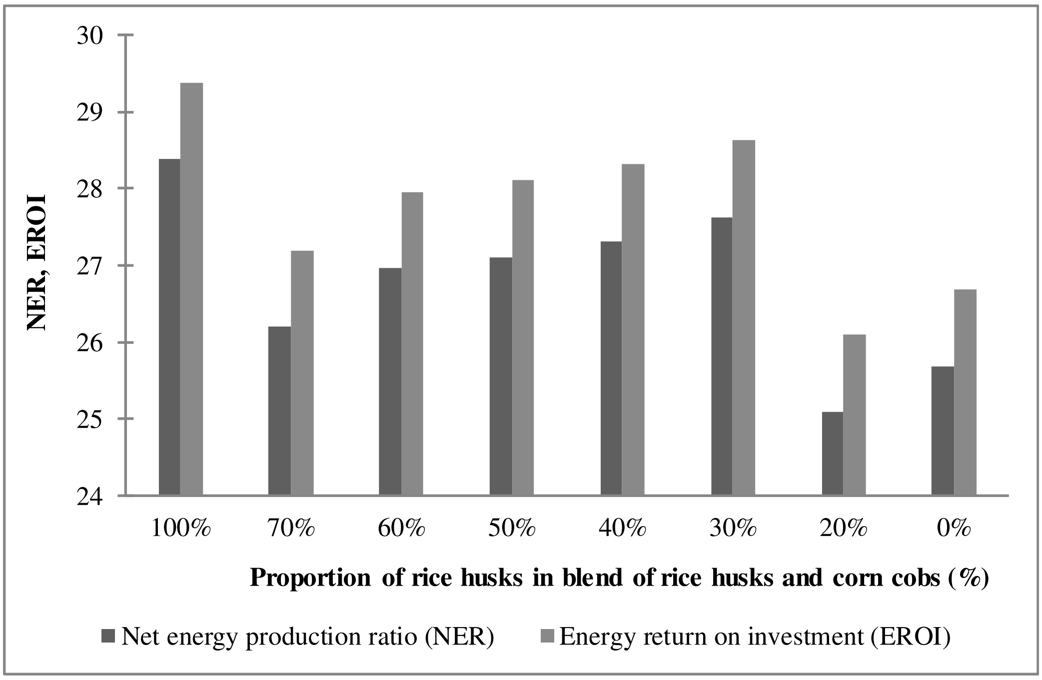


Figure 39: NER and EROI of fuel briquetting with blends of rice husks and corn cobs

7.3.4.3 Life cycle impact assessment of rice husks and corn cobs briquetting

Figure 40 to Figure 44 shows the potential environmental impact of producing 1 MJ of fuel briquette energy content, for all the blends of rice husks and corn cobs. From Figure 40 to Figure 44, the biggest environmental impact of briquetting was on HT and GWP, and least impact on ODP. The large impact of briquetting on HT and GWP can be attributed to the high embodied impact of plant facilities, and impacts from operational and transport stages respectively. Findings by other authors [e.g., Zhong et al, 2010; Waewsak et al, 2013] also showed a high impact of briquetting on GWP, and minimal impact on ODP [e.g., Waewsak et al, 2013]. For example, Chiew & Shimada, [2013] reported a GWP and HT with values of 43.74 kg CO_2-eq and 10 kg 1, 4-DB-eq respectively, from briquetting of 1 t of empty fruit bunches (EFB).

The main sources of the GWP include CO_2, CH_4 and N_2O emissions mainly from fossil fuel (e.g., diesel, coal) in operational use of the briquetting equipment, with CO_2 contributing over 80% to the total GWP [e.g., Tsalidis et al, 2014].

The main contributors to HT include emissions of heavy metals such as zinc and nickel associated with primary production of briquetting equipment, and manganese during sea transportation of this equipment.

The environmental impact of producing rice husk and corn cob briquettes with 1 MJ energy content was in the range of 4.7E-2 to 5.1E-2 kg CO_2-eq for GWP, 6.6E-3 to 7.3E-3 kg SO_2-eq for AP, 1.3E-1 to 1.5E-1 kg 1,4-DB-eq for HT, 2.6E-8 to 2.8E-8 kg CFC-11-eq for ODP, and 2.8E-5 to 3.1E-5 kg 1,4-DB-eq for ET. LCA results are widely different (Muazu et al, manuscript in review), and the values obtained in this study fall within a realistic range of values obtained by some authors [e.g., Waewsak et al, 2013] but much lower than those obtained by other authors [e.g., Chiew & Shimada, 2013].

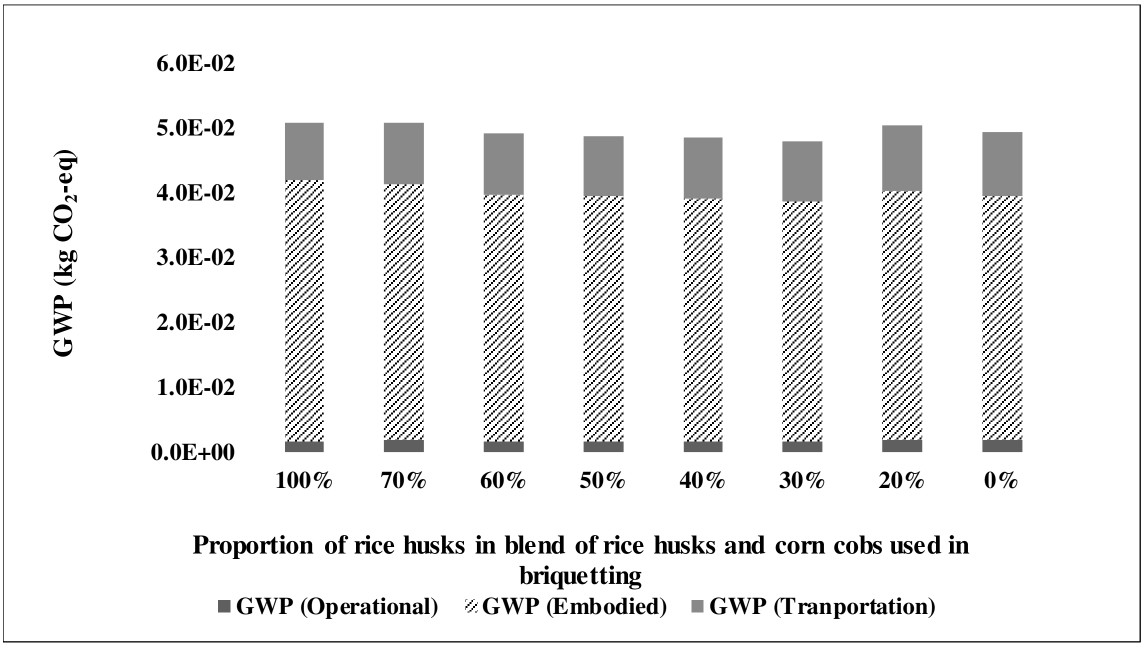


Figure 40: Life cycle Global warming potential (GWP) for briquetting various blends of rice husks and corn cobs biomass

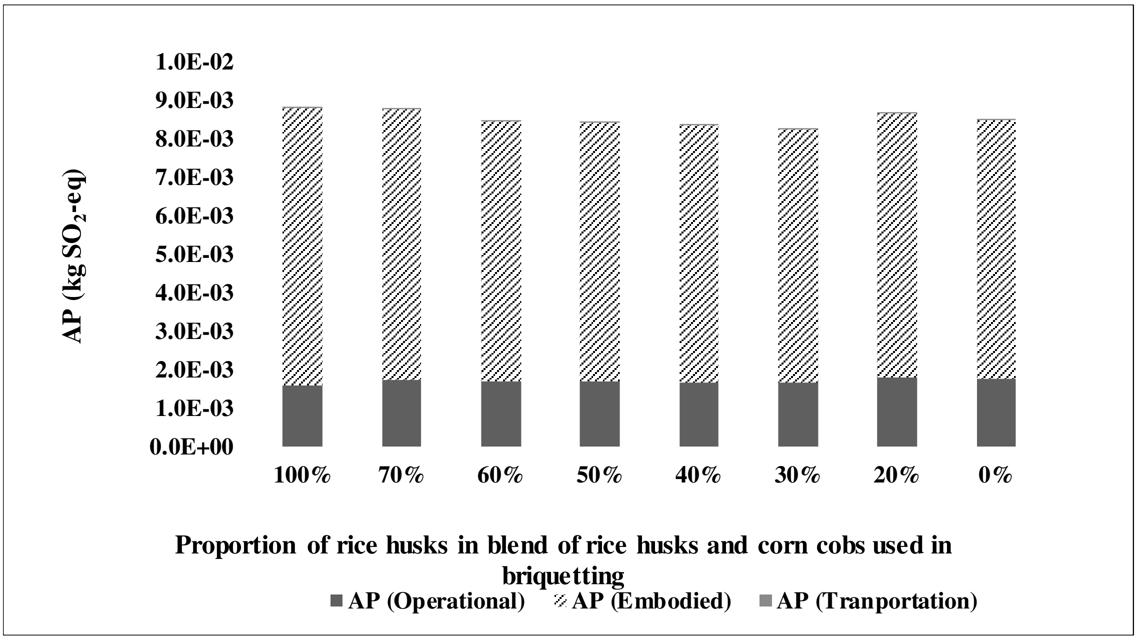


Figure 41: Life cycle Acidification potential (AP) for briquetting various blends of rice husks and corn cobs biomass

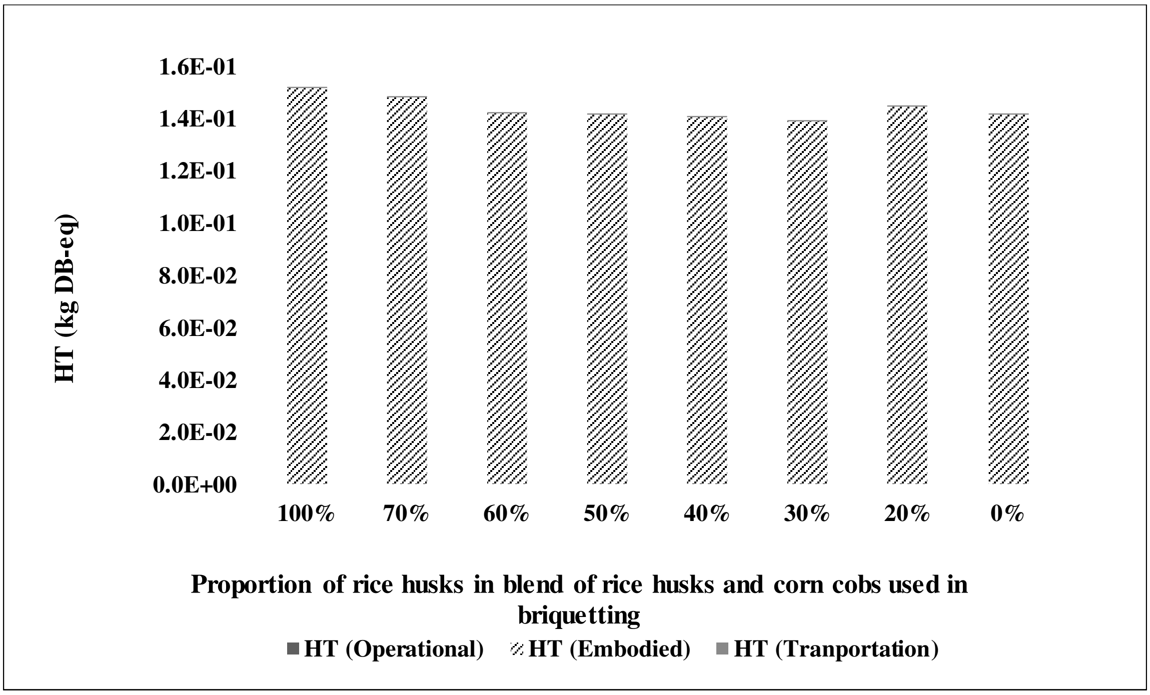


Figure 42: Life cycle Human toxicity (HT) for briquetting various blends of rice husks and corn cobs biomass

