

Czech University of Life Sciences Prague

Faculty of Engineering



Diploma Thesis

**THE POTENTIAL OF ENERGY RECOVERY FROM
BIODEGRADABLE WASTE AND BY-PRODUCTS FROM SMALL
AGRICULTURAL FARMS**

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DIPLOMA THESIS ASSIGNMENT

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Technology and Environmental Engineering

Thesis title

The potential of energy recovery from biodegradable waste and by-products from small agricultural farms

Objectives of thesis

The aim of this diploma thesis is based on a literary review of current state of utilization of by-products and wastes from small agricultural farms, which often end up unused with other biodegradable waste. This is followed by an assessment of existing technical facilities for processing and analysis of the potential for energy utilization. Methods will be chosen based on the classification, quality and specification of type and quantity of suitable waste materials, analysis of legislation in the field of waste management, Design and calculation of suitable technology for processing of selected waste materials will be carried out.

Practical part of the thesis includes analysis of available technical equipment for energy utilization, description of the initial state of waste management in the chosen area, description of technology used on farms and municipal waste management, determination of possible system modifications with economic assessment. Finally, the student will prepare a proposal assessment that will follow from analysis of physico-chemical properties of samples of chosen materials obtained from farms during field work.

Methodology

The diploma thesis will consist of the following sections:

1. Introduction
2. Objectives and methods
3. Literature review
4. Definition of the problem
5. Design of solution and results
6. Discussion and conclusions
7. Literature
8. Attachments

The proposed extent of the thesis

50 – 60

Keywords

elemental analysis, gross calorific value, stoichiometry, combustion properties, emission

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Malaťák, J.; Jevič, P.; Vaculík, P.: Účinné využití tuhých biopaliv v malých spalovacích zařízeních s ohledem na snižování emisí znečišťujících látek. 2010, Powerprint, Praha, pp. 240, ISBN 978-80-87415-02-3

Malaťák, J.; Vaculík, P.: Biomasa pro výrobu energie. ČZU v Praze, Technická fakulta, tisk. Powerprint, Praha 2008, 206 s., ISBN: 978-80-213-1810-6

Obroučka, K.: Termické zneškodňování odpadů. VŠB Ostrava, Ostrava 1997, 140 s.

Pastorek, Z.; Kára, J.; Jevič, P.: Biomasa – obnovitelný zdroj energie, nakladatelství FCC Public, Praha 2004, 284 str., ISBN 80-86534-06-5

Směrnice Evropského Parlamentu a Rady 2009/28/EC o podpoře užívání energie z obnovitelných zdrojů a o změně a následném zrušení směrnic 2001/77/ES a 2003/30/ES. Štrasburk, 23.4.2009 (OR. en)

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Declaration

I hereby declare that the diploma thesis titled “the potential of energy recovery from biodegradable waste and by-products from small agricultural farms” was worked on by myself and all the sources used were cited and mentioned in the reference section.

In.....on.....

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Musa Bappah

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ABSTRACT

Global increase in human population leads to increase in agricultural production, which as well results in rise in the production of agricultural by-products both at farm and industrial levels. Agricultural by-products are renewable energy sources from which essential amount of energy can be recovered, which can be used to replace the use of conventional fossil fuel, reduces the potential of greenhouse gas (GHG) emission and at the same time reduces deforestation, especially in rural areas. Significant attention has been directed towards the reutilization of by-products which result from primary processing of agricultural produce for the production of high value-added products. Heat can be generated from biomass combustion using small and medium scale units. Energy values of biomass from small Agricultural farms, in particular waste generated from different tropical crops, viz; Maize cobs, Millet, Rice and Sorghum husks and Groundnut pods were determined, to ascertain their potentials as alternative fuel sources for rural use. The Energy values of the by-products considered ranged between 11.68 MJ.kg⁻¹ to 17.48 MJ.kg⁻¹ with Groundnut pods and millet husk having the highest and least respectively. With the exception of millet and rice husks whose ash contents and heating values does not meet the given standards, all the by-products can be used as standard feedstock for pellet or briquette production.

Keywords: by-products, biomass, energy value, feedstock.

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1.0. INTRODUCTION

The global increase in human population leads to increase in agricultural production, which as well results in rise in the production of agricultural by-products both at farm and industrial levels.

Agricultural waste comprises both natural (organic) and non-natural wastes which can either be solid, liquid or slurries resulting from growing and first processing of agricultural products. Uncontrolled or improper handling of which may lead to environmental pollution (Zhang et al., 2012). Crop residues include straw from barley, rice, soy bean and wheat, Stover from maize bagasse from sugar cane” (Bentsen et al., 2014), rice husk, corn cobs, cocoa pods, fruit shells (Titiloye et al., 2013), sorghum husk, millet husk and groundnut pods.

Energy can be derived from agricultural wastes produced through agricultural practices (Bentsen et al., 2014). The type of waste, its quantity and geographical location, and also the handling practice by local farmers determines the ways through which the energy can be recovered (Jana & De, 2015). Some properties of agricultural waste enables them to be utilized for energy generation through various processes using modern technology (Titiloye et al., 2013). This can be determined through physico-chemical analysis of the waste material (McKendry, 2002b). The form of such energy is also important, such as the use of straw for fodder, combustion or gasification, for heating or electricity generation (Jana & De, 2015).

In order to achieve changes required to address impacts of global warming, the use of renewable energy sources becomes necessary, which biomass is the most common form (McKendry, 2002a). When compared with fossil fuel, biomass has lower greenhouse gas emission which gives it opportunity to be used in converting climate change (SRU, 2007)

Maize, rice, millet, Sorghum and groundnut are among the highly produced crops in Bauchi state of Nigeria, from which different by-products were obtained which can be used for energy generation to supplement current usage of fossil fuels.

2.0. PROBLEM, OBJECTIVES AND HYPOTHESIS

2.1. Problem statement

Continuous increase in agricultural by-products generation and greenhouse gas emission resulting from the burning of fossil fuels necessitate the search for possible supplements to fossil fuel in forms which may be generated from these by-products. Literature on energy values of groundnut pods, and the husks of sorghum and millet are also very scanty.

HYPOTHESIS – the chosen agricultural by-products are suitable for the combustion process in small combustion devices with minimum environmental impact.

2.2. Objectives of the study

The main aim of this study is to determine the potential of recovering energy from the selected agricultural by-products. In order to achieve the main aim, the following specific objectives were set:

1. To determine the right material for combustion process in mentioned combustion equipment and their evaluation – elemental and ultimate analysis.
2. To determine theoretical emissions from the by-products using stoichiometric analysis.
3. To determine the possibility of using the by-product as feedstock for pellet or briquette production.

3.0. REVIEW OF LITERATURE

3.1. Current state of utilization of by-products and waste from small agricultural farms

Maize, rice and wheat account for more than three quarters of the total production of residues from barley, maize, rice, soybean, sugar cane and wheat (Bentsen et al., 2014). Significant attention has been directed towards the reutilization of by-products which result from primary processing of agricultural produce for the production of high value-added products (Galanakis, 2018). Arable crops residue such as stalks, straw, husk, shells, organic materials, animal manure and animal bedding are sources of agricultural by-products which can be used for energy production and therefore serves as an excellent opportunity for rural communities (Rosendahl, 2013).

3.1.1. Maize cobs

Maize (*Zea mays L.*) is also known as corn, a native of Central and South America, currently extensively cultivated all over the world, it is an annual plant belonging to the grass family (*Gramineae*) (Galanakis, 2018). The relative yield of maize cobs is between 10% and 20% of the product mass whose moisture content ranges from 10-12%. They are left on the farmers' yard after threshing, which are later used as fuel for combustion facilities, especially in rural areas of developing countries (Martinov et al., 2011). Maize cobs (Figure 1) are currently being used for heat in some parts of Europe (F. John Hay, 2015), and as animal bedding.



Figure 1. A capture of Maize cobs obtained during a farm visit in Bauchi, Nigeria.

3.1.2. Rice husk

Rice (*Oryza sativa*) is among the world most commonly produced and consumed cereal crops. Rice husk removal is the first step in its milling (Galanakis, 2018; Nambi et al., 2017). The husk (Figure 2) is the outermost covering that protects the grain, forming 20% of the product (Abu, Yahya, & Neon, 2016; Nambi et al., 2017). It decomposes slowly due to its rich silica content and can therefore not be considered for use as fodder (Ndindeng et al., 2015; Vaisman, 2018), it is rather used in horticulture for soil aeration. Various thermochemical conversion processes can be used to obtain different types of fuels and chemical feedstock as renewable energy source due to its high content of lignocellulose materials (Vaisman, 2018). Direct combustion is often utilized for biomass to produce heat and power for energy services (Dunnigan et al., 2018).



Figure 2. *Rice husk*

Source: (Vaisman, 2018)

3.1.3. Millet husk

Millet (*Pennisetum glaucum*) is a cereal crop which is native of Africa and Asia and can be produced within a very short period of time. Due to its cost effectiveness, renewability, biodegradability, and high cellulose content, the husk can be used for thermal conversion. It grows under different climatic conditions and the husk which is neither consumed nor used (Figure 3), is left on the farm after harvest and that way become shelter for microorganisms which shelter diseases (Abba et al., 2017).



Figure 3. A capture of Millet husk obtained during a farm visit in Bauchi, Nigeria

3.1.4. Groundnut pods

Groundnut (*Arachis hypogaea* L.) is one of the most important cash crops in West Africa, from which cooking oil is produced and its paste is used to prepare local dishes (Baributsa et al., 2017). The by-product that remained after first processing operation of groundnut is called Groundnut pods (Figure 4), which is about 20–30% by weight of the dried groundnut. It is often discarded and burnt which as a result pollutes the environment (Deeba et al., 2017).



Figure 4. A caption of Groundnut pods obtained during a farm visit in Bauchi, Nigeria

3.1.5. Sorghum husk

Sorghum is fifth leading cereal crop after wheat, maize, rice, and barley which is grown in the tropical, subtropical and arid regions with an annual production of about 57 million tons globally (Wizi et al., 2018). Grain and other by-products which are either combusted or used as animal fodder are the main purposes of growing Sorghum (Monteiro et al., 2012), the husk of which is easy to obtain, inexpensive and readily available (Kshirsagar et al., 2017; Wizi et al., 2018), can be used as a source of natural functional dye (Wizi et al., 2018). Sorghum husk (Figure 5) is a very efficient biodegradable by-product possessing high amount of cellulose and hemicellulose content which can be used in bio-fuel industry (Kshirsagar et al., 2017).



Figure 5. A caption of Sorghum husk obtained during a farm visit in Bauchi, Nigeria

3.2. Biomass

Biomass is any organic matter that has stored sunlight in the form of chemical energy such as “plants, agricultural crops and residues, organic waste and algae”. The building block of biomass is formed from carbohydrate which is produced from the reaction of carbon dioxide, water and sunlight via photosynthesis (McKendry, 2002a). Even though in rural areas and developing countries biomass is used as domestic fuel in its raw form through direct combustion (Garivait et al., 2006; Gravalos et al., 2010; Purwanto & Supramono, 2009; WORLD ENERGY COUNCIL, 2016), it can also be transformed into various forms of biofuel (solid, liquid and gas) which can be used in different sectors of life, ranging from transportation, heating, cooking

and many other industrial purposes (WORLD ENERGY COUNCIL, 2016). It is the primary energy source which more than 50% of the world population depends on for energy generation and it is getting more interest due to its renewability and the role it is playing in reducing over dependence on fossil fuels which contribute more in global warming (Garivait et al., 2006; Gravalos et al., 2010).

3.2.1. Biomass characteristics

The energy value of a biomass material depends on its physical and chemical properties which include its moisture, ash, organic matter and elemental composition (Akhmedov et al., 2017; Garivait et al., 2006; Kraszkievicz et al., 2015; Obernberger & Thek, 2010). The type of appropriate technology that can be used effectively for biomass feedstock conversion and its environmental impacts depends on the chemical elemental characteristics of the biomass (Garivait et al., 2006).

Moisture content

Moisture content is very important characteristic of biomass feedstock that always need to be considered due to its influence in design, control and optimization of boiler settings. Higher flue-gas content, longer burn-out time and longer residence time in the boiler are negative aspects associated to feedstock with high moisture content (Rosendahl, 2013). Usually fresh biomass contain moisture of about 50% (Obernberger & Thek, 2010). It is therefore regarded as one of the most important characteristics of biomass which is considered when determining the energy conversion technology that can be used. Though, biomass with low moisture content are more appropriate for thermal conversion technology, fermentation and anaerobic digestion are the most appropriate conversion technology for biomass with high moisture content (Garivait et al., 2006).

Ash content

The ash content as the mass of inorganic matter remaining after combustion of a fuel under specified conditions (Kraszkievicz et al., 2015; Obernberger & Thek, 2010; Rosendahl, 2013), suffer considerable variation in its content and composition between feedstock, ranging from below 0.5 wt% (d.b.) in wood pellets to 5–10 wt% (d.b.) in agricultural residues, straws and miscanthus. The ash-forming elements and the ash melting point also vary considerably between biomasses, Silicon, calcium, magnesium, sodium and potassium are the major ash-forming elements, the concentrations of which are of great importance for the combustion

characteristics. The temperature at which the ash starts to flow and eventually melt (melting point) leading to slag formation on the grate and in the bed increases by magnesium and calcium and decreases by potassium and sodium (Jagustyn et al., 2011; Rosendahl, 2013). Handling ash is cost effective, it has to be included in the conversion cost for biomass with high ash content, thereby raising the price (Garivait et al., 2006). Agricultural biomass are considered to have higher ash content than wood biomass, which has a negative impact on both combustion process and heating value (Jagustyn et al., 2011).

Calorific value

The calorific value of the biomass is the measure of heat released after combusting the biomass in a controlled environment. The heat released is proportional to the calorific value of the substance (Gravalos et al., 2010; Sadaka & Johnson, 2010). Calorific value depends on the moisture content of the biomass feedstock, it increases with decreasing moisture content (Jagustyn et al., 2011). The type of feedstock used and the combustion efficiency of the appliance determines the amount of heat that will be produced by combusting the feedstock (Sadaka & Johnson, 2010).

Elemental composition

Elemental composition is the content of carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine in biomass feedstock. Harmful emissions are produced by nitrogen and sulfur during combustion (Kraszkievicz et al., 2015) and high emission of oxides of nitrogen (NO_x) is attributed to high nitrogen content of the biomass (Jagustyn et al., 2011). Due to their negative impact on environment, chlorine, nitrogen and sulfur are considered to be undesirable components of fuel combustion, with chlorine and sulfur being corrosive on the technological equipment used for energy conversion (Jagustyn et al., 2011).

3.3. Crops Production

Data extracted from the statistical data of Bauchi State Agricultural Development Programme (BSADP), shows the rate of production of maize, rice, millet, sorghum and groundnut (Table 1), from which large quantity of by-products are generated every year, which can be used as biomass for renewable energy generation. They are the major crops that are produced in Bauchi state, which has land are of 49.119 km² and a population of 4,653,066 people according to 2006 census.

Agricultural crops residue production depends on annual crops yield which varies from one year to another, depending on precipitations, area cultivated, types of crops, soil condition and farming practices between local farmers (Scarlat et al., 2010).

