National Centre for Energy and Environment, Energy Commission of Nigeria, University of Benin:
ISSN 2504-9593
DOI: 10.5281/zenodo.19102300
https://ijree.com/index.php/publications/article/view/55
Int. J. Renew. Energ & Environ Vol.4 (1), pp 279-296(2026)

THE POTENTIALS, PROBLEMS AND PROSPECTS OF BIOMASS ENERGY: A REVIEW

[1]Abdulsalam, I. A., [2]Akande, F. B., [1]Olaniyan, A. R., [2]Omoyeni, O. D. and [2]*Oladejo, C. B.
[1]Department of Agricultural Engineering, Osun State University, Osogbo.
[2]Department of Agricultural Engineering, Ladoke Akintola University of Technology, Ogbomoso
*Corresponding Author: +2347032748105, oladejocb@lautech.edu.ng

ABSTRACT
Global increase in energy demand and dependence on fossil fuels have highlighted the need for sustainable alternatives, prompting expanded research into biomass as a renewable energy resource. Biomass are materials that have their route from organic materials like plants and animals, including by-products of agricultural, food and livestock industries have been confirmed as a source of renewable energy. This review provides an extensive assessment of energy derivative from biomass, their properties, prospect and challenges in utilisation as a source of energy. Papers from different authors were reviewed and their results point towards the problems encountered in their utilization; the merits proclaimed by authors of previous research have been pointed. Despite the hype in sustainability, reliability and environmental conserving properties, most countries are still over-reliant on fossil fuel. Therefore, this review highlights the merits and demerits of the use of biomass energy as a close substitute for conventional forms of energy It is concluded that most of the harmonisation techniques of using biomass a source of energy is still at the laboratory scale in some developing countries and ways of commercialising this technology was suggested.
Keywords: Renewable energy, biomass, Biomass conversion, Agricultural residues

INTRODUCTION

1.0 Background of study

Biomass is a term used to describe all organic matter produced by photosynthesis, existing on the earth's surface. They include all water- and -land based vegetation and trees, all waste biomass such as municipal solid waste, municipal bio-solids (sewage), and animal wastes (manures), forestry and agricultural residues, and certain types of industrial waste (Waluyo et al., 2022). Biomass resources mainly come from traditional plantation, natural forests, forest plantation, home gardens and other agricultural lands. Further, oil-rich algae, animal wastes and the organic component of municipal and industrial waste
are also important forms of biomass resources (Malik et al., 2015).
Biomass function as a sort of natural battery for storing solar energy, through the process of photosynthesis, chlorophyll in plants captures the suns energy by converting carbon dioxide

from air and water from the ground into carbohydrates (complex compounds composed of carbon, hydrogen and oxygen) (Chandrakanth and Anilkumar, 2025; D. S. Kumar et al., 2024; Mallikarjun and Jyothi, 2025). When these carbohydrates are burned, they turn back into carbon dioxide and water and release the suns energy they contain. The energy released can be converted to thermal energy, liquid, solid or gaseous fuels and other products through a variety of conversion processes (Adams et al., 2018).
Massive utilization of energy in recent years has become a worldwide phenomenon, with fossil fuel consumption being the main source of energy (Fournel et al., 2015). As a result, research on new forms of energy has been conducted that promotes the

development of new sustainable technologies using renewable raw materials (Dudin et al., 2019; Østergaard et al., 2020). Biomass can be considered as one of those new and renewable products (Goyal et al., 2008). Biomass is abundant in nature and broadly dispersed globally with its distribution being dependent on geographical area. Countries such as Brazil and Nigeria have significant natural resources to produce transportation biofuels, bio-power and bio-products from biomass (Ben-Iwo et al., 2016). Biomass provides a measure of energy to many countries including green technologies, biofuels and bioproducts, effective for decreasing greenhouse gas emissions and global warming, while meeting humanity's energy requirements (Mensah and Yankson, 2025). However, supporting technologies are not widely accepted, largely because of low returns for biomass producers (Antar et al., 2021; Nunes, 2024; Sherwood, 2020).

Despite the environmental benefits of biomass as a renewable energy source, the method of its utilization is critical (Adekoya et al., 2023; Kumar, 2022). While bioenergy with carbon capture and storage (BECCS) systems are considered essential for achieving net-zero greenhouse gas emissions, process safety considerations remain paramount due to the inherent risks associated with handling and converting biomass (Ogle et al., 2025). The need for sustainable bioenergy systems that consider both environmental and social impacts is increasingly recognized, especially in the context of energy justice in developing countries (Baqir et al., 2024; Benoist et al., 2024; Grant et al., 2021). The issue of biomass waste management is complicated, this highlights the need for effective pre-treatment techniques to ensure the quality and safety of biomass as a fuel source (González-González et al., 2023; Sahil et al., 2024). To mitigate these hazards, there is a global push towards cleaner conversion technologies such as gasification, pyrolysis, and anaerobic digestion, coupled with stringent emission controls and circular resource management (Elboughdiri et al., 2024; Foong et al., 2020; González-González et al., 2023; Y. Jiang et al., 2024). These advanced approaches aim to transform biomass waste into value-added products, minimizing environmental impact and promoting sustainable development (Lin et al., 2024; Oluyinka et al., 2022; Usmani et al., 2021). The aim of these work is to review the potentials of biomass resources while identifying their environmental impact and their feasibility as an alternate source of energy.

2.1 Environmental/ Health Hazard Associated with Conventional Methods of Utilization and Disposal of Biomass

Municipal waste, industrial waste and agricultural residues can have serious impacts on local environments. Cumulatively, human-produced waste represents an issue of global concern (Pintana et al., 2020). The environmental effects of traditional modes of disposal of municipal wastes in rivers, ponds, ocean and on land are; anaerobic decomposition of solid wastes in landfills and open dumps leading to methane (a greenhouse gas) emission, leaching which leads to pollution of water bodies, incineration of waste leads to emission of dust, metals, organic compounds, acids, dioxins and other pollutants (Palmisano and Barlaz, 2020).

The utilization and disposal of biomass through conventional means, particularly open burning and inefficient combustion, pose significant environmental and health hazards globally (Dirisu, Oyedepo, et al., 2024; Lazaro and Baba, 2023). These hazards originate from the release of complex mixture of pollutants into the atmosphere, contributing to air pollution, climate change, and various adverse health outcomes (Chen et al., 2023). One of the primary environmental hazards associated with biomass combustion is the emission of particulate matter (PM) (Chen et al., 2023; Krecl et al., 2023; Lazaro and Baba, 2023). Particulate matter are fine particles, whose diameter are on the micro scale. They are characterized by long distances travel and can penetrate deep into the human respiratory system (Deuja et al., 2024; Krecl et al., 2023). Beyond particulate matter, biomass combustion also liberates a variety of hazardous gases and organic compounds. These include carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) (Lazaro and Baba, 2023; Verma et al., 2021). PAHs are particularly concerning due to their carcinogenic and mutagenic properties. Research on emissions from burning different biomass fuels identified 11 out of 16 priority PAHs, highlighting the potential cancer risks associated with these practices (Verma et al., 2021).