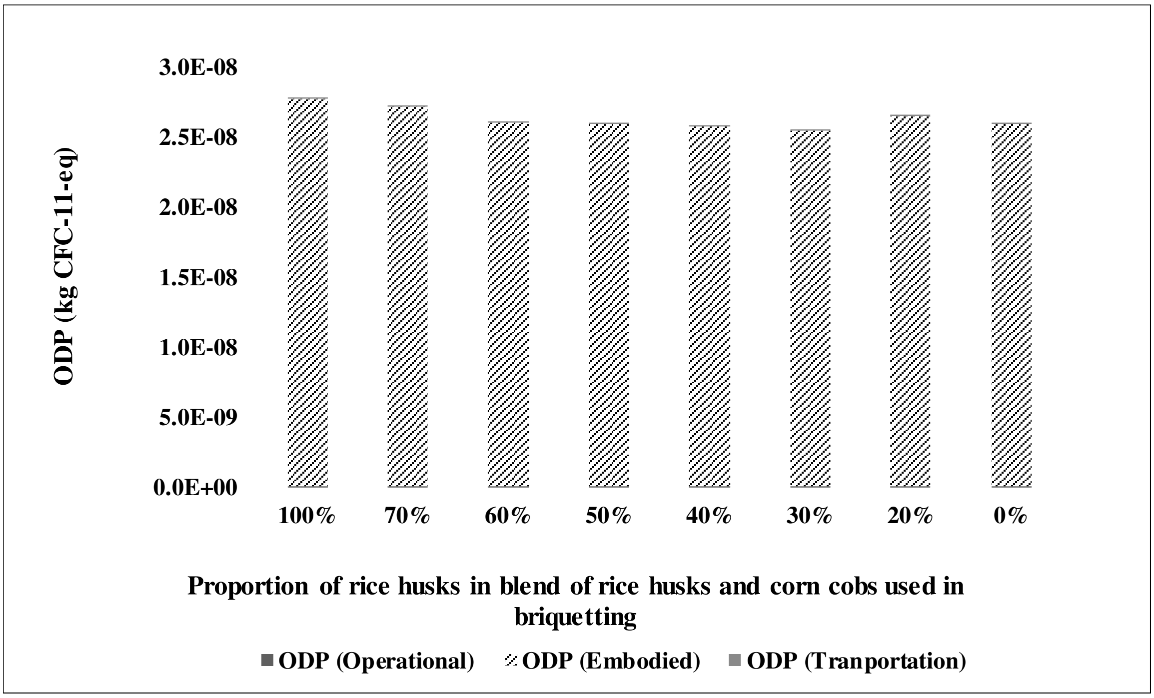


Figure 43: Life cycle Ozone layer depletion (ODP) for briquetting various blends of rice husks and corn cobs biomass

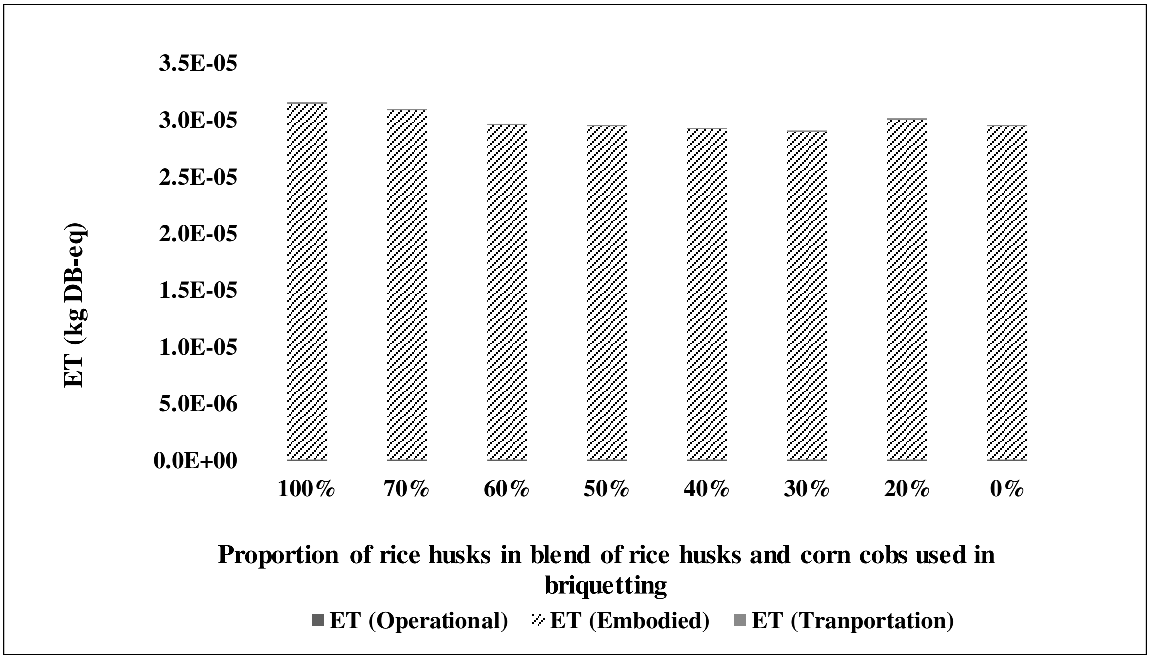


Figure 44: Life cycle Ecotoxicity (ET) for briquetting various blends of rice husks and corn cobs biomass

7.3.4.4 Sensitivity analysis

Table 18 shows the results of sensitivity analysis carried out for briquetting with blends of rice husks and corn cobs. Columns 2 to 5 of Table 18 show the LCA input variables, and columns 6 to 9 of Table 18 show the LCA outputs. The main input parameters selected for the analysis include, 1) The variation in feed biomass properties and/ expected briquette density, denoted with (D), 2) The type of briquetting technology used, i.e., equipment design denoted with (T) (curing equipment A had higher capacity and lower energy consumption, and B had lower capacity and higher energy consumption), 3) The material of construction of principal building component in the briquette production plant, denoted with (B), and 4)The change in briquette scale of production, denoted with (S).

Table 18 demonstrates that the life cycle environmental impacts of briquetting vary widely depending on the factors employed in the analysis. For example, a range of 0.2 to 1.7 MJ per MJ of fuel briquette energy content resulted from changes in the LCA input parameters across the 8 runs, and the influence of other factors such as technological differences in briquetting equipment.

Most LCA studies do not consider the problem of interaction for the purpose of simplicity, however, in reality, interaction within LCA calculation model and correlation among input parameters are main issues within the LCA process, which may result in inaccurate conclusion of the outcome [Wei et al, 2014]. The current model integrated various process variables and their interaction effects on the LCA, which provides a robust and transparent way of understanding the underlying causes of variations in the LCA outcomes. The main (individual) and interaction (two-factor and three-factor) effects of the LCA input parameters are further discussed.

Table 18: Sensitivity analysis results of LCA model of briquetting

FACTORS					RESPONSES (units per MJ briquette energy content)			
S/NO	Biomass variability (variation in density (D) (kg/m3)	Briquetting Technology (Equipment type (T)*	Material for main building structure (B)	Scale of Production (S) (kg briquettes//day)	Total life cycle energy (MJ)	GWP ($kgCO_2$-eq)	Acidification potential ($kgSO_2$-eq)	Human toxicity (kg1,4,DB-eq)
1	354	B	concrete	20000	1.7E+00	1.5E-01	1.3E-02	2.7E-01
2	1062	B	concrete	60000	1.2E+00	1.0E-01	7.9E-03	1.6E-01
3	354	A	concrete	60000	2.2E-01	5.1E-02	7.2E-03	1.5E-01
4	1062	A	concrete	20000	2.5E-01	5.5E-02	7.8E-03	1.6E-01
5	354	B	steel	60000	1.6E+00	1.2E-01	5.3E-03	1.6E-01
6	1062	B	steel	20000	1.7E+00	1.3E-01	5.7E-03	1.7E-01
7	354	A	steel	20000	2.9E-01	5.4E-02	5.0E-03	1.5E-01
8	1062	A	steel	60000	2.3E-01	3.4E-02	2.8E-03	8.8E-02

*briquetting equipment A had lower capacity and lower energy consumption and B had higher capacity and higher energy consumption

*curing equipment A had higher capacity and lower energy, and B had lower capacity and higher energy consumption

The use of briquetting equipment with lower capacity had a significant negative effect ($p<0.05$) on total life cycle energy and GWP, while its interaction with scale of production and biomass variability, had a positive effect on both energy and GWP. The technological differences in equipment design can have significant effect on the LCA result. For example, the use of counter flow cooler for briquette curing reduced the contribution of the curing unit to the total LCA result by a factor of 8, compared with a box dryer. This was attributed to the high equipment weight and longer residence time required using the box dryer.

The use of concrete building increased the impact of briquetting on energy and GWP of briquetting compared with steel building (Table 18), which can be associated to the differences in primary production of the materials of construction. Findings by Johnson [2006], Guggemos & Horvath [2005] and Bjorklund et al [1996] indicated that concrete frame production had higher GWP (kg CO_{2}-eq) compared with steel, however, the recyclability of steel was not the main reason for this difference as reducing the recycled content of steel by 25% changed CO_2 emission by only 2.5%. The main cause of the higher CO_2 emission from concrete production was associated with the pyroprocesing stage.

The scale of production had small negative effect on energy and GWP, but its interaction with briquetting equipment had a significant positive effect on HT. Biomass variability yielded a significant positive main effect on HT, but had no apparent effect on the remaining indicators.

For all the variables included in the analysis, briquetting technology and scale of production show the most impact on the LCA output, which indicates a need to further assess the uncertainty associated with these sources and improve the reliability of the LCA output.

7.3.5 General discussion

So far, existing LCA has been focused on other bioenergy processes such as the biomass cultivation stage (7.1). This model focuses specifically on the briquetting process and addresses common but important issues faced in many bioenergy processes such as wide variability in biomass feedstock and the differences in its various conversion processes [e.g., Cherubini & Stronmann, 2011; Borrion et al, 2012]. The LCA model can be used to improve the sustainability of an existing briquetting plant or guide towards development of more sustainable future briquetting systems.

The various measurements and data obtained in this study including materials, operational, equipment embodied and transport input variables, are all associated with errors. Data obtained from standard inventories had co-efficient of variations (CV) (ratio of standard deviation and the mean). The embodied energy and carbon of materials for equipment and buildings had CVs in the range of 0.3 to 27.3. Measurement of biomass raw materials and briquettes characteristics (e.g., density) had CVs in the range of 0.063 to 0.19 and 15 to 102 respectively. The errors associated with the overall briquetting LCA model (comprising of operational input parameters and emissions data) were between 8 to 15%, for changes in biomass variability, and up to 95%, for building and briquetting technology. There is need to improve on the accuracy and availability of data on briquetting equipment, as well as optimisation of the current briquetting technologies.

In terms of model accuracy and sensitivity, the complete accuracy of the briquetting LCA model is impacted by the high degree of uncertainty in the various components, however, the LCA model is fairly accurate for a comparative assessment of the briquetting system. The error associated with a comparative analysis is much connected between the scenarios, as such, the comparative differences are largely a consequence of differences between systems [Williams et al, 2006]. This means that the uncertainty is uniform across the model for all the cases.