An average of 1,385,454.68 ha is cultivated every year for the production of those five crops, with mean annual yield of 28,661,192.94 Mt (BSADP, 2017)

Table 1. Bauchi state crops production estimate 2013-2017

Crop	2013		2014		2015		2016		2017		Mean	
	Area (ha)	Yield (Mt)	Area (ha)	Yield (Mt)	Area (ha)	Yield (Mt)	Area (ha)	Yield (Mt)	Area (ha)	Yield (Mt)	Area (ha)	Yield (Mt)
Millet	298530.7	554485.2	309085.0	309987.7	278176.5	292920.0	243393.4	250431.3	292920.2	335121.0	284421.6	348589.1
Sorghum	623224.0	982026.8	451681.0	483789.0	478781.9	536235.7	360764.0	449093.0	536235.0	729140.0	490137.2	636056.9
Maize	334470.0	785680.0	205768.0	300918.4	174903.0	244864.0	178481.2	252821.0	190974.9	399102.0	216919.4	396677.1
Rice	402052.4	419647.3	71208.0	104791.4	85450.0	140907.0	116647.0	211113.2	127145.2	132552.0	160500.5	201802.2
Groundnut	433414.0	502966.3	200550.0	198270.2	194535.0	182668.0	153498.5	190853.0	186379.4	238789.0	230075.4	262709.3
Annual p	2091691.1	3244805.5	1238292.0	1397756.5	1210846.4	1397594.7	1052784.1	1354311.4	1333654.8	1834704.0		

Source: (BSADP, 2017).

3.4. Residue Production

There is a great variation between different crops on the relationship between residue production and crop yield, which depends on the types of crops, agricultural practices, yield and cultivated area (Scarlat et al., 2010). Bentsen et al. (2014) provides the relation for estimating residue production from crop yield and area cultivated as:

$$RP = A.RY \quad (1)$$

Where:

RP – residue production (kg.yr^{-1}),

A – harvested area (ha),

RY – crop residue yield ($\text{kg.ha}^{-1}.\text{yr}^{-1}$).

For more accurate estimate of the crop residue production, relationship between the residue-to-product ratios and crop yield can be used (Scarlat et al., 2010). Therefore, an exponential relation of the general form was assumed for the determination of Residue yield (equation 3) from the residue to product ratio (RPR) for each crop which is proportional to the crop yield (equation 2) (Bentsen et al., 2014).

$$RPR = ae^{bY} \quad (2)$$

$$RY = Y.ae^{bY} \quad (3)$$

Where:

RPR – residue to product ratio,

RY – crop residue yield ($\text{kg.ha}^{-1}.\text{yr}^{-1}$),

Y – crop yield ($\text{kg.ha}^{-1}.\text{yr}^{-1}$),

a – field/land factor,

b – crop factor.

The direct proportionality of residue yields and crop yields holds to a certain level in practice, after which the residue yield remains constant (Bentsen et al., 2014). Accurate data on the

availability and their local and annual variability is required for the use of agricultural by-products for bioenergy production (Scarlat et al., 2010).

3.5. Exhaust Gases

Gaseous emissions from biomass combustion differ significantly according to the properties of the fuel burned and its ash contribution to emissions of particulate matter such as carbon monoxide (CO) and some hydrocarbons resulting from an incomplete combustion and to operational problems such as fouling and slagging which may disturb the whole combustion process and reduces boiler efficiency (Bhatia, 2012; Fournel, Marcos et al., 2015). Increase in the emission of oxides of nitrogen (NO_x), sulfur dioxide (SO₂) and hydrogen chloride (HCl) is brought about by High amounts of nitrogen (N), sulfur (S) and chlorine (Cl) in agricultural biomass respectively (Fournel et al., 2015), which are the primary pollutants from the burning of biomass, similar to those produced by burning fossil fuels (Rosendahl, 2013).

Smoke and other gases which are dangerous for human health, having the possibility of causing "Acute Respiratory Infections (ARI), lungs cancer, and eye disease" are among the emissions produced during biomass combustion (Purwanto & Supramono, 2009).

Biomass combustion is attributed to release of some principle emissions, out of which particulate matter (PM) and NO_x are considered to be the most significant pollutants. The combination of primary and secondary aerosols formed in the atmosphere as a result of gaseous compound (SO₂ and NH₃) conversion brings about PM whose sizes are categorized into PM₁₀ (less than or equal to 10µm) and PM_{2.5} (less than or equal to 2.5µm) based on their impacts to human health and environment. With the significant impact of NO_x on the environment which can react with SO₂ and other substances to form acid rain, NO₂ directly affect human health negatively, causing irritation in the lungs (IrBEA, 2016).

Particulate Matter (PM) include salts, soot, condensable organic compounds (COCs), volatile organic compounds (VOCs) and intermediate products. NO_x include nitric oxide (NO), nitrogen dioxide (NO₂) and nitrous oxide (N₂O). Oxides of Carbon (CO_x) include CO and carbon dioxide (CO₂). Oxides of Sulfur (SO_x) include sulfur dioxide (SO₂) and sulfur trioxide (SO₃). Dioxins/furans include polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polychlorinated/polybrominated biphenyls (PCBs/PBBs) (IrBEA, 2016).

Emissions of NO_x gases is one of the greatest concerns for combustion systems no matter the source of the feedstock (Rosendahl, 2013).

In its effort to limit the emissions of certain pollutants into the air from medium combustion plants, European union (EU) has set a directive (Medium Combustion Plant (MCP) Directive: (EU) 2015/2193) targeted to regulates pollutant emissions from the combustion of fuels in both existing and new medium combustion plants with a rated thermal input equal to or greater than 1 megawatt (MW) and less than 50MW. The directive gives emission limit for existing and medium combustion plants which is to be achieved by 1st January, 2030, as shown in Table 2. It enforces that member States shall take the necessary measures to ensure that no new medium combustion plant is operated without a permit or without being registered (EU Council, 2015).

Table 2. Emission limit values (mg.Nm^{-3}) for existing medium combustion plants, other than engines and gas turbines

Pollutants	Solid biomass	Other solid fuels	Liquid fuels other than gas		Gaseous fuels other than natural gas	
			Gas oil	oil	Natural gas	natural gas
SO_2	200 ⁽¹⁾⁽²⁾	1 100	-	350	-	200 ⁽³⁾
NO_x	650	650	200	650	250	250
Dust	50	50	-	50	-	-

⁽¹⁾The value does not apply in the case of plants firing exclusively woody solid biomass; ⁽²⁾300 mg.Nm^{-3} in the case of plants firing straw; ⁽³⁾400 mg.Nm^{-3} in the case of low calorific gases from coke ovens in the iron and steel industry.

Source: (EU Council, 2015)

Biofuels are commonly considered to be CO_2 neutral, emission of which is of less concern because of its short circulation time from the fuel being burned to it being reabsorbed by plants through photosynthesis (Rosendahl, 2013).

3.6. Stoichiometric Calculation

Certain amount of air consisting 21% of oxygen and 79% of nitrogen is required for complete combustion of biomass, the stoichiometric of which include carbon dioxide, water vapor and nitrogen, were heat is generated. 100% of the biomass energy is extracted when it is completely combusted and that will result to less emission of CO in the flue gas. Equation 1 provides the stoichiometric for the combustion of biomass (Sadaka & Johnson, 2010).



During combustion, certain amount of toxic gases are produce, which can be estimated through combustion analysis, using which maximum combustion efficiency can be achieved. The concentration of flue gas including O₂, NO_x, SO₂, HCs, volatile organic compounds (VOCs) and soot, which are produced from the combustion process are harmful by-products that need to be minimized (Sadaka & Johnson, 2010). This may be achieved by having optimum level of air temperature and air flow, thereby controlling the locally available and the stoichiometric air ratio (Nussbaumer, 2003; Sadaka & Johnson, 2010).

3.6.1. Gross and net calorific value

Gross calorific value or GCV refers to the quantity of heat produced by combustion when the water produced by combustion is permitted to return to the liquid state. While the net calorific value or NCV refers to the quantity of heat produced by combustion when the water produced by combustion continues to be in a gaseous state. Water releases heat when it condenses. In net calorific value the water produced by combustion remains gaseous. So gross calorific value is greater than net calorific value. Gross calorific value is also known as higher heating value while net calorific value is also referred to as lower heating value. The dependence between the gross calorific value of Q_s^r and net calorific value Q_i^r can be expressed according to (ČSN 44 1352):

$$Q_i^r = Q_s^r - (0.02442 \cdot 1000) \cdot (\sigma(W_t^r) + 8.94 \cdot \sigma(H_t^r)), \text{ (kJ.kg}^{-1}, \text{kJ.m}^{-3}\text{N)} \quad (5)$$

Where: $\sigma(W_t^r)$ – water content of the analytical sample (%),

8.94 – coefficient for hydrogen to water conversion,

$\sigma(H_t^r)$ – hydrogen content in analytical sample (%),

0.02442 – value that corresponds to the energy consumed for heating and evaporating
1% water at 25 ° C.

The conversion of the net calorific value Q_i^r at a total water content $\sigma(W_t^r)$ to a different water content $\sigma(W_{ii}^r)$ is done according to the formula:

$$Q_{in}^r = \frac{100 - \sigma(W_{ii}^r)}{100 - \sigma(W_t^r)} \cdot (Q_i^r + 0.02442 \cdot \sigma(W_t^r)) - 0.02442 \cdot \sigma(W_{ii}^r), \text{ (kJ.kg}^{-1}, \text{kJ.m}^{-3}\text{N)} \quad (6)$$

Where: $\sigma(W_{ii}^r)$ – content of all the water to be converted (%),

$\sigma(W_t^r)$ – content of all water in the original sample (%),

Q_i^r – net calorific value of the original sample ($\text{kJ}\cdot\text{kg}^{-1}$, $\text{kJ}\cdot\text{m}^{-3}\text{N}$).

Gross calorific value can be determined most accurately by measuring in a bomb calorimeter (ČSN 44 1352). In technical practice, the calorific value and calorific value are determined by calculation, using the results of elementary and fuel analysis (Malat'ák & Bradna, 2017).

3.6.2. Stoichiometry of combustion processes

Stoichiometric calculations of combustion processes complement the fuel characteristics and are the basis for any heat calculation of a combustion device. They are particularly important for addressing a wide range of design practice issues as well as for controlling the operation of existing combustion plants. These calculations shall specify (Malat'ák & Bradna, 2017):

- i. Calorific value of fuel (waste)
- ii. The amount of oxygen (air) needed to completely burn fuel (waste)
- iii. The amount and composition of the flue gas
- iv. Flue gas production for a weight unit of fuel
- v. Adiabatic, theoretical and realistic combustion temperature.

3.6.3. Air consumption calculations and flue gas quantity

Combustion processes are classified into two groups according to the conditions which are created for it:

Complete combustion

Here all combustible components in the fuel are fully oxidized, so that the resulting flue gas does not contain any flammable compounds.

Perfect combustion with a theoretical excess of air (L_{\min}), which can be calculated from the stoichiometric relationships of combustion equations, can only be achieved with complete fuel-air mixing and ideal combustion conditions. However, in practical operation, air (oxygen) supply is greater than the theoretical to ensure complete combustion, and depends on the type of fuel, combustion plant, main combustion mechanism (Sadaka & Johnson, 2010) (diffusion or kinetic controlled), etc. The ratio between actual and theoretical air consumption is called the excess air coefficient n and is equal to:

$$n = \frac{L_{skut}}{L_{min}} = \frac{O_{skut}}{O_{min}} \doteq \frac{20,95}{20,95 - O_2} \doteq \frac{CO_{2,max}}{CO_2} \quad (7)$$

Excess air is required to ensure perfect combustion. On the other hand, however, the harmfulness of too much excess must be taken into account. The more air involved in the combustion, the more heat is carried away by the flue gas, the combustion temperature decreases, the fuel utilization coefficient decreases, and so on. Therefore, it is necessary to have optimum excess air (Malat'ák, Bradna, Kučera, Černý, & Passian, 2013).

Incomplete combustion

This is a combustion process in which there is a certain content of combustible substances in the flue gas.

This type of combustion always occurs at $n < 1$. However, it can also occur if $n = 0$ or $n > 1$ when the fuel and oxidizer are incompletely mixed. This method of combustion, which deteriorates the thermal efficiency of combustion is in most cases undesirable and is used exceptionally for technological reasons for combustion.

The calculation of the air consumption and the amount of flue gas can be done by these methods according to the elemental analysis using stoichiometric equations (analytical method):

Volumetric: 21% O₂, 78.05% N₂. From this composition, the ratio of oxygen, nitrogen, and air from the relationship can be calculated:

$$O_2 : N_2 : air = \frac{21}{21} : \frac{78,05}{21} : \frac{100}{21} = 1 : 3,716 : 4,76 \quad (8)$$

The volume composition of dry air without water vapour, neglecting the noble gases contained in minute amounts, is shown in Table 4.

Table 3. Volume compound of dry air.

Gas	Volume composition (%)
O ₂	21,000
N ₂	78,050
Ar	0,920
CO ₂	0,030

However, the atmospheric air used for combustion contains some water vapour, which is dependent on air temperature and relative air humidity. The volume of water vapour per m³ of dry air at 0°C is approximately 1.04.

When calculating the volume quantities of the combustion products (flue gases) and the required combustion air volume, the combustion is based on the molecular weight of the individual combustible elements. The molecular weights of the elements are shown in Table 5 (Malat'ák & Bradna, 2017).

Table 4. Molecular masses of elements in combustible matter.

Element	Kilomol Volume (m ³)
Hydrogen H	2.016
Carbon C	12.01
Oxygen O	32.00
Sulfur S	32.06
Nitrogen N	28.02

3.6.4. Combustion of solid fuels

By using the molecular weights of the individual elements, the stoichiometric equations can be expressed for the oxidation reactions during combustion:

Combustion of carbon into carbon dioxide:



$$12 \text{ kg} + 32 \text{ kg} = 44 \text{ kg} + 406.3 \text{ MJ}$$

$$12.01 \text{ kg} + 22.39 \text{ m}^3 = 22.27 \text{ m}^3$$

The calorific value of 1 kg of pure carbon is 33.85 MJ.kg⁻¹.

Combustion of hydrogen to water vapour:



$$2 \text{ kg} + 16 \text{ kg} = 18 \text{ kg} + 241 \text{ MJ}$$

$$4.032 \text{ kg} + 22.39 \text{ m}^3 = 44.81 \text{ m}^3$$

The calorific value of 1 kg of hydrogen is 120.5 MJ.kg⁻¹.

Combustion of sulfur to sulfur dioxide:



$$32 \text{ kg} + 32 \text{ kg} = 64 \text{ kg} + 290 \text{ MJ}$$

$$32.06 \text{ kg} + 22.39 \text{ m}^3 = 21.89 \text{ m}^3$$

The calorific value of 1 kg of sulfur is 9/0625 MJ.kg⁻¹.

The conversion of other elements and moisture (water) into the gas phase is valid:

For Nitrogen:



$$28.013 \text{ kg} = 28.013 \text{ kg}$$

$$28.013 \text{ kg} = 22.40 \text{ m}^3$$

For oxygen:



$$31.999 \text{ kg} = 31.999 \text{ kg}$$

$$31.999 \text{ kg} = 22.39 \text{ m}^3$$

For moisture:



$$18.015 \text{ kg} = 18.015 \text{ kg}$$

$$18.015 \text{ kg} = 22.41 \text{ m}^3$$

All volumes of combustion air and flue gas in the above equations (9 -14) are given under normal conditions, i.e. at temperature $t = 0 \text{ }^\circ\text{C}$ and pressure $p = 101.325 \text{ kPa}$ (Malat'ák et al., 2013).

Malatak & Bradna (2017) provide relationships for determining the combustion properties;

The theoretical amount of oxygen $O_{2,min}$ ($m^3.kg^{-1}$) is based on the equation:

$$O_{2,min} = V_m(O_2) \left(\frac{C}{M(C)} + \frac{H}{M(2 \cdot H_2)} + \frac{S}{M(S)} - \frac{O}{M(O_2)} \right) \quad (15)$$

Where:

C , H , S , and O – contents of carbon, hydrogen, sulfur and oxygen in the sample (% wt.),

$V_m(O_2) = 22.39 \text{ m}^3.kmol^{-1}$ – molar volume of oxygen gas at normal conditions and

$M(X)$ – molar masses of hypothetical species X that combine with O_2 ($kg.kmol^{-1}$).

