Environmental Research and Technology
https://dergipark.org.tr/en/pub/ert
DOI: https://doi.org/10.35208/ert.1612524

Environmental Research & Technology

Review Article

Sustainable and effective biomass bioenergy production in Nigeria: An overview

Tolulope KOLAJO[1], Nabil ELKAOUD[2*], Iyinoluwa ADEDOKUN[1]
Oluwaseun KADIRI[3], Temitayo AJIBADE[4]

[1]University of Ibadan, Department of Wood Products Engineering, Nigeria
[2]Al-Azhar University, Assiut Branch, , Faculty of Agricultural Engineering, Egypt, Postdoctoral Fellowship at Yellow River Delta Intelligent Agricultural Machinery Equipment Industry Academy, Dongying 257300, China
[3]Yellow River Delta Intelligent Agricultural Machinery Equipment Industry Academy, Dongying 257300, China
[4]University of Ibadan, Department of Veterinary Physiology, Biochemistry and Pharmacology, Nigeria

ARTICLE INFO

Article history
Received: 03 January 2025
Revised: 21 January 2025
Accepted: 29 January 2025

Key words:
Biomass, biofuels, bioenergy, sustainable, fossil fuels, vital

ABSTRACT

Nigeria, the largest economy in Africa, relies on conventional fossil fuels for several energy demands, including transportation and power generation. The negative environmental impacts and carbon emissions from burning fossil fuels highlight the urgent need to consider viable alternatives such as bioenergy, which is renewable energy derived from biological materials. The utilization of biofuels and bioproducts would significantly reduce the carbon footprint with other social and economic benefits such as income stability and improved public health, especially in rural communities. Although bioenergy research in Nigeria has been ongoing for several decades, the knowledge curve for utilization is very steep, despite the relative abundance of the raw materials needed to produce it. This review provides an overview of the biomass types used as feedstock for bioenergy production in Nigeria, discusses their characteristics, explores pretreatment and conversion techniques, and highlights their various applications.

Cite this article as: Kolajo T, Elkaoud N, Adedokun I, Kadiri O, Ajibade T. Sustainable and effective biomass bioenergy production in Nigeria: An overview. Environ Res Tec 2025;8(4) 1061-1079.

INTRODUCTION

For a long time, energy generation in Nigeria has always revolved around the use of conventional fossil fuels. But the country is blessed by a vast deposit of crude oil and natural gas. However, greenhouse gas emissions have become a global concern, and the current energy generation level is grossly insufficient to meet demand, making renewable energy imperative. Perhaps one of the most important goals of sustainable development for developing countries is to enhance the utilization of renewable energy sources in all sectors in general and the agricultural sector in particular [1]. The use of biomass as an energy resource solves the problem of environmental pollution and reduces dependency on fossil fuels [2]. Other benefits may include income stabilization in rural areas and reduced carbon emissions to the atmosphere [3,4]. There is a huge abundance of biomass that can be tapped into for renewable energy production. Approximately 530,000 full-time equivalent direct jobs are currently provided by the direct collection of fuelwoods and the production of charcoal, which employs around one-fifth of the population [5]. Agricultural land covers over 70% of total land area, and about 37.3% of this agricultural area is arable land. Agriculture is key to increased potential for future bioenergy production and utilization. The yields of selected crops across different locations in the country should be con-

***Corresponding author.**
*E-mail address: NabilElkaoud.50@azhar.edu.eg

sidered, thus enabling higher production of both food and fuel [6]. [7] asserted that in order to circumvent the food-vs-fuel debate, high-energy crops like cassava, potatoes, oil palm, sugarcane, sorghum, and maize can be grown expressly as biomass feedstock. Large amounts of waste in urban and rural areas of Nigeria pollute the environment. Pollution is an issue of concern to the community for environmental security. This waste can be used as raw material for biofuel production. Biomass, as defined by the Energy Information Administration [8], includes complex, renewable organic materials derived from plants and animals.. [9] described biomass as all living organisms, microorganisms, and biochemical materials such as cellulose, lignin, sugars, fats, and proteins originating from plants. The most popular renewable energy source at the moment is biomass, and its use is growing as a result of growing awareness of the negative consequences of using fossil fuels [10]. Soils frequently contain biomass in the form of bacteria, fungi, and meiofauna, even though deadwood and organic soil matter are not regarded as biomass [11]. Therefore, to be more inclusive, biomass can be defined as anything that has an organic matrix, whether it be plants or animals, terrestrial or marine, that is produced directly or indirectly through the process of photosynthesis involving chlorophyll, or that is cultivated by humans. In essence, any material that is a part of a living organism that could be used as feedstock for bioenergy production may be considered as biomass [12].

CLASSIFICATION OF BIOMASS FEEDSTOCK - BY ORIGIN

Biomass classifications, being a very broad concept, are often mixed up. However, according to [13], biomass classifications based on their origin of production can be divided into agricultural, forest, aquatic, and municipal solid wastes, with the first three directly relating to biomass sources as Figure 1 according to [14]. [15] reported that the sugarcane produced is widely used in the production of sugar and 1G ethanol, leaving behind a huge amount of bagasse as waste. However, sugarcane bagasse also has some end-use value, for example, its utilization for the production of methanol, 2G ethanol, and electricity. Although the technologies for the production of these value-added products are well established, it is important to analyze the social, economic, and environmental impacts associated with their production processes.

[16] explained that sugarcane (Saccharum officinarum) bagasse (SCB) is a biomass of agricultural waste obtained from sugarcane processing that has been found in abundance globally. Due to its abundance in nature, researchers have been harnessing this biomass for numerous applications such as in energy and environmental sustainability as Figure 2. So, The SCB is a biomass with great potential to meet global energy demand and encourage environmental sustainability.

Agricultural biomass refers to biomass grown on agricultural land that is either arable, under permanent crops, or under permanent pastures [17]. All agricultural products fall under this category, regardless of their chemical makeup (such as lignocellulosics, starch, oil seeds, etc.) or whether they are edible (such as food or energy crops). [18] stated that it can be further categorised into primary, secondary, and primary sources. The primary sources are grown as either crops or key products, such as sugarcane and short-rotation energy plantations. This group of biomass comprises both herbaceous and woody biomass and is in the top three important biomass sources in the world [19]. Secondary sources are residues from the production processes, for example, sugarcane bagasse, rice husks, and corn stover. Sugarcane bagasse, produced post-juice extraction from cane stalks in sugar mills, serves as a solid biofuel for generating steam and electricity necessary for the sugar production process, as noted by [20]. Oil palm trunks, oil palm shells, and oil palm fronds are among the lignocellulosic biomass wastes produced by the palm oil industry, as shown in Figure 3 [21]. Tertiary sources are by-products, residues, and wastes produced during and after production processes, for example, organic portions of municipal solid waste, sewage treatment sludge, wood waste, etc. Remarkably, these three source categories are abundantly represented in Nigeria.

The majority of agricultural biomass, as highlighted by [22], consists of lignocellulosic materials. A source of sugars with a high concentration of polysaccharides, lignocellulosic biomass has the potential to be a valuable feedstock for the production of a relatively broad range of materials in addition to liquid and solid biofuels [23]. They can actually provide the hydrocarbon chains and other building blocks that humanity needs to meet its massive demand for synthetic polymers, basic organic chemicals, pharmaceuticals, and a variety of other goods over the long term. Lignocelluloses have received great acclaim due to their significant content of different fermentable sugars that can be processed into bioethanol [24]. Additionally, it is acknowledged that using fuel ethanol made from lignocelluloses can help diversify rural economies in some circumstances (e.g., dedicated energy crops) and allow for a net reduction in greenhouse gas emissions, thus potentially offering great socioeconomic and environmental advantages. Additionally, the "food vs. fuel" conundrum can be resolved in an environmentally and socially sustainable manner with lignocelluloses, potentially opening up Nigeria's abundant biomass resources [25]. Regrettably, the primary disadvantage of lignocelluloses is their recalcitrance, which means that different pretreatment methods must be used to break down their complex structure in order to extract their valuable sugars. Furthermore, the most widely used industrial enzymatic microorganisms are unable to efficiently absorb all of the sugars released during processing. This presents a number of challenges for the international scientific and engineering community since it lowers the process's overall yield and deters large-scale, commercial projects for the production of bioethanol from lignocellulosic materials. However, the development of microbial co-culturing systems may facilitate the conversion and degradation of lignocellulose, resulting in an effective lignocellulosic biorefinery that maximises the benefits of agricultural biomass [26]. Forest Biomass stands out as the most abundant source of renewable energy on the planet, as noted by [4]. [27] stated that a forest is any land larger than 0.5 hectares that has trees taller than 5 meters and a canopy cover greater than 10 percent, or trees that can reach these levels on-site. This excludes land that is mostly used for urban or agricultural purposes, as well as other wooded areas. 4.06 billion hectares (ha), or roughly 31% of the total land area, are covered by forests worldwide. Despite the fact that forest areas are not geographically distributed evenly, this translates to 0.52 hectares per person. Most of the world's forests are found in the tropical region (45 percent), which is followed by the temperate, subtropical, and boreal regions. The World Bank records about 214,636 square kilometers as Nigeria's forest area in 2021, accounting for about 7.7% of its total land area [28]. Forest biomass is generally classified by [29] into two categories: industrial roundwood and fuelwood. Fuelwood, a major renewable resource is harvested from forestlands and either burned directly to produce usable heat or converted into bioenergy and biofuel to produce heat and power. Because of its high content of organic matter and macromolecular carbohydrates like cellulose, it is a suitable feedstock for thermochemical conversion, biological conversion, liquefaction, and gasification [30,31]. The fact that forest biomass is intrinsically linked to a number of industries and can be burned directly in boilers and other equipment, or in conjunction with fossil fuels to generate electricity [32], is one of its main advantages. Direct combustion involves burning the biomass outdoors or with excess air at extremely high temperatures, converting its stored chemical energy into heat [33]. [34] noted that this results in the emission of carbon dioxide and other harmful substances, but this is still less than that which is caused by burning fossil fuels. One major problem with forest biomass utilization is the vastness of forests and the complexity of forest biomass compilation. As such, inability to access these resources is a serious threat to power (electricity) generation from forest biomass. Furthermore, the waste resources generated during these activities are generally far from residential and industrial areas. To solve these concerns, forest biomass-based industries be located within a 120 km radius of forests. However, this requires a significant financial investment and storage space [35]. The phrase "aquatic biomass" describes any plant or animal matter that grows in water, including macro and micro algae and aquatic plants. Due to their greater biomass production, higher photosynthetic efficiency, and quicker growth in a variety of environmental conditions, this group of biomasses has been recognised as an offering renewable biomass feedstock for the creation of chemicals and fuels in comparison to lignocelluloses [36]. According to [37], using them could also result in a 90% reduction in greenhouse gas emissions. Algae composition contrasts widely from that of lignocellulosic biomass types. Algae are composed of various carbohydrates combined with different proteins, lipids, and inorganic material, whereas lignocelluloses are composed of lignin, hemicellulose and cellulose, and varying amounts of extractive compounds, both organic and inorganic [38]. Microalgae exist as unicells, colonies or extended filaments and represent a range of genetic variety [39]. Since approximately the 19th century, it has since seen an increase in research that has evolved into third generation biofuels in the past twenty years [40]. This is because of its possible high lipid content for biodiesel production [41]. A class of eukaryotic photosynthetic marine organisms, macroalgae are also known as seaweed [42]. There are generally three groups of seaweeds: brown, red and green. The chemical makeup of the polysaccharides in each group dictates the bioenergy pathway; those with a high polysaccharide content are candidates for bioethanol, those with a high lipid content may be used for biodiesel, and those with a sufficient carbon-nitrogen ratio may ferment to produce biogas. Water hyacinth and duckweed as shown in Figure 4 are two other aquatic plants that are invasive and can clog waterways and take over entire bodies of water. Their high moisture content prevents them from being easily burned. Therefore, in order to preserve an intact biological system, they must be removed manually or with the use of costly machinery. Thus, hydrothermal liquefaction has been suggested as a method to process such invasive aquatic species when they are not cultivated especially for the production of biofuel.