7.3.6 Model limitations and future development

As it is with many models, there are limitations associated with the LCA model including;

1. Model doesn't combine two different transport means (e.g., road, rail) of briquetting plant equipment, for single assessment.
2. The model can only be used with two different biomass residues at a time or combined properties of many biomass materials into two main categories.
3. The ICE data within the model inventory can only be used for energy and carbon dioxide emissions assessment.
4. There is also need to integrate sensitivity analysis tool into the model, as currently sensitivity analysis can only be carried out within the input page, on a separate tab within the model, or export to a separate software.

5. Future development of the model will include; improving and updating the current database and possible expansion of model scope by integrating upstream (agriculture) and downstream (thermal application) of briquette.
6. The LCA model output is limited to fuel briquetting (gate-to-gate system boundary).
7. The LCA output is also limited by variations in data sources used in the literature, however, model users have option to override the model built-in inventory data.
8. The accuracy of the model results is also limited by assumptions made in the absence of required data.

7.4 Summary

This chapter has developed a simple LCA model for the briquetting process, and has demonstrated the significance of providing such model as a way of addressing current research gaps in the bioenergy system. The model was used in assessing the environmental impact of briquetting with blends of rice husks and corn cobs biomass, for up to 10 blend ratios.

Results showed that, for all the briquette production stages, the briquetting (densification) unit itself made the largest contribution to the total life cycle operational energy, with an input energy of 42% of the total life cycle operational energy. The total life cycle energy was in the range of 0.2 to 0.3 MJ/MJ fuel briquette energy content, indicating small influence of rice husks and corn cobs variability on the LCA results. For the same blend ratios, a total life cycle energy of briquetting in the range 0.2 to 1.7 MJ per MJ of fuel briquette energy content was also obtained with change in other LCA input parameters, in a sensitivity test.

A positive net energy balance was achieved for all the blends of rice husks and corn cobs, this had an energy return on investment (EROI) and net energy production ratio (NER) greater than 1.

The increase in ratio of rice husks in the blend with corn cobs increased the overall GWP, AP, HT, ODP, and ET of the briquetting system but reduced the life cycle energy (MJ/MJ briquette energy) requirement of the system. For the same listed impact categories, the 30/70 % ratio of rice husks to corn cobs had the lowest environmental impact.

8 CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This research has developed new and advanced knowledge related to the production of high quality fuel briquettes, and the environmental impacts of briquetting process within the bioenergy system.

The research has demonstrated that blending of different biomass residues can be used to produce briquettes of consistent quality that conform with CEN/TS 14961 [2004], e.g., for use in gasification and other thermochemical conversion processes. Briquettes produced from 3:7 blends ratio of rice husks and corn cobs, with starch binder, had a unit density of up to 1.9 times the loose biomass bulk density, and were stronger than briquettes from the individual materials.

Statistical analysis of the results showed that the proportion of corn cobs and a higher compaction pressure had positive effects on briquette green and relaxed densities, as well as compressive strength. Starch and water binder addition were necessary to achieve measurable unconfined compressive strengths, but significantly reduced the green and relaxed densities of the briquettes. The negative effect of starch binder on briquette density indicated the need to explore other sources of binder.

The research further explored the suitability of the use of novel binding agents including enhanced treated biosolids, and microalgae, as binders for briquette production, using blends of rice husks, corn cobs and bagasse biomass. The physical and combustion characteristics of briquettes produced with biosolids, microalgae and starch binders, were evaluated.

Results from statistical analysis, showed that the addition of microalgae to the blends of rice husks, corn cobs and bagasse, had positive effects on briquette density and strength, with unit density of up to 3.3 times the loose biomass bulk density and unconfined compressive strength of 175 kPa. The addition of biosolids also improved briquette density, but had a negative effect on briquette compressive strength.

Of all the briquettes produced with the three binders, those containing the microalgae binder were found to be most durable, with a higher energy value, slower mass loss during briquette combustion, and a higher afterglow time. Although the source of the biomass did not affect briquette strength, it had a significant effect on biomass densification.

The associated energy and environmental impact of fuel briquetting, was carefully investigated using the LCA approach. A detail review of the existing LCA studies on fuel briquetting found that these studies provide insufficient and inconsistent information, due to different choices in system boundary, data sources, functional unit, allocation procedure, briquetting technology and biomass/briquette properties.

Most of the reviewed studies attributed most of the energy use and greenhouse gas (GHG) emissions to transportation, drying, size reduction and densification. The energy and GHG emissions of the gate-to-gate densification system were highly sensitive to the technology and feed material used in densification, and scale of production.

Apart from one study with zero energy consumption as a result of the use of manual operations, the normalised values of energy consumption for the reviewed studies ranged from 0.02 to 0.9 MJ/MJ densified biomass energy content. Neglecting three outlier values, GHG emissions for the reviewed studies ranged from 0.0006 to 0.05 kg CO_2-eq/MJ densified biomass energy content. Similar variations in result and outlier cases have been reported for other bioenergy processes, by other authors. Assuming that the biggest impact of densification processes is on transport fuel use, and based on 5 studies that reported densification ratios, the net energy and GHG emissions savings resulting from densification ranged from 0.2 to 1 MJ/MJ biomass energy content and 0.009 to 0.05 kg CO_2-eq/MJ biomass energy content, respectively. On this basis, it can be concluded that biomass densification is a worthwhile addition to the biomass energy conversion system. There is a need for more transparent reporting and analysis of uncertainty in the modelling, to better understand the wide variation in outcomes.

This research has successfully developed a comparative LCA model of multiple biomass briquetting, and made this available in a user accessible format (Microsoft Excel). The model has been verified and used to carry out the LCA of rice husks and corn cobs biomass residues. Results showed that the briquetting unit itself made the largest contribution, 42%, to the total life cycle operational energy of the briquetting system. For all the blends of rice husks and corn cobs explored in this study, the total life cycle energy of briquetting was in the range 0.2 to 0.3 MJ per MJ of fuel briquette energy content. For the same blend ratios, a total life cycle energy of briquetting in the range 0.2 to 1.7 MJ per MJ of fuel briquette energy content was also obtained with change in other LCA input parameters, in a sensitivity test. A positive net energy balance was achieved for all the blends of rice husks and corn cobs, this had an EROI and NER greater than 1.

An increase in rice husks content of the blend increased the environmental impact of briquetting including the global warming potential (kg CO2-eq), acidification potential (kg SO2-eq), human toxicity (kg 1,4-DB-eq), ozone layer depletion (kg CFC-11-eq), and terrestrial ecotoxicity (kg 1,4-DB-eq) per MJ briquette energy content, as it was associated with a lower briquette density, which increased the energy required for handling.

For all the blends of rice husks and corn cobs considered, the briquetting system had highest impact on the human toxicity and global warming potential with average values of 0.05 kg CO_2-eq and 0.14 kg 1,4-DB-eq respectively, while the ozone layer depletion had the least with average value of 4.1 x 10-8 kgCFC-11-eq, for 1 MJ of fuel briquette energy content at gate of the briquetting plant. The high global warming was dominated by fossil emission of CO_2, in operation of the briquetting plant, while the human toxicity was dominated by emission of heavy metals such as zinc, and nickel, in primary production of materials of construction, for the briquetting equipment.

In conclusion, this research has demonstrated the benefits of densification, which is particularly relevant to developing countries with high agricultural productivity, such as Nigeria (2.4.5.2). The production of good quality briquettes from a variety of biomass materials will reduce dependence on fossil fuels, and reduce energy shortages particularly in rural areas. Food productivity will be encouraged, leading also to local employment, and local farmers can benefit from selling agricultural wastes from their farms. Turning agricultural wastes into briquettes will also reduce environmental impacts associated with current methods of handling agricultural waste.

Original contributions to knowledge include the following:

a) The research has investigated and established the benefits of blending different biomass residues for improved briquette quality (particularly density and strength).

b) The research has statistically evaluated the effect of key briquetting variables including compaction pressure, biomass variability, and binders, in the briquetting process and on fuel briquette quality.

c) The research has explored the suitability of novel binders, including biosolids and microalgae, for biomass briquetting, and has evaluated the effect of these binders on briquette physical and combustion properties.

d) The research has carried out the first review of the existing studies on LCA of fuel briquetting, and has identified key research gaps, and suggested future approaches for LCA of briquetting systems. The study also identified and classified possible sources of uncertainty in the LCA of fuel briquetting, which is essential but has not been reported in the existing studies.

e) The research has developed the first user accessible LCA model that focused specifically on the briquetting system. This type of model has been developed for other product and process systems, such as transportation fuels (e.g., biodiesel and bioethanol) and agricultural systems, which have limited application for the briquetting process. Hence the need for the model, particularly with the rising interest in biomass utilisation for energy and densification of loose biomass before thermal conversion.

f) The LCA model developed in this study specifically modelled the briquetting process, and integrated variables that have influence on the briquetting process, into the LCA process.

g) The model provides practitioners with a quicker assessment by saving time required for sourcing of specific briquetting data when using other general LCA software, and also improves the transparency of the LCA output.

h) The model addresses common but important issues faced in many bioenergy processes such as wide variability in biomass feedstock and the differences in its various conversion processes.

i) The LCA model developed in this study can be used to improve the sustainability of an existing briquetting plant or guide towards development of more sustainable future briquetting systems.

Contributions [a to c] have been validated by publication of peer reviewed journal papers, whereas contributions [d to i] are currently under peer review in journal submissions (as listed in 1.5).

8.2 Recommendations for future work

Research is needed to explore effects of biomass particle size and mould geometry, in the briquetting of mixed biomass.

The impact of storage conditions and duration on the durability of the fuel briquettes is required. The continuous search for more sustainable binders for briquetting, is also recommended.

In order to address some of the highlighted issues in the in the fuel briquetting LCA, future LCA of fuel briquetting should consider the following;

- Studies should expand their analysis to cover a detailed and wider range of potential environmental impacts of briquetting biomass residues.
- Since lignocellulosic biomass appears to be highly variable in its characteristics, the effect of briquetting one type of residue should be compared to another, to develop a critical understanding of how these properties, can potentially increase or decrease the environmental impact of the biomass briquetting system.
- Due to the inconsistency in the information available for LCA's of biomass briquetting, there is need to develop a good database which will take into account all the key stages of the biomass fuel briquette LC, using standard guidelines and procedures, this will increase the harmonisation and reliability of study outcomes.

Further work is also required in key areas of the LCA model, and includes the following;

- Expansion of model system boundary, to cover both upstream (agriculture) and downstream (briquette application) of the briquetting process.
- Inclusion of some of the components of the briquetting LCA which were excluded in this model (e.g., impact of personnel movement on site, impact of other utilities consumption and waste disposal on site).
- Since the current model allows the user to select a maximum of 30 different briquetting equipment/facilities, and a maximum of 25 materials for each briquette

production stage, from the built-in inventory, improvement in the briquetting process inventory, and materials inventory, is required to allow wider range of options to be investigated.

- Further assessment of environmental burdens of the mixed rice husk and corn cob briquetting using specific existing briquetting plants, is needed to improve the reliability of the LCA outcome.
- Further work is also required to investigate the effect of binder addition and type on the LCA of briquetting systems.

Lastly, since the briquettes were made for thermal application purposes, there is need to explore their use in these processes (e.g., gasification). On this basis, the research has modelled and run a few experiments to investigate the use of the fuel briquettes in a fluidised bed reactor (Appendix II) (10.2). However, further experimental investigation is urgently required to provide a practical information on the use of these briquettes. It is also important to investigate the effect of main briquetting variables (e.g., pressure, binder) on the gasification products.