The theoretical amount of dry air L_{min} ($m^3_N.kg^{-1}$) is determined from the equation:

$$L_{min} = O_{2,min} \cdot \frac{100}{C_{atm}(O_2)} \quad (16)$$

Where:

$C_{atm}(O_2) = 21\% \text{ vol.}$ – volumetric concentration of oxygen in air.

The real amount of air for perfect combustion L_{skut} ($m^3_N.kg^{-1}$) is determined using:

$$L_{skut} = O_{2,min} \cdot \frac{100}{21} \cdot n \quad (17)$$

Theoretical amount of dry flue gases $v_{fg,min}$ ($m^3.kg^{-1}$) is based on the equation:

$$v_{fg,min} = \frac{V_m(CO_2)}{M(C)} \cdot C + \frac{V_m(SO_2)}{M(S)} \cdot S + \frac{V_m(N_2)}{M(N_2)} \cdot N + \frac{C_{atm}(N_2)}{100} \cdot L_{min} \quad (18)$$

Where:

$V_m(X)$ – molar volumes of flue gas components ($m^3.kmol^{-1}$),

$C_{atm}(N_2) = 78.05\% \text{ vol.}$ – concentration of N_2 in air.

Theoretical amount of emission concentrations of $CO_{2,max}$ ($m^3_N.kg^{-1}$) is based on the equation:

$$CO_{2,max} = \frac{M(C) \cdot C}{V_m(CO_2) \cdot v_{fg,min}} \cdot 100 \quad (19)$$

Volumetric amounts of combustion products:

$$v(CO_2) = \frac{V_m(CO_2)}{M(C)} \cdot C + \frac{C_{atm}(CO_2)}{100} \cdot L \quad (20)$$

$$v(H_2O) = \frac{2 \cdot V_m(H_2O)}{2 \cdot M(H_2)} \cdot H + \frac{V_m(H_2O)}{M(H_2O)} \cdot W \quad (21)$$

$$v_{N_2} = \frac{V_m(N_2)}{M(N_2)} \cdot N + O_{2,min} \cdot \frac{C_{atm}(N_2)}{C_{atm}(O_2)} \quad (22)$$

$$v_{SO_2} = \frac{M(C)}{M(S)} \cdot S \quad (23)$$

$$v_{O_2} = O_{2,min} \cdot (n-1) \quad (24)$$

$$v_{Ar} = 0.0092 \cdot L_{skut} \quad (25)$$

Where: W – Moisture content in the fuel (% wt).

3.7. Biomass Combustion Appliances

Transformation of biomass from traditional application with negative environmental impact, low efficiency and energy waste, to modern application without negative impact to the environment is more in industrialized countries than in developing countries (Rosillo-Calle et al., 2007). Heat can be generated from biomass combustion using small and medium scale units (Nussbaumer, 2003). Depending on the scale of application and the fuel type to be combusted, IrBEA (2016) and Nussbaumer (2003) identified variety of biomass combustion appliances that can be utilized, which include:

- i. Fireplaces (open, closed or partly closed)
- ii. Wood pellet and log stoves
- iii. Wood pellet and log boilers
- iv. Wood chip boilers
- v. Stoker burner boilers
- vi. Underfeed stoker boiler (automatically fed)
- vii. Moving grate boiler (automatically fed)

3.7.1. Fireplaces

Fireplaces are a traditional type of biomass appliance having a basic combustion chamber that is connected to the chimney. Fireplaces are classified into open and close (Figure 6). The open fireplace uses radiation as the means of transferring heat to the room, characterized with low efficiency and high emissions resulting from incomplete combustion of the biomass. The Closed fireplaces are more efficient and produce less emissions than their Open counterparts. This is because they are designed with a front door and a system for discharging exhaust gasses and distribution of combustion gasses as well (IrBEA, 2016; Sadaka & Johnson, 2010). The main forms of biomass fuels used to heat fireplaces are Logs, lump wood and biomass briquettes (IrBEA, 2016) and they are used for chilling off the room during mild spring and fall weather (Sadaka & Johnson, 2010)

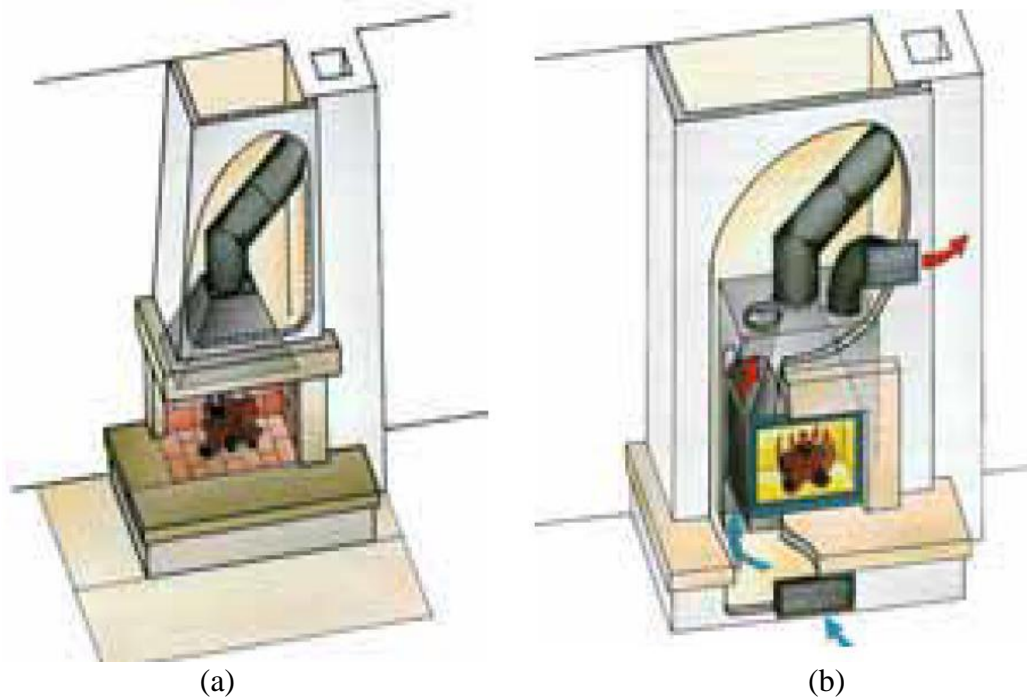


Figure 6. Open Fireplace (a), Closed Fireplace (b)

Source: (IrBEA, 2016)

3.7.2. Wood pellet and log stoves

A wood stove is a free-standing appliance for heating the space within which it is located, without the use of ducts. Stoves release useful heat energy by radiation and convection to their surroundings. Although all stoves utilize both forms of heat transfer, they are generally classified as radiating or circulating (convection) stoves, depending on the main mode of heat transfer. The firebox walls and the firebox hearth are typically lined with fire-resistant

materials. Some stoves are equipped with ash grates, normally with an ash box under the grate. Others have no grate and ashes are taken out directly from the hearth. The combustion chamber can be equipped with horizontal and inclined baffles made of rigid insulating material or steel, and secondary air is normally preheated and introduced at strategic locations. In many stoves, a viewing window is provided in the front door, which not only contributes to the aesthetics of wood heat, but gives the operator a much better opportunity to adjust the stove for optimal combustion (Koppejan et al., 2008).

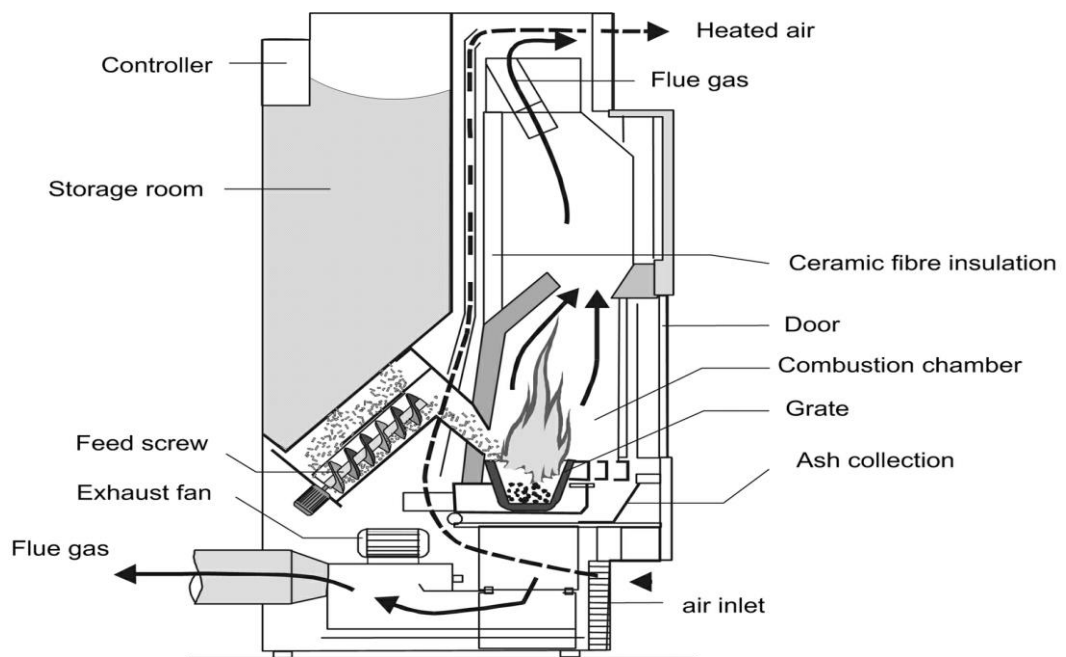


Figure 7. *Wood Pellet stove*

Source: (Koppejan et al., 2008)

3.7.3. Wood pellet and log boilers

Wood boilers are characterized into:

- i. Over-fire boilers
- ii. Under-fire boilers
- iii. Down-draught combustion and
- iv. Up-draught combustion

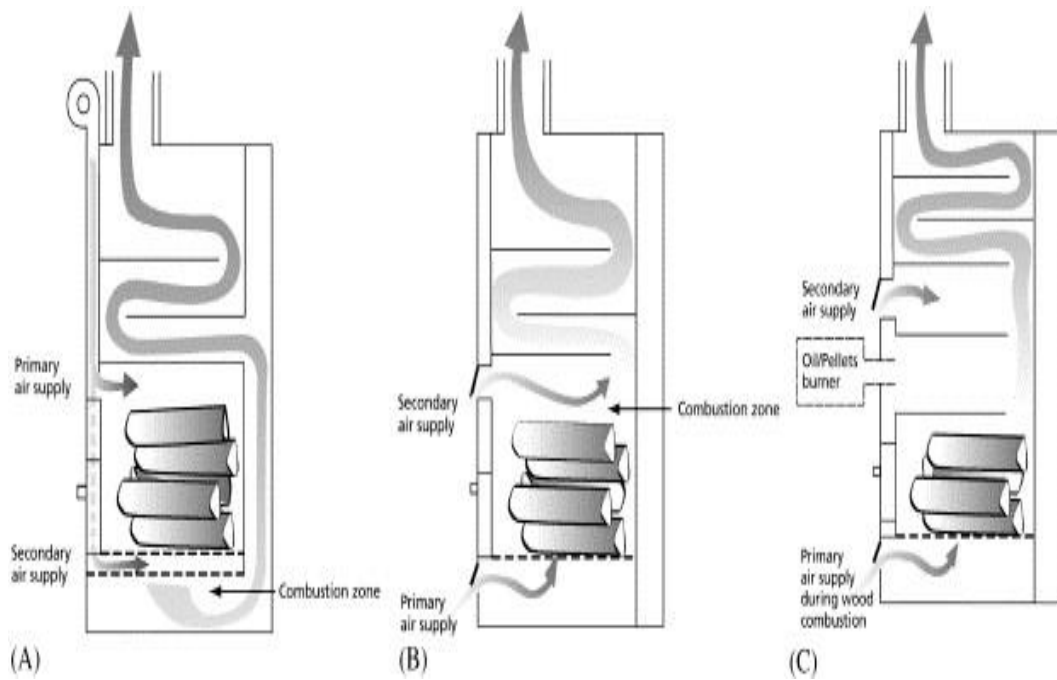


Figure 8. Wood boiler designed for down-draught combustion (A), a wood boiler designed for up-draught combustion (B), and a multi-fuel boiler (C), which can burn wood, oil, or pellets

Source: (Johansson et al., 2004)

3.7.4. Wood chip boilers

Woodchips can also be burned in under-fire boilers. Wood chip boilers (Figure 9) are similar to under-fire wood log boilers, but fuel storage is normally made of better material to avoid corrosion. Today, under-fire boilers are not very common for woodchip combustion because automatic combustion units have been replacing them (Koppejan et al., 2008).

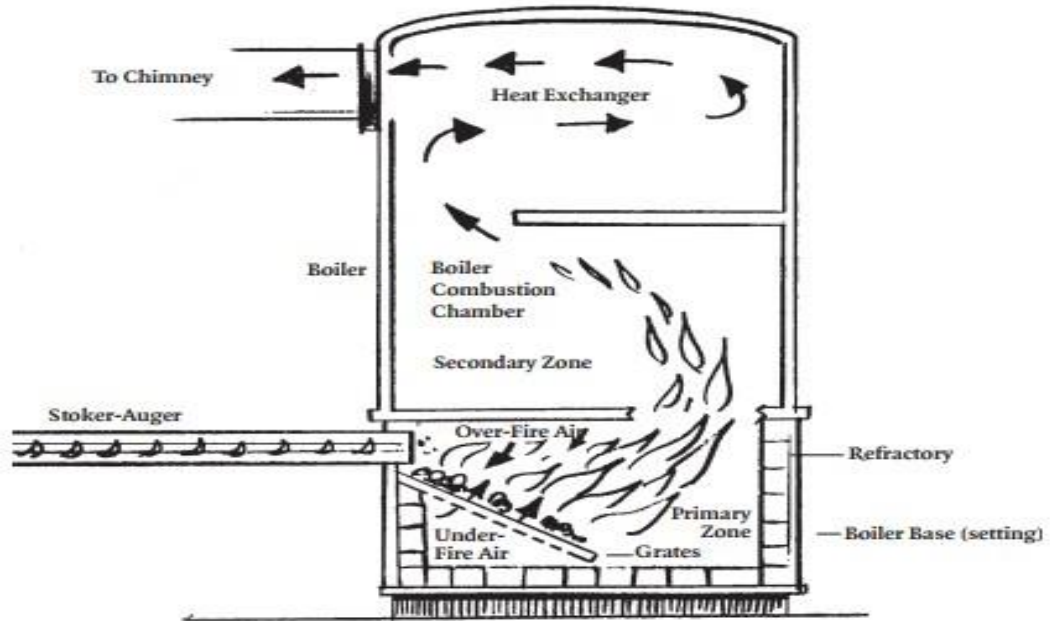


Figure 9. *Wood chip boiler*

Source: (Timothy M. Maker, 2004)

3.7.5. Stoker burner boilers

Stoker burners (Figure 10) are automatic woodchip combustion devices placed inside the firebox of the boiler which is quite similar to pellet burners, with higher heat output, up to 1MW (Koppejan et al., 2008). Fuels with relatively low ash content like wood chips are mostly used (Nussbaumer, 2003). The fuel is fed precisely into the burner where it is conveyed using a screw feeder, and combusted according to the heat demand. The burner consists of a cast iron, refractory-lined or water-cooled horizontal cylinder. In some burners, the durability of the burner materials is ensured by water-cooling, which makes insulation of the burner easier. When using dry fuels the temperature inside the burner rises above 1000°C (Koppejan et al., 2008).