[43] reported that water hyacinth (Eichhornia crassipes) usually found in freshwater course has remain an unresolved challenge for many countries round the world. The existence of these intrusive weeds from past studies revealed the weighty consequences it poses to the aquatic environment that indirectly affect human health and activities. The presence of the weed in fresh water has become a major threat to economic, social activities especially to individuals who obtain their source of livelihood and survival from waterways, lack of access to clean water resulting to increased spread of water borne diseases and health implications is equally noted as continuous threat of this weed as shown in Figure 5. Several efforts made to eradicate this weed have proved unsuccessful as the invasive weed outgrow the control methods.

[44] showed that the widespread proliferation of water hyacinth (Eichhornia crassipes) in aquatic ecosystems has raised significant ecological, environmental, and socioeconomic concerns globally. These concerns include reduced biodiversity, impeded water transportation and recreational activities, damage to marine infrastructure, and obstructions in power generation dams and irrigation systems. It has been evaluateي the challenges posed by water hyacinth (WH) and investigates potential strategies for converting its biomass into value-added agricultural products, specifically nano nutrients-fortified, biochar-based, green fertilizer. Also, it has been reviewed examines various methods for producing functional nanobiochar and green fertilizer to enhance plant nutrient uptake and improve soil nutrient retention. These methods include slow or fast pyrolysis, gasification, laser ablation, arc discharge, or chemical precipitation used for producing biochar which can then be further reduced to nano-sized biochar through ball milling, a top-down approach. Through these means, utilization of WH-derived biomass in economically viable, eco-friendly, sustainable, precision-driven, and smart agricultural practices can be achieved as shown in Figure 6.

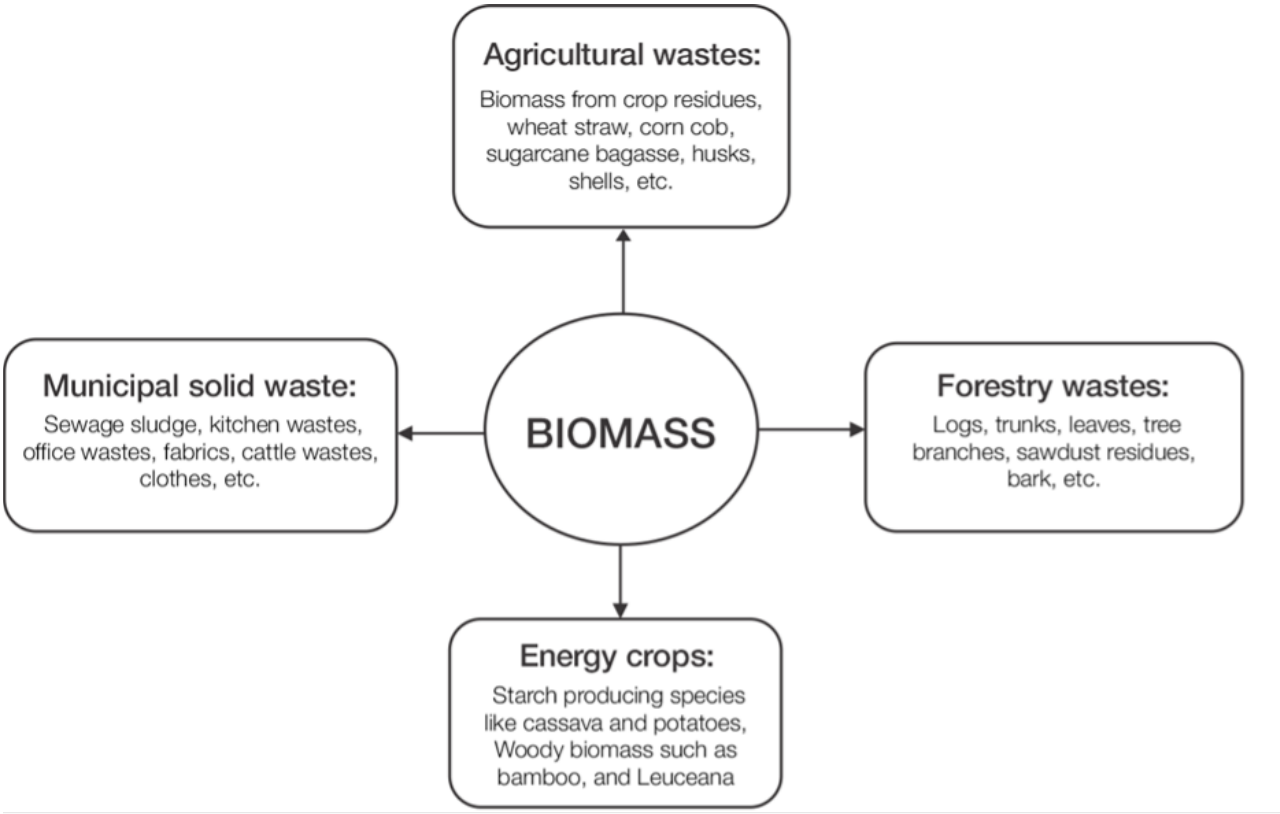

Figure 1. Classification of biomass sources (According to [14])

Figure 2. Sugarcane, a primary energy source (According to [16])

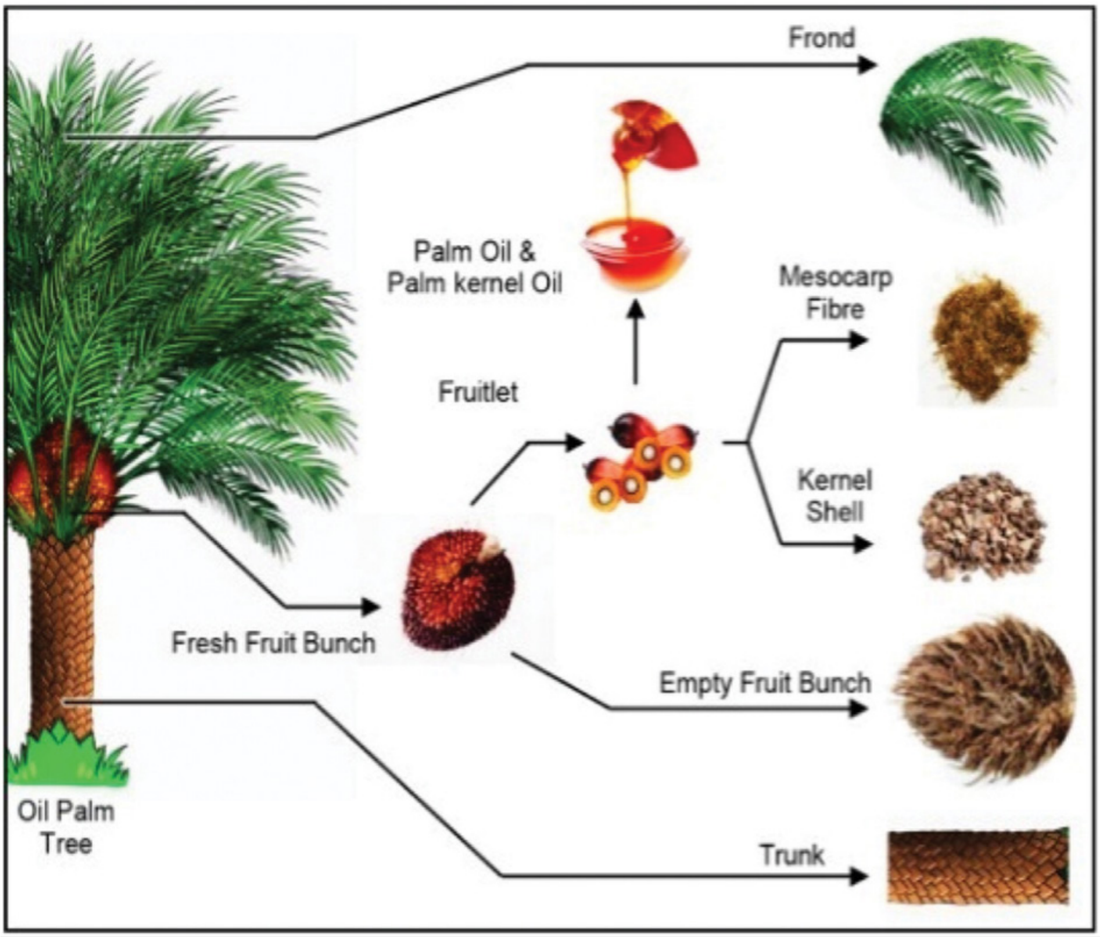

Figure 3. Oil palm biomass and derivatives. Reused with permission from [21]

Figure 4. Water hyacinth, a popular aquatic biomass in Nigeria

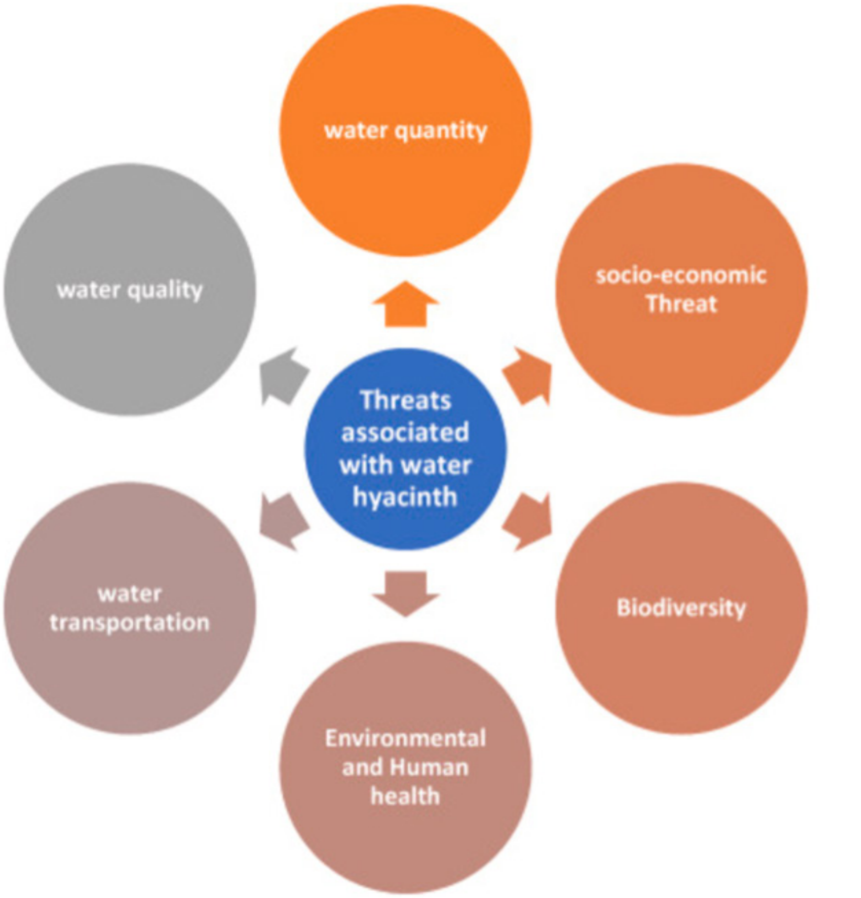

Figure 5. Showing threats of water hyacinth [43]