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10 APPENDICES

10.1 **APPENDIX I:** Examples of LCA Model Pages: Equipment and materials inventory

Material inventory for briquetting plant																				
Material	**Energy requirement (Mj/kg)**	**(kgCO2/kg)**	**(kg CH4/kg)**	**(kg N2O/kg) GWP**	**(kg SO2/kg)**	**(kgN2O/kg) AP**	**(kg HF/kg)**	**(kg Pb/kg)**	**(kg Hg/kg)**	**(kg As/kg)**	**(kg Mn/kg)**	**(kg Halon 1301/kg)**	**(kg Halon 1211/kg)**	**(kg CFC-10/kg)**	**(kgCFC-114/kg)**	**(kg Hg/kg)**	**(kg Cu/kg)**	**(kg Zn/kg)**	**(kg Br/kg)**	**(kg Ni/kg)**
Steel lowalloyed (RoW)-Eletricity	8.1E+00	5.7E-01	4.5E-02	7.1E-03	2.8E-03	1.1E-03	2.0E-03	4.1E-02	1.2E+00	9.3E-02	1.9E-01	8.5E-09	3.5E-09	6.4E-10	7.7E-09	2.3E-04	1.6E-05	8.3E-05	1.5E-05	5.6E-06
Unalloyed (RoW) production- converter	2.0E+01	2.1E+00	1.8E-01	9.2E-03	5.5E-03	2.7E-04	-	6.9E-02	3.9E-02	6.2E-02	3.5E-01	1.8E-08	3.1E-09	2.1E-09	4.9E-09	8.2E-06	1.6E-05	5.9E-06	5.1E-06	3.9E-06
Chromium steel 18/8 (RoW) production-electricity	5.4E+01	3.9E+00	2.8E-01	-	1.9E-02	7.5E-03	-	5.1E-01	1.2E+00	6.4E-01	8.8E-01	5.8E-08	4.2E-08	2.4E-09	3.7E-08	2.4E-04	2.3E-04	1.9E-04	3.4E-05	4.7E-05
Re-enforcing steel (RoW)	2.5E+01	2.3E+00	1.9E-01	-	6.7E-03	3.2E-03	-	8.4E-02	2.0E-01	1.5E-01	6.2E-01	2.5E-08	1.0E-08	2.2E-09	9.9E-09	3.9E-05	2.9E-05	2.0E-05	1.1E-05	7.1E-06
Cast iron (RoW) production	1.8E+02	1.6E+01	5.6E-01	-	9.3E-02	2.4E-03	1.3E+00	1.2E-01	3.2E-01	1.5E+00	4.4E+00	1.6E-07	1.5E-07	1.1E-07	5.5E-08	8.4E-05	8.0E-05	1.3E-05	6.6E-05	4.3E-05
Aluminium ingot (GLO) production	5.6E+01	4.0E+00	2.6E-01	3.0E-01	4.8E-01	2.6E-02	-	7.7E+01	-	1.4E+02	1.5E+02	5.7E-08	4.4E-08	1.4E-08	5.1E-08	-	2.7E-02	1.7E-03	-	9.5E-03
Copper (RoW) production primary	3.6E-01	2.2E-02	1.4E-03	3.0E-04	1.3E-04	3.3E-05	-	1.8E-03	1.3E-04	7.0E-04	5.9E-03	1.5E-10	3.9E-10	1.9E-11	6.5E-10	7.4E-08	1.8E-07	5.5E-08	2.3E-07	5.7E-08
Copper (RoW) treatmentof metal part	2.2E+01	1.9E+00	1.7E-01	-	6.3E-03	2.7E-03	-	7.4E-02	1.2E+00	1.2E-01	3.9E-01	1.8E-08	4.5E-09	4.4E-09	9.4E-09	2.4E-04	2.0E-05	8.5E-05	1.3E-05	6.9E-06
Polystyrene (RoW) general purpose	8.8E+01	2.7E+00	7.6E-01	-	7.4E-03	3.0E-03	5.2E-04	4.3E-03	1.3E-03	6.1E-03	1.2E-02	2.5E-10	-	1.0E-09	6.7E-11	-	2.8E-06	-	7.0E-06	1.5E-08
Nylon6 (RoW) production plastics	1.2E+02	5.5E+00	1.2E+00	2.6E+00	1.7E-02	1.1E-02	1.5E-03	1.6E-03	6.9E-03	1.5E-02	1.9E-02	6.8E-10	1.1E-10	3.6E-09	2.1E-10	1.4E-06	7.8E-07	-	1.8E-05	1.8E-05
Nylon66 (RoW) production plastics	1.4E+02	6.6E+00	1.2E+00	2.2E-01	1.8E-02	7.6E-03	2.5E-03	1.3E-03	4.6E-03	1.5E-02	1.8E-02	5.0E-10	5.7E-11	1.3E-09	1.1E-10	9.1E-07	4.5E-07	-	1.9E-05	1.2E-05
Packaging film (RoW) LDPE	9.0E+01	2.4E+00	4.6E-01	-	7.9E-03	3.3E-03	-	6.0E-03	3.2E-03	2.8E-02	1.4E-01	1.0E-08	8.3E-09	1.5E-09	1.5E-08	1.9E-06	8.8E-06	1.5E-06	1.6E-05	1.5E-06
Synthetic rubber production (RoW)	9.9E+01	3.5E+00	4.0E-01	-	1.4E-02	4.3E-03	1.4E-03	1.5E-03	2.2E-03	7.2E-03	9.4E-03	2.9E-10	4.0E-11	1.1E-09	7.3E-11	1.5E-07	3.0E-07	1.1E-07	9.2E-06	-
Rubber (polybutadiene(RoW))	9.0E+01	2.8E+00	2.9E-01	3.4E-02	1.0E-02	3.5E-03	-	7.3E-02	1.4E-02	1.4E-01	4.9E-01	2.0E-07	2.0E-08	3.2E-09	2.4E-08	4.6E-06	2.1E-05	5.7E-06	2.0E-05	7.5E-06
Flat glass (uncoated) production (RoW)	1.3E+01	1.0E+00	4.2E-02	-	6.7E-03	2.6E-03	6.4E-03	9.8E-03	3.2E-03	1.8E-02	8.3E-02	2.5E-08	2.4E-09	3.3E-10	3.0E-09	9.1E-07	6.6E-06	1.1E-06	4.0E-05	2.0E-06
Glassfibre (RoW) production	3.4E+01	2.3E+00	1.8E-01	9.7E-02	1.4E-02	5.6E-03	-	2.5E-02	-	1.1E+00	4.0E-01	1.8E-08	4.2E-08	2.0E-09	2.5E-08	4.1E-06	1.3E-05	-	-	-
Alkyl paint white without water (60% solution state (RoW))	7.9E+01	5.0E+00	3.8E-01	1.7E-01	3.0E-02	8.1E-03	-	9.6E-02	7.4E-02	2.4E-01	1.1E+00	8.1E-08	5.2E-08	2.9E-07	4.2E-08	-	6.1E-05	-	5.8E-05	-
Sawnwood ,raw,airdried (RoW) production	1.5E+02	7.9E+01	4.3E+00	3.0E+00	2.9E-01	3.5E-01	-	2.6E+00	1.8E+00	3.0E+00	2.0E+01	3.0E-06	4.8E-07	6.5E-08	1.0E-06	4.1E-05	3.3E-03	1.8E-03	5.7E-04	3.1E-04
Normal concrete (RoW) production	1.5E+02	3.8E+02	1.0E+01	-	2.7E+00	5.6E-01	-	2.6E+00	6.8E+00	4.7E+00	2.4E+01	5.5E-06	4.5E-07	-	8.9E-07	1.4E-03	3.0E-03	1.4E-04	6.9E-04	5.9E-04
Concrete high exacting requirement (RoW) production	1.9E+02	4.7E+02	1.2E+01	-	8.3E-01	6.8E-01	-	3.0E+00	8.4E+00	5.6E+00	2.9E+01	6.6E-06	5.6E-07	3.4E-07	1.1E-06	1.7E-03	3.4E-03	4.0E-03	8.5E-04	7.1E-04
window frame, wood-metal u=1.6w/m2 k (Row)	4.8E+02	3.6E+02	2.1E+01	4.9E+00	1.9E+00	6.0E-01	1.4E+01	9.1E+00	7.9E+00	2.9E+01	9.6E+01	5.0E-06	2.9E-06	2.9E-06	3.0E-06	2.1E-03	3.4E-03	4.2E-03	2.8E-03	1.1E-03
Doors outer, wood-alluminium (RoW)	1.2E+02	1.3E+02	7.2E+00	-	5.4E-01	2.1E-01	3.3E+00	9.4E+00	4.0E+00	1.4E+01	3.7E+01	1.7E-06	1.0E-06	7.1E-07	7.5E-07	1.3E-03	1.4E-03	4.7E-03	8.6E-04	3.6E-03

Fuel type	**Emission**																		
	(kg CH_4/kWh)	**(kg N2O/kWh)**	**(kg CO_2/kWh)**	**(kg SO_2/kWh)**	**(kg HF/kWh)**	**(kg Pb/kWh)**	**HT (kg Hg/kWh)**	**(kg As/kWh)**	**(kg Mn/kWh)**	**(kg Halon 1301/kWh)**	**(kg Halon 1211/kWh)**	**(kg CFC-10/kWh)**	**(kg CFC-114/kWh)**	**ET (kg Hg/kWh)**	**(kg Cu/kWh)**	**(kg Zn/kWh)**	**(kg Br/kWh)**	**(kg Ni/kWh)**	**AP (kg N_2O/kWh)**
Oil (high voltage electricity) GLO	3.50E-03	2.30E-04	2.48E-01	1.32E-03	-	1.70E-03	4.19E-04	4.34E-04	1.32E-03	1.45E-08	2.00E-10	-	1.50E-10	-	4.70E-06	-	4.60E-07	4.32E-06	0.00047
Coal (high voltage electricity) GLO	-	3.00E-03	3.05E-01	1.71E-03	-	2.01E-03	-	7.87E-03	7.18E-02	2.20E-10	2.45E-11	1.20E-11	4.02E-11	6.90E-07	2.80E-07	1.90E-07	4.60E-08	2.00E-07	0.000498
COUNTRY MIX(GB)	-		1.70E-01	5.40E-04	-	5.69E-04	3.90E-04	0.00126	2.36E-02	6.86E-10	2.40E-09	2.10E-10	4.10E-09	3.40E-07	2.30E-07	1.00E-07	2.30E-07	1.40E-07	0.000162