Figure 10. *Overfed stoker burner boiler*

Source: (IrBEA, 2016)

3.7.6. Underfeed stoker boiler

Underfeed stokers (Figure 11) represent a cheap and operationally safe technology for small and medium scale systems up to a nominal boiler capacity of 6MW. The fuel is fed into the combustion chamber by screw conveyors from below and is transported upwards on an inner or outer grate. Primary air is supplied through the grate, secondary air usually at the entrance to the secondary combustion chamber (Koppejan et al., 2008).

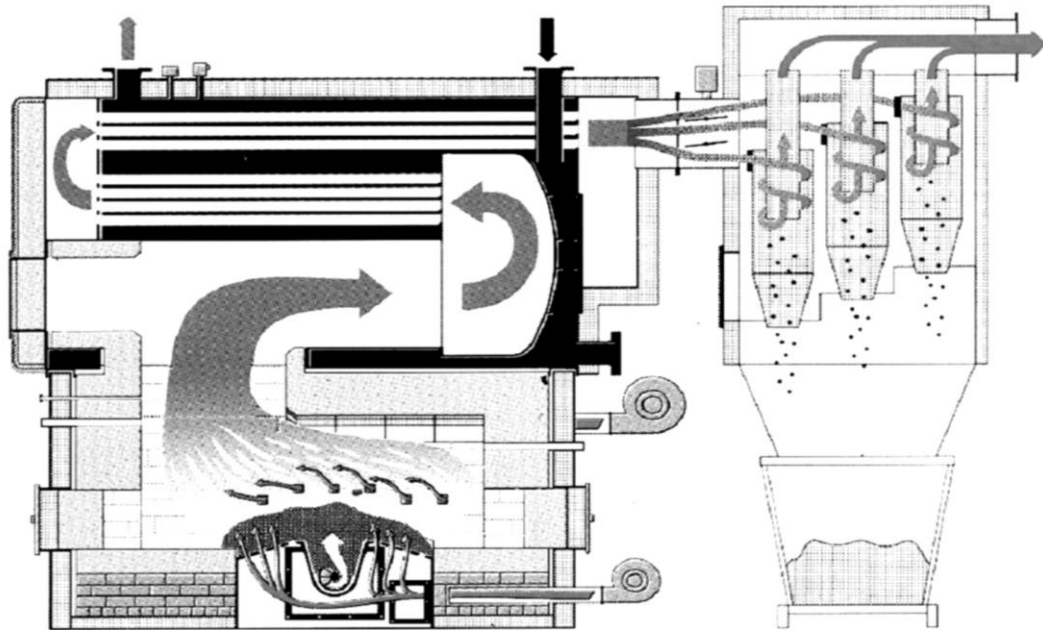


Figure 11. *Underfeed stoker furnace*

Source: (Koppejan et al., 2008)

3.7.7. Moving grate boiler/firing

In a grate-fired plant (Figure 12), the fuel is transported along a moving or vibrating grate and is combusted before it reaches the end. Primary air is supplied from below the grate creating an intense combustion zone directly above the bed. The ash left over from combustion is transported to an ash pit at the end of the grate and removed (Rosendahl, 2013). The ash and char are retrieved simultaneously with feeding the fuel by movement of the bed (Obernberger & Thek, 2010). It is highly attractive for biomass combustion due to its simplicity and that the typical fuel-feeding systems are mechanical stokers (Rosendahl, 2013), requiring fuel of regular shape and composition (Obernberger & Thek, 2010).

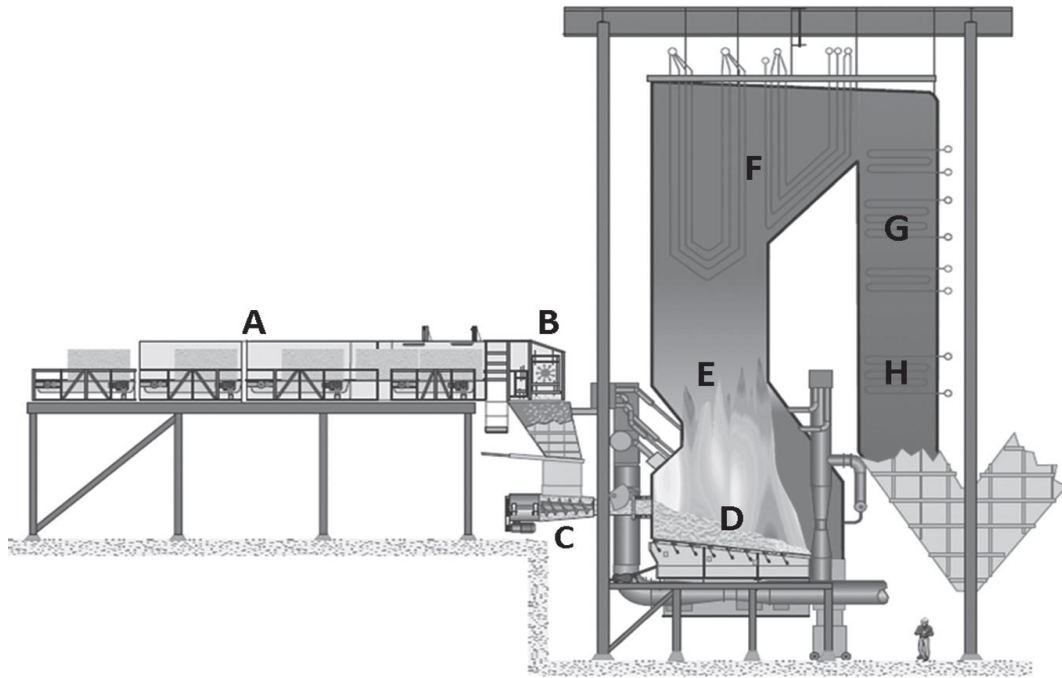


Figure 12. Modern straw- fired vibrating- grate boiler. straw transport belt (A); straw rotary rake (B); stoker screw (C); fuel bed on a water- cooled vibrating grate (D); freeboard (E); second and third superheaters (F); first superheater (G); economizer (H)

Source: (Rosendahl, 2013)

3.8. Municipal Solid Waste Management

Municipal solid waste are waste resulting from various human activities carried out at different levels both industrially and domestically which have negative impact on the environment, management of which is the global challenge of urban areas (Asian Productivity Organization, 2007; Kumar, 2010). Many factors including “health, economic, engineering, conservation, aesthetic and other environmental consideration” must be considered though all the processes involved in waste management from generation to disposal (Asian Productivity Organization, 2007). Open dumping and landfill are the main practices that are used for disposing municipal solid waste in developing countries which are associated with much environmental pollution (Asian Productivity Organization, 2007; Kumar, 2010).

Organic waste amounting to 70% of the waste stream, mainly generated from agriculture, processing and municipal waste can be transformed to various forms for energy, organic fertilizer or animal feeds through modern innovations and technology (Asian Productivity Organization, 2007).

Kumar (2010) proposes different alternative ways which can be used independently or a combination of two or more in handling municipal solid waste;

- i. Waste recycling
- ii. waste reduction
- iii. waste separation,
- iv. incineration
- v. land filling with lixiviate treating and gas energy recovery, and
- vi. organic waste composting

Cities with high percentage of organic waste generation have the opportunity of converting it to valuable materials that can be used for agriculture through compost production or taken to processing units where biogas, electricity, alcohol or biodiesel can be generated. Special attention should therefore be given to organic waste (Kumar, 2010).

3.9. Pellets and Briquettes

Pellets are solid fuels produced from compressed materials (Alakangas, E. and Paju, 2002; Obernberger & Thek, 2010). its combustion is obvious at district heating stations and even at power plants (Alakangas, E. and Paju, 2002). Pellets (Figure 13) are cylindrical with typical dimensions of 6–10mm (Alakangas, E. and Paju, 2002; Koppejan et al., 2008) and less than 30mm length (Obernberger & Thek, 2010) which can be used for automatically charged stoves and boilers due to their size and easy manipulation (Koppejan et al., 2008). They are suitable fuels which are used not only in stoves and central heating system, but also in large scale plants due to their consistent qualities which include "low moisture content, high energy density and homogeneous size and shape" (Obernberger & Thek, 2010).



Figure 13. *Wood pellets*

Source:(Alakangas, E. and Paju, 2002)

briquettes are usually cylindrical compressed wood fuel products made of by-products of mechanical wood-processing industry (Alakangas, E. and Paju, 2002) having a typical dimensions of diameter 30–100mm which are primarily used instead of firewood for manually charged domestic stoves (Koppejan et al., 2008).

Both pellets and briquettes can also be compressed from milled and dried fresh biomass, bark and forest chips (Alakangas, E. and Paju, 2002).

3.9.1. Pellet production process

The processes involved in pellet production are drying, milling, conditioning, pelletizing, cooling, fine separation and packaging/storage (Alakangas, E. and Paju, 2002; Koppejan et al., 2008), as shown in figure 14.

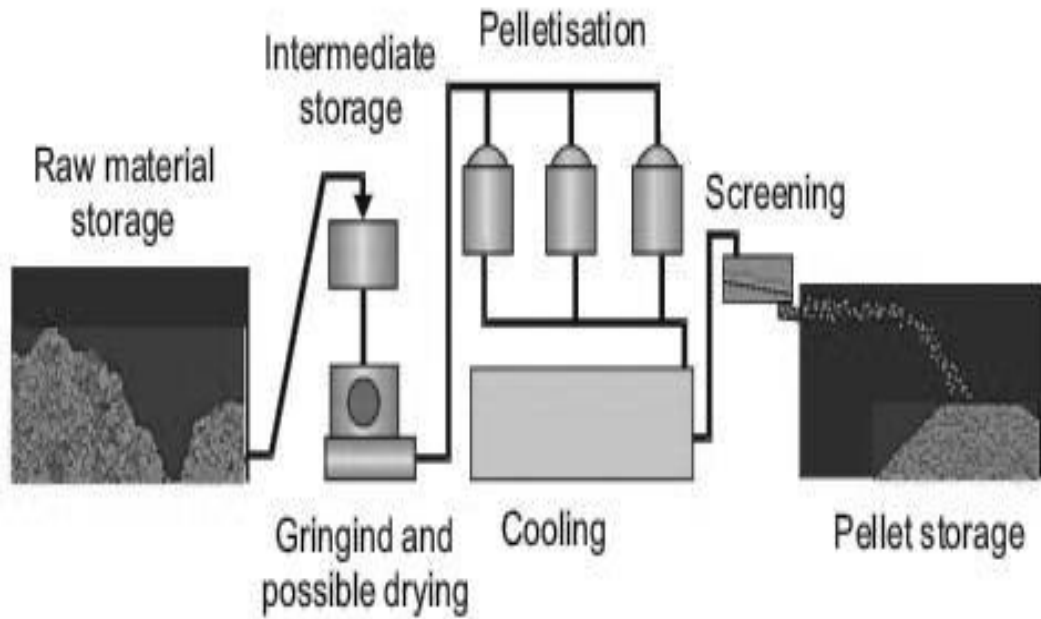


Figure 14. Schema of pellet processing unit

Source: (Alakangas, E. and Paju, 2002).

Drying

Certain amount of moisture is contained in biomass irrespective of its source or form, which must be reduced to achieve desired combustion (Sadaka & Johnson, 2010). Moisture content of the raw material should not be too dry or too wet, it must there for be between 8 and 12wt% (w.b.) before entering the pellet press, depending on the kind of biomass used (Koppejan et al., 2008).

Milling

This involves reduction and homogenizing the particle size of the raw material, usually using hammer mill, depending on the diameter of the pellets that will be produced (Koppejan et al., 2008; Obernberger & Thek, 2010). The screen through which the material passes through after grinding determines the particle size (Obernberger & Thek, 2010).

Conditioning

This is the improvement of adhesion between the particles by introducing steam and covering the surface with thin layer of moisture (Koppejan et al., 2008; Obernberger & Thek, 2010). Adding steam can provide the materials with right temperature required for pelletization, which

depends on the pellets milling technology that will be used. Conditioning can also be achieved by using biological additives, which can be thoroughly mixed with the material before pelletizing (Obernberger & Thek, 2010).

Pelletizing

Pelletization is the production of solid materials of uniform shapes and sizes from powdery or coarse material of partly dissimilar particle size (Obernberger & Thek, 2010). This involve compressing the milled particles in flat or vertical mounted die which bound the pellets by cohesion of inner surface, by fibrous parts of particles and primarily by adhesion caused by lignin (Alakangas, E. and Paju, 2002).

The main designs of pellet mill are ring and flat die (Figure 15). Materials are fed from the sides of the roller and pressed through the die holes of a ring die pellet mill which consist of a die ring that runs around fixed rollers. In flat die pellet mills, materials are conveyed from above onto the flat horizontal die and the roller rotate on top to force it through the die holes (Obernberger & Thek, 2010).

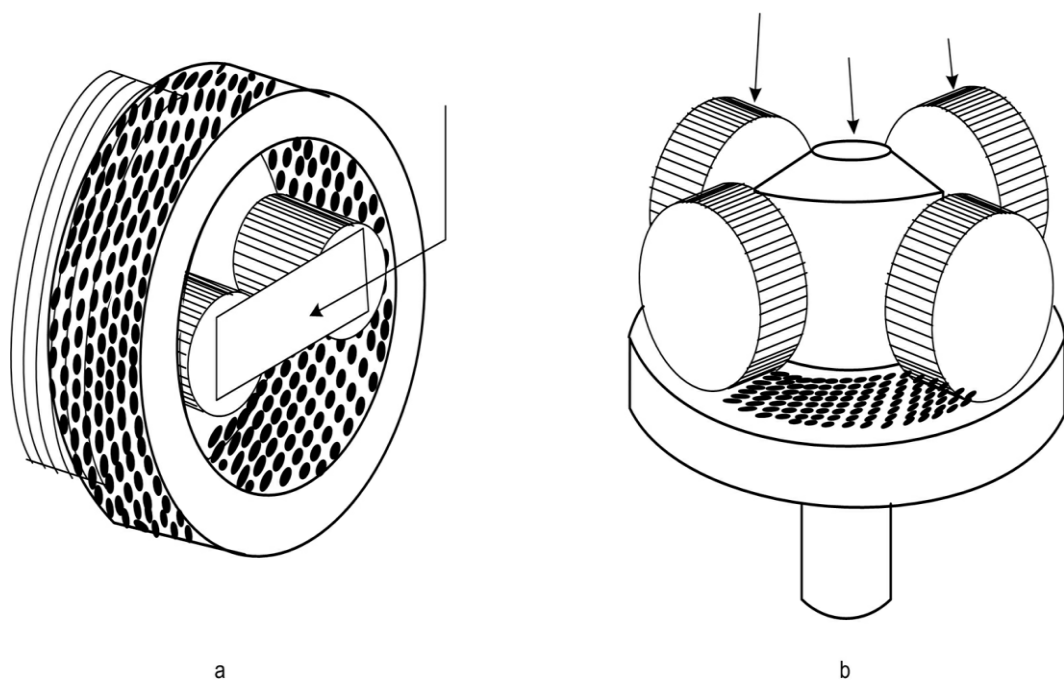


Figure 15. Ring die pelletizer (a) and flat die pelletizer (b)

Source: (Koppejan, Jaap and Van Loo, 2008)

Cooling

In order to have proper and desired quality, the pellets have to be properly cooled (Oberberger & Thek, 2010). The temperature of the pellets is usually around 90°C after compression, it therefore needs to be cooled in order to stabilize and harden the lignin melt on its surfaces, in order to maintain the shape of the pellets (Alakangas, E. and Paju, 2002).