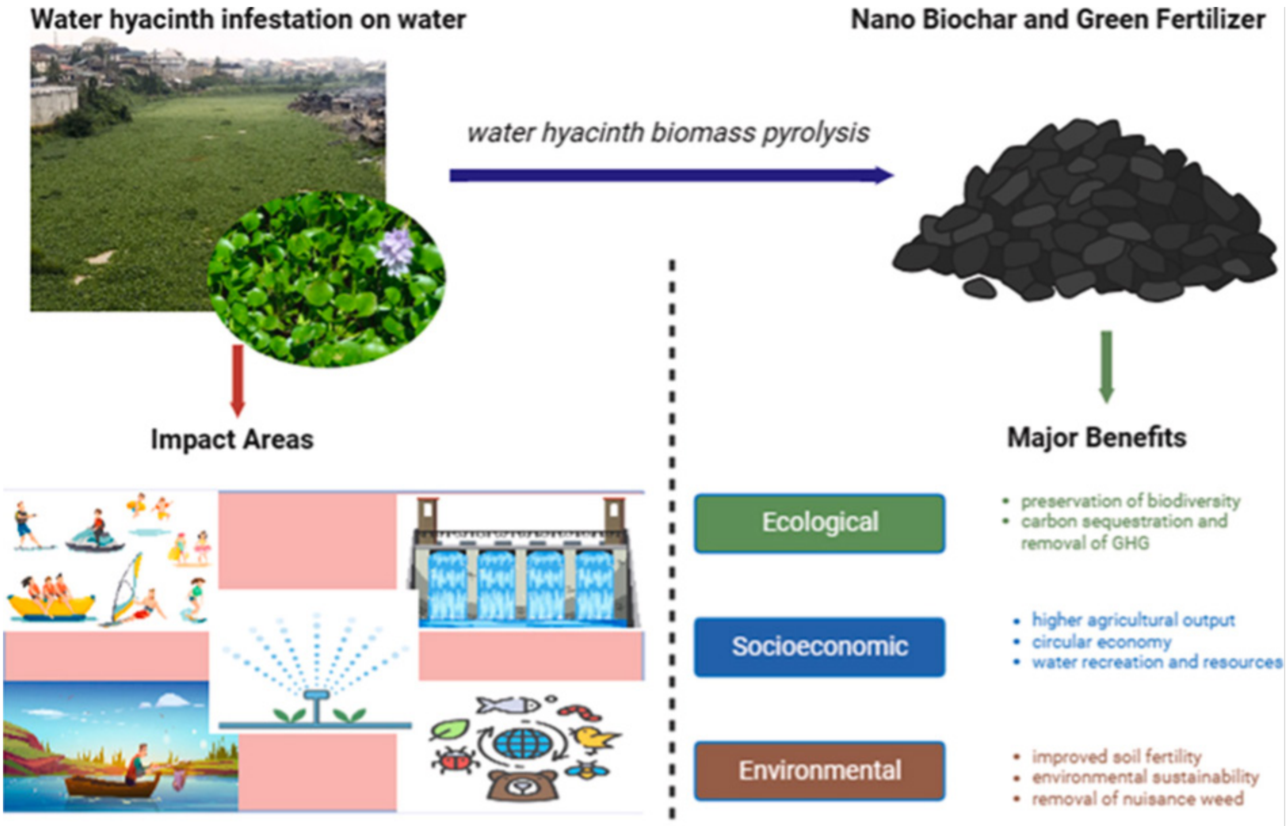

Figure 6. To propose a possible mechanism for the action of water hyacinth biochar-based nano fertilizer [44]

Asides the aforementioned advantages of aquatic biomass utilization, others include: an immense range of valuable co-products, and avoidance of food-vs-fuel controversies because arable land is not needed to grow them [45]. The downsides to energy generation from aquatic biomass are: high water content of aquatic species [39], occasional presence of high sodium content which inhibits methanation [13] and the huge financial cost of production [46]. Its economic viability is feasible only considering the biorefinery approach (i.e. a setup where all available parts of the biomass are exploited and every step of the value chain adds value).

Biomass feedstock may also be grouped as edible food (first generation), non-edible biomass (second generation), algal biomass (third generation) and metabolically engineered species (fourth generation). First generation feedstock is made of up a variety of edible human food (from sugar, starch, and triglyceride sources). Corn and sugarcane are the popular examples of first-generation sugar- and starch-based biomass, while sunflower, jatropha and canola oils are examples of triglyceride biomass. Second-generation biomass arose to mitigate the use of edible food as feedstock. Agricultural residues and non-edible oils such as sugarcane bagasse, corn stover, jatropha oil and castor oil are examples. These agricultural residues contain cellulose and hemicellulose which can be processed into fermentable sugars while the oils are raw material for biodiesel production. Third generation feedstock refers to algal and aquatic biomass which are a source of lipids and sugars for alternative jet fuel production [36]. Interestingly, this group of feedstocks are not part of the 'food-vs-fuel' debate, since they grow in water bodies and not cultivation land. Fourth generation feedstock involves the degradation of metabolically engineered species (such as algae and other microbes) with high lipid contents into polymeric hydrocarbons and other bioproducts [47]. Although this class of biomass guarantees high production rate, research is still in early days and requires huge financial investment. Table 1 shows the Feedstock generations, sources and examples according to [13].

BIOMASS CONVERSION TECHNOLOGIES

The most likely form of energy conversion process/technology, conversion efficiency, and production cost are determined by the chemical composition, physical state, toxicity, and energy content of biomass feedstock found in nature [48]. However, [49] stated that the logistics of processing green energy crops (better suited to biological conversion like fermentation) is even more demanding than that of dry herbaceous feedstock (suited to thermochemical conversion). Tree species with a high oil content are suitable raw materials for the production of biodiesel [50]. However, the cost of producing biodiesel from edible and non-edible vegetable oils is significant [51]. Energy crops can also be directly co-combusted with wood chips or coal, but this leads to alterations in ash composition [52].

Table 1. Feedstock generations, sources and examples

Feedstock generation	Sources	Examples
First generation feedstock	Edible human food	Corn, sugarcane, oil palm, sunflower oil, etc.
Second generation feedstock	Agricultural residues and non-edible oils	Sugarcane bagasse, corn stover, jatropha oil, etc.
Third generation feedstock	Algal and aquatic biomass	Microalgae, macroalgae, water hyacinth, etc.
Fourth generation feedstock	Metabolically engineered species	Algae, bacteria, fungi and other microbes.

BIOMASS PRETREATMENT

The aim of biomass pretreatment is to produce raw material that consistently meets conversion specifications. This is important to consider because of the varying characteristics of biomass feedstock available in nature vis-à-vis biorefinery requirements and energy requirements [53]. Pretreated feedstock that is conversion ready flows better during processing, yields more, improves operational reliability, and reduces operating costs of biorefineries. Aside from this, pretreatment depots can create diverse by-products that serve other customer bases, including biofuel producers, agriculture and horticulture sectors, and so on [48]. Biomass pretreatment techniques are divided majorly into physical, thermal, biological, chemical, and combination (or multiple) pretreatments as shown in Figure 7 and Figure 8.

Physical (or mechanical) pretreatment involves using high-impact and shear forces to break anatomical fractions of biomass, exposing the cellulose to further enzymatic engagement. These techniques have high energy requirements and include shredding, chopping, milling, grinding, air classifying, pulverisation, screening, etc. However, they are difficult to apply to biomass with heterogeneous properties or tissue differences. Corn stover, an abundantly available agricultural residue [55] in Nigeria, is a great example. High impact forces will crush the more delicate parts (like the pith and leaf), while they will only break the tough parts (like the cob and husk). In pretreatment reactors, this may result in an uneven mass flow, heat, and mass transfer due to the wide particle-size distribution [48]. However, fractionating maize stover into its major anatomical components first, then processing each one separately, is a way to get around this method. This approach is only profitable if one or more of the parts have high-value utility. Biological pretreatment is a pretreatment method that could be exploited as a first step default pretreatment on its own or in combination with another pretreatment method. It involves using microorganisms like fungi or bacteria as whole cells or enzymes (e.g., laccase and peroxidases) to degrade biomass structure prior to enzymatic hydrolysis—although fungi are the best suited, as they are capable of degrading cellulose, hemicelluloses, and lignin. This technique, particularly with white rot fungi [56], has the ability to degrade whole lignocelluloses and remove antimicrobial substances, thus improving the efficiency of the enzymatic hydrolysis process. Compared to other pretreatment techniques, biological pretreatment is low cost and energy efficient, does not generate toxic compounds or effluents [57], and improves yield because there are no generation inhibitors to fermentation during the process [58]. The challenge, however, with biological pretreatment is that it is difficult to scale up for industrial purposes. This is due to its slow processing time of 10-14 days [54], the consumption of some carbohydrate fraction by the degrading microorganisms [59], the requirement of strict growth conditions, and the requirement of large space to carry out this pretreatment method. Thermal pretreatment involves dewatering, microbe removal, and viscosity reduction in feedstock by the use of heat [14]. This happens by drying and torrefaction. Drying is the removal of moisture from feedstock. In torrefaction, feedstock is heated in an oxygen-depleted environment to about 2000C - 3000C until the significant moisture is removed, leaving conversion-efficient feedstock with high energy density and low hygroscopic nature. Care should be taken to ensure that feedstock is subjected to extreme temperatures for extended periods to avoid unexpected reactions that trigger the buildup of inhibitors. Chemical pretreatment involves the use of different chemicals (such as acids, bases, ionic liquids) to degrade the lignin-carbohydrate bond and crystalline cellulose structure in lignocelluloses, thus improving its digestibility during processing. Some common chemicals used in this method include hydrochloric acid (HCl), sulfuric acid (H2SO4), aqueous ammonia (NH3. H2O), sodium hydroxide (NaOH), potassium hydroxide (KOH), lime (Ca(OH)2), hydrogen peroxide (H2O2), etc. Pretreatment is done in batch or continuous mode using concentrated or diluted forms of these chemicals as shown in Figure 9 [14, 56], however, dilute acid pretreatment is the most effective choices [41]. The presence of catalysts enhances the overall pretreatment process but in excess, causes increase in pH and the loss of some fermentable sugars - causing lower productivity.

Ionic liquids, sometimes referred to as "designer solvents," are a class of molten salts with melting points lower than 100°C. They are made up of small organic and inorganic anions and organic cations, and there are countless ways to combine them to create a variety of different properties and uses [59]. Although research is still ongoing and there are challenges with usage, ionic liquids like 1-butyl-3-methylimidazolium chloride (abbreviated as [C4C1Im][Cl]) were shown to readily solubilize cellulose for further enzymatic digestibility [56]. Combining two or more pretreatment techniques may be part of other pretreatment strategies. Physical/physical, physical/chemical, chemical/chemical, and chemical/biological are examples of common combinations. Examples include biochemical pretreatments like organogold fractionation, depolymerization, and solubilization; physicochemical pretreatments like steam explosion, which employs both chemical and mechanical forces; liquid hot water (LHW), which uses water at high temperatures and pressures up to 5 MPa; ammonia fiber explosion (AFEX), which releases pressure abruptly after heating liquid ammonia in a closed vessel; and ammonia recycle percolation (ARP).