The reliance on solid fuels especially wood, for cooking, in developing countries is a major contributor to indoor air pollution. This disproportionately affects women and children who spend more time indoors, exposing them to concentrations of pollutants that can be 10-100 times higher than World Health Organization guidelines (Neumann et al., 2024), lead to acute lower respiratory infections, chronic obstructive pulmonary disease (COPD), ischemic heart disease, and lung cancer (Cummings et al., 2023; Neumann et al., 2024). Furthermore, biomass storage, particularly wood chips in heating plants, can lead to the proliferation of phytopathogens and fungal aerosols, posing respiratory health risks to workers (Br\kagoszewska and Pawlak, 2021; Lieskovský and Gejdoš, 2023).

Improper disposal and storage of biomass also present risks of Landfilling of organic waste including biomass, methane (CH_4, a potent greenhouse gas) generation and produces leachate that can contaminate groundwater with heavy metals and organic toxins (Blair and Mataraarachchi, 2021). The ash produced from biomass combustion can also be a significant environmental concern (Bonfim and de Paula, 2021; Munawar et al., 2021). Depending on the biomass source and combustion conditions, ash may contain heavy metals and other toxic substances, posing risks through soil contamination and bioaccumulation (Bonfim and de Paula, 2021; Sharma et al., 2023). While biomass ash can have potential applications as supplementary cementitious material, its proper management and characterization are crucial to avoid environmental problems (Bonfim and de Paula, 2021). The increasing use of biomass for power generation means that the quantity of ash from power plants is also rising, leading to challenges in handling and utilization (Munawar et al., 2021).

Although, agricultural residues constitute an important source of energy in rural areas of developing countries. It was estimated that over than three billion people depend on solid fuels, including biomass (wood, dung and agricultural residues) and coal, to meet their most basic energy needs: cooking, boiling water and heating (Kumar et al., 2023). Traditionally, these materials are also employed as natural fertilizers when left on fields to decay, improving the fertility of the soil (Ayamba et al., 2021; Sarkar et al., 2020; Singh et al., 2019). It is important to note that all residues do not have the same effect on the soil (Fu et al., 2021). Some residues such as corncobs, rice husk, juke sticks, cotton stock, coffee pruning's and coconut shells do not decompose easily and have adverse effect on faming activities (Biswas, 2022; Thakur et al., 2025), there by rendering such residues un-useful for soil reclamation purposes (Naveen et al., 2018). Aside burning which poses threat to human health and environment (Jakhar et al., 2023), these residues can be used in the production of energetic materials which can add to the world economy at large (Ribeiro and Junior, 2023).

2.2 Biomass as a Renewable Energy Resources

The development and growth of a nation depends greatly on adequate supply, security and efficient use of energy (Abdallah et al., 2015). The global energy crisis and global warming impacts has raised alarm for the diversification of energy sources from the utilization of fosil fuels (Farghali et al., 2023; Gajdzik et al., 2024). Alternative forms of energy include energy sources that are clean, sustainable and renewable and are being sourced from the exploration of wind, solar, hydroelectric, geothermal and biomass energy sources (Nautiyal and Ramlal, 2021). Biomass provide about 70% of the total energy consumption in some developing countries (Jekayinfa et al., 2020). It is the dominant energy source in Nigeria due to the huge reliance on the energy source for cooking and heating purpose. Biomass energy potential of Nigeria is approximately about 800 MJ, 13 million hectares of woody lands, and 61 million tons per annum of animal waste crop residue (Chanchangi et al., 2023).

Biomass is a naturally occurring carbonaceous resource. It refers to materials that stems from biological origin and is a complex renewable material with enormous chemical variability (Bonechi et al., 2017). Biomass may be grouped into classes according to their origin which include woody biomass, herbaceous biomass, aquatic biomass, animal and human waste biomass (Tursi, 2019). United States department of Agriculture has defined wood and woody biomass as trees and woody plants including limbs, tops, needles, leaves and other woody parts grown in a forest, woodland that are by-product of forest management (Mayhead and Shelly, 2011). Herbaceous biomass stems from plants with non-woody stem. These plants die at the end of the growing season. They include grain and seeds crops and by-products of food processing industries and can be grouped into agricultural residues and energy crop (Tursi, 2019). Agricultural residues are by-products of agricultural and food industries while energy crops are crops grown mainly for bioenergy purposes. Table 1, show the theoretical energy potential of agricultural residues available in Nigeria (Jekayinfa et al., 2020).

Aquatic biomass includes algae and emerging plants which may include seaweed, kelp, lake weed and water hyacinth (Tursi, 2019). Developing countries including Nigeria have abundant stock of untapped resources which have several potential uses including power generation (Orisaleye et al., 2018) and are either underutilised or used in ways that are not beneficial and poses harmful treats to the environment.

Biomass can be utilised for energy and power generation through a series of conversion process. Adenaiya et al. (2018) highlighted several ways in which energy from biomass can be improved, which include use of fuel-efficient stove, production of briquette (densification) and pyrolysis. Biomass can be fermented by anaerobic bacteria to produce a very versatile and cheap fuel gas (Adenaiya *et al*., 2018). Over the years, the technology for harnessing energy of biomass has developed into a more efficient and cleaner form (Olaoye et al., 2016). For example, by direct combustion to provide het for use in heating for steam production and hence, electricity generation; by gasification to provide a fuel gas for combustion for heat or in an engine or turbine (Bridgwater et al., 1999).

3.1 Drive for Renewable Energy Production from Biomass

The treat of climate change due to global atmospheric pollution caused by emissions from use of fossil fuels has resulted in worldwide interest in using biomass to produce heat and liquid fuels for power generation (Heinimö and Junginger, 2009). The depletion of fossil fuels (i.e. natural gas and oil) and the discussion about CO_2-induced climate change have resulted in political decisions triggering the use of biomass f or heat and power production in Europe and other continents (D. Chen et al., 2023; Lee et al., 2023; Stelte et al., 2012).

Table 1: Energy potential of agricultural residues in Nigeria

Product	Residue	Residue to Product Ratio	Residues in 1000tones	Energy content (kj/kg)	Energy potential (PJ/year)
Cassava	Peels	0.64	37,773.5	16,400	619.49
	Stalks	0.60	35,691.5	17,000	606.76
Cocoa	Husks	1.50	492.3	15,119	7.44
Coconut	Husks	1.01	291.5	13,515	3.94
	Shells	0.41	118.3	17,700	2.09
Coffee	Husks	1.00	1.6	16,000	0.03
Cowpea	Shells	1.55	5285.5	17,900	94.61
Groundnut	Husks/shells	0.79	1899.7	15,958	30.31
Maize	Cobs	1.00	11,192.0	25,330	283.49
	Husk	0.25	2798.0	18,135	50.74
	Stalks	2.44	27,308.5	17,740	484.45
Millet	Straws	1.48	2212.5	15,400	34.07
Oilpalm	Empty bunches	0.31	2405.4	16,730	40.24
	Fiber	0.61	4694.4	17,967	84.34
	Shells	0.53	4073.7	20,950	85.34
Plantain	Leaves	0.38	1186.8	16,620	19.73
	Stem	4.46	14,099.6	16,130	227.43
Potato	Peels	1.14	6039.9	21,100	127.44
Rice	Husks	0.26	2564.7	15,205	39.00
	Straws	2.18	21,504.2	12,440	267.51
Sorghum	Straws	4.13	28,623.4	15,400	440.80
Soybean	Straws	2.37	1730.1	17,900	30.97
Sugarcane	Bagasse	0.61	906.2	7850	7.11
Wheat	Straws	1.25	83.3	16,210	1.35
Yam	peels	0.06	2876.6	16,433	47.27

Source: extracted from Jekayinfa et al. (2020).