Screening

Screening is the separation of raw material dust from the pellets, usually using vibrating screen, and taking the dust back into the pelletization process (Alakangas, E. and Paju, 2002; Huang, 2016).

3.9.2. Briquette production process

Briquetting is one of the oldest techniques which has been used in Europe since the 19th century to make fuel from low-grade peat and brown coals, even though its use for conversion of agricultural residues is comparatively recent (Eriksson & Prior, 1990). The basic use of briquette can be to substitute wood and coal thereby conserving natural wealth (Grover & Mishra, 1996).

The process involved in the production of briquette are crushing, drying, compaction and cooling (Sharma et al., 2015; Solano et al., 2016).

Crushing

Crushing is the process of reducing the size of particles of the raw material to the energy conversion technology requirement (Solano et al., 2016).

Drying

This is the reduction of the moisture content of biomass through natural processes by exposing it to solar radiation or wind, without supplying any heat externally, or through forced drying by industrial processes (Solano et al., 2016).

The optimum moisture content of raw materials for briquetting is 8-9% and 10-15% for screw extruder and piston press respectively (Grover & Mishra, 1996; Sharma et al., 2015). High moisture content will pose problems in grinding and will require excessive energy for drying (Grover & Mishra, 1996).

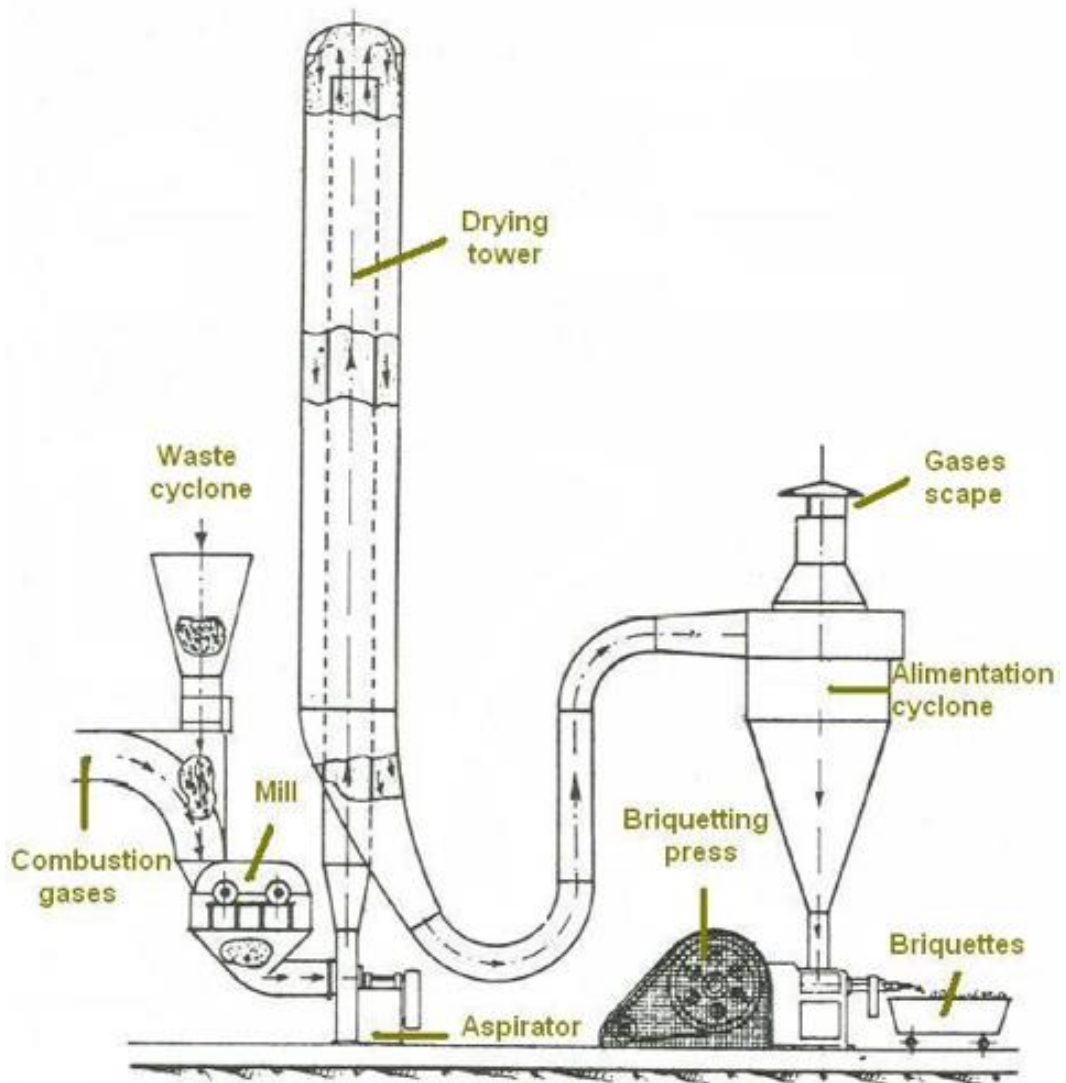


Figure 16. Schema of typical stages in briquette manufacturing

Source: (Solano et al., 2016)

Compaction

This process is called briquetting, which represents the set of technologies used for converting biomass to fuel (Grover & Mishra, 1996). High compaction technology or binderless technology includes the piston press and the screw press (Sharma et al., 2015).

In a screw extruder (Figure 17), the rotating screw takes the material from the feed port, through the barrel, and compacts it against a die which assists the build-up of a pressure gradient along the screw, during which the biomass is forced into intimate and substantially sliding contact with the barrel walls. The temperature generated due to friction in the closed system helps in

heating the biomass, which is then forced through the extrusion die, where the briquette with the required shape is formed (Grover & Mishra, 1996).

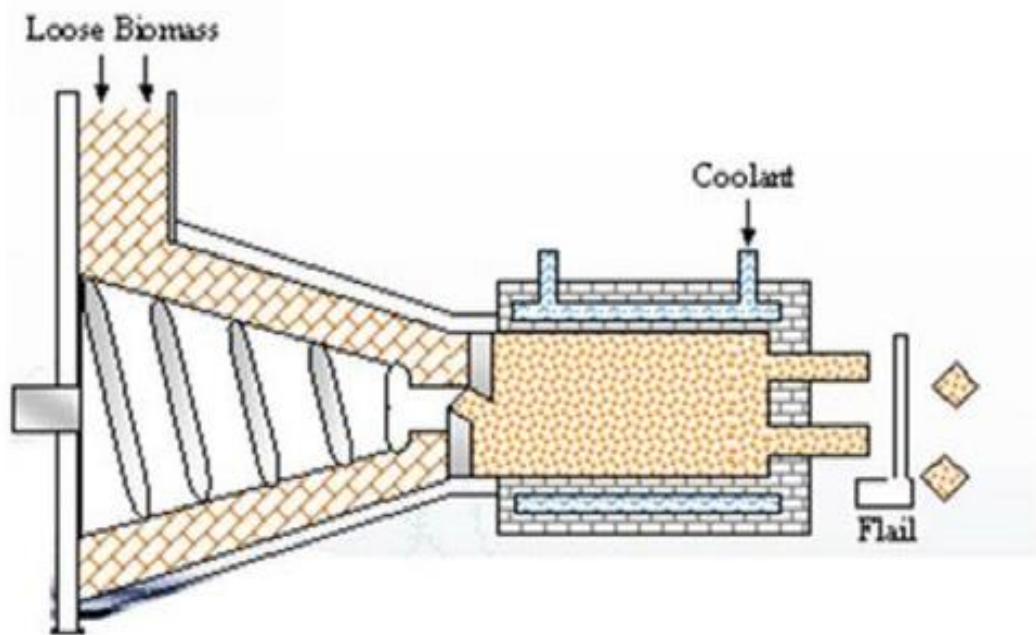


Figure 17. Schema of a screw pressing briquetting machine

Source: (Solano et al., 2016).

In piston press briquetting (figure 18), the pressure is exerted by a cylinder operated by a hydraulic or pneumatic system (Solano et al., 2016) where the biomass is pressed in a die by a reciprocating ram at a very high pressure (Grover & Mishra, 1996).

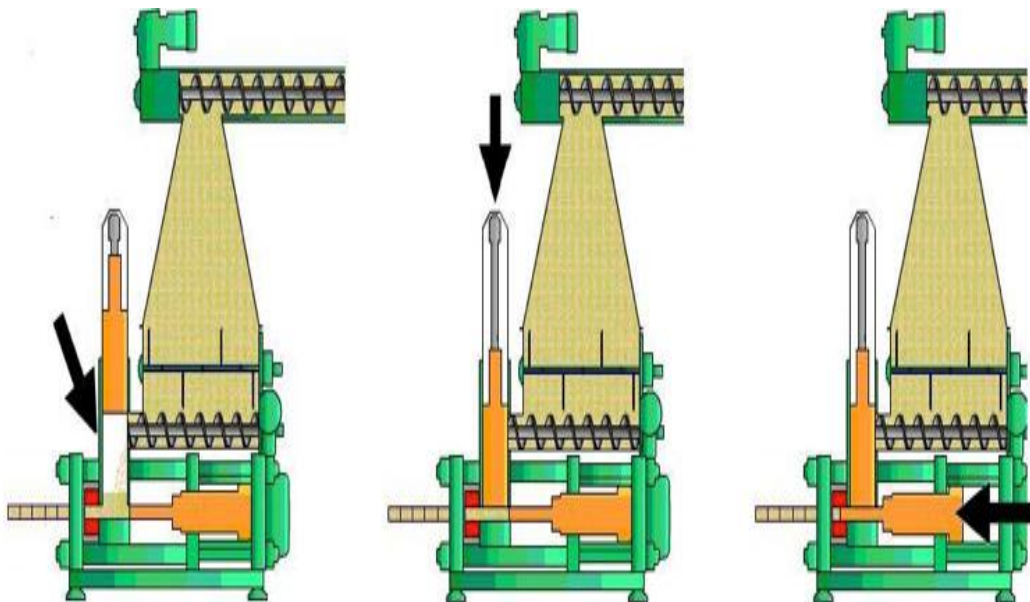


Figure 18. Schema of a hydraulic pressing briquetting machine

Source: (Solano et al., 2016).

4.0. METHODOLOGY OF THE WORK

The study was carried out in three stages which comprised:

- i. Field work (collection of sample)
- ii. Laboratory work
- iii. Data analysis

4.1. Field Work: samples collection

Samples were collected in September 2018 during harvest, from different parts of Bauchi state Nigeria. A digital weighing balance and a container were used in collecting the samples at the points of threshing and their mass were determined using equation (26).

$$m_s = m_1 - m_0 \quad (26)$$

Where: m_s – mass of the sample (g), m_1 – mass of container filled with sample (g), m_0 – mass of empty container (g)

The samples collected are presented in Table 5, together with their quantity.

Table 5. Quantity of samples collected

S/No.	Sample collected	Quantity (g)
1	Maize cobs	1012.5
2	Rice husk	1168.8
3	Millet husk	520.0
4	Groundnut pods	384.0
5	Sorghum husk	876.0

All the samples collected were packaged, labeled and transported to Czech University of Life Sciences Prague, where all the laboratory tests were carried out.

4.2. Laboratory Study

The laboratory tests were carried out through a number of steps as follow:

4.2.1. Samples preparation

For each sample, 200g was separated for the preparation of laboratory samples. The samples were milled to 1mm screen fraction, using the Retsch SM100 impact milling machine (Figure 19) in accordance with BS EN 14780:2011. The by-products were milled through different screen sizes (Appendix A) before achieving the desired sample sizes.

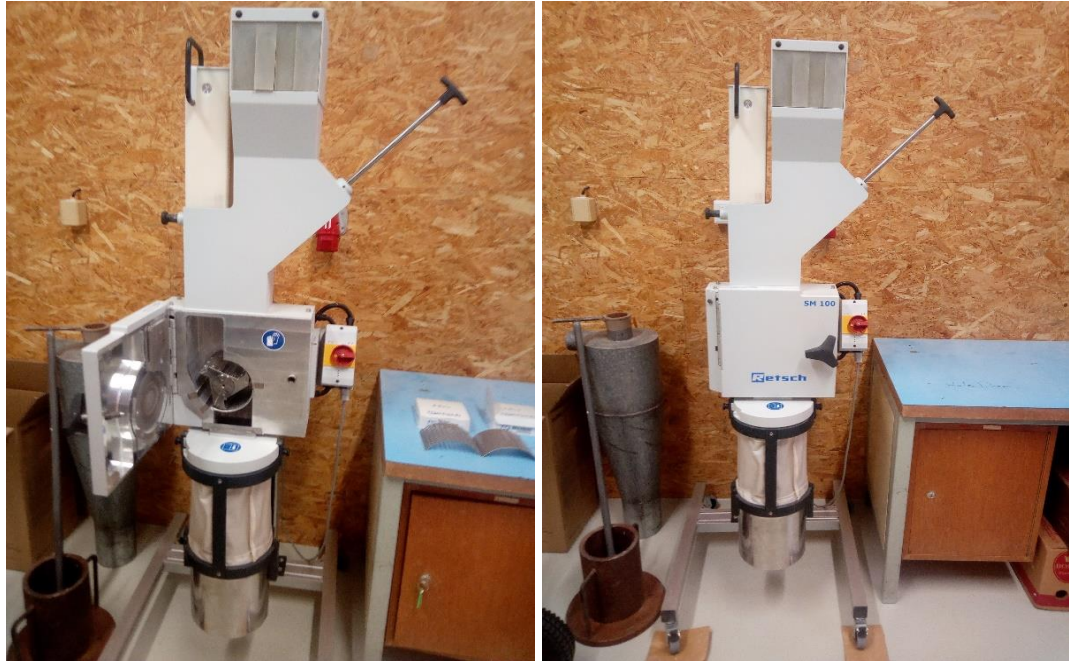


Figure 19. The Retsch SM100 impact milling machine used for particle size reduction

4.2.2. Determination of moisture content

Moisture contents of the raw by-products were determined according to EN ISO 18134–3:2015, using Gallenkamp UF30 hot air laboratory oven (Mettler GmbH, Germany) (Figure 20) at $105\pm 3^\circ\text{C}$ and calculated using equation (27) (Havrland et al., 2013; Pňakovič & Dzurenda, 2015).

$$w = \frac{m_0 - m_1}{m_0} \times 100 \quad (27)$$

Where: w – moisture content, % (in as received basis), m_0 – mass of the samples before drying (g), m_1 – mass of the samples after drying (g).

4.2.1. Thermogravimetric analysis

Thermogravimetric analysis were carried out using LECO TGA701 Thermogravimetric Analyzer (Figure 21) manufactured by LECO corporation; Saint Joseph, Michigan USA. The tests were conducted according to EN ISO 18122:2015 (EN ISO 18122, 2015). The equipment measures weight loss as a function of temperature in a controlled environment..



Figure 20. A caption of Laboratory Oven obtained during laboratory work at Faculty of Engineering, CULS



Figure 21. A caption of Thermogravimetric Analyzer (LECO TGA701) obtained during laboratory work at Faculty of Engineering, CULS

4.2.2. Calorific value

Higher heating value (gross calorific value) of the biomass were measured according to ISO 1928:2009 (Obernberger & Thek, 2010; Pňakovič & Dzurenda, 2015), using LECO AC 600 Calorimeter (Figure 2) manufactured by LECO corporation; Saint Joseph, Michigan USA. Lower Heating Value (Net Calorific Value) of dry basis of the biomass samples were calculated using equation (28) (Obroučka et al., 2005).

$$LHV = (HHV - 212w_{Hd} - 0.8 \cdot (w_{Od} + w_{Hd})) \cdot (1 - 0.01M_T) - 24.43M_T \quad (28)$$

where: LHV – lower heating value, $MJ.kg^{-1}$, HHV – higher heating value, $MJ.kg^{-1}$, w_{Od} – oxygen content in dry state, %wt., w_{Hd} – hydrogen content in dry state, %wt., M_T – target moisture, %wt.