		DATA SOURCE : ICE V1.6a (2008)			
	1	2	3	4	5
Category	**Materials**	**Coeeficient of Variation (σ/μ)**	**Embodied energy (Mj/kg)**	**Embodied carbon ($kgCO_2/kg$)**	**Boundaries**
Metals	Steel: General (Average, Inc. RCC; 47.2%-GLO)	1.57	20.1	1.37	cradle to gate
	steel : General (Virgin)	3.1	35.3	2.75	cradle to gate
	Steel: General (Predominantly Recycled)	2.8	9.4	0.44	cradle to gate
	Steel: Stainless (Average; most popular grade-GL	7.77	56.7	6.15	cradle to gate
	Steel: Bar & rod (General)	27.3	24.6	1.71	cradle to gate
	Steel: Bar & rod (Virgin)	27.3	36.4	2.68	cradle to gate
	Steel: Bar & rod (Recycled)	27.3	8.8	0.42	cradle to gate
	Engineering steel: (Recycled)	27.3	13.1	0.68	cradle to gate
	Steel: Pipe (Virgin)	27.3	34.27	2.7	cradle to gate
	Steel: Plate (Virgin)	27.3	34.44	2.7	cradle to gate
	Steel: Section (General)	27.3	25.4	1.78	cradle to gate
	Steel: Section (Virgin)	27.3	36.8	2.78	cradle to gate
	Steel: Section (recycled)	27.3	10	0.44	cradle to gate
	Steel: Sheet (Virgin)	27.3	31.5	2.51	cradle to gate
	Steel: Galvanised (Virgin)	27.3	39.0	2.82	cradle to gate
	Steel: Wire (Virgin)	27.3	36	2.83	cradle to gate
	Aluminium: General	1.5	155	8.24	cradle to gate
	Aluminium: General (Virgin)	3.27	218	11.46	cradle to gate
	Aluminium General (RCC; 32% - GLO)	2.03	28.8	1.69	cradle to gate
	Aluminium: Cast products	1.84	159	8.28	cradle to gate
	Aluminium:Cast (Virgin)	1.84	226	11.7	cradle to gate
	Aluminium: Cast (RCC; 32% - GLO)	1.84	24.5	1.35	cradle to gate
	Aluminium: Extruded	1.84	154	8.16	cradle to gate
	Aluminium: Extruded (Virgin)	1.84	214	11.2	cradle to gate
	Aluminium: Extruded (RCC; 32% - GLO)	1.84	34.1	1.98	cradle to gate
	Aluminium: Rolled	1.84	155	8.26	cradle to gate
	Aluminium:Rolled (Virgin)	1.84	217	11.5	cradle to gate
	Aluminium: Rolled (Recycled)	1.84	27.8	1.67	cradle to gate
	Copper: General (Average, RCC; 46%)	1.84	47.5	3.01	cradle to gate
	Copper: Virgin	2.68	70	3.83	cradle to gate
	Cpper: Recycled from high grade scrap	1	17.5	0.96	cradle to gate
	Copper: Recycled from low grade scrap	1	50	2.75	cradle to gate
	Iron (General)	3.28	25	1.91	cradle to gate
	Lead (Inc. 61% RCC)	1.3	25	1.33	cradle to gate
Plastics	Plastics: General (Avergae, RER)	2.79	80.5	2.53	cradle to gate
	Polyethylene: General	2.73	83.1	1.94	cradle to gate
	High density polyethylene: HDPE	3.13	76.7	1.6	cradle to gate
	HDPE pipe	3.13	84.4	2	cradle to gate
	Low density polyethylene: LDPE	4.77	78.1	1.7	cradle to gate
	Nylon 6	2.64	120.5	5.5	cradle to gate
	Nylon 6,6	2.64	138.6	6.5	cradle to gate
	Expanded Polystyrene	2.73	88.6	2.5	cradle to gate
	PVC: General	3.36	77.2	2.41	cradle to gate
	PVC Injection Moulding	3.36	95.1	2.2	cradle to gate
	UPVC Film	2.64	69.4	2.5	cradle to gate
	PVC pipe	3.36	67.5	2.5	cradle to gate
Rubber	Rubber: General (Assumes NR; 35% of market)	2.9	101.7	3.18	cradle to gate
	Natural rubber	7.36	67.6	1.63	cradle to gate
	Synthetic rubber	2.68	120	4.02	cradle to gate
Glass	Glass: General (UK Typical)	2.11	15	0.85	cradle to gate
	Glass: Fibre (Glasswool)	2.99	28	1.53	cradle to gate
	Glass: Toughened	1	23.5	1.27	cradle to gate
Paint	Paint: General	1.27	68	3.56	cradle to gate
	Paint: Single coat (assume 6.6 sqm cov./kg)	1.27	10.2	0.53	cradle to gate
	Paint: Double coat (assume 6.6 sqm cov./kg)	1.27	20.4	1.06	cradle to gate
	Paint: Triple coat (assume 6.6 sqm cov./kg)	1.27	30.6	1.6	cradle to gate
Timber	Timber: General (UK)	1.48	8.5	0.46	cradle to gate
Site floor and admin building	Concrete: General	0.33	0.95	0.13	cradle to gate
	Reinforced concrete	0.33	0.26	0.018	cradle to gate
	Concrete blocks- 8 Mpa (CS)	0.33	0.6	0.061	cradle to gate
	Concrete blocks- 10 Mpa (CS)	0.33	0.67	0.074	cradle to gate
	Concrete blocks- 12 Mpa (CS)	0.33	0.71	0.08	cradle to gate
	Concrete blocks- 13 Mpa (CS)	0.33	0.81	0.098	cradle to gate
	Prefabricated concrete	2.79	2	0.061	cradle to gate
	Sand (General)	0.91	0.1	0.005	cradle to gate
	Soil (General) Rammed	1.73	0.45	0.023	cradle to gate
	Sealant & Adhesive (Epoxide Resin)	153.8	139.3	5.91	cradle to gate
	Window (Single glazed, Timber framed)/W		286	14.6	cradle to gate
	Window (Double glazed, Air or Ar filled)/W		-	-	cradle to gate
	Vinyl flooring (General)	1.54	65.64	2.29	cradle to gate
	Vinyl composite Tile (VCT)	1.54	13.7	-	cradle to gate
	Carpet (General)	1.06	74.4	3.89	cradle to gate
Miscellaneous	Quartz powder	1	0.85	0.02	cradle to gate
	Terazzo tiles	1	1.4	0.12	cradle to gate
	Silicon	1	2355	0	cradle to gate
	Straw	1	0.24	0.01	cradle to gate
	Water	1	20	0	cradle to gate
	Hydraulic fluid		52	5	cradle to gate
	Lubricants: General		1	1	cradle to gate
	Wax	1	52	4.1	cradle to gate
	Wood stain/Vanish	1	50	5.35	cradle to gate
	Doors(outer)wood-aluminium frame(ROW)				

EQUIPMENT DESIGN DETAILS

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S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Ratio of total surface area for Construction/demolition to floor area	Energy Consumption	Total Weight per Equipment	Operating Temperature	Product Temperature	Net Weight per Equipment	Floor Dimension (Length)	Floor Dimension (Width)	Ratio of total surface area to floor area/maintenance	Equipment BASE Area	Building Construction energy	Building Maintenance energy	Building Demolition enrgy	Reference
-	-	-	-	-	kg/m^3	kg/hr	m2/m2	kWh	kg/Equip	°C	°C	kg/m2			m2/m2	m2	MJ/m2	MJ/m2	MJ/m2	
1	Storage Unit	Steel-walls	BLD-0	Steel-walls-BLD-0(2kg/hr)	354	2	3.61	0.0086	1383821	25	25	4070	34	10	6.58	340	39.48	31.6	12.15	
2	Storage Unit	Concrete-walls	BLD-1	Concrete-walls-BLD-1(2kg/hr)	354	2	3.61	0.0086	950921	25	25	2797	34	10	6.58	340	36.72	31.6	11.4	
3	Storage Unit																			
4	Storage Unit																			
5	Storage Unit																			

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Dummy Column 2	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area				
-	-	-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C		m	m	m	m2				
1	Conveyor Unit	AGICO	GC-LXSSJ	AGICO-GC-LXSSJ(550kg/hr)	354	550	1.6	2	130	25	25		4.3	0.56	0.5	3.6				
2	Conveyor Unit	AGICO	GC-PDSSJ	AGICO-GC-PDSSJ(600kg/hr)	354	600	1.7	3	120	25	25		2.11	0.91	0.7	2.9				
3	Conveyor Unit																			
4	Conveyor Unit																			

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Mixing time	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area				
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	mins				m2				
1	Blending Unit	Ultra Febtech	DCM	Ultra Febtech-DCM(531kg/hr)	354	531	1.5	6	2500	25	25	20	33	4	2	173				
2	Blending Unit	Tapasya ENG	SAI-DC10	Tapasya ENG-SAI-DC10(991.2	354	991.2	2.8	14.91	1000	25	25	10	4	5	3	28				
3	Blending Unit																			
4	Blending Unit																			
5	Blending Unit																			

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Dummy Column 2	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area				
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C					m2				
1	Briquetting Unit	LancaFuels	MPP550	LancaFuels-MPP550(550kg/hr	354	550	3.42119E-05	27.5	2400	25	25		2.5	1.73	1.5	6.4875				
2	Briquetting Unit	AGICO	GC-MBP-500	AGICO-GC-MBP-500(500kg/hr	354	500	1.25664E-05	35	4000	25	25		3.2	1.5	1.5	7.2				
3	Briquetting Unit	AGICO	GC-MBP-1000	AGICO-GC-MBP-1000(800kg/h	354	800	7.85398E-05	45	7000	25	25		2.5	1.74	2.04	6.525				
4	Briquetting Unit	Lantian	LTM-6000	Lantian- LTM-6000(2800kg/hr	170	2800	3.42119E-05	45	3800	25	25		3	1.96	1.2	8.82				
5	Briquetting Unit	Lantian	LTM	Lantian-LTM(3000kg/hr)	354	3000	2.01062E-06	18.5	300	25	25									
6	Briquetting Unit	GEMCO	GC-HBP125	EMCO-GC-HBP125(1000kg/hr	210	1000	0.000153938	9	1200	25	25									
7	Briquetting Unit	AGICO	GCBA-I	AGICO-GCBA-I(210kg/hr)	354	210	3.63168E-05	21	585	25	25									
8	Briquetting Unit	AGICO	GCBA-II	AGICO-GCBA-II(350kg/hr)	354	350	7.85398E-05	31	1300	25	25									
9	Briquetting Unit	AGICO	GCBC-I	AGICO-GCBC-I(210kg/hr)	354	210	0.000435802	19.4	700	25	25									
10	Briquetting Unit	AGICO	GCBC-II	AGICO-GCBC-II(350kg/hr)	354	350	0.000760265	22.9	1000	25	25									
11	Briquetting Unit	AGICO	GC-HBP60	AGICO-GC-HBP60(60kg/hr)	354	60	3.42119E-05	5.5	650	25	25									
12	Briquetting Unit	AGICO	GC-HBP125	AGICO-GC-HBP125(125kg/hr)	354	125	3.42119E-05	7.5	1100	25	25									
13	Briquetting Unit	AGICO	GC-HBP250	AGICO-GC-HBP250(250kg/hr)	354	250	3.42119E-05	11	2800	25	25									
14	Briquetting Unit	AGICO	GC-HBP350	AGICO-GC-HBP350(350kg/hr)	354	350	3.42119E-05	22	3500	25	25									
15	Briquetting Unit	AGICO	GC-HBP500	AGICO-GC-HBP500(500kg/hr)	354	500	3.42119E-05	37	4200	25	25									
16	Briquetting Unit	AGICO	GC-HBP1000	GICO-GC-HBP1000(1000kg/hr	354	1000	3.42119E-05	55	6000	25	25									
17	Briquetting Unit	LancaFuels	MPP550	LancaFuels-MPP550(500kg/hr)	354	500	0.000201062	27.5	2400	25	25									
18	Briquetting Unit	LancaFuels	MPP60	LancaFuels-MPP60(60kg/hr)	354	60	7.85398E-05	5.5	680	25	25									
19	Briquetting Unit	LancaFuels	MPP180	LancaFuels-MPP180(180kg/hr)	354	180	0.000153938	9.2	1200	25	25									
20	Briquetting Unit	LancaFuels	MPP350	LancaFuels-MPP350(350kg/hr)	354	350	0.000153938	27.5	2200	25	25									

S/N	Category	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Curing Cycle	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area				
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	hrs	m	m	m	m2				
1	Curing Unit	GongyiLan1	BOXDRY-2t	GongyiLan1-BOXDRY-2t(2000k	1200	2000	1.6	35	5443	105	25	7	5.8	2.2	2	19.14				
2	Curing Unit	GongyiLan	BOXDRY-2.5t	GongyiLan-BOXDRY-2.5t(2500	1200	2500	1.5	2.95	6000	105	25	5	5.8	2.2	2	19.14				
3	Curing Unit	AZS	Counterflow SKLN1.5	AZS-Counterflow SKLN1.5(300	1200	3000	1.5	0.75	634	30	25	0.5	1.1	1.3	3.2	2.145				
4	Curing Unit	AZS	Counterflow SKLN2.5	AZS-Counterflow SKLN2.5(500	1200	5000	2.5	0.75	680	30	25	0.5	5.8	2.2	2	19.14				