Energy is a fundamental input to economic activity; however, a major transformation is required in the way we produce, deliver and consume energy. The current energy system is largely dependent on fossil fuels, which negatively impact air quality, and contribute significantly to carbon emissions. There is currently a window of opportunity to undertake transformational change in the energy supply sector to meet economic and environmental objectives through the creation of industry leaning towards energy production by renewable sources (Lv, 2023).

Biomass currently accounts for a significant share of global renewable energy supply, with a large proportion utilized in the residential sector for cooking and heating. Approximately 40 EJ of biomass energy is consumed in end-use sectors, representing about 94–95% of renewable energy used for heating and cooking applications worldwide (Dirisu, Salawu, et al., 2024). Large quantities of Agricultural residue produced annually are mostly under-utilised (Maina et al., 2019). For this reasons, several promising waste management practices have been developed which include, densification (Wongsiriamnuay and Tippayawong, 2015), gasification (Nanda et al., 2016) and pyrolysis (Salifu et al., 2024).

International Energy Agency (2019)showed that the total primary energy supply in Nigeria was 157.51 Mtoe (Mega tonne of Oil equivalent) in 2019. According to IEA (2024) statistics, an estimates of energy distribution in Nigeria on sectoral basis revealed that total energy consumption was 5,674,250.00 TJ, of which the residential sector consumed the lion's share of the total energy supply (4359864 TJ) in the country. This is followed by transport (796264 TJ) and industry (309899 TJ), while the least energy was consumed by Agriculture and forestry (187 TJ). Moreover, biomass has been the dominant source of energy in Nigeria, contributing 82.2% of the energy source in the country due to the huge reliance on the energy source for cooking and heating purposes by majority of Nigerian people, hydropower on the other hand contributes a total of 0.4% of Nigeria's energy source (International Energy Agency, 2022).

The over dependence of a significant fraction of Nigerian populace on wood biomass has contributed to the widespread deforestation encountered in the country (Orimoogunje and Asifat, 2015; Oyediji and Adenika, 2022). There is therefore a growing concern about the unchecked exploitation of Nigerians forest resources, evident from a recent observation that there is a massive threat to sustainable land use and the wellbeing of the people due to continuous deforestation (Mike and Sunday Bontur, 2025; Omaliko et al., 2025; Schubert et al., 2009). If not addressed, life sustenance will be threatened due to global warming and in particular, an imminent shortage of wood biomass. Thus, exploring ways of either expanding the current energy source base or developing appropriate technologies which can efficiently convert raw bio-materials into energy may be the panacea to meeting the energy needs in the country (Adenaiya et al., 2018).

3.2 Biomass Conversion Processes

Conversion of biomass involves its transformation into different fuel types, and this depends on several factors such as the method applied, the type of feedstock, moisture content, end use and the economy of the process (Ben-Iwo et al., 2016). Several technologies for conversion of biomass to energy fuel are available, these technologies could produce solid, liquid or gaseous fuels. Biomass conversion could be classified into physical or mechanical conversion, thermochemical conversion and biochemical conversion. These conversion technologies are as reviewed;

3.2.1 Physico-mechanical conversion

This involves the conversion of biomass into fuel or energy products using mechanical process including; grinding, milling, chipping (John et al., 2024) and densification by altering the physical structure of the biomass cellulosic configuration (Gnanasekaran et al., 2023). Densification of biomass may include the following:

i. Pelletization

Palletization involves the physical alteration of the structure of cellulose by the application of mechanical pressure on the biomass through a suitable holed plate called “die”, to obtain pellets with diameters in the range 2-12 mm diameter and heights in the range 12-18 mm (Hu et al., 2016). it is typically achieved by using rollers to press ground material through a die that is shaped either as a ring or a plate with holes to allow for passage and densification of the ground biomass (Ciolkosz, 2009). The palletization process consists of certain sub processes such as grinding, drying, milling and pelleting. The properties of these sub-processes are defined in terms of end use of the pellets. The main purpose of pelletizing a raw material is to reduce the volume and thereby increase the energy density (Garcia-Maraver and Carpio, 2015).

Several studies (Abdulsalam et al., 2024; Jekayinfa, Ola, et al., 2024; Kambo and Dutta, 2014; Unpinit et al., 2015) have been carried out on biomass densification through pelletization. Cui, Yang, and Wang (2021) reviewed die design and process parameters associated with biomass pelletization as it affects the performance of the pellet mill and the quality of the pellets produced. They concluded that more studies in the design of conical press channel inlet and the surface are is important as it appears to be key parameters in the process optimization. Another study by Nielsen and Mandø (2020) investigated the effects of countersink angle and depth. Their result showed that the lowest energy consumption was obtained with a 60o countersink. Other researches in this area include the work of (Cui, Yang, Wang, et al., 2021; Jekayinfa, Abdulsalam, et al., 2024; Yilmaz et al., 2020).

ii. Briquetting

Briquetting and pelletizing are often confused with each other as they both occur under high pressure and are both closely related techniques (Preradovic et al., 2023). The main difference being in the processing and the size of products. Briquettes are made with the use of a piston or screw press while pellets are made in a pellet mill. The size of the final products is different; pellets have a cylindrical shape and are about 6 to 25 mm in diameter and 3 to 50 mm in length (Alakangas, 2010). Meanwhile, briquetting is a process in which the raw material physical structure is disrupted under high pressure, which causes the lignin in the wood or biomass to be liberated so that it binds the material into a firm compact material. Briquetting is a way to make use of biomass residues that would otherwise go to waste, and replace the use of wood and charcoal as well as fossil fuels, thus cutting greenhouse gas emissions (Luque and Speight, 2015).

Different researches relating to briquetting include; (Wang et al., 2018) which study the effect of particle size on the rice straw briquetting process and Krizan and Soos (2009) carried out theoretical analysis of parameters which have an impact on briquette quality. (Bhattacharya et al. (2002) presents experimental data on rice husk briquetting and details the design and operating parameters of die heating stove to reduce electricity consumption. (Zhang et al., 2018) in their own study reviewed the binders for briquetting and mechanisms.

iii. Bailing

Harvesting, storage, transportation, and processing can contribute up to 50% of feedstock cost in biofuel production which originates from the low mass- and energy-densities of biomass feedstocks (Hess et al., 2007). Although traditional hay and forage systems have been used to harvest biomass crops, performance limitations such as inadequate machinery and low product density exist (Shinners and Friede, 2018). To improve the techno-economics of the transportation of biomass feedstock's from the source point to the bio-refinery, efficient baling systems have been introduced for lignocellulosic biomass (Holm-Nielsen and Ehimen, 2014). Bailing therefore involves the collection, gathering, packaging of biomass to a bale which can be either round or square. Large square bales are made with tractor pulled balers. A bale accumulator is pulled behind the baler that collects the bales in group of 4 and leaves them on the field. At a later date, an automatic bale collector travels through the field and collects the bales to the biorefinery (Ibitoye et al., 2021).