The procedure involves production of pellet from 1g of the milled samples using a pressing die (Appendix A).



Figure 22. A caption of Calorimeter (LECO AC600) obtained during laboratory work at Faculty of Engineering, CULS

4.2.3. Elemental analysis

The composition of biomass in wt% of carbon, hydrogen, oxygen, nitrogen and sulfur were determined through elemental analysis of the by-products (Ivanova et al., 2018; McKendry, 2002a)



Figure 23. A caption of Leco CHN628 and 628 S obtained during laboratory work at Faculty of Engineering, CULS

in accordance with the provision of BS EN ISO16948:2015 (BS EN ISO 16948:2015, 2015), using Leco CHN628/628 S, manufactured by LECO corporation; Saint Joseph, Michigan USA (Figure 23). The sample mass and name were entered into the login. 1g of the sample was sealed into a 502-186 Tin Foil Cup in three replicates and placed to the appropriate position of the sample carouse before initiating the analysis. The results were automatically generated after combustion at 1050°C.

4.3. Combustion Characteristics

Equation (15) - (25) were used for the calculations. In practice, real molar gas volumes are used for conversion (Malat'ák et al., 2013).

Theoretical amount of oxygen for perfect combustion:

$$O_{2,\min} = \frac{22.39}{12.01} \cdot C + \frac{22.39}{4.032} \cdot H + \frac{22.39}{32.06} \cdot S - \frac{22.39}{31.99} \cdot O \quad , \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

Theoretical amount of oxygen for perfect combustion:

$$L_{\min} = O_{2,\min} \cdot \frac{100}{21}, \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

The actual amount of air for perfect combustion:

$$L_{\text{skut}} = O_{2,\min} \cdot \frac{100}{21} \cdot n, \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

Theoretical volume of dry flue gas:

$$v_{fg,\min} = \frac{22.27}{12.01} \cdot C + \frac{21.89}{32.06} \cdot S + \frac{22.40}{28.013} \cdot N + 0.7805 \cdot L_{\min}, \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

Theoretical concentration of CO₂ emission:

$$CO_{2,\max} = \frac{12.01 \cdot C}{V_m(CO_2) \cdot v_{fg,\min}} \cdot 100 \quad (\%)$$

Volumetric amount of CO₂ emission:

$$v(CO_2) = \frac{22.27}{12.01} \cdot C + \frac{C_{\text{atm}}(CO_2)}{100} \cdot L_{\min} \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

Volumetric amount of H₂O:

$$v(H_2O) = \frac{44.82}{4.032} \cdot H + \frac{22.41}{18.015} \cdot W \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

Volumetric amount of N₂:

$$v_{N_2} = \frac{22.40}{28.013} \cdot N + O_{2,\min} \cdot \frac{27.05}{21} \quad (\text{m}^3_{\text{N}} \cdot \text{kg}^{-1})$$

5.0. RESULTS AND DISCUSSION

Proximate and elemental compositions of as received, dry and dry ash-free samples of different biomass materials studied are presented in Tables 6 – 8 along with the associated measures of uncertainty at confidence levels of 95%. The moisture level of the by-products sampled was approximately 7% in dry basis.

For the samples analyzed in as received basis, Groundnut pods and Rice husk had the highest and lowest heating values respectively (Table 6). Ash content in rice husks and millet husk was 22% and 30% respectively, which are higher than the levels observed in other samples whose ash contents were below 10% (Table 6).

High carbon content of 47.68% was observed in groundnut pods, with millet husk having 33.34% as the lowest. Hydrogen content, both including water and in combustible remains intact for all the products with maize cobs having the highest and millet husk having the least. Groundnut pods had relatively high nitrogen content of 1.14% in comparison with the remaining products which had 0.41%-0.86%. The by-products generally had negligible sulfur content of less than 0.05%. Millet husk and maize cobs had relatively lower and higher oxygen content of 26.36% and 39.52% respectively (Table 6).

There was a slight increase in the ash content of dry basis of all the by-products tested. Just like as received basis, the ash content of rice husk and millet husk remains as high as 23.58% and 32.16% respectively. Groundnut shell had 51.78% as the highest content of carbon in dry basis, and the least was millet husk with 35.23%. Hydrogen content also reduces slightly from as received to dry basis, where maize cobs had 5.75% as the highest (Table 7). Slight increase was observed in the nitrogen content of dry basis relative to as received basis of the by-products and sulfur content remains negligible. Like its carbon counterpart, oxygen content of dry basis also increases significantly within the range of 27.85% for millet husk to 42.75% for maize cobs (Table 7). Dry basis of the by-products had higher heating values than their as received counterparts, where groundnut pods leads with 19.19 MJ.kg⁻¹ and milled husk produces 12.48 MJ.kg⁻¹ as the least (Table 7).

Table 6. Proximate and ultimate composition of the analysed biomass together with their respective uncertainties

Sample	<i>W</i> (% wt.)	<i>A</i> (% wt.)	<i>C</i> (% wt.)	<i>H</i> incl. water (% wt.)	<i>H</i> in combustable (% wt.)	<i>N</i> (% wt.)	<i>S</i> (% wt.)	<i>O</i> (% wt.)	<i>HHV</i> <i>MJ.kg⁻¹</i>	<i>LHV</i> <i>MJ.kg⁻¹</i>
Rice	6.63±0.11	22.02±0.15	35.96±0.38	5.37±0.06	4.61±0.06	0.86±0.03	<0.05	29.91±0.42	14.48±0.04	13.32±0.05
Sorghum	7.26±0.09	8.42±0.69	42.29±0.57	5.78±0.08	4.97±0.08	0.41±0.07	<0.05	36.65±0.90	15.93±0.28	14.66±0.16
Groundnut	7.92±0.07	3.19±0.25	47.68±0.26	6.14±0.07	5.26±0.07	1.14±0.05	<0.05	34.83±0.37	18.81±0.07	17.48±0.07
Maize	7.56±0.05	1.66±0.17	45.54±0.26	6.16±0.07	5.32±0.07	0.41±0.05	<0.05	39.52±0.33	17.59±0.16	16.25±0.16
Millet	5.37±0.24	30.43±2.35	33.34±1.48	4.45±0.21	3.85±0.18	0.85±0.12	<0.05	26.36±1.94	12.65±0.48	11.68±0.48

w – moisture content, *A* – ash content, *C* – carbon content, *H* – hydrogen content, *N* – nitrogen content *O* – oxygen content, *HHV* – higher heating value, *LHV* – lower heating value

Table 7. Composition of dry biomass

Sample	<i>A^d</i> (% wt.)	<i>C^d</i> (% wt.)	<i>H^d</i> (% wt.)	<i>N^d</i> (% wt.)	<i>S^d</i> (% wt.)	<i>O^d</i> (% wt.)	<i>HHV</i> <i>MJ.kg⁻¹</i>	<i>LHV</i> <i>MJ.kg⁻¹</i>
Rice	23.58 ± 0.16	38.52 ± 0.41	4.94 ± 0.07	0.92 ± 0.03	<0.05	32.04 ± 0.45	15.52 ± 0.05	14.44 ± 0.05
Sorghum	9.08 ± 0.74	45.60 ± 0.62	5.36 ± 0.08	0.44 ± 0.08	<0.05	39.52 ± 0.97	17.17 ± 0.17	16.00 ± 0.17
Groundnut	3.46 ± 0.27	51.78 ± 0.28	5.71 ± 0.07	1.24 ± 0.05	<0.05	37.82 ± 0.40	20.44 ± 0.08	19.19 ± 0.08
Maize	1.79 ± 0.19	49.26 ± 0.29	5.75 ± 0.07	0.44 ± 0.05	<0.05	42.75 ± 0.35	19.03 ± 0.17	17.78 ± 0.17
Millet	32.16 ± 2.48	35.23 ± 1.56	4.07 ± 0.20	0.89 ± 0.13	<0.05	27.85 ± 2.04	13.37 ± 0.50	12.48 ± 0.51

A^d – ash content in dry state, *C^d* – carbon content in dry state, *H^d* – hydrogen content in dry state, *N^d* – nitrogen content in dry state, *S^d* – sulfur content in dry state *O^d* – oxygen content in dry state, *HHV* – higher heating value, *LHV* – lower heating value

Higher ash content of millet husk can be attributed to contamination with sand or dust particles during threshing and sample collection (Pňakovič & Dzurenda, 2015; Titiloye et al., 2013). Carbon content was higher in the samples with low ash content. Energy values were also higher in materials with low ash content and high carbon content (Table 6). Energy values of the by-products considered ranged between 11.68 – 17.48 MJ.kg⁻¹. Groundnut pods had significantly higher energy values, compared to other materials (Table 6). With the elimination of moisture from product samples, Carbon contents improved significantly, though, no significant change in ash contents was observed for all of the biomass tested (Table 7). Lower moisture content of the biomass favor better thermal conversion (Demirbas, 2007; Palackaa et al., 2017; Titiloye et al., 2013).

Inorganic residue ash of the dry biomass with their respective heating values and ultimate composition are presented in Table 7. Ash content of maize cobs was the least (1.79% wt). Ash content of rice husks was 23.58% which is less than the value reported by (Titiloye et al., 2013) but comparable to that of commercial coal which falls within the range of 5–20% wt (Palackaa et al., 2017). In this state, energy values of the pods of groundnut were the highest, being 19.19 MJ.kg⁻¹ while those of dried millet husks stood at 12.48 MJ.kg⁻¹, comparable to values reported in similar works (Titiloye et al., 2013).

In dry, ash-free basis, however, similar compositions of combustible materials were observed in all five by-products with high content of carbon and oxygen (Table 8) which is greater than their as received and dry basis counterparts. Nitrogen and sulfur levels in the feedstock were low, which indicates a favorable risk of associated oxide emission during combustion (Akhmedov et al., 2017; Garivait et al., 2006; Pňakovič & Dzurenda, 2015). Of all the five samples tested, Groundnut pods had the highest energy value of 19.88 MJ.kg⁻¹ while sorghum husks had 17.59 MJ.kg⁻¹ as the least. These values represent significant proportions and potentials for thermal conversion.

Dried samples have higher energy values than undried samples (Demirbas, 2007; Jagustyn et al., 2011; Kraszkievicz et al., 2015; Palackaa et al., 2017; Paudel et al., 2017; Rosillo-Calle et al., 2007; Titiloye et al., 2013), attributable to low carbon and oxygen content of the undried biomass (Kraszkievicz et al., 2015). More energy may therefore be generated in ash-free basis than the dried and as received basis of the by-products. Agricultural biomass can be improved

Table 8. Chemical composition of combustible matter in dry biomass

Sample	C^{daf} % wt.	H^{daf} % wt.	N^{daf} % wt.	S^{daf} % wt.	O^{daf} % wt.	HHV $MJKg^{-1}$	LHV $MJKg^{-1}$
Rice	50.41 ± 0.05	6.46 ± 0.09	1.20 ± 0.04	<0.05	41.93 ± 0.60	20.30 ± 0.08	18.89 ± 0.08
Sorghum	50.16 ± 0.80	5.89 ± 0.10	0.49 ± 0.08	<0.05	43.46 ± 1.13	18.88 ± 0.10	17.59 ± 0.45
Groundnut	53.63 ± 0.33	5.91 ± 0.08	1.28 ± 0.06	<0.05	39.17 ± 0.43	21.17 ± 0.10	19.88 ± 0.10
Maize	50.16 ± 0.31	5.86 ± 0.07	0.45 ± 0.06	<0.05	43.53 ± 0.37	19.38 ± 0.18	18.10 ± 0.18
Millet	51.94 ± 1.29	5.99 ± 0.19	1.32 ± 0.18	<0.05	41.06 ± 2.61	19.70 ± 0.18	18.40 ± 0.82

C^{daf} – carbon content in dry ash-free state, H^{daf} – hydrogen content in dry ash-free state, N^{daf} – nitrogen content in dry ash-free state O^{daf} – oxygen content in dry ash-free state, HHV – higher heating value, LHV – lower heating value

Table 9. Theoretical combustion properties of the by-products

<i>Volume combustion</i>		Rice husk (m³.kg⁻¹)	Sorghum husk (m³.kg⁻¹)	Groundnut pods (m³.kg⁻¹)	Maize cobs (m³.kg⁻¹)	Millet husk (m³.kg⁻¹)
O_{min}	Theoretical amount of oxygen for perfect combustion	0.72	0.81	0.94	0.87	0.65
L_{min}	Theoretical amount of air for perfect combustion	3.42	3.85	4.46	4.13	3.10
v_{spmin}^s	Theoretical volumetric amount of dry flue gas	3.34	3.79	4.38	4.08	3.05
v_{CO2}	Volumetric amount of CO ₂	0.67	0.79	0.89	0.85	0.62
v_{H2O}	Volumetric amount of H ₂ O	0.88	0.97	1.06	1.03	0.76
v_{N2}	Volumetric amount of N ₂	5.61	6.31	7.33	6.78	5.09
v_{O2}	Volumetric amount of O ₂	0.79	0.89	1.03	0.96	0.72

through pelletization by reducing its moisture content, increasing bulk density and as well increasing its heating value (Jagustyn et al., 2011; Rosillo-Calle et al., 2007).

Simple and cheap Technology can be used for biomass in domestic heating using pellet as a pure combustible material with minimum ash residue which can be easily disposed. Modern heating systems, which include fireplaces, boilers, burners and stoves are fed with pellet for heat generation (Gravalos et al., 2010; Rosillo-Calle et al., 2007). fixed-bed combustion (FxBC), fluidized bed combustion (FBC) and dust combustion (DC) are industrial combustion systems which can be used for biomass combustion (Rosillo-Calle et al., 2007).

5.1. Stoichiometry of Combustion Processes

Theoretical combustion properties of the by-products were calculated from elemental analysis and the result were summarized in Table 9. Excess air were found to be the same for all the by-products (Appendix). As sulfur was discovered to be negligible during elemental analysis, SO₂ emission was found to be zero. In all the samples tested, emission of Argon were discovered to be very low, as shown in the Appendix.

Calorific value of all the the by-products were discovered to increase with decreasing moisture content of the samples as shown in figure 24. This tally with what was discovered in elemental analysis and also what was reported in the literatures as discussed.

