

Review

Technologies and Innovations for Biomass Energy Production

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Abstract: Biomass is considered one of the prospective alternatives to energy and environmental challenges. The use of biomass as bioenergy has gained global interest due to its environmentally benign, renewable, and abundant characteristics. Numerous conversion technologies have been developed over time to convert biomass into various energy products. This review presents a summary of the different biomass conversion technologies used for bioenergy production. These include thermochemical, biological, physical, biochemical, and hybrid system technologies. It summarizes the production of different bioenergy products such as bio-oil, biodiesel, and fuel via various conversion technologies. The competitive advantages, potential environmental impacts, and challenges of these biomass conversion technologies are discussed. The recycling of biomass can solve a lot of current energy challenges. However, conversion technologies exhibit some challenges relative to upscaling and commercialization due to their immense operational and investment expenses and high energy usage.

Keywords: biomass; bioenergy; conversion technology



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1. Introduction

Owing to the exhaustion of fossil resources as well as the ongoing decline of environmental value, the use of renewable resources is essential. Among the numerous renewable resources, biomass is considered a better option for non-renewable fossil resources. It is abundant, cost-effective, and environmentally friendly [1]. The world's fourth largest source of energy is biomass, and it is competent to manage rural development and energy security [2]. Presently, biomass supplies approximately 8–15% of society's energy supplies as electricity, heat, and fuels for transportation, and about 40–50% in many developing countries. It is anticipated that nearly 33–50% of primary energy consumption in the world could be met in 2050 via biomass [3–5]. There are various kinds of biomass, such as municipal solid waste (textiles, plastics, and paper), agricultural waste (animal farm byproducts, agro-industries, and crops), forestry biomass (wood products activities), energy crops, and algae [6]. It is important to develop technologies that would convert waste biomass into bioenergy and chemical products, bearing in mind the environmental influence and thermodynamic efficacy [7,8]. Based on the circular economy, waste-to-energy conversion technologies seem to be one of the major background subjects of biomass research.

In recent years, several researchers have studied various process types for the conversion of biomass. Different processes, such as thermochemical and biochemical, have been used to convert biomass into valuable forms of energy [9]. The conversion technology option is dependent on the amount of property, the type of biomass feedstock, the nature of the energy anticipated, i.e., endues requirements, commercial settings, environmental values, and project-specific aspects. Biomass could be converted into three major products, which include chemical feedstock, transportation fuels, and power/heat generation [10,11]. Thermochemical and chemical processes are typically reported by different

researchers. There are not many reports on the use of physical processes and the hybrid system. Physically converted biofuels have been widely used in rural areas for domestic purposes (cooking and heating), and hybrid systems are still under research. Therefore, in this review, we present a summary of different biomass conversion technologies used for bioenergy production, including thermochemical, biological, physical, biochemical, and hybrid/combined systems technologies (Figure 1, Table 1). It summarizes the production of different bioenergies such as biodiesel, fuel, bio-oil, and other chemical products from biomass feedstocks and how these processes are carried out. The potential environmental impacts, benefits/advantages, and challenges of these biomass conversion technologies will be discussed. Their economic sustainability and the potential future of bioenergy derived from biomass feedstocks will also be highlighted.

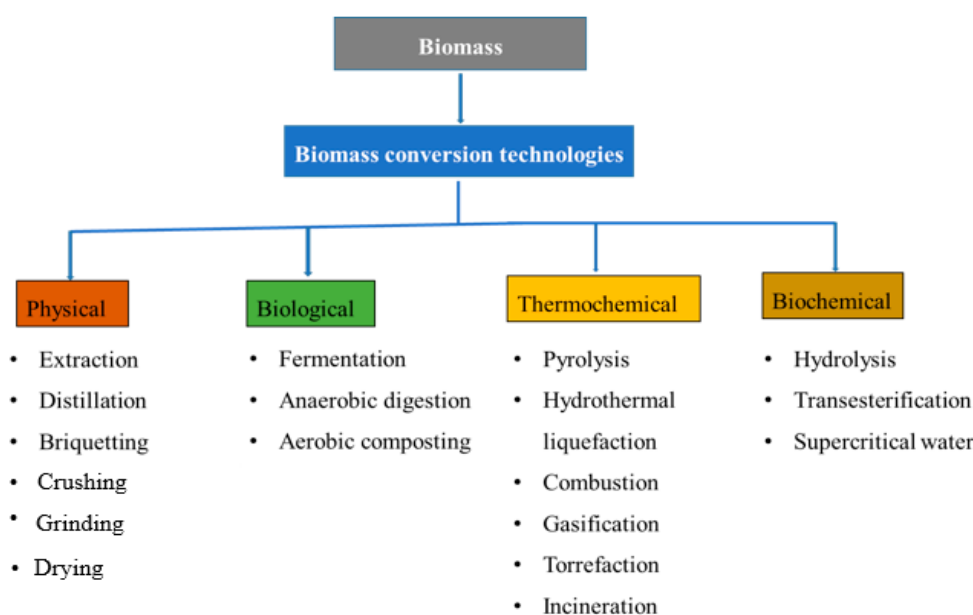


Figure 1. Summary of biomass conversion technologies.