Studies in baling include that of Afzalinia (2005) who studied the pressure-density relationship and the pressure distribution in the compression chamber of New Holland BB960 large square bale. Baldasano et al. (2003) also reviewed the chemical, physical and biological processes and the environmental performance of Municipal solid waste. Lemos et al. (2014) in their own study estimates the economic efficiency indicators of round and square bale systems for sugarcane straw and Dyjakon (2018) assess the feasibility of using apple tree pruning residues in the form of bales for energetic purposes. All the authors identify the feasibility of using biomass resources as renewable energy system.

3.2.2 Thermochemical Conversion process

Thermochemical conversion involves the generation of energy from biomass by the application of heat and chemical processes. Existing thermochemical conversion process include combustion, pyrolysis, gasification and liquefaction (Tursi, 2019). These processes and others are reviewed below.

i. pyrolysis

Biomass pyrolysis involves the heating of solid biomass in the absence of air or oxygen to produce gaseous, liquid and solid products (Oochit et al., 2017). Pyrolysis technology has the capability to produce bio-fuel with high fuel-to-feed ratios. Therefore, pyrolysis has been receiving more attention as an efficient method in converting biomass into bio-fuel in past decades (Demirbas, 2004). The ultimate goal of this technology is to produce high-value bio-oil for competing with and eventually replacing non-renewable fossil fuels. There has been an enormous number of researches (Amenaghawon et al., 2021; Christoforou and Fokaides, 2019; Muigai and Ravi, 2020; Nasirudeen et al., 2024; Quevedo-Amador et al., 2024; D. Wang et al., 2020; Xiu et al., 2017) in the area of thermochemical conversion of biomass into bio-fuels (bio-oil, bio-char and bio-gas) through pyrolysis technology due to its several socio-economic advantages as well as the fact it is an efficient conversion method compared to other thermo-chemical conversion technologies (Jahirul et al., 2012).

(Aboelela et al., 2023; Brownsort, 2009; Manyà et al., 2018; Titiladunayo et al., 2012; Varma et al., 2018) among others has reviewed various pyrolysis process stating the temperature conditions for the maximization of either of pyrolysis products. (Garcia-Nunez et al., 2017; Uddin et al., 2018; Yang et al., 2014) had reviewed the key features of fast pyrolysis and the resultant liquid product and describes the major reaction systems that have been developed over the years. Soka and Oyekola (2020) and Zein and Antony (2022) in their respective discuss the feasibility of pyrolysis process on industrial scale. Among other literatures.

ii. Gasification

Gasification is a process that exposes biomass to high temperature and limited oxygen, to produce a gaseous fuel. The product of gasification is mixture of gases including carbon monoxide, carbon dioxide, nitrogen, hydrogen and methane (Abubackar et al., 2019). The advantage of gasification over burning of solid fuels is the resultant gases, methane which can be treated and used in a similar way as natural gas and can use low-value feedstocks and convert into electricity and transportation fuels. Another advantage of gasification is that it produces a fuel with less impurities and could therefore cause fewer pollution problems when burnt (Kumar et al., 2009).

Among the literatures (Heidenreich and Foscolo, 2015; Molino et al., 2016; Sikarwar et al., 2016) in gasification, Heidenreich and Foscolo (2015) reviewed in detail the concept of gasification highlighting the need for process integration and combination to enable higher process efficiency, better products and lower investment costs; Ahrenfeldt (2012) published a handbook on biomass gasification to disseminate the results of the European Gasification network to a wider audience; Bain and Broer (2011) wrote a chapter titled Gasification in Thermochemical processing of biomass: conversion into fuels, chemicals and power; Molino et al. (2016) discuss in details the state of the art of biomass gasification evaluating the potential use of syngas (a product of gasification) and the application of the biomass gasification.

iii. Direct combustion

This is the simplest method of extracting energy from biomass. Industrial biomass combustion facilities can burn many types of biomass fuel, including wood, agricultural residues, wood pulping liquor, municipal solid waste (WSW) and refuse-derived fuel (David et al., 2019; Jenkins et al., 2019; Quispe et al., 2017). Biomass is burned to produce steam which is mostly used to power turbine engines. because of potential ash build-up, which fouls boilers, reduces efficiency and increase costs incurred in gasification, only certain types of biomass materials are used for direct combustion (Kumar et al., 2015). Direct combustion has been in use since the seventies as a means of upgrading biomass materials and is the most convenient and most economical method (Cansado et al., 2025). Biomass is burned by direct combustion to produce steam, the steam turns a turbine and the turbine drives a generator producing electricity (Demirbas, 2007).

Various researches (Glushkov et al., 2021; Xin-Gang et al., 2015; Zhu et al., 2019) has focused to improve the gasification process of different raw materials. Machado et al. (2017) breed elephant grass purposely for energy production via gasification and present result relating to the potential of some group of grass with greatest aptitude for bioenergy generation and suggest genetic modification for increased reliability. Gutiérrez et al. (2020) studied the energy potential of agricultural, livestock and slaughterhouse biomass waste through direct combustion and anaerobic digestion in Columbia, there results show higher bioenergy potential per year with higher potentialities for direct combustion.

iv. Torrefaction

Torrefaction is the thermal processing of biomass through heating at moderate temperatures in the absence of oxygen and under atmospheric pressure to improve its energy density (Thilakaratne et al., 2014). During the treatment, biomass starts to decompose and releases combustible volatile matter, mainly composed by organic compounds, together with moisture. Thereby increasing the energy density of the torrefied biomass. Moreover, during torrefaction, the structure of the biomass is changed, becoming powdery and thus much easier to grind (Jiang et al., 2013).

Cahyanti et al. (2020) treated the principles of torrefaction and production technology paying attention to the economics and efficiency of the process. Adeleke et al. (2021), Ivanovski et al., (2023) and Mamvura and Danha (2020) reviewed torrefaction process looking into the system energy efficiency and conclude that the system energy efficiency can be improved by reintroducing the material lost during torrefaction as a source of heat. Several authors torrefied different materials, including rice husk (Zhang et al., 2017); sugar cane bagasse (Kanwal et al., 2019); Pine chips (Borén et al., 2020); Sawdust (Alizadeh et al., 2022); pine, eucalyptus, Chestnut, holm oak, olive pruning and vine shoot (Álvarez et al., 2018)and white spruce saw dust (Onyenwoke et al., 2023).