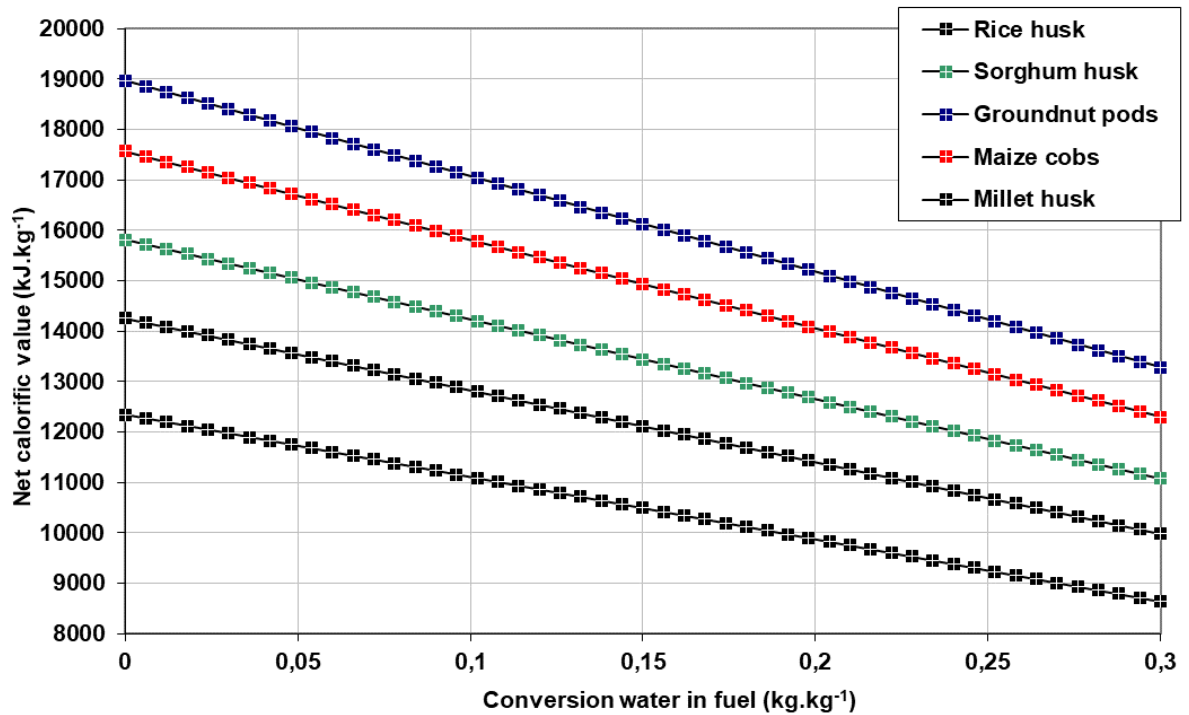


Figure 24. Relationship between NCV and moisture content

5.2. Standards for Pellet and Briquette

The properties of the by-products tested were compared with the given standard limits for graded wood pellet, graded wood briquette, graded non-woody pellet and graded non-woody briquette and were found to meet the requirement for use as one or more of the set standard grade as summarized in Table 10. Due to their high ash content and low calorific value, rice husk and millet husk does not meet the standard of any grade.

Table 10. Comparison of the properties of by-products tested with standard Values

Property	Unit	Graded wood pellets ⁽¹⁾			Graded non-woody pellets ⁽²⁾		Graded wood briquettes ⁽³⁾			Graded non-woody briquettes ⁽⁴⁾		Rice husk	Sorghum husk	Groundnut pods	Maize cobs	Millet husk
		A1	A2	B	A	B	A1	A2	B	A	B					
Moisture	w-% ar	≤ 10 [▣]	≤ 10 [▣]	≤ 10 [▣]	≤ 12 [▣]	≤ 15 [▣]	≤ 12 [▣]	≤ 15 [▣]	≤ 15 [▣]	≤ 12 [▣]	≤ 15 [▣]	6.63	7.26	7.92	7.56	5.37
Ash	w-% d	≤ 0.7	≤ 1.2	≤ 2.0 [♥]	≤ 6 [♥]	≤ 10 ^{♥♥}	≤ 1.0	≤ 1.5	≤ 3.0 [♥]	≤ 6 ^{♥♥}	≤ 10 ^{♥♥}	23.58	9.08	3.46	1.79	32.16
Net calorific value	MJkg ⁻¹ ar	≥ 16.5 [♠]	≥ 16.5 [♠]	≥ 16.5 [♠]	≥ 14.5 ^{♥♥}	≥ 14.5 ^{♥♥}	≥ 15.5 ^{♥♥}	≥ 15.3 ^{♥♥}	≥ 14.9 ^{♥♥}	≥ 14.5 ^{♥♥}	≥ 14.5 ^{♥♥}	13.32	14.66	17.48	16.25	11.68
Nitrogen	w-% d	≤ 0.3	≤ 0.5 ^{♥♥}	≤ 1.0 ^{♥♥♥}	≤ 1.5 [▣]	≤ 2.0 [▣]	≤ 0.3	≤ 0.5 [♥]	≤ 1.0 ^{♥♥♥}	≤ 1.5 [▣]	≤ 2.0 [▣]	0.92	0.44	1.24	0.44	0.89
Sulfur	w-% d	≤ 0.04 [▣]	≤ 0.05 [▣]	≤ 0.05 [▣]	≤ 0.20 [▣]	≤ 0.30 [▣]	≤ 0.04 [▣]	≤ 0.04 [▣]	≤ 0.05 [▣]	≤ 0.20 [▣]	≤ 0.30 [▣]	<0.05	<0.05	<0.05	<0.05	<0.05

ar—as received, d—dry basis, [♠]—Rice husk fulfilled the requirement, [♥]—Sorghum husk fulfilled the requirement, [♦]—Groundnut pods fulfilled the requirement, [♥]—Maize cobs fulfilled the requirement, [♣]—Millet husk fulfilled the requirement, [▣]—All the by-products fulfilled the requirement

⁽¹⁾(EN ISO 17225-2, 2015)

⁽²⁾(BS EN ISO 17225-6, 2014)

⁽³⁾(EN ISO 17225-3, 2014)

⁽⁴⁾(BS EN ISO 17225-7, 2014)

6.0. CONCLUSION

The energy value of some tropical Agricultural by-products were investigated under three different states.

Heating values increases with decreasing moisture content and decreases with increasing ash content.

There was an increase in the amount of carbon and oxygen as the moisture content of the samples tested were decreased.

In the elemental analysis, the dry ash free basis of all the samples tested has the highest heating value, while as received basis has the least.

The biomass have favorable heating values under all the three states.

Small burners (5-16 kW) with moving grate are recommended for these by-products due to their higher ash content. This is to enable automatic ash removal and prevent slag formation in the combustion chamber by ensuring cyclical stirring of furnace in which the ash accumulation and slag formation occur. Continuous removal of combustion products prevent clogging of combustion chamber and does not affect the efficiency of device.

With the exception of millet and rice husks having high ash content and low heating values, all the by-products can be used as standard feedstock for pellet or briquette production.

Sieving millet husk may reduce the sand particles present in it, which may in turn reduces the ash content and increases the heating value.

Mixing rise husk with groundnut shell or maize cobs may help in meeting the standard for utilizing rise husk as feedstock for pellet or briquette production.

Stoves, burners and boilers are heating systems in which the by-products can be used after transformation to pellet or briquette.

The research is intended to continue at doctorate study, where combustion of the by-product may be carried out to determine their true stoichiometry. Modifications by mixing with materials with better combustion properties may be carried out on by-products with low heating

values to improve their heating values and reduces their ash contents. The by-products could be pelletized or briquetted and their various properties may be determined.

7.0. REFERENCES

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8.3. List of Abbreviations and Symbols

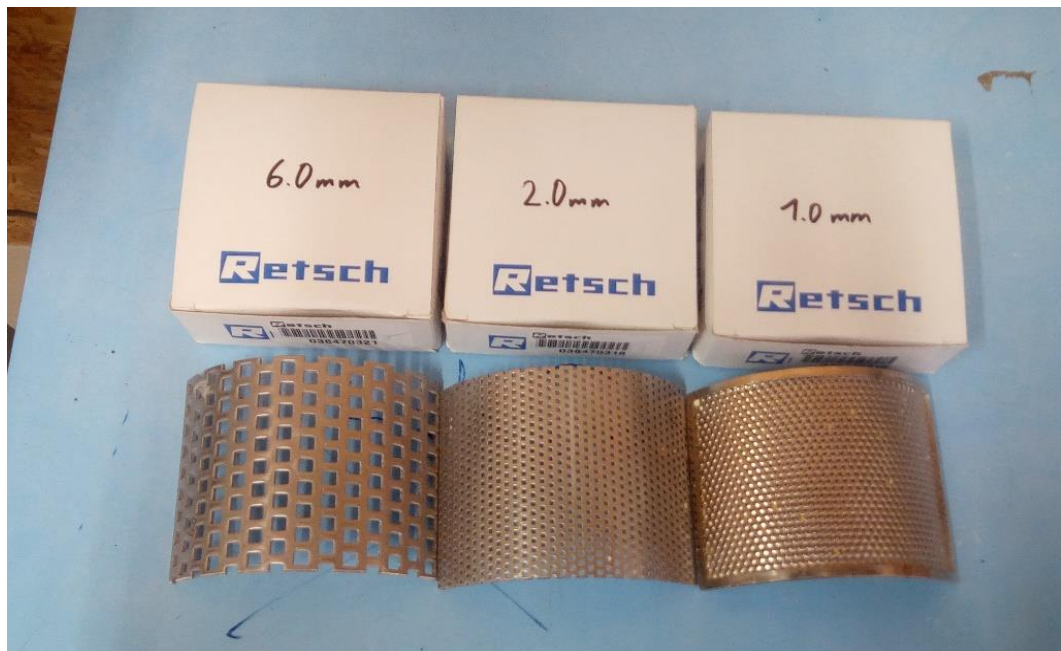
db	dry basis
NO _x	oxides of nitrogen
CO	carbon monoxide
ha	hectare
Mt	metric tone
BSADP	Bauchi state Agricultural development programme
RP	residue production (kg.yr ⁻¹)
RY	residue yield (kg.ha ⁻¹ .yr ⁻¹)
RPR	residue product ratio
Y	crop yield
SO ₂	sulfur oxide
HCl	hydrogen chloride
N	nitrogen
S	sulfur
Cl	chlorine
PM	particulate mater
PM ₁₀	Particulate matter whose diameter is less then or equals to 10µm
PM _{2.5}	Particulate matter whose diameter is less then or equals to 2.5µm
NO	nitrogen oxides
N ₂ O	nitrous oxide
CO _x	oxides of carbon
CO ₂	carbon dioxide
SO _x	oxides of sulfur
SO ₃	sulfur trioxide
EU	European Union
MW	megawatt
wb	wet basis
m _s	mass of sample (g)
w	moisture content (%wt)
LHV, Q _i '	lower hearing value (Net Calorific value) (MJ.kg ⁻¹)
HHV, Q _s '	Higher heating value (Gross Calorific value) (MJ.kg ⁻¹)
A	ash content (%wt)

C	carbon content	(%wt)
H	hydrogen content	(%wt)
N	nitrogen content	(%wt)
S	sulfur content	(%wt)
O	oxygen content	(%wt)
A ^d	ash content in dry state	(%wt)
C ^d	carbon content in dry state	(%wt)
H ^d	hydrogen content in dry state	(%wt)
N ^d	nitrogen content in dry state	(%wt)
S ^d	sulfur content in dry state	(%wt)
O ^d	oxygen content in dry state	(%wt)
C ^{daf}	carbon content in dry ash-free state	(%wt)
H ^{daf}	hydrogen content in dry ash-free state	(%wt)
N ^{daf}	nitrogen content in dry ash-free state	(%wt)
S ^{daf}	sulfur content in dry ash-free state	(%wt)
O ^{daf}	oxygen content in dry ash-free state	(%wt)
n	excess water coefficient	
V _m (X)	molar volume of flue gas specie X	(m ³ .kmol ⁻¹)
M(X)	molar mas of element X that combine with oxygen	(kg.kmol ⁻¹)
L _{min}	theoretical amount of dry air	(m ³ _N kg ⁻¹)
C _{atm} (X)	volumetric concentration of gas 'X' in air	
O _{2min}	theoretical amount of oxygen	(m ³ _N kg ⁻¹)
L _{skut}	real amount of air for perfect combustion	(m ³ _N .kg ⁻¹)
V _{fg}	theoretical amount of dry flue gases	(m ³ _N kg ⁻¹)
CO _{2max}	theoretical concentration of CO ₂ emission	(m ³ _N kg ⁻¹)

Appendix A



A caption of Pressing die for the preparation of pellet obtained during laboratory work at Faculty of Engineering, CULS



Milling screens for the Retsch SM100 impact milling machine.

Appendix B

Stoichiometric calculation of combustion processes

Mass combustion: Rice husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	1,03	kg.kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	4,44	kg.kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	9,32	kg.kg ⁻¹
n	Excess air coefficient	2,10	
m_{sp}^v	Mass amount of wet flue gas	10,36	kg.kg ⁻¹
m_{sp}^s	Mass amount of dry flue gas	9,51	kg.kg ⁻¹
m_{spmin}^s	Theoretical mass amount of dry flue gas	6,68	kg.kg ⁻¹
m_{CO_2}	Mass amount of CO ₂	1,32	kg.kg ⁻¹
m_{SO_2}	Mass amount of SO ₂	0,00	kg.kg ⁻¹
m_{H_2O}	Mass amount of H ₂ O	0,85	kg.kg ⁻¹
m_{N_2}	Mass amount of N ₂	7,04	kg.kg ⁻¹
m_{O_2}	Mass amount of O ₂	1,13	kg.kg ⁻¹
m_{Ar}	Mass amount of Ar	0,01	kg.kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical mass concentration of carbon dioxide in dry flue gas	19,75	%
SO_{2max}	Theoretical mass concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	12,77	%
SO_2	Sulphur dioxide	0,01	%
H_2O	Water	8,24	%
N_2	Nitrogen	67,94	%
O_2	Oxygen	10,93	%

Volumetric combustion: Rice husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,72	m ³ .kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	3,42	m ³ .kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	7,17	m ³ .kg ⁻¹
n	Excess air coefficient	2,10	
V_{sp}^v	Volumetric amount of wet flue gas	8,01	m ³ .kg ⁻¹
V_{sp}^s	Volumetric amount of dry flue gas	7,13	m ³ .kg ⁻¹
V_{spmin}^s	Theoretical volumetric amount of dry flue gas	3,34	m ³ .kg ⁻¹
V_{CO_2}	Volumetric amount of CO ₂	0,67	m ³ .kg ⁻¹
V_{SO_2}	Volumetric amount of SO ₂	0,00	m ³ .kg ⁻¹
V_{H_2O}	Volumetric amount of H ₂ O	0,88	m ³ .kg ⁻¹
V_{N_2}	Volumetric amount of N ₂	5,61	m ³ .kg ⁻¹
V_{O_2}	Volumetric amount of O ₂	0,79	m ³ .kg ⁻¹
V_{Ar}	Volumetric amount of Ar	0,07	m ³ .kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical volumetric concentration of carbon dioxide in dry flue gas	19,96	%
SO_{2max}	Theoretical volumetric concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	8,35	%
SO_2	Sulphur dioxide	0,00	%
H_2O	Water	11,00	%
N_2	Nitrogen	69,97	%
O_2	Oxygen	9,85	%

Mass combustion: Sorghum husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	1,16	kg.kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	5,00	kg.kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	10,49	kg.kg ⁻¹
n	Excess air coefficient	2,10	
m^v_{sp}	Mass amount of wet flue gas	11,71	kg.kg ⁻¹
m^s_{sp}	Mass amount of dry flue gas	10,77	kg.kg ⁻¹
m^s_{spmin}	Theoretical mass amount of dry flue gas	7,33	kg.kg ⁻¹
m_{CO_2}	Mass amount of CO ₂	1,56	kg.kg ⁻¹
m_{SO_2}	Mass amount of SO ₂	0,00	kg.kg ⁻¹
m_{H_2O}	Mass amount of H ₂ O	0,94	kg.kg ⁻¹
m_{N_2}	Mass amount of N ₂	7,92	kg.kg ⁻¹
m_{O_2}	Mass amount of O ₂	1,28	kg.kg ⁻¹
m_{Ar}	Mass amount of Ar	0,01	kg.kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical mass concentration of carbon dioxide in dry flue gas	21,16	%
SO_{2max}	Theoretical mass concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	13,28	%
SO_2	Sulphur dioxide	0,01	%
H_2O	Water	8,03	%
N_2	Nitrogen	67,68	%
O_2	Oxygen	10,89	%