Table 1. Advantages and disadvantages of biomass conversion technologies.

Technology	Advantages	Disadvantages	References
Thermochemical	Its fast reaction and takes seconds or minutes to be completed	High energy usage and hazardous conditions	[12,13]
Biological	Ambient pressure and temperature, waste material variety, no CO ₂ accumulation, and cost-effectiveness	Slow process and can take hours, days, weeks, or years to be completed	[14,15]
Biochemical	Requires less external energy input	The challenging structural veracity of plant cell wall materials aimed to attack the degradation of microbial	[16,17]
Physical	Easy handling and less consumption of chemicals	High energy consumption and not economically feasible	[18]

2. Biomass Conversion Technologies

2.1. Thermochemical Conversion

The biomass thermochemical process converts biomass into a higher-quality fuel or H₂-rich syngas to chemicals via Fischer-Tropsch (F-T) production [19]. Drying, pyrolysis, heterogeneous char, and homogeneous reforming reactions of pyrolysis materials are the major phases involved in the thermochemical process [20]. This process is commercially more attractive due to its improved flexibility, product selectivity, quicker conversion degree, higher process effectiveness, and different market for byproducts [21].

Thermochemical technology mostly uses process settings that entail costly resources in the process equipment and conditions that use high temperatures and pressure [22]. The challenge with thermochemical is that it is expensive to obtain and install the infrastructure as compared to the feedstock's low cost. Therefore, to enable cost-effectiveness, more research and development associated with the industry is desirable [23].

Most current biomass thermochemical conversion processes use comprise pyrolysis, hydrothermal liquefaction, gasification, combustion, torrefaction, and incineration (Table 2).

Table 2. Thermochemical technologies.

Technology	Biomass Type	Product	Temperature (°C)	Advantages	Disadvantages	References
Pyrolysis	Lignocellulosic biomass	Bio-oil, biochar, and syngas	500–1000	High efficiency, flexibility, and high-quality fuel	High operational and investment cost	[24–26]
Hydrothermal liquefaction	Algae, animal manure, etc.	Bio-oil gases	300–350	Feedstock versatility, higher yield and quality bio-oil, capability to turn wet materials, and its beneficial environmental and economic potential	Energy consumption in high-pressure processes requires longer residence time and is expensive	[12,27,28]
Gasification	Municipal plastic waste (MSP)	Syngas	800–1000	Flexible, better emission control, various uses of produced syngas	Complex multi-stage process and formation of tars and char	[5,29,30]
Combustion	Wood	Thermal energy	800–1000	The high calorific value of biomass and multiple fuel production	Only feasible for biomass with moisture volume below 50%	[31,32]
Torrefaction	Wood	Solid Fuel	200–300	Low energy, reduction in moisture, and increase in energy density	Process control, upscaling, and sustainability difficulties	[33,34]
Incineration	Municipal solid waste (MSW)	Heat, CO ₂	900–1100	Appropriate for high calorific value, reduce volume and mass by up to 80% and 70%, respectively	Higher moisture, low energy content, high maintenance, and operating capital costs	[35,36]

2.1.1. Pyrolysis

The pyrolysis technique is a biomass thermal breakdown process at 500–1000 K temperatures in the absence of oxygen, resulting in a solid residue, liquid, and gas (Figure 2). The solid residue well known as biochar or charcoal, which is a carbonaceous composite with a porous form [37]. A highly heterogeneous product mixture is formed during the pyrolysis process. This product mixture contains a liquid phase, a solid phase/char, and gaseous material, which are carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), and hydrogen (H₂). Pyrolysis oils entail solid particles, aromatic compounds, oxygenated aliphatic, high water content ranging from 15–30 wt%, several oxygenates, and nitrogen

compounds. So, further processing is needed before it can be used as a transportation fuel [38]. The pyrolysis process is influenced by various factors like catalysts, temperature, and retention time [39].