3.2.3 Biochemical conversion

Biochemical conversion processes for biomass include anaerobic digestion, fermentation and transesterification (Pecenka et al., 2020).

i. Fermentation

Fermentation is an extension of the process which have been used for centuries, where yeasts and other microorganisms are used to ferment the sugar of various plants into ethanol. It is a process where carbohydrates (sugar and starch) are converted to ethanol by a variety of microorganisms (Taveira et al., 2021). Researches in this area include fermentation process of Puer tea (Qin et al., 2025); fermentation process for the production of hydrogen (Jain et al., 2024; Martino et al., 2021) and industrial yogurt manufacture (Moineau-Jean et al., 2020; Rehman et al., 2022). Liang et al. (2024) studied the kinetics of fermentation process and identified three basic types. These are growth associated products arising directly from the energy of metabolism supplied by carbohydrates, indirect products of carbohydrate metabolism and products apparently unrelated to carbohydrate oxidation.

ii. Digestion

Digestion works by the utilization of anaerobic bacteria. These are microorganisms which live at the bottom of swamps or in other places where there is no air, consuming dead organic matter to produce methane and hydrogen (Chauhan et al., 2025). Digestion is achieved by feeding organic materials such as animal dung or sewage into tanks called digesters and adding bacteria. The emitted gas is then collected to use as an energy source. This process is an efficient means of extracting usable energy from biomass, usually up to two-third of the fuel energy of the dungs could be recovered using digestion (Abubakar et al., 2022). (Obileke et al., 2021) reviewed biogas production via anaerobic digestion of energy crops and organic waste. they concluded that methane derived from anaerobic digestion is competitive in efficiencies and costs to other biomass energy forms including heat, synthesis gases and ethanol proving the effectiveness of the system for bioenergy generation.

iii. Transesterification

Transesterification is the process used to reduce viscosity of animal fats and vegetable oils. It generates products commonly known as biodiesel (Knothe et al., 2005). Transesterification can be classified into two types; catalysed or non-catalysed transesterification. Further classification of catalysed transesterification is based on the type of catalyst used. These classifications may include homogenous, heterogeneous and enzymatically catalysed transesterification and a non- catalysed supercritical process employed to mitigate critical issues in the production process. Catalyst employed in transesterification include, Acid-based or alkali-based catalyst (Ong et al., 2013). (Adewale et al., 2015) have reviewed in details the various types and processes of transesterification reaction looking at the processes in different perspectives.

3.3 Current Status of Biomass Conversion

The industrial sector accounts for about 40% of global total final energy consumption (2024–2025), and fossil fuels still supply well over two-thirds of industrial energy demand, particularly for high-temperature process heat, despite gradual growth in electrification and renewables (IEA, 2026). Despite the relatively higher increase in the consumption of waste and renewables (128% rise in the same period), fossil fuels still dominate the world's final energy consumption in industry, and coal is the most used energy source (Malico et al., 2019). The share of renewable energy used in the European Union's final energy consumption has grown substantially to about 25.2% of gross final energy consumption in the EU in 2024 derived from renewable sources. Industry renewables and biofuels accounted for around 11–12% of industrial final energy consumption, with solid biomass, biogas and other bioenergy forms making up most of that contribution (Figiel et al., 2025).

This renewable fuel offers the possibility, sometimes through pre-processing technologies, of greater industrial uptake of clean, low-carbon technologies, and is especially well suited for heat and combined heat and power (CHP)production and therefore for industrial use (around two thirds of the final energy demand of the EU28 industry is in the form of heat (Phogat, 2025) Over the years, the technology of harvesting energy from biomass has developed into a more efficient and cleaner form (Olaoye et al., 2016). Several works have been done to research into products generated from various biomass conversion technologies. Jekayinfa et al. (2019) investigated various aspects of biomass densification. Obi et al. (2014) reviewed the factors that limit the commercialization of biomass briquetting in Nigeria and suggested that appropriate briquetting machines for the commercialization of biomass briquetting in Nigeria need to be developed.

4.1 Conclusion

The availability of energy is the key to the development of any country. Owing to the epileptic supply of power in Nigeria, the hazards related to uncontrolled burning of plant residues, global warming impact, and several environmental hazards occurring from burning of fossil fuel. The call for diversification of energy through the utilization of renewable sources is increasing in developed countries. The accumulated energy potential of biomass has studied by various researchers calls for efficient utilization of biomaterials for safe energy production, reduction in environmental pollution and improving human health and wellbeing.

The method of disposal and traditional use of biomass for cooking in many countries of the world exposes our environment and human habitat into danger. Some of the identified problems arising from these methods include; depletion of ozone layer, destruction of useful soil microorganism, poisoning of forest resources and direct or indirect poisoning of water bodies. The identified problems in one way or the other have been shown in several studies to have negative impacts on human systems ranging from skin diseases, kidney problems, respiratory disorder, lung diseases and so on. Also, problems arising from uncontrolled disposal of crop residue of non-decomposing origin, such as blocking of water ways which could lead to waterlogging and erosion on farms and in streets.

Biomass has been used in many cases in some developed countries as energy source. Plant residues can be incinerated to generate electricity, liquid fuels (e.g. ethanol) can be produced by fermentation of biomass, biogas ca be generated from peels of fruit and variation of plant residue through digestion among other systems of energy generation from biomass. The use of biomass has been proven to be a sustainable way to avoid various environmental pollution and a renewable source. Due to their abundance and availability are considered as renewable source of energy and can help reduce dependence on fossil fuels

4.2 Recommendation

Research works aimed at the successful conversion and utilization of biomass is still at the laboratory scale. It is recommended that more works should be aimed at the harvesting of biomass mostly agricultural residues on the field and on field densification to aid their transportation to biomass conversion plant. Commercialization of the experimented conversion plants/ system into industrial scale should be encouraged by government or non-governmental organizations in terms of capital to aid the implementation of safe cleaning on the farm and beyond. Thereby encouraging the generation of power/energy from renewable sources.

REFERENCES

Abdallah, S. M., Bressers, H., and Clancy, J. S. (2015). Energy reforms in the developing world: Sustainable development compromised? *International journal of sustainable energy planning and management*, *5*, 41-56.

Abe, M., Takaoka, N., Idemoto, Y., Takagi, C., Imai, T., and Nakasaki, K. (2008). Characteristic fungi observed in the fermentation process for Puer tea. *International Journal of Food Microbiology*, *124*(2), 199-203.

Abolhosseini, S., Heshmati, A., and Altmann, J. (2014). A review of renewable energy supply and energy efficiency technologies. IZA Discussion Papers, No. 8145, Institute for the Study of Labor (IZA), Bonn.

Abubackar, H. N., Veiga, M. C., and Kennes, C. (2019). Syngas fermentation for bioethanol and bioproducts. In *Sustainable Resource Recovery and Zero Waste Approaches* (pp. 207-221). Elsevier.

Achakpo, G. C., Achakpo, M. N., Datau, S. G., and Martins, Y. D. (2015). Harnessing Renewable Energy Sources in Nigeria: It's Challenges and Implications. In *Proceedings of the Interdisciplinary Academic Conference on Uncommon Development* (Vol. 4, No. 3).