S/N	TYPE	Manufacturer	Manufacturer Code	Adopted Code	Base Material Density	Design Capacity	Maximum Design Volume	Energy Consumption	Net Weight per Equipment	Operating Temperature	Product Temperature	Mass per bag	Equip Dimension (Length)	Equip Dimension (Width)	Equip Dimension (Height)	Equipment BASE Area				
		-	-	-	kg/m^3	kg/hr	m^3	kWh	kg/Equip	°C	°C	kg	cm	cm	cm	m2				
1	Packaging Unit	AGICO	TSP	AGICO-TSP(550kg/hr)	1200	550	0.004	5	60	25	25	5	12	5.2	6.3	62.4				
2	Packaging Unit	HGELGOOG	GG402	HGELGOOG-GG402(550kg/hr)	1000	550	0.005	5	50	25	25	5	1.2	0.52	0.63	0.624				
3	Packaging Unit	HGELGOOG	GG403	HGELGOOG-GG403(550kg/hr)	1200	550	0.004	5.5	50	25	25	5	1.2	0.55	0.55	0.66				
4	Packaging Unit																			
5	Packaging Unit																			

10.2 **APPENDIX II:** Investigation of fuel briquette use in thermochemical application (fluidised bed gasification)

World Academy of Science, Engineering and Technology
International Journal of Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering Vol:9, No:5, 2015

Fluidised Bed Gasification of Multiple Agricultural Biomass Derived Briquettes

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International Science Index Vol:9, No:5, 2015 waset.org/Publication/10001714

Abstract**—**Biomass briquette gasification is regarded as a promising route for efficient briquette use in energy generation, fuels and other useful chemicals. However, previous research has been focused on briquette gasification in fixed bed gasifiers such as updraft and downdraft gasifiers. Fluidised bed gasifier has the potential to be effectively sized to medium or large scale. This study investigated the use of fuel briquettes produced from blends of rice husks and corn cobs biomass, in a bubbling fluidised bed gasifier. The study adopted a combination of numerical equations and Aspen Plus simulation software, to predict the product gas (syngas) composition base on briquette density and biomass composition (blend ratio of rice husks to corn cobs). The Aspen Plus model was based on an experimentally validated model from the literature. The results based on a briquette size 32 mm diameter and relaxed density range of 500 to 650kg/m^3, indicated that fluidisation air required in the gasifier increased with increase in briquette density, and the fluidisation air showed to be the controlling factor compared with the actual air required for gasification of the biomass briquettes. The mass flowrate of CO_2 in the predicted syngas composition increased with an increase in air flow, in the gasifier, while CO decreased and H_2 was almost constant. The ratio of H_2 to CO for various blends of rice husks and corn cobs did not significantly change at the designed process air, but a significant difference of 1.0 was observed between 10/90 and 90/10 % blend of rice husks and corn cobs.

Keywords**—**Briquettes, fluidised bed, gasification, Aspen Plus, syngas.

I. INTRODUCTION

GASIFICATION is a thermochemical process used to convert carbon-based products such as biomass and coal into a gas mixture known as synthetic gas (syngas) which has various applications such as heat and electricity generation in gas turbine or generator engines, hydrogen production, Fischer Tropsch diesel, liquid synthesis and chemicals. Biomass gasification has been identified as a promising route for the utilisation of agricultural residues for energy generation. However, the low bulk density of loose agricultural residues can lead to increase requirement for storage space, increase cost of transportation, non-uniform feeding into the gasifier and inefficient thermal conversion of these residues. This has prompted the densification of loose biomass residues into briquettes and pellets of higher density prior to gasification.

Briquette application in gasification has attracted attention in recent years e.g. [16], [19], [22], but most of the work carried out so far on briquettes gasification has been focused on fixed bed gasifiers such as updraft and down draft gasfiers e.g. [22], [23]. Unlike the fixed bed fluidised bed gasifiers have the potential to be effectively sized to medium or large scale [17], [21]. This can be associated with the several benefits that fluidised bed possessed over fixed bed gasifiers such as better heat transfer between particles (gases and solids) as a result of intensive mixing in the bed, and the flexibility of fluidised bed gasifiers to changes in feed particle size.

A major drawback that may be encountered in fluidised bed gasification of biomass briquettes is the concentration of high-molecular-weight species (Tars). This may be attributed to increase in biomass feed particle size which occurs during the briquetting process. The increased particle size of feed biomass was reported to aid the formation of tars and polycyclic aromatic hydrocarbons (PAHs) [20], and CO_2 formation in the product gas [18], [20]. Tars are major impurities associated with biomass gasification syngas, which hinders the utilization of syngas [11].

Since the purpose of briquetting is to improve the bulk and energy density of loose biomass, it becomes imperative to investigate the implication of briquetting loose biomass prior to gasification.

The gasification model approach was adopted in this study because it helps account for the fundamental hydrodynamics of fluidisation and the gasification of solid materials. It also serves as a predictive tool which helps in the design, optimisation and scale-up of fluidised bed gasifiers [7].

The gasification simulation models can be grouped into four main categories including; Thermodynamic Equilibrium model, Kinetic model, Computational Fluid Dynamic (CFD) and the Artificial Neural Network. Unlike the equilibrium model, the kinetic model takes into account the gasifier geometry as well as its hydrodynamics [3]. The equilibrium and Kinetic approach have been utilised in many studies of the gasification process e.g. [4], [6], [9], [14].

Advanced System for Process ENgineering (Aspen) Plus is used to model and predict the performance of a process [1], [2], and this has found applications in the modelling and simulation of various gasification processes including, coal, plastic, rubbers, Polyethylene (PE) and biomass materials.

The fluidised bed gasification process has been modelled and simulated using ASPEN PLUS, to study and investigate the influence of various parameters of the gasification process and gasification products, for example, Begum [4], modelled

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and simulated the gasification of solid waste (wood) using ASPEN PLUS; Kannan [15] used ASPEN PLUS simulation to investigate the gasification of waste plastics; Nikoo & Maphinpey [9] used it to model sawdust gasification process, and addressed both hydrodynamic parameter and reaction kinetics.

For all the works carried out on fluidized bed gasification of solid biomass, the fuel briquettes has not been widely explored, and this is important with the increasing need for densification of biomass prior to gasification and the transition from small to large (commercial) scale biomass gasification process.

The specific objectives of this paper were to investigate the impact of fuel briquette density, material composition (blend ratio of rice husks to corn cobs) on the fluidisation velocity and gasification air requirement, and product syngas composition, using numerical equations and Aspen Plus simulation software.

II. MATERIALS AND METHODS

A. Briquettes Production

The biomass briquette data, used in the numerical equations and Aspen Plus simulation of the briquette gasification process, were original research data obtained from biomass briquette production in the laboratory from blends of rice husks and corn cobs, using a hand mold and hydraulic compression machine [8]. The produced briquettes were of 32 mm diameter, and density range of 490 to 650 kg/m^3 for 50/50 and 30/70 blends of rice husks to corn cobs. The proximate, ultimate and particle size properties of feed briquettes used for the gasification process, were obtained from literature [13], [12] and laboratory characterisation by [8].

B. Model Approach

The briquette gasification model was based on an experimentally validated model by [7] for gasification of olive kernel in a bubbling fluidised bed reactor, and it is referred to as the "BASE MODEL" in this study, while the new model in this study is referred to as the "CURRENT MODEL". The base model was experimentally validated by its authors, and the current study used the reported model to build an Aspen Plus model using briquette properties. This was carried out for the purpose of predicting the syngas composition from the fluidised gasification of multiple biomass derived briquettes, produced by [8].

C. Assumption

The following assumptions were considered for the gasification process of the current model and also according to the base model.

- The process is steady state and isothermal.
- Biomass devolatilisation is instantaneous and volatile products mainly consist of H_2, CO, CO_2, H_2O and CH_4.
- All gases are uniformly distributed within the emulsion phase.
- Feed particles are of uniform size and the average diameter remains constant during the gasification
- Char only contains carbon and ash.
- The simulation was performed using power-law kinetics.

The gasification process generally starts with drying of the biomass feed where water is driven off at temperatures above 100°C, followed by pyrolysis (partial combustion) at temperatures between 300 and 500°C, volatile combustion and char gasification usually above 800°C, to give a mixture of gases (largely H_2 and CO) as the product stream. Fig. 1 shows a simple representation of biomass gasification in a fluidised bed.

Biomass fuel mainly consists of carbon, hydrogen, oxygen, nitrogen and sulphur. During the gasification process, in the combustion zone, carbon dioxide is formed from the carbon in the feed biomass and water (in the form of steam) is also obtained from the hydrogen present in the fuel biomass (1 and 2) [3], [7]. The products from the combustion zone including other partially cracked pyrolysis volatiles further passed through a bed of hot char where reduction reactions take place (3 to 4).

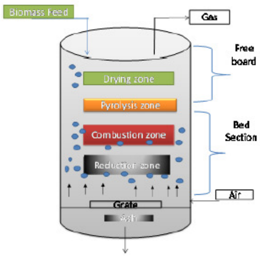

Fig. 1 A simple representation of different zones in biomass gasification process

III. REACTION KINETICS

Combustion Zone

$$C + \frac{1}{2}O_2 \rightarrow CO \tag{1}$$

$$C + O_2 = CO_2 \tag{2}$$

Reduction Zone

$$C + CO_2 = 2CO \tag{3}$$

$$C + H_2O = CO + H_2 \tag{4}$$

$$CO + H_2O = CO_2 + H_2 \tag{5}$$

$$C + 2H_2 = CH_4 \tag{6}$$

$$CO_2 + H_2 = CO + H_2O \tag{7}$$

IV. HYDRODYNAMICS

A. Assumptions

The following assumptions were considered in the calculation and simulation of the hydrodynamic parameters.

- The same reactor/gasifier dimension was assumed for all cases of briquette's density and composition.

International Science Index Vol:9, No:5, 2015 waset.org/Publication/10001714

- The fluidised bed is divided into two regions, bed and freeboard.
- The fluidisation state in the bed is maintained in the bubbling regime.
- The volume fraction of solids decreases with increasing height, similar to the grouping of bubbles in with solid particles returning to the bed.
- Gas velocity in the reactor is equal to the fluidisation velocity.
- Volumetric flow rate of gas increases with height corresponding to the production of gaseous products.
- Solid particles mixing consisting of char, ash and bed materials, are considered perfect.
- The reactor is divided into a finite number of equal elements with constant hydrodynamic parameters.
- The fluidised bed is one dimensional and any variation in conditions is considered to occur in axial direction.

The process parameters were calculated based on different briquettes density and composition (50/50 to 30/70 blend ratio of rice husks to corn cobs). To test the effect of only biomass composition on product gas composition, the blend ratio of rice husks to corn cobs was further varied between 90/10 and 10/90 rice husks to corn cobs.