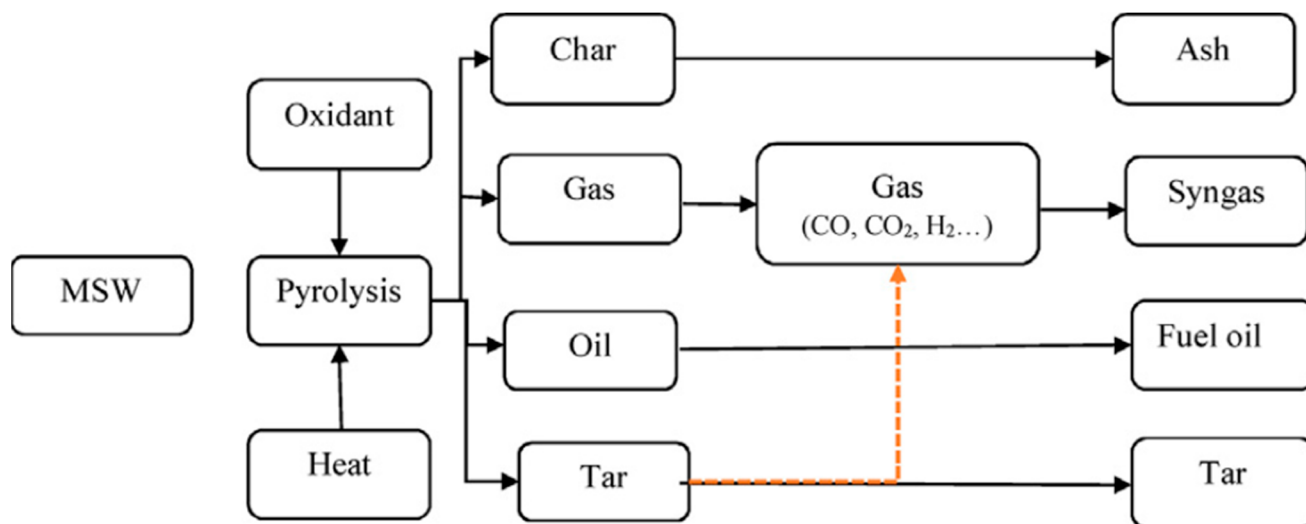


Figure 2. Representation of the pyrolysis process [36]. Reprinted with permission from Ref. [36]. Copyright 2018 Elsevier.

The pyrolysis process can be separated into three subsets depending on the operational settings, i.e., fast, flash, and slow /conventional pyrolysis [40,41].

Fast Pyrolysis involves the thermochemical breakdown of biomass materials in the absence of air, producing liquid (bio-oil), a combustible gas mixture (syngas), and biochar (Figure 3) [42]. This process comprises lignocellulosic feedstock thermal disintegration at about 773 K via a high quenching and heating degree with a fluidized bed reactor. As for the bio-oil product to be successfully produced, it takes around 0.5–3 s of residence time and 400–600 °C thermal treatment, which might be improved for hydrocarbon liquid fuels [43]. Of the three types of pyrolysis, fast pyrolysis has the highest bio-oil yield of 50–75%, while roughly 10–20% is converted into char [44,45]. Quick cooling of pyrolysis vapor, controlled reaction temperatures, and extremely high heating and heat transfer rates are the main characteristics of a fast pyrolysis process [46].