Adenaiya, Adewunmi and Onakpoma, Ighoyivwi and Ogunsanwo, Olukayode. (2018). Improving energy production through efficient and sustainable wood utilization in nigeria. Proceedings of the 39th Annual Conference of the Forestry Association of Nigeria held in Ibadan, Oyo State, Nigeria.

Adewale, P., Dumont, M. J., and Ngadi, M. (2015). Recent trends of biodiesel production from animal fat wastes and associated production techniques. *Renewable and Sustainable Energy Reviews*, *45*, 574-588.

Afzalinia, S. (2005). Modeling and validation of the baling process in the compression chamber of a large square baler. *A Doctoral dissertation*, University of Saskatchewan.

Ahrenfeldt, J. (2012). Handbook biomass gasification. H. Knoef (Ed.). *Enschede*: BTG biomass technology group.
Aigbodion, A. I., Bakare, I. O., Fagbemi, E. A., Abolagba, E. O., Omonigho, B., Ayeke, P. O., ... and Musa, E. (2018). Viability of biogas production from manure/biomass in nigeria using fixed dome digester. *Univers. J. Agric. Res*, *6*, 1-8.
Alakangas, E. (2010). "New European Pellets Standards". *European Pellet Conference*.
Álvarez, A., Nogueiro, D., Pizarro, C., Matos, M., and Bueno, J. L. (2018). Non-oxidative torrefaction of biomass to enhance its fuel properties. *Energy*, *158*, 1-8.
Antar, M., Lyu, D., Nazari, M., Shah, A., Zhou, X., and Smith, D. L. (2021). Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. *Renewable* and *Sustainable Energy Reviews*, *139*, 110691.
Bain, R. L., and Broer, K. (2011). *Gasification* (No. NREL/CH-5100-53165). National Renewable Energy Lab. (NREL), Golden, CO (United States).
Baldasano, J. M., Gasso, S., and Pérez, C. (2003). Environmental performance review and cost analysis of MSW landfilling by baling-wrapping technology versus conventional system. *Waste Management*, *23*(9), 795-806.
Ben-Iwo, J., Manovic, V., and Longhurst, P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. *Renewable* and *sustainable energy reviews*, *63*, 172-192.
Bergman, P. C., and Kiel, J. H. (2005, October). Torrefaction for biomass upgrading. In *Proc. 14th European Biomass Conference, Paris, France* (Vol. 2005, pp. 17-21).
Bhattacharya, S. C., Leon, M. A., and Rahman, M. M. (2002). A study on improved biomass briquetting. *Energy for sustainable development*, *6*(2), 67-71.
Bonechi, C., Consumi, M., Donati, A., Leone, G., Magnani, A., Tamasi, G. and Rossi, C. (2017). Biomass. In *Bioenergy Systems for the Future* (pp.3-42). 10.1016/B978-0-08-101031-0.00001-6.
Bridgwater, A. V., and Peacocke, G. V. C. (2000). Fast pyrolysis processes for biomass. *Renewable and sustainable energy reviews*, *4*(1), 1-73.
Caceres, K. R., Patino, F. B., Duarte, J. A., and Kafarov, V. (2016). Assessment of the energy potential of agricultural residues in non-interconnected zones of Colombia: case study of Chocó and Putumayo. *Chemical Engineering Transactions*, *50*, 349-354.
Chen, D., Zheng, Z., Fu, K., Zeng, Z., Wang, J., and Lu, M. (2015). Torrefaction of biomass stalk and its effect on the yield and quality of pyrolysis products. *Fuel*, *159*, 27-32.
Chynoweth, D. P., and Isaacson, R. (1987). Anaerobic digestion of biomass. United Kingdom.
Chynoweth, D. P., Owens, J. M., and Legrand, R. (2001). Renewable methane from anaerobic digestion of biomass. *Renewable energy*, *22*(1-3), 1-8.
Dalena, F., Basile, A., and Rossi, C. (Eds.). (2017). Bioenergy systems for the future: prospects for biofuels and biohydrogen. *Woodhead Publishing*.
Demirbas, A. (2004). Combustion characteristics of different biomass fuels. *Progress in energy* and *combustion science*, *30*(2), 219-230.
Demirbas, A. (2007). Combustion systems for biomass fuel. *Energy Sources, Part A*, *29*(4), 303-312.
Demirbas, A., and Arin, G. (2002). An overview of biomass pyrolysis. *Energy sources*, *24*(5), 471-482.
Dyjakon, A. (2018). Harvesting and baling of pruned biomass in apple orchards for energy production. *Energies*, *11*(7), 1680.

Ephraums, J. J., and Jenkins, G. J. J. (1992). *Climate change 1992*. Cambridge University Press.
European Commission (2016). Mapping and Analyses of the Current and Future (2020–2030) Heating/Cooling Fuel Deployment (Fossil/Renewables). *Work package 1: Final energy consumption for the year 2012*.
Fleiter, T., Steinbach, J., Ragwitz, M., Dengler, J., Köhler, B., Reitze, F., and Reiter, U. (2016). Mapping and analyses of the current and future (2020-2030) heating/cooling fuel deployment (fossil/renewables). *European Commission, Directorate-General for Energy*.
Fournel, S., Palacios, J. H., Morissette, R., Villeneuve, J., Godbout, S., Heitz, M., and Savoie, P. (2015). Influence of biomass properties on technical and environmental performance of a multi-fuel boiler during on-farm combustion of energy crops. *Applied Energy*, *141*, 247-259.
Garcia-Maraver, A., and Carpio, M. (2015). Biomass pelletization process. *Biomass Pelletization: Standards and Production WIT Transactions on State of the Art in Science and Engineering*, *85*, 53-66.
Garcia-Maraver, A., Rodriguez, M. L., Serrano-Bernardo, F., Diaz, L. F., and Zamorano, M. (2015). Factors affecting the quality of pellets made from residual biomass of olive trees. *Fuel Processing Technology*, *129*, 1-7.
Glushkov, D. O., Nyashina, G. S., Anand, R., and Strizhak, P. A. (2021). Composition of gas produced from the direct combustion and pyrolysis of biomass. *Process Safety and Environmental Protection*, *156*, 43-56.
Gunaseelan, V. N. (1997). Anaerobic digestion of biomass for methane production: a review. *Biomass and bioenergy*, *13*(1-2), 83-114.
Guragain, Y. N., Wilson, J., Staggenborg, S., McKinney, L., Wang, D., and Vadlani, P. V. (2013). Evaluation of pelleting as a pre-processing step for effective biomass deconstruction and fermentation. *Biochemical engineering journal*, *77*, 198-207.
Gutiérrez, A. S., Eras, J. J. C., Hens, L., and Vandecasteele, C. (2020). The energy potential of agriculture, agroindustrial, livestock, and slaughterhouse biomass wastes through direct combustion and anaerobic digestion. The case of Colombia. *Journal of Cleaner Production*, *269*, 122317.
Hamid, A. A., Usman, L. A., Elaigwu, S. E., and Zubair, M. F. (2010). Environmental and health risk of bush burning. *Advances in environmental biology*, *4*(2), 241-249.
Heidenreich, S., and Foscolo, P. U. (2015). New concepts in biomass gasification. *Progress in energy and combustion science*, *46*, 72-95.
Heinimö, J., and Junginger, M. (2009). Production and trading of biomass for energy–an overview of the global status. *Biomass* and *Bioenergy*, *33*(9), 1310-1320.
Hess, J. R., Wright, C. T., and Kenney, K. L. (2007). Cellulosic biomass feedstocks and logistics for ethanol production. *Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy*, *1*(3), 181-190.
Holm-Nielsen, J. B., and Ehimen, E. A. (2014). Biorefinery plant design, engineering and process optimisation. In *Advances in Biorefineries* (pp. 89-111). Woodhead Publishing.
Homdoung, N., Dussadee, N., Sasujit, K., Kiatsiriroat, T., and Tippayawong, N. (2019). Performance investigation of a gasifier and gas engine system operated on municipal solid waste briquettes. *International Journal of Renewable Energy Development*, *8*(2), 179-184.
Hu, Q., Yang, H., Yao, D., Zhu, D., Wang, X., Shao, J., and Chen, H. (2016). The