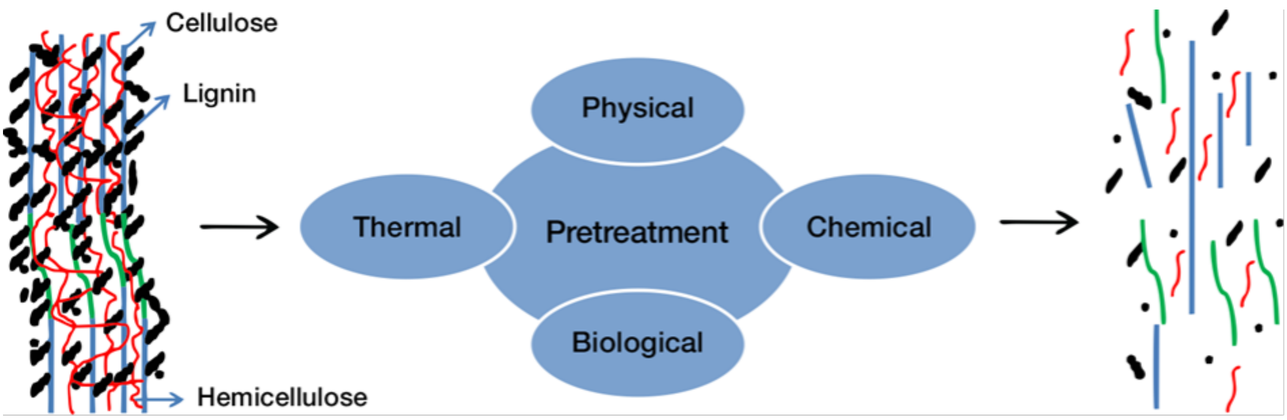

Figure 7. Effects of pretreatment on biomass components [14]

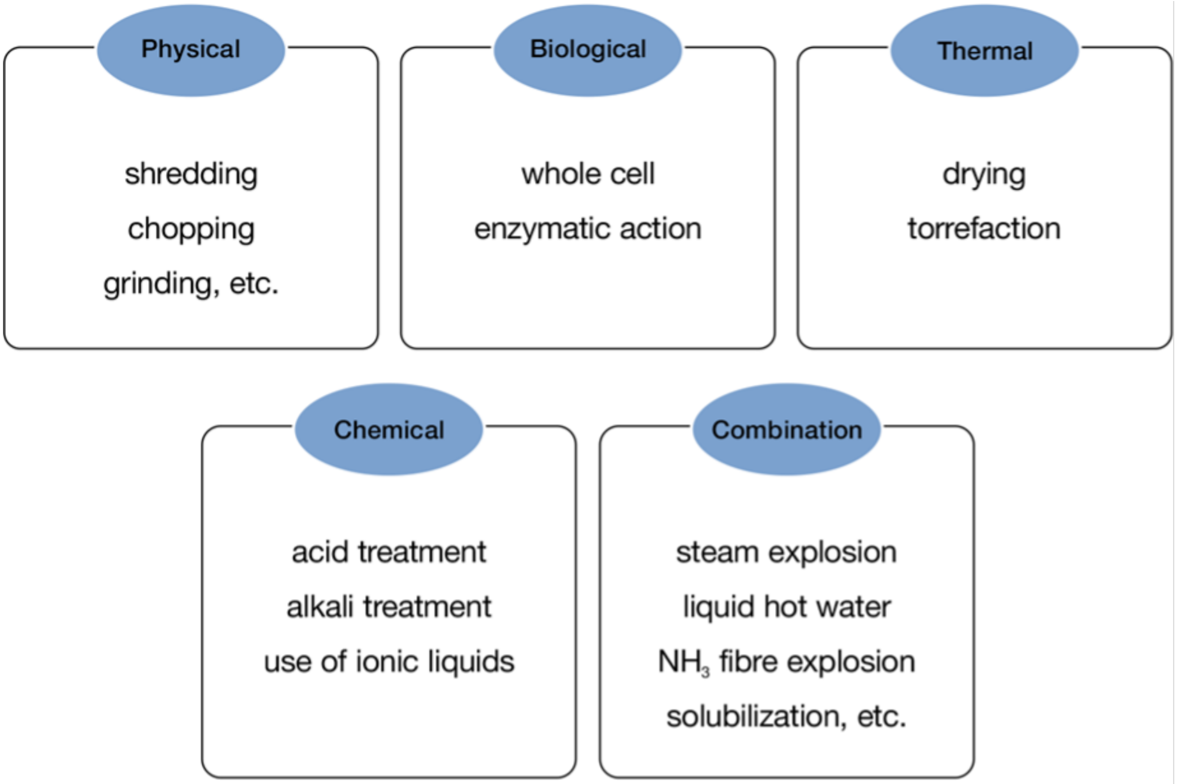

Figure 8. Biomass pretreatment overview [48,54]

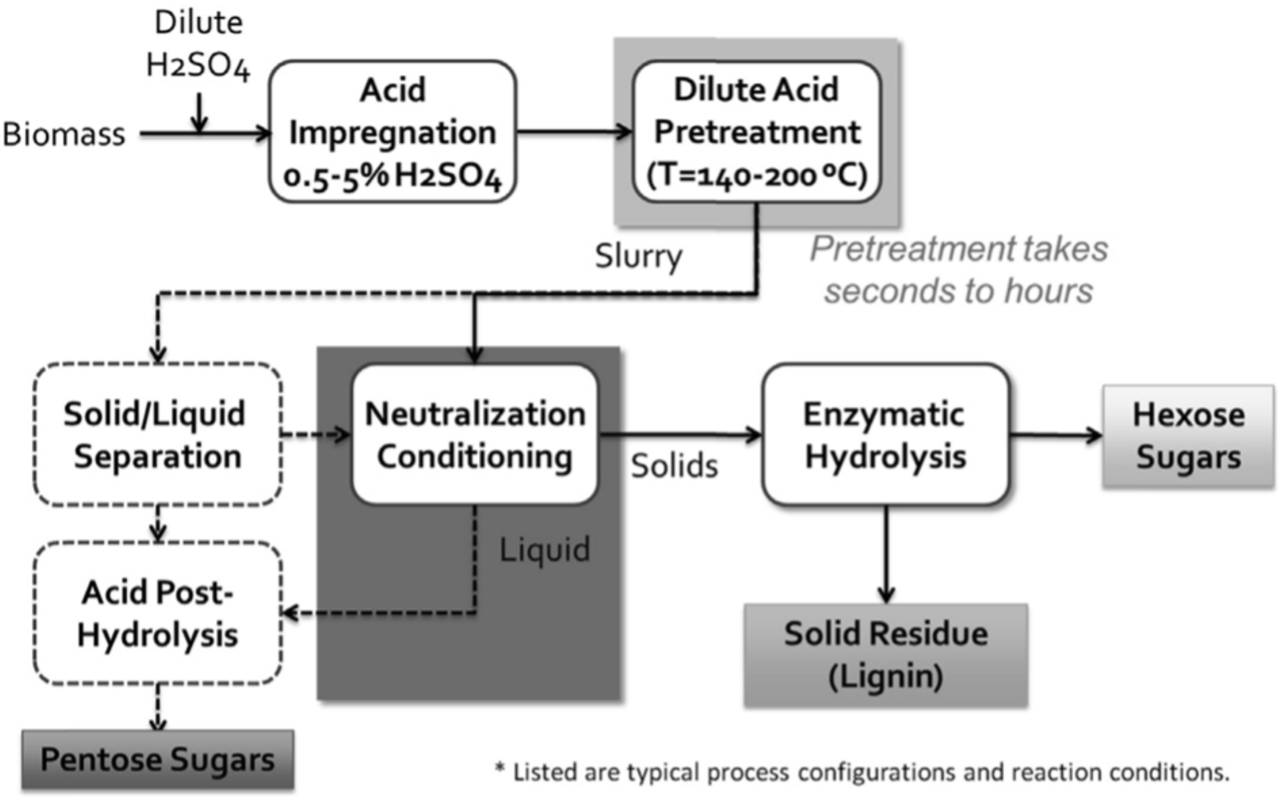

Figure 9. Biomass pretreatment overview [56]

BIOMASS PROCESSING TECHNOLOGIES

Biomass processing involves the conversion of raw biomass into energy, less complex organic residues, and valuable inorganic by-products [4]. This is complicated because, considering available biomass and their different characteristics and other energy production factors, it is impossible to generalise a unified model for biomass treatment and conversion. Nonetheless, energy recovery efficiency and economic competitiveness are the most important factors in considering current technologies and the development of new bioprocessing technologies and strategies. [60] categorised biomass conversion technologies into two (2) primary groups: bio-chemical processes (anaerobic digestion, fermentation, and transesterification) and thermo-chemical conversion processes (direct combustion, pyrolysis, and gasification). These can be further divided into the following: pyrolysis (for biochar, gas, and oils), gasification (for carbon monoxide and hydrogen-rich syngas), fermentation (of sugars for alcohols), transesterification (for biodiesel), anaerobic digestion (for methane-rich gas), and direct combustion (for power). Depending on the particular end products, these six procedures can then be followed by additional secondary treatments (like stabilisation, dewatering, upgrading, and refining). The main distinction between thermochemical and biochemical conversion is that the former uses high temperatures to heat biomass with or without oxygen, while the latter uses enzymes, bacteria, and other microorganisms to break down biomass. The products of thermal transformation are thermal energy and a range of fuels that can be used for other purposes, such as electricity generation [4], while outputs of biochemical processes are liquid and gaseous fuels, including biogas or bioethanol. Generally, thermochemical conversions are less technologically demanding and can be carried out without the use of catalysts, although catalysis has notable effects on the end products.

Direct Combustion

According to [8], woody biomass combustion is the most developed sector of biomass conversion worldwide and is frequently used for the conversion of lignin-rich biomass to provide heat and light energy for cooking and heating. It can be applied in two ways: direct combustion or co-combustion with coal or other fuel material. Compared with other conversion techniques, combustion is mostly non-selective in terms of feedstock; however, factors like the air supply of the system, energy composition, the presence of inorganic fractions, and volatile matter in the feedstock are also important to consider when choosing combustion systems. This is because sufficient oxygen is required to mix with volatile matter released during heating for faster combustion to take place as shown in Figure 10 [61]. High amounts of volatile matter decrease combustion time, lead to quicker reduction to char and finally, ash. Biomass feedstock + heat + excess O_2/air → Char + heat energy + volatile↑

Anaerobic Digestion

Anaerobic digestion is arguably the most common and cost-effective conversion technology for biomass feedstock like animal waste [62]. It involves the metabolic treatment of feedstock by microorganisms in the presence of limited oxygen to produce methane-rich biogas (which can be combusted directly as fuel or upgraded to natural gas) and digestate (which can serve as fertiliser for agricultural purposes). The anaerobic digestion process consists of four sequential steps: hydrolysis, fermentation, acetogenesis, and methanogenesis. The biggest advantage of anaerobic digestion is that little or no waste is generated by the process, making it highly sustainable. Biomass feedstock + Microorganisms → Biogas + Digestate.