Volumetric combustion: Sorghum husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,81	m ³ .kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	3,85	m ³ .kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	8,08	m ³ .kg ⁻¹
n	Excess air coefficient	2,10	
v^v_{sp}	Volumetric amount of wet flue gas	9,03	m ³ .kg ⁻¹
v^s_{sp}	Volumetric amount of dry flue gas	8,06	m ³ .kg ⁻¹
v^s_{spmin}	Theoretical volumetric amount of dry flue gas	3,79	m ³ .kg ⁻¹
v_{CO_2}	Volumetric amount of CO ₂	0,79	m ³ .kg ⁻¹
v_{SO_2}	Volumetric amount of SO ₂	0,00	m ³ .kg ⁻¹
v_{H_2O}	Volumetric amount of H ₂ O	0,97	m ³ .kg ⁻¹
v_{N_2}	Volumetric amount of N ₂	6,31	m ³ .kg ⁻¹
v_{O_2}	Volumetric amount of O ₂	0,89	m ³ .kg ⁻¹
v_{Ar}	Volumetric amount of Ar	0,07	m ³ .kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical volumetric concentration of carbon dioxide in dry flue gas	20,68	%
SO_{2max}	Theoretical volumetric concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	8,71	%
SO_2	Sulphur dioxide	0,00	%
H_2O	Water	10,70	%
N_2	Nitrogen	69,91	%
O_2	Oxygen	9,85	%

Mass combustion: Groundnut pods			
O_{min}	Theoretical amount of oxygen for perfect combustion	1,34	kg.kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	5,80	kg.kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	12,17	kg.kg ⁻¹
n	Excess air coefficient	2,10	
m^v_{sp}	Mass amount of wet flue gas	13,49	kg.kg ⁻¹
m^s_{sp}	Mass amount of dry flue gas	12,45	kg.kg ⁻¹
m^s_{spmin}	Theoretical mass amount of dry flue gas	8,13	kg.kg ⁻¹
m_{CO_2}	Mass amount of CO ₂	1,75	kg.kg ⁻¹
m_{SO_2}	Mass amount of SO ₂	0,00	kg.kg ⁻¹
m_{H_2O}	Mass amount of H ₂ O	1,04	kg.kg ⁻¹
m_{N_2}	Mass amount of N ₂	9,20	kg.kg ⁻¹
m_{O_2}	Mass amount of O ₂	1,48	kg.kg ⁻¹
m_{Ar}	Mass amount of Ar	0,02	kg.kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical mass concentration of carbon dioxide in dry flue gas	21,49	%
SO_{2max}	Theoretical mass concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	13,01	%
SO_2	Sulphur dioxide	0,01	%
H_2O	Water	7,71	%
N_2	Nitrogen	68,20	%
O_2	Oxygen	10,97	%

Volumetric combustion: Groundnut pods			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,94	m ³ .kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	4,46	m ³ .kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	9,38	m ³ .kg ⁻¹
n	Excess air coefficient	2,10	
v^v_{sp}	Volumetric amount of wet flue gas	10,39	m ³ .kg ⁻¹
v^s_{sp}	Volumetric amount of dry flue gas	9,33	m ³ .kg ⁻¹
v^s_{spmin}	Theoretical volumetric amount of dry flue gas	4,38	m ³ .kg ⁻¹
v_{CO_2}	Volumetric amount of CO ₂	0,89	m ³ .kg ⁻¹
v_{SO_2}	Volumetric amount of SO ₂	0,00	m ³ .kg ⁻¹
v_{H_2O}	Volumetric amount of H ₂ O	1,06	m ³ .kg ⁻¹
v_{N_2}	Volumetric amount of N ₂	7,33	m ³ .kg ⁻¹
v_{O_2}	Volumetric amount of O ₂	1,03	m ³ .kg ⁻¹
v_{Ar}	Volumetric amount of Ar	0,09	m ³ .kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical volumetric concentration of carbon dioxide in dry flue gas	20,19	%
SO_{2max}	Theoretical volumetric concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	8,54	%
SO_2	Sulphur dioxide	0,00	%
H_2O	Water	10,18	%
N_2	Nitrogen	70,52	%
O_2	Oxygen	9,93	%

Mass combustion: Maize cobs			
O_{min}	Theoretical amount of oxygen for perfect combustion	1,25	kg.kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	5,37	kg.kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	11,27	kg.kg ⁻¹
n	Excess air coefficient	2,10	
m^v_{sp}	Mass amount of wet flue gas	12,58	kg.kg ⁻¹
m^s_{sp}	Mass amount of dry flue gas	11,57	kg.kg ⁻¹
m^s_{spmin}	Theoretical mass amount of dry flue gas	7,73	kg.kg ⁻¹
m_{CO_2}	Mass amount of CO ₂	1,67	kg.kg ⁻¹
m_{SO_2}	Mass amount of SO ₂	0,00	kg.kg ⁻¹
m_{H_2O}	Mass amount of H ₂ O	1,01	kg.kg ⁻¹
m_{N_2}	Mass amount of N ₂	8,51	kg.kg ⁻¹
m_{O_2}	Mass amount of O ₂	1,37	kg.kg ⁻¹
m_{Ar}	Mass amount of Ar	0,01	kg.kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical mass concentration of carbon dioxide in dry flue gas	21,61	%
SO_{2max}	Theoretical mass concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	13,32	%
SO_2	Sulphur dioxide	0,01	%
H_2O	Water	7,99	%
N_2	Nitrogen	67,68	%
O_2	Oxygen	10,89	%

Volumetric combustion: Maize cobs			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,87	m ³ .kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	4,13	m ³ .kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	8,68	m ³ .kg ⁻¹
n	Excess air coefficient	2,10	
v^v_{sp}	Volumetric amount of wet flue gas	9,69	m ³ .kg ⁻¹
v^s_{sp}	Volumetric amount of dry flue gas	8,66	m ³ .kg ⁻¹
v^s_{spmin}	Theoretical volumetric amount of dry flue gas	4,08	m ³ .kg ⁻¹
v_{CO_2}	Volumetric amount of CO ₂	0,85	m ³ .kg ⁻¹
v_{SO_2}	Volumetric amount of SO ₂	0,00	m ³ .kg ⁻¹
v_{H_2O}	Volumetric amount of H ₂ O	1,03	m ³ .kg ⁻¹
v_{N_2}	Volumetric amount of N ₂	6,78	m ³ .kg ⁻¹
v_{O_2}	Volumetric amount of O ₂	0,96	m ³ .kg ⁻¹
v_{Ar}	Volumetric amount of Ar	0,08	m ³ .kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical volumetric concentration of carbon dioxide in dry flue gas	20,72	%
SO_{2max}	Theoretical volumetric concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	8,74	%
SO_2	Sulphur dioxide	0,00	%
H_2O	Water	10,65	%
N_2	Nitrogen	69,93	%
O_2	Oxygen	9,85	%

Mass combustion: Millet husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,93	kg.kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	4,03	kg.kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	8,45	kg.kg ⁻¹
n	Excess air coefficient	2,10	
m^v_{sp}	Mass amount of wet flue gas	9,39	kg.kg ⁻¹
m^s_{sp}	Mass amount of dry flue gas	8,65	kg.kg ⁻¹
m^s_{spmin}	Theoretical mass amount of dry flue gas	6,27	kg.kg ⁻¹
m_{CO_2}	Mass amount of CO ₂	1,23	kg.kg ⁻¹
m_{SO_2}	Mass amount of SO ₂	0,00	kg.kg ⁻¹
m_{H_2O}	Mass amount of H ₂ O	0,74	kg.kg ⁻¹
m_{N_2}	Mass amount of N ₂	6,39	kg.kg ⁻¹
m_{O_2}	Mass amount of O ₂	1,03	kg.kg ⁻¹
m_{Ar}	Mass amount of Ar	0,01	kg.kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical mass concentration of carbon dioxide in dry flue gas	19,50	%
SO_{2max}	Theoretical mass concentration of sulfur dioxide in dry flue gas	0,02	%
CO_2	Carbon dioxide	13,06	%
SO_2	Sulphur dioxide	0,01	%
H_2O	Water	7,86	%
N_2	Nitrogen	68,02	%
O_2	Oxygen	10,94	%

Volumetric combustion: Millet husk			
O_{min}	Theoretical amount of oxygen for perfect combustion	0,65	m ³ .kg ⁻¹
L_{min}	Theoretical amount of air for perfect combustion	3,10	m ³ .kg ⁻¹
L_{skut}	Real amount of air for perfect combustion	6,51	m ³ .kg ⁻¹
n	Excess air coefficient	2,10	
V^v_{sp}	Volumetric amount of wet flue gas	7,24	m ³ .kg ⁻¹
V^s_{sp}	Volumetric amount of dry flue gas	6,49	m ³ .kg ⁻¹
V^s_{spmin}	Theoretical volumetric amount of dry flue gas	3,05	m ³ .kg ⁻¹
V_{CO_2}	Volumetric amount of CO ₂	0,62	m ³ .kg ⁻¹
V_{SO_2}	Volumetric amount of SO ₂	0,00	m ³ .kg ⁻¹
V_{H_2O}	Volumetric amount of H ₂ O	0,76	m ³ .kg ⁻¹
V_{N_2}	Volumetric amount of N ₂	5,09	m ³ .kg ⁻¹
V_{O_2}	Volumetric amount of O ₂	0,72	m ³ .kg ⁻¹
V_{Ar}	Volumetric amount of Ar	0,06	m ³ .kg ⁻¹
Expression of individual flue gas components in %			
CO_{2max}	Theoretical volumetric concentration of carbon dioxide in dry flue gas	20,30	%
SO_{2max}	Theoretical volumetric concentration of sulfur dioxide in dry flue gas	0,01	%
CO_2	Carbon dioxide	8,56	%
SO_2	Sulphur dioxide	0,00	%
H_2O	Water	10,43	%
N_2	Nitrogen	70,28	%
O_2	Oxygen	9,89	%

$\sigma(W_i)$					
All water in fuel	Rice husk	Sorghum husk	Groundnut pods	Maize cobs	Millet husk
(kg.kg ⁻¹)	(kJ.kg ⁻¹)	(kJ.kg ⁻¹)	(kJ.kg ⁻¹)	(kJ.kg ⁻¹)	(kJ.kg ⁻¹)
0	14257	15816	18971	17573	12341
0,006	14172	15721	18857	17467	12267
0,012	14086	15626	18743	17362	12193
0,018	14000	15531	18629	17256	12119
0,024	13915	15436	18516	17151	12045
0,03	13829	15342	18402	17045	11971
0,036	13744	15247	18288	16940	11897
0,042	13658	15152	18174	16834	11823
0,048	13573	15057	18060	16729	11749
0,054	13487	14962	17946	16624	11675
0,06	13401	14867	17833	16518	11601
0,066	13316	14772	17719	16413	11527
0,072	13230	14677	17605	16307	11452
0,078	13145	14582	17491	16202	11378
0,084	13059	14487	17377	16096	11304
0,09	12974	14392	17263	15991	11230
0,096	12888	14298	17150	15885	11156
0,102	12803	14203	17036	15780	11082
0,108	12717	14108	16922	15675	11008
0,114	12631	14013	16808	15569	10934
0,12	12546	13918	16694	15464	10860
0,126	12460	13823	16580	15358	10786
0,132	12375	13728	16466	15253	10712
0,138	12289	13633	16353	15147	10638
0,144	12204	13538	16239	15042	10564
0,15	12118	13443	16125	14936	10490
0,156	12033	13348	16011	14831	10416
0,162	11947	13254	15897	14725	10342
0,168	11861	13159	15783	14620	10267
0,174	11776	13064	15670	14515	10193
0,18	11690	12969	15556	14409	10119
0,186	11605	12874	15442	14304	10045
0,192	11519	12779	15328	14198	9971
0,198	11434	12684	15214	14093	9897
0,204	11348	12589	15100	13987	9823
0,21	11263	12494	14987	13882	9749
0,216	11177	12399	14873	13776	9675
0,222	11091	12304	14759	13671	9601
0,228	11006	12209	14645	13566	9527
0,234	10920	12115	14531	13460	9453
0,24	10835	12020	14417	13355	9379
0,246	10749	11925	14303	13249	9305
0,252	10664	11830	14190	13144	9231
0,258	10578	11735	14076	13038	9157
0,264	10493	11640	13962	12933	9082
0,27	10407	11545	13848	12827	9008
0,276	10321	11450	13734	12722	8934
0,282	10236	11355	13620	12616	8860
0,288	10150	11260	13507	12511	8786

0,294	10065	11165	13393	12406	8712
0,3	9979	11071	13279	12300	8638

P_k	Rice husk	Sorghum husk	Groundnut pods	Maize cobs	Millet husk
(kW)	(kg.h ⁻¹)	(kg.h ⁻¹)	(kg.h ⁻¹)	(kg.h ⁻¹)	(kg.h ⁻¹)
30,00	10,14	9,20	7,73	8,31	11,56
50,00	16,90	15,34	12,88	13,85	19,27
70,00	23,66	21,48	18,03	19,39	26,97
90,00	30,42	27,61	23,18	24,93	34,68
110,00	37,19	33,75	28,34	30,47	42,39
130,00	43,95	39,88	33,49	36,01	50,09
150,00	50,71	46,02	38,64	41,55	57,80
170,00	57,47	52,16	43,79	47,09	65,51
190,00	64,23	58,29	48,95	52,63	73,21
210,00	70,99	64,43	54,10	58,18	80,92
230,00	77,75	70,56	59,25	63,72	88,63
250,00	84,51	76,70	64,40	69,26	96,33
270,00	91,27	82,84	69,55	74,80	104,04
290,00	98,03	88,97	74,71	80,34	111,75
310,00	104,80	95,11	79,86	85,88	119,45
330,00	111,56	101,24	85,01	91,42	127,16
350,00	118,32	107,38	90,16	96,96	134,86
370,00	125,08	113,51	95,32	102,50	142,57
390,00	131,84	119,65	100,47	108,04	150,28
410,00	138,60	125,79	105,62	113,58	157,98
430,00	145,36	131,92	110,77	119,12	165,69
450,00	152,12	138,06	115,92	124,66	173,40
470,00	158,88	144,19	121,08	130,20	181,10
490,00	165,64	150,33	126,23	135,74	188,81
510,00	172,41	156,47	131,38	141,28	196,52
530,00	179,17	162,60	136,53	146,82	204,22
550,00	185,93	168,74	141,69	152,36	211,93
570,00	192,69	174,87	146,84	157,90	219,64
590,00	199,45	181,01	151,99	163,45	227,34
610,00	206,21	187,15	157,14	168,99	235,05
630,00	212,97	193,28	162,29	174,53	242,76
650,00	219,73	199,42	167,45	180,07	250,46
670,00	226,49	205,55	172,60	185,61	258,17
690,00	233,25	211,69	177,75	191,15	265,88
710,00	240,02	217,83	182,90	196,69	273,58
730,00	246,78	223,96	188,06	202,23	281,29
750,00	253,54	230,10	193,21	207,77	289,00
770,00	260,30	236,23	198,36	213,31	296,70

790,00	267,06	242,37	203,51	218,85	304,41
810,00	273,82	248,51	208,66	224,39	312,12
830,00	280,58	254,64	213,82	229,93	319,82
850,00	287,34	260,78	218,97	235,47	327,53
870,00	294,10	266,91	224,12	241,01	335,24
890,00	300,86	273,05	229,27	246,55	342,94
910,00	307,62	279,19	234,43	252,09	350,65
930,00	314,39	285,32	239,58	257,63	358,36
950,00	321,15	291,46	244,73	263,17	366,06
970,00	327,91	297,59	249,88	268,72	373,77
990,00	334,67	303,73	255,03	274,26	381,48
1010,00	341,43	309,86	260,19	279,80	389,18
1030,00	348,19	316,00	265,34	285,34	396,89