densification of bio-char: Effect of pyrolysis temperature on the qualities of pellets. *Bioresource Technology*, *200*, 521–527.

IEA (2018). CO2 Status Report 2017. International Energy agency, 2017.

IEA (2019). Nigeria Energy Outlook; Analysis from Africa Energy Outlook 2019. International Energy Agency.

IEA (2021). World Energy Outlook; Flagship report. International Energy agency.

IPPC (1992). Climate Change: The supplementary report to the IPCC scientific assessment. *Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge*.

IRENA (2015). Global Bioenergy: Supply and demand projections–A working paper for Remap 2030. International renewable energy agency. *Renewable Energy Target Setting, Abu Dhabi, UAE*.

IRENA (2018). Renewable Energy Statistics. International Renewable Energy Agency.

Jahirul, M. I., Rasul, M. G., Chowdhury, A. A., and Ashwath, N. (2012). Biofuels production through biomass pyrolysis—a technological review. *Energies*, *5*(12), 4952-5001.

Jekayinfa, S. O., and Scholz, V. (2013). Estimation of possible energy contributions of crop residues in Nigeria. *International journal of energy technology* and *policy*, *9*(2), 93-109.

Jekayinfa, S. O., Orisaleye, J. I., and Pecenka, R. (2020). An assessment of potential resources for biomass energy in Nigeria. *Resources*, *9*(8), 92.

Khan, S., Paliwal, V., Pandey, V., and Kumar, V. (2015). Biomass as renewable energy. *Int. Adv. Res. J. Sci. Eng. Technol*, *2*, 301-304.

Kim, S., and Dale, B. E. (2015). All biomass is local: The cost, volume produced, and global warming impact of cellulosic biofuels depend strongly on logistics and local conditions. *Biofuels, Bioproducts* and *Biorefining*, *9*(4), 422-434.

Knothe, G., Krahl, J., and Van Gerpen, J. (Eds.). (2015). *The biodiesel handbook*. Elsevier.

Križan, P., Šooš, L., and Vukelić, Đ. (2009). A study of impact technological parametres on the briquetting process. *Facta Universitatis. Series. Working and Living Environmental Protection (Serbia)*.

Kullander, S. (2009). Energy from biomass. *The European Physical Journal Special Topics*, *176*(1), 115-125.

Kumar, A., Jones, D. D., and Hanna, M. A. (2009). Thermochemical biomass gasification: a review of the current status of the technology. *Energies*, *2*(3), 556-581.

Lemos, S. V., Denadai, M. S., Guerra, S. P. S., Esperancini, M. S. T., Bueno, O. D. C., and Takitane, I. C. (2014). Economic efficiency of two baling systems for sugarcane straw. *Industrial crops and products*, *55*, 97-101.

Lequeux, P., Carre, J., Hebert, J., and Lacrosse, L. (1988). Biomass Densification. *Commission of the European Communities, Directorate General for Development*.

Luque, R., and Speight, J. G. (2015). Gasification and synthetic liquid fuel production: an overview. *Gasification for Synthetic Fuel Production*, 3-27.

Machado, J. C., Carneiro, P. C. S., da Costa Carneiro, J., Resende, M. D. V., Vander Pereira, A., and de Souza Carneiro, J. E. (2017). Elephant grass ecotypes for bioenergy production via direct combustion of biomass. *Industrial crops and products*, *95*, 27-32.

Maina, M. B., Oluwole, F. A., and Mukhtar, U. A. (2019). Energy Resource from Agriculture: Prospects and Problems. *ATBU Journal of Science, Technology and Education*, *7*(4), 118-128.

Malico, I., Pereira, R. N., Gonçalves, A. C., and Sousa, A. M. (2019). Current status and future perspectives for energy production from solid biomass in the European industry. *Renewable and Sustainable Energy Reviews*, *112*, 960-977.

Malik, B., Pirzadah, T. B., Islam, S. T., Tahir, I., Kumar, M., and ul Rehman, R. (2015). Biomass pellet technology: A green approach for sustainable development. *Agricultural Biomass Based Potential Materials*, 403-433.

Mani, S., Tabil, L. G., and Sokhansanj, S. (2006). Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. *Biomass and bioenergy*, *30*(7), 648-654.

Maschio, G., Koufopanos, C., and Lucchesi, A. (1992). Pyrolysis, a promising route for biomass utilization. *Bioresource Technology*, *42*(3).

Molino, A., Chianese, S., and Musmarra, D. (2016). Biomass gasification technology: The state of the art overview. *Journal of Energy Chemistry*, *25*(1), 10-25.

Nath, K., Muthukumar, M., Kumar, A., and Das, D. (2008). Kinetics of two-stage fermentation process for the production of hydrogen. *International Journal of Hydrogen Energy*, *33*(4), 1195-1203.

Nielsen, S. K., and Mandø, M. (2020). Experimental and numerical investigation of die designs in biomass pelleting and the effect on layer formation in pellets. *Biosystems Engineering*, *198*, 185-197.

Nielsen, S. K., Mandø, M., and Rosenørn, A. B. (2020). Review of die design and process parameters in the biomass pelleting process. *Powder Technology*, *364*, 971-985.

Nwofor, O. K., Chineke, T. C., Akujor, C. E., and Okoro, U. O. (2007). Energy diversification choices for Nigeria: optimisation by the criteria ranking method. *Energy and environment*, *18*(5), 577-590.

Obi, O. F., Adeboye, B. S., and Aneke, N. N. (2014). Biomass briquetting and rural development in Nigeria. *International journal of sciences, environmental and technology, 3(3), 1043-1052.*

OECD (2011). OECD Green Growth Studies: Energy. Organization for Economic Cooperation and Development

Ogunsanwo, O. Y., Attah, V. I., Adenaiya, O., and Umar, M. (2018). Sustainable Utilization of Firewood as a form of energy in Nigeria. Conference: 37th Annual Conference of the Forestry Association of Nigeria held in Minna, Niger State, Nigeria.