Fermentation

In fermentation, lignocelluloses are broken down into simple sugars, alcohols, and acids by the action of enzymes sourced from microorganisms with/without the action of a catalyst. This process may be aerobic (in the presence of oxygen) or anaerobic (in the absence of oxygen). The two most popular sugars follow the reactions below:

Glucose: $C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$

Xylose: $3C_5H_{10}O_5 \rightarrow 5C_2H_6O + 5CO_2$

In fermentation, the polysaccharides are first converted to monomer sugars during enzymatic hydrolysis before subsequent fermentation to alcohols. Both processes can be carried out concurrently in the same reactor or separately.

Biomass feedstock + Enzymes → Alcohol + Acids

Gasification

According to [57], biomass is completely depolymerised with or without a catalyst at temperatures between 800 - 1000°C at 2 - 3 MPa in the presence of limited oxygen, air and/or steam during gasification. This process generates intermediate syngas (synthesis gas), which is a mixture of carbon monoxide (CO), carbon dioxide (CO2), nitrogen (N2), hydrogen (H2), water vapor, and other short-chain hydrocarbons [63]. The syngas generated in this reaction is used majorly for power generation because of its combustibility [64] and further production of some liquid organic mixtures and transport fuels [14]. There are two (2) kinds of gasification mechanisms: fixed and fluidised bed. The fixed bed mechanism is used for processing gases with lower calorific values; however, the fluidised bed mechanism is preferred today because it ensures uniform distribution of temperature during the process.

Biomass feedstock + heat + partial oxidation → syngas + tar + biochar

Pyrolysis

Pyrolysis, a costly and energy-intensive process, involves the decomposition of triglycerides at high temperatures in the absence of oxygen. This results in the production of solid charcoal, liquid bio-oil, and gaseous fuel products that bear chemical similarities to petroleum gasoline and diesel [65].

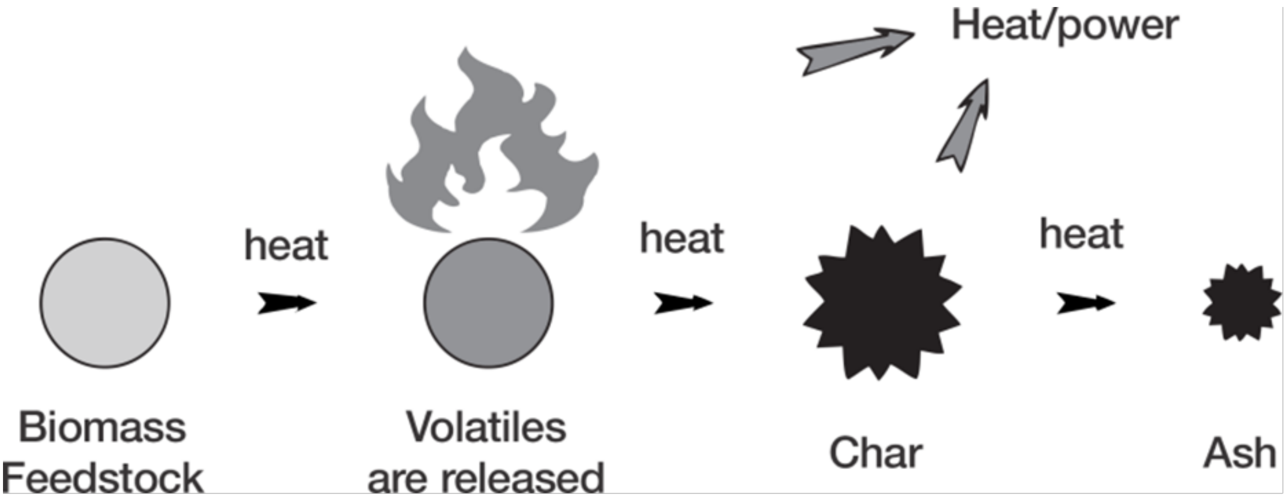

Figure 10. Feedstock combustion route [61]

Table 2. Biomass conversion technologies and end products [62]

Category	Conversion Technology	Product	By-products
Thermochemical conversion	Direct combustion	Heat/power, char	Volatiles, ash
	Pyrolysis	Biochar	Bio-oil, gases
	Gasification	Intermediate syngas	Tar, biochar
Biochemical conversion	Anaerobic Digestion	Biogas	Digestate
	Fermentation	Bio-alcohols	Acids
	Transesterification	Biodiesel	Glycerol, effluents

Transesterification

Transesterification, also known as alcoholysis, is the most developed method of biodiesel production. It is very similar to hydrolysis in that it involves the catalytic substitution of the alcohol in an ester compound with another alcohol, instead of water. In this case, alcohol reacts with vegetable oil (triglycerides) in the presence of an acid/alkali catalyst to produce biodiesel. Methanol is the popular alcohol choice for this reaction because it is cheap and reacts very quickly. Biodiesel produced via this method has a high cetane value, high combustion efficiency, and low emissions; however, proper disposal of conversion by-products (glycerol and wastewater) is a major issue to consider [66].

Biomass feedstock + alcohol + catalyst → Biodiesel + glycerol + waste water

POPULAR BIOPRODUCTS

As seen in the previous section, the final product obtained after biomass conversion is largely dependent on the feedstock type and the conversion technology of choice. There are four main products obtained from biomass conversion, namely bio-oils, biogas, biofuels, and biochar, in addition to other valuable by-products.

Bio-Oil

When the volatile vapors generated during pyrolysis of biomass feedstock are condensed, they form a liquid called bio-oil. According to [60], these oils are a mixture of numerous organic compounds, and they serve as alternatives to fossil fuels. Their nature requires catalytic hydrodeoxygenation to make them directly usable as liquid fuels; however, they can also be blended with conventional fuels. Figure 11 shows that application of bio-oils according to [67].

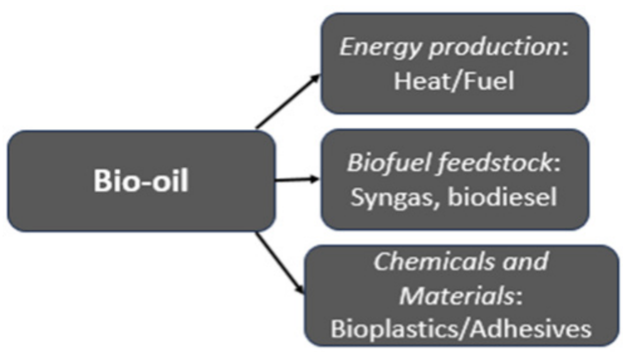

Figure 11. Application of bio-oils [67]

Biogas

Biogas is generated by an anaerobic digestion process from biomass feedstock with high moisture content, especially agricultural residue and waste byproducts. It is a mixture of about 50-70% methane (CH_4), 30-50% carbon dioxide (CO_2), and trace amounts of gases like ammonia (NH_4), hydrogen sulfides (H_2S), and water vapor [68]. Biogas, easily produced at domestic or industrial levels, can be utilized directly for cooking and power generation or processed further to create various energy products, showcasing its versatility and utility as a renewable energy source. Figure 12 shows that biogas production process flow according to [14].

Biofuels

Biofuels are classified based on feedstock and conversion technology into first, second, third, and fourth-generation biofuels. These products exist in solid, liquid, or gaseous forms. Examples of these biofuels include biodiesel (mono-alkyl esters derived from triglyceride sources), bio-alcohols (generated through the hydrolysis and fermentation of carbohydrates or cellulose), bio-syngas (a mixture generated during gasification), biogasoline (obtained from fourth-generation feedstock), and pure vegetable oils (obtained through cold pressing and extraction from seeds of oil plants). Some other examples include bio dimethylfuran (bioDMF) and bio-hydrogen. These biofuels can be used directly as transport fuels or upgraded to produce other energy products. Compared to conventional fossil fuels, biofuels are biodegradable, eco-friendly, and renewable, making them major alternative sources for meeting the challenges of the global rising demand for clean energy [69].

Biochar

Biochar is the solid charcoal-like residue (RIT, 2023) generated from the thermochemical conversion of biomass feedstock. In direct combustion, char is the intermediate residue obtained after the release of the volatiles during heating, before subsequent degradation to ash. Although it is produced during gasification, it is a major product of pyrolytic reactions (especially slow pyrolysis, where yields may be up to 30-35%). [60] stated that the use of this carbon-rich product is important in carbon sequestration biogas and lowering greenhouse emissions globally; besides that, it is also used as a soil enhancer to increase crop yields and sustain soil biodiversity. Figure 13 shows that biogas production process flow according to [14].

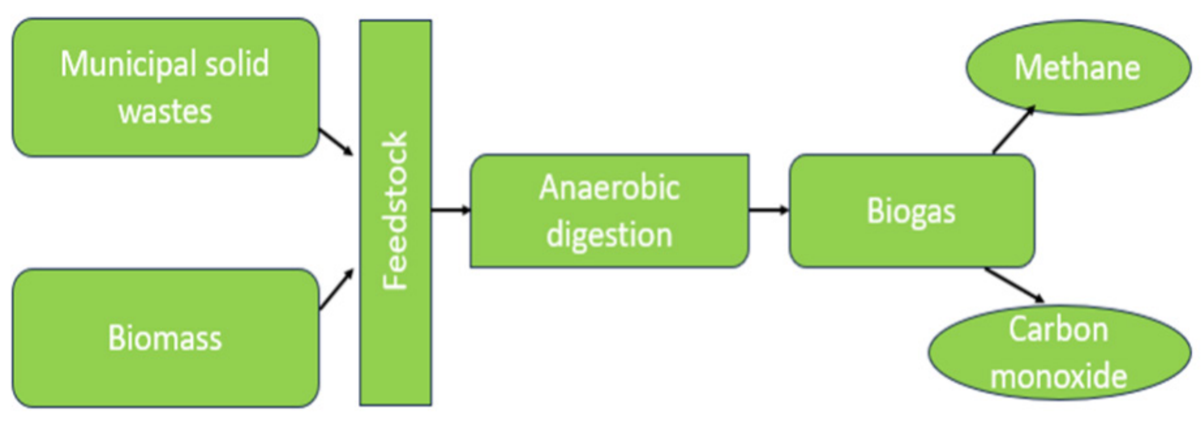

Figure 12. Biogas production process flow [14]