1) Briquette Mass Flow

The briquette mass flow rate was calculated using (8) [3].

$$\mathrm{M_f} = \frac{Q}{LHV_{bm}\eta_{gef}} \tag{8}$$

2) Gasification Air Requirement

The gasification air as well as fluidisation air requirement were determined using (9) and (10).

$$M_a = m_{th}ER \tag{9}$$

The fluidisation air requirement was determined using (10) [3]:

$$f_a = \rho_{\mathrm{air}}\, \mu_{\mathrm{mf}}\, \mathrm{A_b} \tag{10}$$

According to [3], the minimum fluidisation velocity can be determined from (4).

$$\mu_{mf} = \frac{\mu}{d\rho}\mathrm{R\acute{\tilde{e}}}_{mf} \tag{11}$$

V. ASPEN PLUS SIMULATION

Five different stages were considered in the Aspen Plus modelling and simulation of the briquette gasification process including drying, biomass decomposition, Volatile reactions, char gasification and gas-solid separation (Fig. *2*). Although a built-in model for customised fluidised bed gasification modelling was not available in Aspen Plus at the time of the Base Model, the software provided facility for user to input their own models using FORTRAN/Excel codes as well as reactions embedded within the input file [1], [2]. The following steps were used in the Aspen Plus model development [1], [2], and Fig. 2 shows the process flow sheet.

- Stream class specification and property method selection.
- System component specification (Aspen Plus data bank), and identifying conventional and non-conventional components.
- Defining the process flow sheet using unit operation blocks and connecting mass and energy streams.
- Specifying feed streams (composition, flowrate, thermodynamic condition).
- Specifying unit operation blocks (thermodynamic condition, chemical reaction).

Dry briquettes and ash were specified as non-conventional component in the Aspen Plus by using ultimate and proximate analysis of parent materials (rice husks and corn cobs) on a 50/50 blend ratio of rice husks to corn cobs, and referred to as the "base case" (Tables I-III).

TABLE I
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN ULTIMATE ANALYSIS

Item	Ratio	50/50 ULTANAL (%)							
		ASH	C	H	O	N	S	Cl	TOTAL
RH	50%	7.2	21	2.5	19	0.1	0.0	0.0	50
CC	50%	0.5	24	2.7	22	0.2	0.0	0.0	50
	blend	7.7	45	5.2	40	0.3	0.1	0.0	100

The stream class in the Aspen Plus, was defined as MIXED, NC and PSD (MIXNCPSD) which indicates the presence of non-conventional solids and with particle size distribution. The enthalpy and density model for non-conventional components was selected as HCOALGEN and DCOALIGT.

TABLE II
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN PROXIMATE ANALYSIS

Item	Ratio	50/50 PROXANAL					
		MC (%)	F/C (%)	VM (%)	ASH (%)	HV (kj/kg)	Total
RH	50%	4.1	10.7	32.1	7.19	8000	50
CC	50%	7.5	6.8	42.7	0.50	9000	50
	blend	11	17	74	7.2	17000	100

TABLE III
RICE HUSKS AND CORN COBS 50/50 BLEND RATIO IN SULFUR ANALYSIS

Item	Ratio	50/50 SULFANAL			
		Pyritic	Sulfate	Organic	Total
RH	50%	0.009	0.002	0.009	0.020
CC	50%	0.018	0.004	0.018	0.040
	blend	0.027	0.006	0.027	0.060

These are built-in Aspen Plus model for computing the heat of formation, heat of combustion and heat capacity of coal, while the density model DCOALIGT is used for computing the true density of coal on a dry basis using ultimate and sulphur analysis, and was adopted for the biomass materials.

The base model by [7] was slightly modified by removing the N and S separator situated before the RYIELD in the base model, and also by introducing the process air through the mixer instead of the RGIBBS (Fig. 2). The removal of the N and S separator was done to reduce the capital investment cost of the process since it was assumed that most of the N used in the drier (RSTOIC) went out with water in the Exhaust. Also, the introduction of air in the RGIBBS was observed to aid combustion of char before the RPFR in the briquette gasification.

A. Aspen Plus Gasification Flow Process

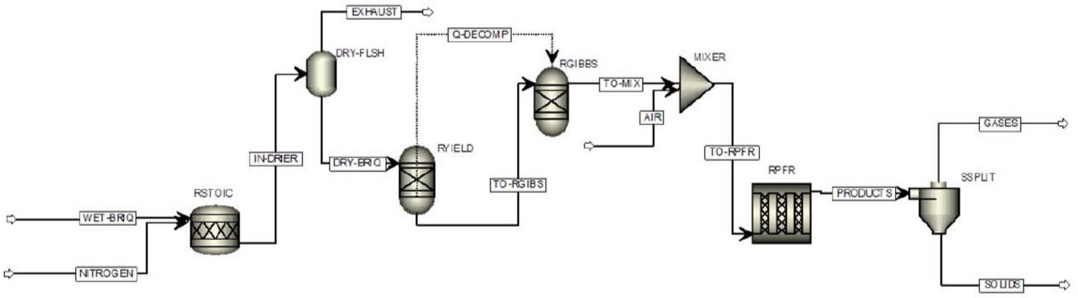

Fig. 2 Aspen Plus briquette gasification flow sheet

1) Briquettes Drying

The Aspen Plus stoichiometric reactor block (RSTOIC) was used to simulate the feed briquette drying process. The quantity of water removed from the briquettes was based on the proximate analysis of feed biomass which was determined by the blend ratio of rice husks to corn cobs. A calculator was attached to the RSTOIC in which an Aspen Plus provided FORTRAN CODE was used for the drying reaction. The mixture of dry briquette and gaseous water were separated using the separation column model DRY-FLSH. The dried feed briquettes were then moved into the next Aspen Plus block for decomposition process.

2) Briquette Decomposition

Briquettes feed decomposition process was simulated using the Aspen Plus yield reactor RYIELD. In this reactor, biomass material was converted into its constituent components including C, H_2, O_2, N_2, S and ash, by specifying the yield fraction of each component based on the biomass ultimate analysis.

3) Volatile Reactions

The Aspen Plus reactor block RGIBBS was used for the volatile reactions which uses the Gibbs free energy minimization to calculate the chemical equilibrium of the conventional components in the reactor. The RGIBBS does not require the user to specify reaction stoichiometry, and it automatically uses the temperature and pressure of the incoming feed (TO-RGIBBS) (Fig. 2), to establish the block and products exit temperature and pressure. In the RGIBBS, it was assumed that a small portion of the carbon that forms the gaseous phase, takes part in the volatile reactions, while the remaining solid phase char (carbon and ash) were moved to the RPFR for gasification reaction.

4) Char Gasification

The Aspen Plus block reactor RPFR was used to model the char gasification, a mixer was place before the RPFR where air for the gasification was introduced to mix with the products from RGIBBS. The char gasification was performed in the RPFR by specifying the gasification reactions and chemical kinetic. Similar to the base model, the hydrodynamic and kinetic parameters such as superficial velocity and voidage were kept constant.

5) Gas-Solid Separation

The separation of solid carbon and gas mixture was carried out using a CYCLONE SEPARATOR block in the Aspen Plus model. The final product consisting of mixture of gases received as main products of the gasification process. Other components of the product gas include Tars which were not considered in the current model. The gas was further scrubbed and dewatered.

VI. RESULTS AND DISCUSSION

A. Effect of Briquette Density on Minimum Fluidisation Velocity and Air Requirement

Fig. 3 shows the effect of briquette density on the minimum fluidisation velocity, the fluidisation medium (air) required and the gasification air based on an equivalence ratio of 0.25 for air gasification (9). The minimum fluidization velocity (U_{mf}) is the point of transition between a fixed bed regime and a bubbling regime in a fluidized bed [10], it quantifies the drag force needed to attain solid suspension in the gas phase which makes it an important parameter in characterizing the hydrodynamics in the fluidised bed [5].

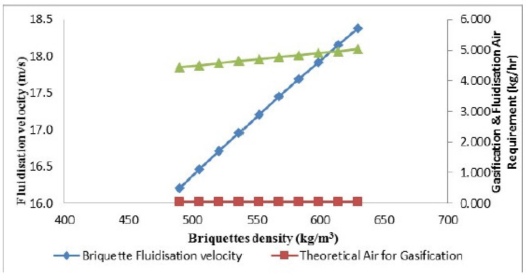

Fig. 3 Effect of briquette density on Umf and air requirement for fluidisation and gasification

From Fig. 4, the fluidisation velocity significantly increases with increasing briquette density with over 18 m/s of minimum fluidisation velocity required to transfer briquettes particles of 650 kg/m^3 into the bubbling phase in the reactor. This agrees well with findings from [5] using glass beads and wood chips. There is also an increase of air requirement for the level of fluidisation in the reactor as density of briquettes increase, which is consistent with expectation as well as findings presented by [24]. The gasification air is the actual air required for conversion of the solid biomass (gasification reaction kinetics), is significantly lower than the fluidisation air required. Since the gasification air is independent of the hydrodynamics in the reactor, it is not affected by the change in briquette density but varies with change in briquette composition. The result shows that, the fluidisation air is limiting in the current gasification process which implies excess air supply for the gasification reaction.

B. Effect of Process Air Flow on Product Gas Composition

Fig. 4 shows the mass flow rate (kg/hr) of the Aspen Plus predicted syngas composition versus the gasification process air flow in the range of 1 to 10 kg/hr. The air flow range was based on the designed air requirement of 4.5 kg/hr (Fig. 4), calculated for the minimum briquette density used in this study.

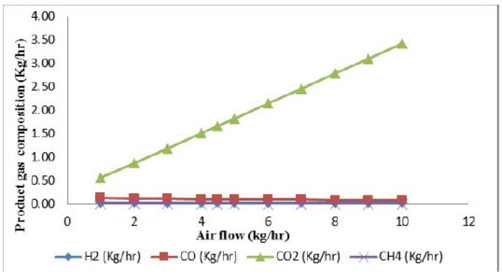

Fig. 5 Product gas composition at 50%RH/50%CC

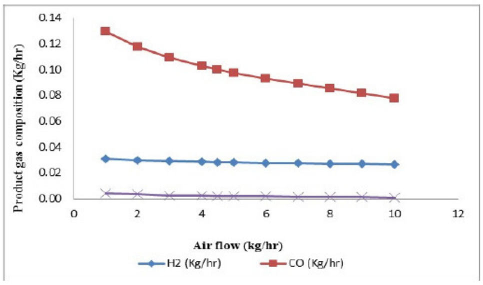

Fig. 6 Product gas composition at 50%RH/50%CC without CO_2

The CO formation decreases with increasing air flow which also resulted in increased CO_2 while CH_4 formation appears to be constant. The H_2 formation profile in the product gas initially increases but became constant with increased gasification process air supply. Ideally, the syngas should consist of mainly CO and H_2 in the appropriate ratio, and while this remains important, the syngas composition in Fig. 4 shows a reduction in quality of the syngas as process air supply increases which can be attributed to the increased oxidation reaction. Fig. 5 provides clear formation profiles of CO, H_2 and CH_4 in the absence of CO_2 in the product gas.

C. Effect of Airflow on H2/CO Ratio in Product Gas for Various Blends of Rice Husks and Corn Cobs

Fig. 6 shows the H_2/CO ratio for all the blends of rice husks to corn cobs briquettes considered in this study. From Fig. 6, the H_2/CO ratio increased with increase process air flow. The H_2/CO ratio at the design air of 4.5 (Fig. 3), was 0.3 which increased to about 0.6 at 16 kg/hr of air supply. The H_2/CO ratio for the briquette gasification is low compared with a recommended ratio of 0.5 to 1. The low H_2/CO ratio can be associated with a low H_2 formation in the gasification process which was almost constant as the process progresses. The increased H_2/CO ratio as air flow increases, was due to the increased formation of CO_2 as CO decreases. This highlights the requirement for optimisation of H_2 formation in briquette gasification process as well improve CO at an optimum air flow.