Ojolo, S. J., Orisaleye, J. I., and Abolarin, S. M. (2012). Technical potential of biomass energy in Nigeria. *Ife Journal of Technology*, *21*(2), 60-65.

Olaoye, T., Ajilore, T., Akinluwade, K., Omole, F., and Adetunji, A. (2016). Energy crisis in Nigeria: Need for renewable energy mix. *American Journal of Electrical* and *Electronic Engineering*, *4*(1), 1-8.

Ong, L. K., Kurniawan, A., Suwandi, A. C., Lin, C. X., Zhao, X. S., and Ismadji, S. (2013). Transesterification of leather tanning waste to biodiesel at supercritical condition: Kinetics and thermodynamics studies. *The Journal of Supercritical Fluids*, *75*, 11-20.

Orisaleye, J. I., Ogbonnaya, M., Ogundare, A. A., and Ismail, S. O. (2018). Development and performance evaluation of a natural draft mixed-type solar dryer for agricultural products. *Journal of Science and Technology*.

Phanphanich, M., and Mani, S. (2011). Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresource technology*, *102*(2), 1246-1253.

Pintana, P., Thanompongchart, P., Dussadee, N., and Tippayawong, N. (2020). Overview of Pelletisation Technology and Pellet Characteristics from Maize

Residues. *Chemical Engineering Transactions*, *78*, 121-126.

Ravindranath, N. H. and Usha Rao, K., (2005). Environmental Effects of Energy from Biomass and Municipal Wastes. in Interactions: Energy/Environment, edited by Jose Goldemberg, in *Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO*, Eolss Publishers, Paris, France.

Rehfuess, E., and World Health Organization. (2006). *Fuel for life: household energy* and *health*. World Health Organization.

Ru, B., Wang, S., Dai, G., and Zhang, L. (2015). Effect of torrefaction on biomass physicochemical characteristics and the resulting pyrolysis behavior. *Energy and Fuels*, *29*(9), 5865-5874.

Schäpper, D., Alam, M. N. H. Z., Szita, N., Lantz, A. E., and Gernaey, K. V. (2009). Application of microbioreactors in fermentation process development: a review. *Analytical and bioanalytical chemistry*, *395*(3), 679-695.

Schulte-Bisping, H., Bredemeier, M., and Beese, F. O. (1999). Global availability of wood and energy supply from fuelwood and charcoal. *Ambio*, *28*(7), 592-594.

Seglah, P. A., Wang, Y., Wang, H., and Bi, Y. (2019). Estimation and efficient utilization of straw resources in Ghana. *Sustainability*, *11*(15), 4172.

Shankar Tumuluru, J., Sokhansanj, S., Hess, J. R., Wright, C. T., and Boardman, R. D. (2011). A review on biomass torrefaction process and product properties for energy applications. *Industrial Biotechnology*, *7*(5), 384-401.

Shelly, J. R. (2011). Woody biomass factsheet–WB1. *University of California Berkeley: Berkeley, CA, USA*.

Shinners, K., and Friede, J. (2018). Energy requirements for biomass harvest and densification. *Energies*, *11*(4), 780.

Sittisun, P., Tippayawong, N., and Wattanasiriwech, D. (2015). Thermal degradation characteristics and kinetics of oxy combustion of corn residues. *Advances in Materials Science* and *Engineering*, *2015*.

Soukoulis, C., Panagiotidis, P., Koureli, R., and Tzia, C. (2007). Industrial yogurt manufacture: monitoring of fermentation process and improvement of final product quality. *Journal of dairy science*, *90*(6), 2641-2654.

Sriram, N., and Shahidehpour, M. (2005, June). Renewable biomass energy. In *IEEE Power Engineering Society General Meeting, 2005* (pp. 612-617). IEEE.

Staton, D. M., and Harding, M. H. (1998). Health and environmental effects of cooking stove use in developing countries. *The Renewable Energy Policy Project* and *the Center for Renewable Energy* and *Sustainable Technology.*

Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., and Henriksen, U. B. (2012). Recent developments in biomass pelletization–A review. *BioResources*, *7*(3), 4451-4490.

Thilakaratne, R., Wright, M. M., and Brown, R. C. (2014). A techno-economic analysis of microalgae remnant catalytic pyrolysis and upgrading to fuels. *Fuel*, *128*, 104-112.

Tippayawong, N., Rerkkriangkrai, P., Aggarangsi, P., and Pattiya, A. (2017). Biochar production from cassava rhizome in a semi-continuous carbonization system. *Energy Procedia*, *141*, 109-113.

Tolón-Becerra, A., Lastra-Bravo, X., and Bienvenido-Bárcena, F. (2011). Proposal for territorial distribution of the EU 2020 political renewable energy goal. *Renewable Energy*, *36*(8), 2067-2077.

Tursi, A. (2019). A review on biomass: importance, chemistry, classification, and conversion. *Biofuel Research Journal*, *6*(2), 962-979.

Van Fan, Y., Lee, C. T., Lim, J. S., Klemeš, J. J., and Le, P. T. K. (2019). Cross-disciplinary approaches towards smart, resilient and sustainable circular economy. *Journal of cleaner production*, *232*, 1482-1491.

Vassilev, S. V., Baxter, D., Andersen, L. K., and Vassileva, C. G. (2010). An overview of the chemical composition of biomass. *Fuel*, *89*(5), 913-933.

Wang, C., Peng, J., Li, H., Bi, X. T., Legros, R., Lim, C. J., and Sokhansanj, S. (2013). Oxidative torrefaction of biomass residues and densification of torrefied sawdust to pellets. *Bioresource technology*, *127*, 318-325.

Wang, C., Peng, J., Li, H., Bi, X. T., Legros, R., Lim, C. J., and Sokhansanj, S. (2013). Oxidative torrefaction of biomass residues and densification of torrefied sawdust to pellets. *Bioresource technology*, *127*, 318-325.

Wang, Y., Wu, K., and Sun, Y. (2018). Effects of raw material particle size on the briquetting process of rice straw. *Journal of the Energy Institute*, *91*(1), 153-162.

Wongsiriamnuay, T., and Tippayawong, N. (2015). Effect of densification parameters on the properties of maize residue pellets. *Biosystems Engineering*, *139*, 111-120.

Xin-Gang, Z., Tian-Tian, F., Yu, M., Yi-Sheng, Y., and Xue-Fu, P. (2015). Analysis on investment strategies in China: the case of biomass direct combustion power generation sector. *Renewable and Sustainable Energy Reviews*, *42*, 760-772.

Zhang, G., Sun, Y., and Xu, Y. (2018). Review of briquette binders and briquetting mechanism. *Renewable and Sustainable Energy Reviews*, *82*, 477-487.

Zhu, Y., Liang, J., Yang, Q., Zhou, H., and Peng, K. (2019). Water use of a biomass direct-combustion power generation system in China: A combination of life cycle assessment and water footprint analysis. *Renewable and Sustainable Energy Reviews*, *115*, 109396.