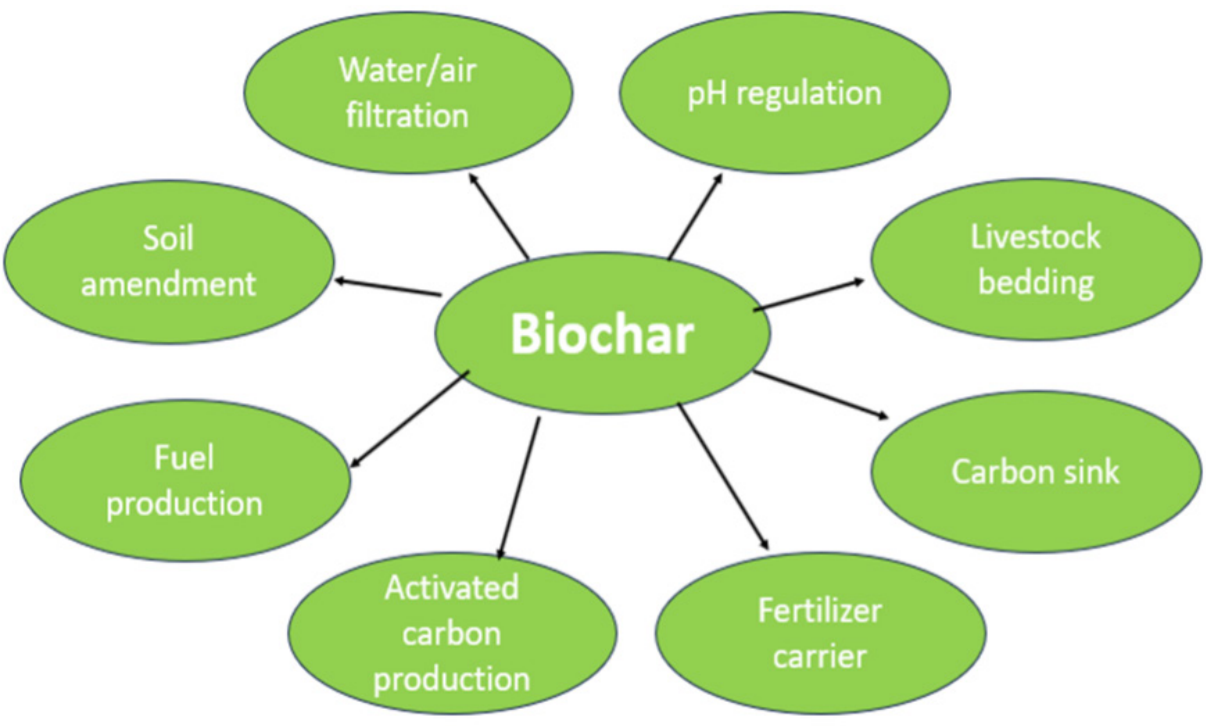

Figure 13. Potential benefits of biochar [14]

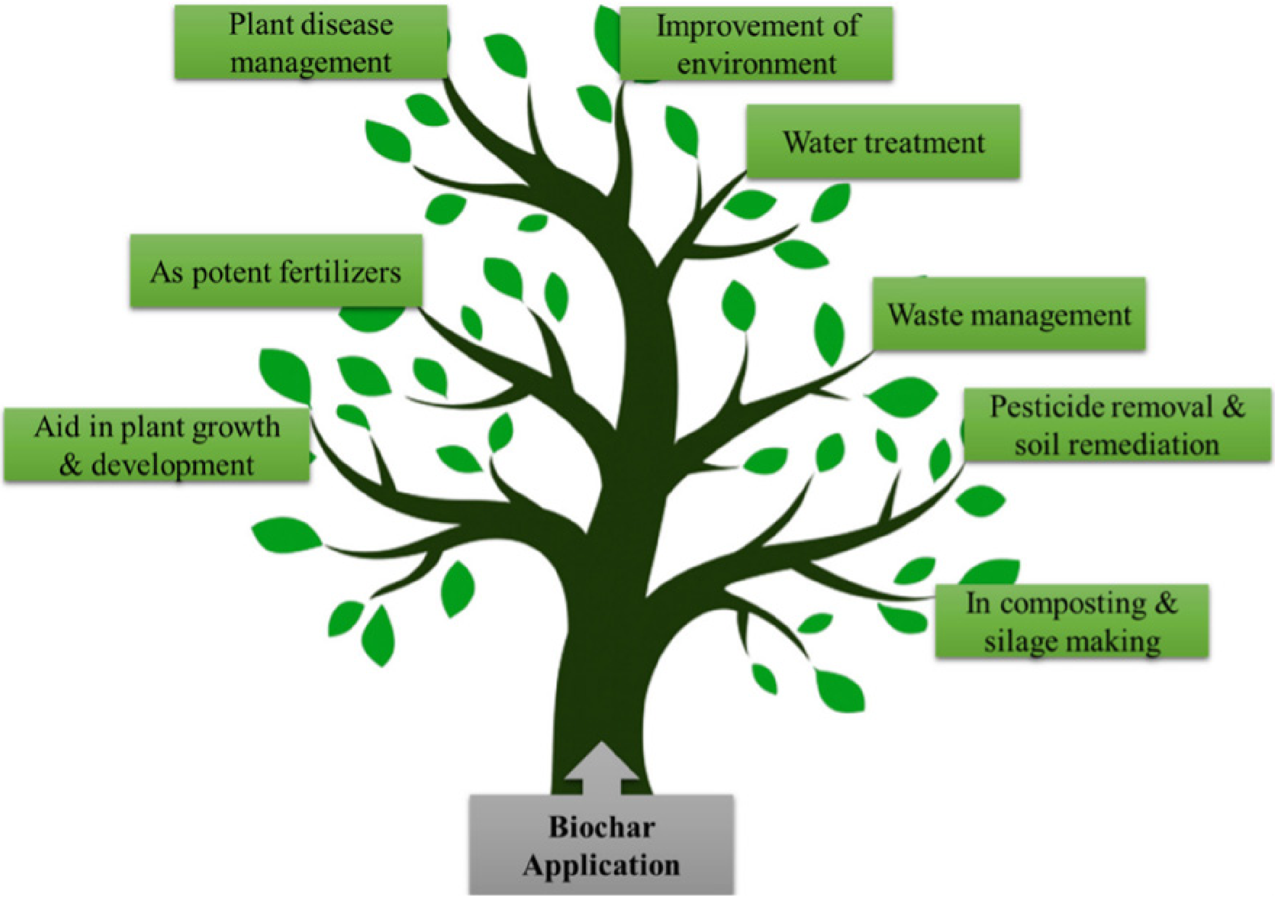

Figure 14. The wide range of applications of biochar in agriculture [71]

Biochar refers to the carbonaceous black solid residue product obtained from the thermochemical decomposition of waste biomass typically under an oxygen-limited environment. There are many thermochemical methods for biochar production from solid waste streams, prominent are pyrolysis, torrefaction, and hydrothermal carbonization. However, the yield and properties of biochar depend mainly on the production methods and the process parameters, such as temperature, residence time, heating rate, gas environment, feedstock types, among others [70]. [71] reported that biochar has a profound application in agriculture because of its properties which have direct positive effects on soil, microbial consortium as well as on plants as Figure 14. Properties like porosity and ability to undergo natural oxidation lead to the generation of functional organic compounds make it a perfect candidate for water treatment, pesticide management, controlled release fertilizers, waste management. Moreover, the presence of nutrient and nutrient retention capacity makes it an impeccable fertilizer. Through different mechanisms, it also protects the plants from various pathogens and other pests and also helps in environmental remediation.

TECHNOLOGIES AND INNOVATIONS FOR BIOMASS ENERGY

[72] developed an innovative hybrid system (SolBio-Rev system) based on the use of solar and biomass energy to provide heating, cooling, domestic hot water (DHW), and electricity in both residential and non-residential buildings. The system includes novel components such as solar collectors with thermoelectric generators, a high efficiency biomass boiler and a reversible organic Rankine cycle/heat-pump. The innovative SolBio-Rev system shown in Figure 15. The system configuration was optimized for a continental European climate and is made of the following components: Solar collectors with integrated thermoelectric generators (TEGs); short-term storage and thermal buffer tank; reversible heat pump/ORC; biomass boiler; and dry cooler.

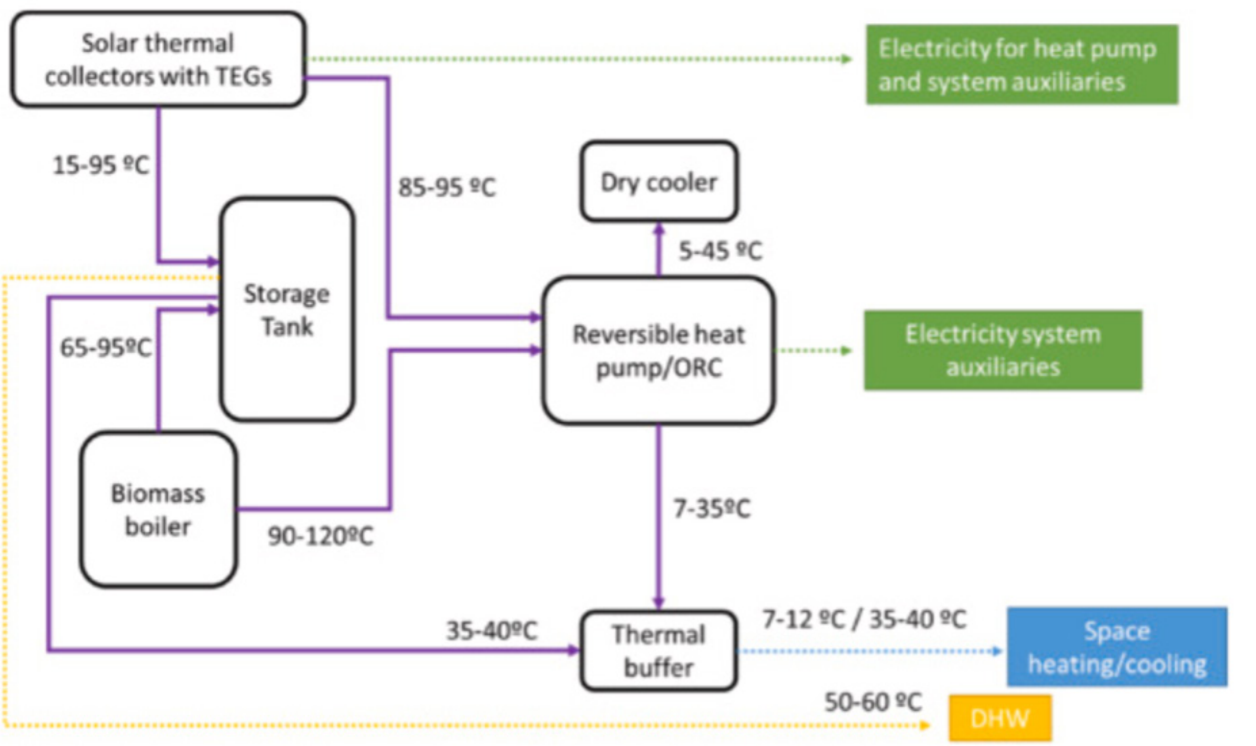

Figure 15. The innovative SolBio-Rev system [72]

[73] emphasized the huge potential of using agricultural waste to produce briquettes and granules, which remains largely untapped. Continued technological innovation and collaboration are essential to remove waste from the fields and promote this energy alternative. By addressing these barriers, the research contributes to promoting sustainable energy solutions and promoting bioenergy as a viable and scalable option. [74] explored the current mainstream hydrogen preparation paths, including but not limited to hydroelectrolysis (decomposition of water molecules using renewable energy power); gas steam reforming (traditional but efficient hydrogen production methods requiring carbon emission management); biomass gasification and coal gasification (based on innovative utilisation of renewable and fossil resources); and hydrolysis hydrogen production (advanced cutting-edge technology directly using solar energy). Each method shows its unique advantages and potential application scenarios. [75] reported that forest residues, such as branches and treetops, have a high energy potential with calorific values reaching up to 20 MJkg-1 after briquetting. Densifying these residues increases their energy density (achieving up to 1120 kgm-3) and reduces waste and greenhouse gas emissions. Briquetting processes were analyzed economically and environmentally, with studies showing that production costs can be reduced by 25% when using locally sourced residues. Rural and economically disadvantaged regions could benefit from these advancements in briquetting. Technology such as briquetting has the potential to advance renewable energy systems and achieve global climate goals. As climate change impacts the environment negatively, reducing greenhouse gas emissions is one of the most important issues we are facing today.