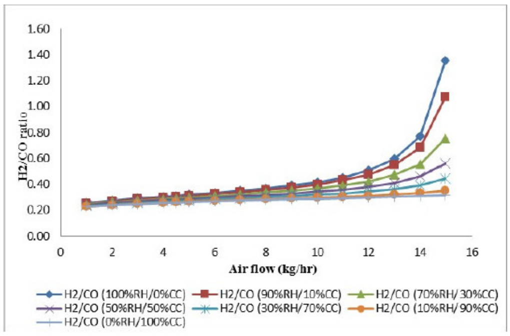

Fig. 7 H2/CO ratio for various blends of rice husks and corn cobs

International Science Index Vol:9, No:5, 2015 waset.org/Publication/10001714

The ratio of H_2 to CO for various blends of rice husks to corn cobs did not significantly vary even at the design air requirement, however, at higher air flow of 10 kg/hr, there was a significant difference between 100/0 and 0/100 ratio of rice husks to corncobs. The higher rice husks in the blend influenced higher H_2/CO ratio of up to 1.4 as air flow increased to 16 kg/hr. A reasonable ratio of 0.8 as reported by [7] was achieved at 70/30 blend ratio of rice husks to corn cobs.

D. Solid Composition in Briquette Gasification Product Stream for Various Blends of Rice Husks and Corn Cobs

Figs. 7 and 8 show the quantity of unreacted carbon and ash in the product stream from gasification of multiple biomass derived briquettes. The use of higher corn cobs in the blend resulted in increased quantity of residual carbon and reduced quantity of ash in the product stream, implying the high carbon and low ash content of the corn cob biomass (Table I).

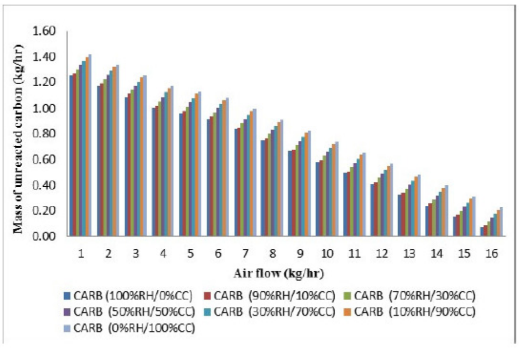

Fig. 8 Mass of unreacted carbon in product stream for various blends of rice husks and corn cobs with change in process air flow

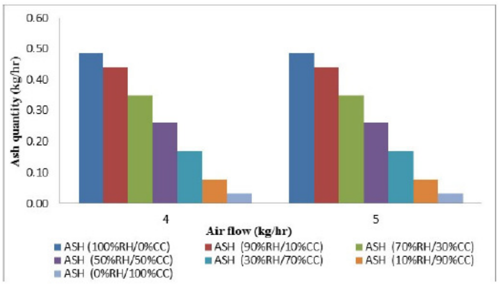

Fig. 9 Mass of ash in product stream for various blends of rice husks and corn cobs at design process air

VII. CONCLUSION

An investigation of the atmospheric fluidised bed gasification of multiple agricultural biomass briquette was carried out using numerical equations and Aspen Plus simulation. It was found that briquette density had significant impact on the fluidisation velocity and process air requirement. The quantity of CO and H_2 were low, and CO decreased with increased air supply in the gasifier, resulting in high CO_2 formation. Hydrogen was constant at above 3 kg/hr of air flow and 4.5 kg/hr feed briquette. The H_2/CO ratio was 0.3 at design process air and increased to 0.6 with an increase in the air flow. The blend ratio of rice husks and corn cobs did not significantly affect the H_2/CO ratio but at higher air flow, the H_2/CO ratio increased with higher ratio of rice husks in the blend. A good H_2/CO ratio of 0.8, was achieved at 70/30 % blend ratio of rice husks to corn cobs, at higher air flow. Briquette with higher blend ratio of rice husks also favored lower quantity of unreacted carbon but higher quantity of ash in the product stream. This implies the need for further understanding of biomass variability and hydrodynamic parameters on product composition from biomass briquette gasification.

ACKNOWLEDGMENT

We would like to express our gratitude to the Nigerian Government through the Petroleum Technology Development Fund (PTDF), for sponsoring this research project.

NOMENCLATURE

Q	= Gasifier output
LHV_{bm}	= Feed biomass heating value
ηgef	= Gasifier efficiency
m_{th}	= Stoichiometric air required for complete combustion of biomass (0.1153C+0.3434(H-O/8)+0.0434S)
ER	= Equivalence ratio (0.25 assumed for air gasification)
ρ_{air}	= Density of gasification medium (air)
μ_{mf}	= Minimum fluidisation velocity
A_b	= Cross sectional area of bed
μ	= Viscosity of fluidisation medium (air)
d	= Particle diameter
$R\acute{\hat{e}}_{mf}$	= Reynolds number at minimum fluidisation velocity
RH	= Rice husks
CC	= Corn cobs

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Experimental Investigation of Fluidised bed gasification of Multiple Biomass-Derived Briquettes

An experimental test was carried out to investigate the use of briquette in a gasification process, loose biomass was also used in the experiments to evaluate the effect of briquetting loose biomass before gasification, on the syngas composition.

Experimental design

A factorial experimental design method was employed in the fluidised bed gasification test for both briquettes and loose biomass materials [Box et al, 2005]. Four variables were investigated based on their expected influence in the gasification process and syngas composition, these variables include; gasifier feed type (i.e., briquette or loose biomass), flowrate of the fluidization medium (nitrogen (N_2)), material ratio (blends of rice husks and corn cobs), and briquette compaction pressure.

Two levels (low and high) were selected for each of the independent variables; the 2^4 factorial design that was used for the gasification experiments, is shown in columns 2 to 5 of Table 19, which also shows the measured responses (gas composition).

The briquettes used in the gasification experiments were 25 mm diameter with relaxed briquette length in the range of 28 to 39 mm, for different blends of rice husks and corn cobs biomass. The briquette production method was reported by Muazu & Stegemann, 2015].

Gasification experiments

The gasification experiments were carried out in a lab-scale bubbling fluidized-bed reactor, which is made of stainless steel with an inner diameter of 60 mm and a height of 1.5 m. Figure 45 and 46 show the schematic diagram of the experimental apparatus and the picture of the experimental rig, respectively. A three-zone electric furnace heats the reactor to ensure the temperature accuracy. N_2 was used as a fluidization medium (gas) to provide an inert atmosphere, and is regulated by a mass flow controller. A stainless steel sintered plate is mounted at the bottom of the reactor to be the gas distributor, below which a layer of inert SiO_2 debris was set to preheat the fluidizing gas and quartz sand was used as bed material.

The reactor was first heated to the desired temperature before the fluidizing gas (N_2) was introduced into the reactor. When the bed temperature reached the steady value of the desired temperature, 10g of biomass material or fuel briquette were dropped into the reactor from the top through a valve-hopper. Since N_2 was used as fludisation medium, the source of available oxygen (O_2) in the gasification process, was from the biomass materials, which was used in the oxidation reactions, forming CO and CO_2.

The generated product gas was cooled immediately in a water condenser, the gas then passed through a fabric filter and further dryer before collection in a gas bag.

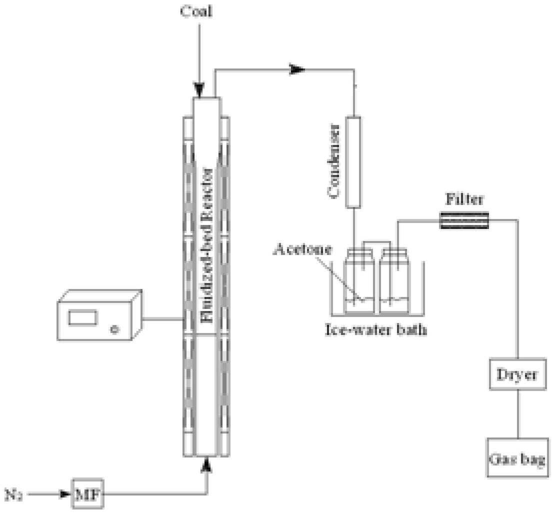

Figure 45: Schematic of the fluidised bed gasifier used for briquette gasification test (Note: Tar collection apparatus was not used in the experiment)

Figure 46: Picture of actual gasification rig used in briquette gasification test

The product gas from the briquette gasification tests was analysed using the gas chromatography mass spectrometry apparatus (Figure 47), and the product gas composition for the different experimental runs are shown in Table 19.

Figure 47: Analysis of gasification product gas using GCMS

Results

From Table 19, the formation of CO in the product was highest at experimental run 6 (i.e., 5% of the total syngas), while the composition of hydrogen was highest at experimental runs 3, 7 and 11. This may be associated with change in air supply and/or material ratio (biomass composition), for the different experimental runs. For example, the use of lower N_2 flowrate, increased the composition of CO in the product gas, while higher flowrate of 4.5 L/min, increased the composition of H_2. This can be attributed to changes in process variables at low and high fluidization velocity, for example, increase reaction surface area, particle mixing, and heat transfer rate.

Table 19: Gas compositions from gasification of briquettes and loose biomass in a fluidised bed reactor

Experimental Run	Experimental Variables					RESPONSES						
				Gasifier Feed								
	Material Ratio (% mass of rice husks in blend of rice husks)	Pressure (MPa)	Gasification medium flowrate (L/min)	Type	Unit Relaxed and Bulk Densities of Briquette and Loose Biomass(kg/m^3)	CO	N_2	H_2	CH_4	CO_2	C_2H_6	C_2H_4
1	50	37.3	3	Briquette	734	3%	37%	3%	36%	1%	1%	19%
2	30	37.3	3	Briquette	690	3%	29%	3%	42%	2%	2%	20%
3	50	62.2	4.5	Briquette	727	2%	46%	10%	18%	22%	1%	1%
4	30	62.2	4.5	Briquette	805	2%	49%	8%	13%	26%	0%	0%
5	50	37.3	3	Briquette	779	2%	35%	3%	37%	1%	2%	20%
6	30	37.3	3	Briquette	826	5%	65%	6%	21%	2%	0%	1%
7	50	62.2	4.5	Briquette	816	3%	45%	10%	19%	23%	0%	0%
8	30	62.2	4.5	Briquette	853	2%	48%	9%	16%	25%	0%	0%
9	50	0	3	Loose biomass	330	3%	37%	3%	36%	1%	1%	19%
10	30	0	3	Loose biomass	309	3%	29%	3%	42%	2%	2%	20%
11	50	0	4.5	Loose biomass	330	2%	46%	10%	18%	22%	1%	1%
12	30	0	4.5	Loose biomass	309	2%	49%	8%	13%	26%	0%	0%
9*	50	0	3	Loose biomass	330	3%	37%	3%	36%	1%	1%	19%
10*	30	0	3	Loose biomass	309	3%	29%	3%	42%	2%	2%	20%
11*	50	0	4.5	Loose biomass	330	2%	46%	10%	18%	22%	1%	1%
12*	30	0	4.5	Loose biomass	309	2%	49%	8%	13%	26%	0%	0%

*repeated runs

The % composition of CH_4 is also high at lower N_2 flowrate, this indicates that at the lower flowrate of the fluidisation medium used in this study, the reaction was predominantly pyrolysis reaction. The composition of H_2 in the syngas showed a uniform pattern for all the experimental runs, however CO and CO_2 changed significantly with change in experimental conditions. Since the gasification experimental design was based on the primary briquette production process, it indicates a correlation between briquetting variables and gasification product gas composition.

The overall results did not show significant difference in the H_2 and CO composition from both briquettes or loose biomass gasification, however, change in material ratio (biomass composition) and N_2 flowrate showed significant effect on the composition of H_2 and CO.

The ratio of H_2 to CO was significantly high (1 to 4), and greater than those obtained by other workers [e.g., Begum et al, 2014; Michailos & Zabaniotou, 2012], for solid waste, and olive kernel, and that obtained by the authors in a gasification model [Muazu et al, 2015].

Further analysis and statistical evaluation of the gasification test results is being considered.

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