CONCLUSIONS

This review highlights the urgent need for Nigeria in particular and neighboring countries in general to harness renewable energy, reduce negative emissions from fossil fuels and the inability of current conventional energy supplies to meet demand at the country level.. Biomass feedstock from agricultural and forest biomass, production process residues, and large amounts of waste generated in urban and rural areas abound across Nigeria, making it a sustainable alternative energy source. First- and second-generation biomass are the most readily available feedstock sources in Nigeria; however, the use of first-generation feedstock creates a food-vs-fuel debate. Aside from the direct combustion of biomass feedstock, which is quite popular globally, biomass conversion and biofuel production are redundant in Nigeria. This is due to the scientific knowledge gaps and huge financial implications involved in bioenergy generation.

DATA AVAILABILITY STATEMENT

No data was used for the research described in the article.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

1. N.S.M. Elkaoud, R.K. Mahmoud, H.H. Tarabye, and M.S. Adam, "Promoting food security and sustainability with a transportable indirect evaporative solar pre-cooler," Revista Facultad Nacional de Agronomía Medellín, Vol. 77(3), pp. 10865-10876, 2024. https://doi.org/10.15446/rfnam.v77n3.110667
2. N. Gao, L. Zhang, and C. Wu, "Biomass and Wastes for Bioenergy: Thermochemical Conversion and Biotechnologies," BioMed Research International, Vol. 2018, Article ID 9638380, pp. 1-2, https://doi.org/10.1155/2018/9638380
3. J. Wang, S. Liu, T. Gallagher, D. DeVallance, and L. Denes, "Forest Biomass Utilization for Biofuels and Bioproducts," International Journal of Forestry Research, Vol. 2012, pp. 1-2, 2012. https://doi.org/10.1155/2012/656834
4. C. Bonechi, M. Consumi, A. Donati, G. Leone, A. Magnani, G. Tamasi, and C. Rossi, "Biomass: An overview," in F. Dalena, A. Basile, and C. Rossi (Eds.), Bioenergy systems for the future, prospects for biofuels and biohydrogen, Duxford: Woodhead Publishing, Vol. 148, pp. 3-42, 2017. https://doi.org/10.1016/b978-0-08-101031-0.00001-6
5. S.M. Bukar and H.M. Abba. "Vegetation Structure and Diversity in Northern Yobe," Nigeria. Asian Journal of Plant Biology, Vol. 4(1), pp. 36-42, 2022.
6. J. Ben-Iwo, V. Manovic, and P. Longhurst, "Biomass resources and biofuels potential for the production of transportation fuels in Nigeria," Renewable and Sustainable Energy Reviews, Vol. 63, pp. 172-192 2016. https://doi.org/10.1016/j.rser.2016.05.050
7. J. Ogwo, O. Dike, S.O. Mathew, and A. Emmanuel, "Overview of biomass energy production in Nigeria: Implications and challenges," Asian Journal of Natural & Applied Sciences, Vol. 1, pp. 46-51, 2012.
8. EUBIA. "Biomass Processing Technologies," Available at eubia.org/cms/wiki-biomass/biomass-processing-technologies 2023., (accessed 15 February 2023)
9. R.A. Houghton, "Biomass," in S. E. Jorgensen, and B. D. Fath (Eds.), Encyclopedia of ecology, Amsterdam: Elsevier, pp. 448–453, 2008. https://doi.org/10.1016/B978-0-444-63768-0.00462-5
10. A. Tursi, "A review on biomass: importance, chemistry, classification, and conversion," Biofuel Research Journal, Vol 22, pp. 962-979, 2019.
11. A. Mishra, L. Singh, and D. Singh, "Unboxing the black box-one step forward to understand the soil microbiome: A systematic review," Microbial Ecology, Vol. 85(2), pp. 669-683, 2023. https://doi.org/10.1007/s00248-022-01962-5
12. M. Casau, M.F. Dias, J.C.O. Matias, and L.J.R. Nunes, "Residual Biomass: A Comprehensive Review on the Importance, Uses and Potential in a Circular Bioeconomy Approach," Resources. Vol. 11(4), pp. 35, 2022.
13. J. Sánchez, M.D. Curt, N. Robert, and J. Fernández, "Biomass Resources. The Role of Bioenergy in the Bioeconomy," pp. 25–111, 2019. https://doi.org/10.1016/b978-0-12-813056-8.00002-9
14. G.K. Gupta and M.K. Mondal. "Bioenergy generation from agricultural wastes and enrichment of end products,". Refining Biomass Residues for Sustainable Energy and Bioproducts pp. 337-356, 2020. https://doi.org/10.1016/b978-0-12-818996-2.00015-6
15. A.A.A. Abuelnuor, "Analysis of sugarcane bagasse from Kenana and White Nile companies in Sudan," Biomass Conv. Bioref 2024. https://doi.org/10.1007/s13399-024-06358-8
16. E.O. Ajala, J.O. Ighalo, and M.A. Ajala. "Sugarcane bagasse: a biomass sufficiently applied for improving global energy," environment and economic sustainability. Bioresour. Bioprocess pp 8-87, 2021. https://doi.org/10.1186/s40643-021-00440-z
17. OECD, "Agricultural land (indicator)," Available: https://data.oecd.org/agrland/agricultural-land.htm (accessed 19 January, 2023).
18. Q. Kang, L. Appels, T. Tan, and R. Dewil "Bioethanol from Lignocellulosic Biomass Current Findings Determine Research Priorities," The Scientific World Journal p. 1-13, 2014. https://doi.org/10.1155/2014/298153
19. A.F. Cristino, D. Logan, J.C. Bordado, and S.R. Galhano "The Role of Ionic Liquids on Biomass Liquefaction—A Short Review of the Recent Advances," Processes Vol. 9(1214) pp. 1-13, 2021 https://doi.org/10.3390/ pr9071214
20. Ó.J. Sánchez and S. Montoya. "Production of Bioethanol from Biomass: An Overview," in Gupta, V., Tuohy, M. (eds) Biofuel Technologies, Springer, Berlin, Heidelberg, pp. 397–441, 2013. https://doi.org/10.1007/978-3-642-34519-7_16
21. R.A. Ilyas, M.Y.M. Zuhri, M.N.F. Norrrahim, M.S.M. Misenan, M.A. Jenol, S.A. Samsudin, N.M. Nurazzi, M.R.M. Asyraf, A.B.M. Supian, S.P. Bangar, R. Nadlene, S. Sharma, and A.A.B. Omran, "Natural Fiber-Reinforced Polycaprolactone Green and Hybrid Biocomposites for Various Advanced Applications. Polymers, Vol. 14(1)182, pp. 1-28, 2022. https://doi.org/10.3390/polym14010182
22. A.O. Ayeni, F.K.S. Hymore, S.N. Mudliar, S.C. Deskmukh, D.B. Satpute, J.A. Omoleye, and R.A. Pandey, "Hydrogen peroxide and lime based oxidative pretreatment of wood waste to enhance enzymatic hydrolysis for a biorefinery: Process parameters optimization using response surface methodology," Fuel. Vol. 106, pp. 187-194, 2013. https://doi.org/10.1016/j.fuel.2012.12.078

23. X. Ge, C. Chang, L. Zhang, Shaoqing Cui, Xiaolan Luo, Shengjun Hu, Yusheng Qin, and Yebo Li, Chapter Five "Conversion of Lignocellulosic Biomass Into Platform Chemicals for Biobased Polyurethane Application," Editor(s): Yebo Li, Xumeng Ge, Advances in Bioenergy, Elsevier, Vol. 3, pp. 161-213, 2018.
24. M. Broda, D.J. Yelle, and K. Serwańska, "Bioethanol Production from Lignocellulosic Biomass-Challenges and Solutions," Molecules. Vol. 27(24), 8717, 2022.
25. T. Riitonen, V. Eta, S. Hyvärinen, L.J. Jönsson, and J.P. Mikkola, "Engineering Aspects of Bioethanol Synthesis," Advances in Chemical Engineering, Vol. 42, pp. 1–73, 2013. https://doi.org/10.1016/b978-0-12-386505-2.00001-8
26. Y. Liu, Y. Tang, H. Gao, W. Zhang, Y. Jiang, F. Xin, and M. Jiang, "Challenges and Future Perspectives of Promising Biotechnologies for Lignocellulosic Biorefinery," Molecules, Vol. 26(17), 5411, pp. 1-15, 2021. https://doi.org/10.3390/molecules26175411
27. FAO. Global Forest Resources Assessment, Desk reference, Terms and Definitions. FAO Report, 36. Available: https://openknowledge.fao.org/server/api/core/bitstreams/5100a18e-1432-42b1-945e-398daac0176e/content., 2015, (accessed 1 Des. 2024)
28. FAO. Global Forest Resources Assessment, Key findings, Main report. Rome. https://doi.org/10.4060/ca9825en, Available: https://openknowledge.fao.org/server/api/core/bitstreams/9f24d451-2e56-4ae2-8a4a-1bc511f5e60e/content., 2020 (accessed 1 Des. 2024)
29. R. Raunikar, J. Buongiorno, J.A. Turner, and S. Zhu, "Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change," Forest Policy and Economics, Vol. 12(1), pp. 48–56, 2010. https://doi.org/10.1016/j.forpol.2009.09.013
30. Z. Tan, K. Chen, and P. Liu, "Possibilities and challenges of China′s forestry biomass resource utilization," Renewable and Sustainable Energy Reviews, Vol. 41, pp. 368-378, 2015. https://doi.org/10.1016/j.rser.2014.08.059
31. A. Saravanakumar, P. Vijayakumar, A.T. Hoang, E. K. Eilhann, and C. Wei-Hsin, "Thermochemical conversion of large-size woody biomass for carbon neutrality," Principles, applications, and issues, Bioresource Technology, Vol. 370, 128562, 2023.
32. A.I. Calvo, L.A.C. Tarelho, E.R. Teixeira, C. Alves, T. Nunes, M. Duarte, and R. Fraile, "Particulate emissions from the co-combustion of forest biomass and sewage sludge in a bubbling fluidized bed reactor," Fuel Processing Technology, Vol. 114, pp. 58-68, 2023. https://doi.org/10.1016/j.fuproc.2013.03.021
33. M.K. Lam, A.C.M. Loy, S. Yusup, and K.T. Lee. Biohydrogen Production from Algae. Biohydrogen, pp. 219-245. https://doi.org/10.1016/b978-0-444-64203-5.00009-5
34. Q. Yu, Y. Wang, Q. Van Le, H. Yang, H. Hosseinzadeh-Bandbafha, Y. Yang, C. Sonne, M. Tabatabaei, S.S. Lam, and W. Peng, "An Overview on the Conversion of Forest Biomass into Bioenergy Front," Energy Research, Vol. 9, 684234, 2021. https://doi.org/10.3389/fenrg.2021.684234
35. B.S. Hoffmann, A. Szklo, and R. Schaeffer, "An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil," Biomass and Bioenergy, Vol. 45 pp. 295-302, 2012. https://doi.org/10.1016/j.biombioe.2012.06.016
36. G.W. O'Neil, G. Knothe, and C.M. Reddy, "Jet biofuels from algae," Biofuels from Algae, Biomass, Biofuels, Biochemicals, pp. 359-395, 2019. https://doi.org/10.1016/b978-0-444-64192-2.00015-9
37. Y. Dahman, C. Dignan, A. Fiayaz, and A. Chaudhry, "An introduction to biofuels, foods, livestock, and the environment," Biomass, Biopolymer-Based Materials, and Bioenergy pp. 241-276 2019. https://doi.org/10.1016/b978-0-08-102426-3.00013-8
38. P.J. De Wild, "Biomass Pyrolysis for Hybrid Biorefineries," Industrial Biorefineries, White Biotechnology, pp. 341-368, 2015. https://doi.org/10.1016/b978-0-444-63453-5.00010-0
39. J.C.J. Bart, N. Palmeri, and S. "Cavallaro Feedstocks for biodiesel production," Biodiesel Science and Technology pp. 130-225, 2010. https://doi.org/10.1533/9781845697761.13
40. P. Biller, "Hydrothermal liquefaction of aquatic Feedstocks," Direct Thermochemical Liquefaction for Energy Applications, pp. 101-125, 2018. https://doi.org/10.1016/b978-0-08-101029-7.00003-5
41. Y. Dahman, K. Syed, S. Begum, P. Roy, and B. Mohtasebi, "Biofuels: Their characteristics and analysis Biofuels," Biomass, Biopolymer-Based Materials, and Bioenergy, Construction, Biomedical, and other Industrial Applications Woodhead Publishing Series in Composites Science and Engineering, pp. 277-325, 2019. https://doi.org/10.1016/b978-0-08-102426-3.00014-x
42. H.S. El-Beltagi, A.A. Mohamed, H.I. Mohamed, K.M.A. Ramadan, A.A. Barqawi, and A.T. Mansour, "Phytochemical and Potential Properties of Seaweeds and Their Recent Applications: A Review," Marine Drugs. Vol. 20(6), pp. 342, 2022. https://doi.org/10.3390/md20060342
43. E.K. Onyari, G.U. Fayomi, and A.T. Jaiyeola, "Unveiling the situation of water hyacinth on fresh water bodies in Nigeria and South Africa: Management, workable practices and potentials," Case Studies in Chemical and Environmental Engineering, Vol. 10, 100974, 2024. https://doi.org/10.1016/j.cscee.2024.100974
44. A.T. Irewale, C.O. Dimkpa, E.E. Elemike, and E.E. Oguzie, "Water hyacinth: Prospects for biochar-based, nano-enabled biofertilizer development," Heliyon, Vol. 10(17), e36966. pp. 1-18, 2024.

https://doi.org/10.1016/j.heliyon.2024.e36966
45. F.I. Gómez-Castro and C. Gutiérrez-Antonio, "Chapter 1 - Biomass: The driver for sustainable development, Biofuels and Biorefining," Elsevier pp. 1-23, ISBN 9780128241165, 2024. https://doi.org/10.1016/B978-0-12-824116-5.00008-8
46. K. Balina, F. Romagnoli, and D. Blumberga, "Seaweed biorefinery concept for sustainable use of marine resources," Energy Procedia, Vol. 128, pp. 504-511, 2017. https://doi.org/10.1016/j.egypro.2017.09.06
47. H.A. Alalwan, A.H. Alminshid, and H.A.S. Aljaafari, "Promising evolution of biofuel generations, Subject review," Renew Energy Focus Vol. 28, pp. 127-139, ISSN 1755-0084, 2019. https://doi.org/10.1016/j.ref.2018.12.006
48. Q.A. Nguyen, W.A. Smith, B.D. Wahlen, and L.M. Wendt, "Total and Sustainable Utilization of Biomass Resources: A Perspective, Frontiers in Bioengineering and Biotechnology," Vol. 8, pp. 2296-4185, 2020. https://doi.org/10.3389/fbioe.2020.00546
49. Z. Miao, T.E. Grift, A.C. Hansen, and K. Ting, "An overview of lignocellulosic biomass feedstock harvest, processing and supply for biofuel production," Biofuels, Vol. 4(1), pp. 5-8, 2013. https://doi.org/10.4155/bfs.12.76
50. M. Patel, A.O. Oyedun, A. Kumar, and R.A. Gupta, "Techno-Economic Assessment of Renewable Diesel and Gasoline Production from Aspen Hardwood," Waste and Biomass Valorization, Vol. 10, pp. 2745-2760, 2019. https://doi.org/10.1007/s12649-018-0359-x
51. S.U. Shivramu, B.R. Venkatappa, C. Laxman, B. Gowda, R.K. Kodi, and P.K. Thamaiah, "Synthesis and Characterization of Biodiesel from Simarouba glauca," Biofuels and Bioenergy (BICE2016), pp. 51-57, 2017. https://doi.org/10.1007/978-3-319-47257-7_6
52. H. Honkanen and J. Kataja, "Technological aspects of nonfood agricultural lignocellulose transformations," Bioenergy Systems for the Future, pp. 43-59, 2017. https://doi.org/10.1016/b978-0-08-101031-0.00002-8
53. M. Galbe and O. Wallberg, "Pretreatment for biorefineries: a review of common methods for efficient utilization of lignocellulosic materials," Biotechnol Biofuels, Vol. 12, pp. 294, 2019. https://doi.org/10.1186/s13068-019-1634-1
54. V.B. Agbor, N. Cicek, R. Sparling, A. Berlin, and D.B. Levin, "Biomass pretreatment: Fundamentals toward application," Biotechnology Advances, Vol. 29(6), pp. 675-685, 2011. https://doi.org/10.1016/j.biotechadv.2011.05.005
55. M.H. Langholtz, B.J. Stokes, and L.M. Eaton, "Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy," Economic Availability of Feedstocks, Oak Ridge, National Laboratory, Oak Ridge, Tennessee, managed by UT-Battelle, LLC for the US Department of Energy, Vol. 1, pp. 1-411, 2016. https://doi.org/10.2172/12 71651
56. Y. Zheng, J. Shi, M. Tu, and Y.S. Cheng, "Principles and Development of Lignocellulosic Biomass Pretreatment for Biofuels," Advances in Bioenergy, Vol. 2, pp. 1-68, 2017. https://doi.org/10.1016/bs.aibe.2017.03.001
57. K. Robak and M. Balcerek, "Review of Second-Generation Bioethanol Production from Residual Biomass" Food Technology and Biotechnology, Vol. 56(2), 2018. https://doi.org/10.17113/ftb.56.02.18.5428
58. A.W. Bhutto, K. Qureshi, K. Harijan, R. Abro, T. Abbas, A.A. Bazmi, S. Karim, and G. Yu, "Insight into progress in pre-treatment of lignocellulosic biomass," Energy, Elsevier, Vol. 122(C), pp. 724-745, 2017. https://doi.org/10.1016/j.energy.2017.01.005
59. J. Baruah, B.K. Nath, R. Sharma, S. Kumar, R.C. Deka, D.C. Baruah, E..Kalita, "Recent Trends in the Pretreatment of Lignocellulosic Biomass for Value-Added Products," Frontiers in Energy Research, Vol. 6 (141), pp. 1-19, 2018. https://doi.org/10.3389/fenrg.2018.00141
60. M. Saghir, S. Zafar, A. Tahir, M. Ouadi, B. Siddique, A. Hornung, "Unlocking the Potential of Biomass Energy in Pakistan," Front. Energy Research, pp. 7-24, 2019. https://doi.org/10.3389/fenrg.2019.00024
61. M. Mandø, "Direct combustion of biomass. Biomass Combustion Science," Technology and Engineering, pp. 61-83. https://doi.org/10.1533/9780857097439.2.61
62. A. Garba, "Biomass Conversion Technologies for Bioenergy Generation: An Introduction," Biotechnological Applications of Biomass, IntechOpen, 2021. https://doi.org/10.5772/intechopen.93669
63. L.J.R. Nunes, J.C.O. Matias, and J.P.S. Catalão. "Biomass combustion systems: A review on the physical and chemical properties of the ashes," Renewable and Sustainable Energy Reviews, Vol. 53, pp. 235-242, 2016. https://doi.org/10.1016/j.rser.2015.08.053
64. Y. Hu, A. Bassi, and C. Xu (Charles), "Energy From Biomass," Future Energy, Third Edition, pp. 447-471, 2020. https://doi.org/10.1016/b978-0-08-102886-5.00021-9
65. A. Demirbas and G. Arin, "An Overview of Biomass Pyrolysis," Energy Sources, Vol. 24(5), pp. 471-482, 2002. https://doi.org/10.1080/00908310252889979
66. C. Pal, K. Asiani, S. Arya, C. Rensing, D.J. Stekel, D.J. Larsson, and J.L. Hobman, "Metal resistance and its association with antibiotic resistance," Advances in microbial physiology, Vol. 70, pp. 261-313, 2017. https://doi.org/10.1016/bs.ampbs.2017.02.001
67. J. Laesecke, N. Ellis, and P. Kirchen, "Production, analysis and combustion characterization of biomass fast pyrolysis oil–Biodiesel blends for use in diesel engines," Fuel. Vol. 199, pp. 346-357, 2017. https://doi.org/10.1016/j.fuel.2017.01.093

68. R. Bala, V. Gautam, and M.K. Mondal, “Improved biogas yield from organic fraction of municipal solid waste as preliminary step for fuel cell technology and hydrogen generation,” International Journal of Hydrogen Energy, Vol. 44(1), pp. 164-73, 2019. https://doi.org/10.1016/j.ijhydene.2018.02.072
69. R. Bharati and S. Suresh, “A review on nano-catalyst from waste for production of biofuel-via-bioenergy,” InBiofuels and Bioenergy (BICE2016) International Conference, Bhopal, India, Springer International Publishing, pp. 25-32, 2017. https://doi.org/10.1007/978-3-319-47257-7_3
70. T. Sharma, I.G. Hakeem, A.B. Gupta, J. Joshi, K. Shah, A.K. Vuppaladadiyam, and A. Sharma, “Parametric influence of process conditions on thermochemical techniques for biochar production: A state-of-the-art review,” Journal of the Energy Institute, Vol. 7, 101559, 2019. https://doi.org/10.1016/j.joei.2024.101559
71. L. Dorjee, K. Nishmitha, S. Pattanayak, T. Wangmu, S. Meshram, S. Chongtham, and R. Gogoi, “Biochar: A Comprehensive Review on a Natural Approach to Plant Disease Management,” Journal of Pure & Applied Microbiology, Vol. 18(1), 2024. https://doi.org/10.22207/JPAM.18.1.58
72. E. Borri, C. Antonios, P. Valeria, Z. Gabriel, F. Andrea, K. Sotirios, and F. C. Luisa, "Environmental impact of an innovative solar-biomass hybrid system for residential applications," Renewable Energy 239, 122138, 2025. https://doi.org/10.1016/j.renene.2024.122138
73. G. F. Ribeiro, and B. J. Aldo, “Construction of a Roadmap of the Technological Development Barrier and Adaptation of Agricultural Machinery in the Production Chain of Biomass Briquettes and Pellets from Agricultural Waste,”. Available at SSRN: https://ssrn.com/abstract=5084101 or http://dx.doi.org/10.2139/ssrn.5084101
74. K. Shu, B. Guan, Z. Zhuang, J. Chen, L. Zhu L, Z. Ma, Z. Hu, C. Zhu, S. Zhao, H. Dang, T. Zhu, “Reshaping the energy landscape: Explorations and strategic perspectives on hydrogen energy preparation, efficient storage, safe transportation and wide applications,”. International Journal of Hydrogen Energy. Jan 6(9)7, 160-213, 2025. https://doi.org/10.1016/j.ijhydene.2024.11.110
75. K. Roman, and E. Grzegorzewska, “Biomass Briquetting Technology for Sustainable Energy Solutions: Innovations in Forest Biomass Utilization,” Energies, 17(24), 6392, 2024. https://doi.org/10.3390/en17246392