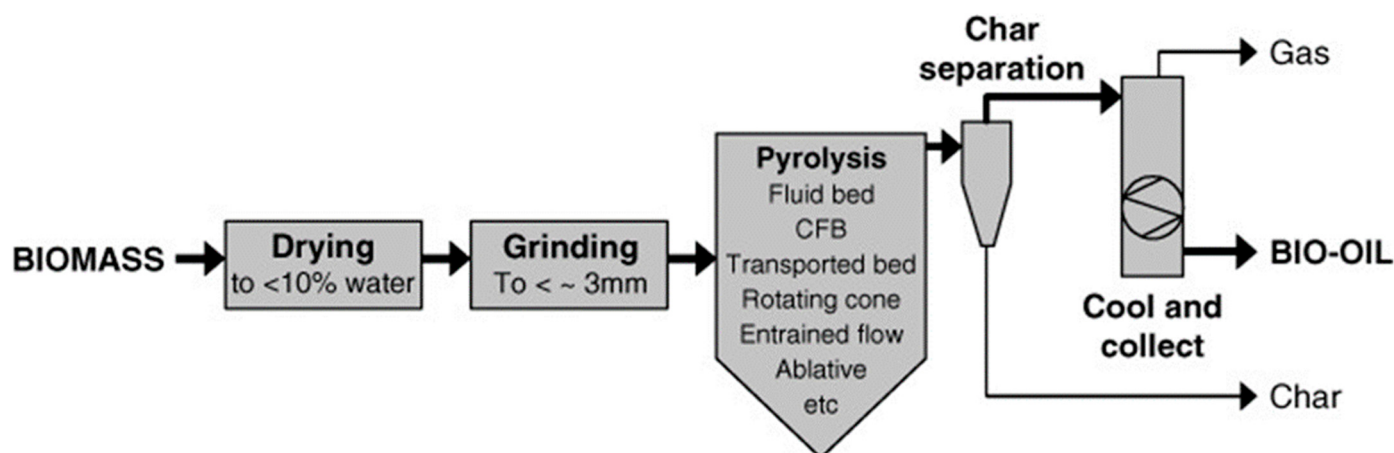


Figure 3. Conceptual fast pyrolysis process [15].

Fast pyrolysis is a simple process. However, the bio-oil produced may complicate the properties obtained from the original feedstock characteristics. This makes it a substandard

fuel alternative [47]. Fast pyrolysis is a well-developed technological process. However, upgrading technologies for this process is still in the beginning phases of the demonstration. Therefore, it will probably take some time before it is widely used on a commercial basis [48].

Flash pyrolysis is considered an enhanced and adapted method of fast pyrolysis. The flash pyrolysis method entails elevated reaction temperatures (400–800 °C), a high heating rate (1000–100,000 °C/s), a small biomass particle size, and a relatively quick gas residence time of about 0.5 s [49]. In flash pyrolysis, the biomass-to-oil conversion efficiency can reach up to 70%. But the quality and stability of the produced oil are a big challenge due to the formation of pyrolysis water [50]. The major problem of using flash pyrolysis on an industrial scale is positioning a reactor whereby the input biomass could occupy for a brief time at exceedingly elevated heating degrees [51].

Slow pyrolysis comprises an extended duration of biomass and typically produces gas and char [47]. As a result, there are fewer liquid and gaseous products, but char production increases [52,53]. Slow pyrolysis is carried out at a heating rate of roughly ~ 10 °C/min for average temperatures between 350 and 750 °C for about an hour of residence time [54,55]. This process produces approximately 35% biochar, 30% condensable substances, and 35% syngas by mass product yield [56]. Based on process factors such as vapor residence time, heating rate, and temperature, biofuel products differ in composition [57]. Additional coke, tar, and heat-stabilized products are produced when a longer residence time results in the secondary conversion of primary products. Thus, slow pyrolysis is sometimes known as carbonization [58]. Slow pyrolysis creates biochar with significant environmental advantages and fewer CO₂ emissions. However, the disadvantages of this process are limited scalability, high cost, and stable feedstock quality [59,60].

2.1.2. Hydrothermal Liquefaction (HTL)

Hydrothermal liquefaction technology converts biomass into hydrothermal biochar in a sealed system with water as the medium under particular in-house pressures and temperatures. This process is effective in converting biomass into biomass with a higher energy density [61]. The HTL process is regulated by a difficult series of reactions and alterations in subcritical water. The mechanism of this process comprises (1) the biopolymers' hydrolysis into water-resolvable peptides and (2) the fragmentation of intramolecular and intermolecular hydrogen linkages into simpler monomers, namely glucose, and additional compounds (furfural compounds, acetic acid, and acetaldehyde) [62].

HTL has various advantages as compared to other thermochemical techniques; it does not need preceding thermal drying, thus resulting in cost-effective wet materials. It utilizes pressurized water as a reactant and reaction medium, and it is versatile and environmentally benign [63].

Also, the bio-oil attained from the HTL method is of higher quality and yield, with lower water and oxygen content. Nonetheless, this process utilizes high pressure, which might result in the equipment required for industrial-scale procedures being expensive [64].

2.1.3. Gasification

Biomass gasification is typically an indirect combustion method of municipal plastic waste (MPW) to synthetic gases or fuel by waste half oxidation in the presence of oxidants [65]. This process involves the alteration of a solid/liquid organic mixture in a solid phase and a gas/vapor phase. The gas phase, also known as syngas, has a great heating capacity and could be used for biofuel or the generation of power (Figure 4) [66].

The product gas mixture of the gasification process comprises nitrogen (N₂), carbon dioxide (CO₂), methane (CH₄), carbon monoxide (CO), and hydrogen (H₂) [68]. The main familiar gasification factors are oxygen, carbon dioxide, steam, and air, where steam and air are commonly used. However, they possess distinct advantages and limitations [69,70].

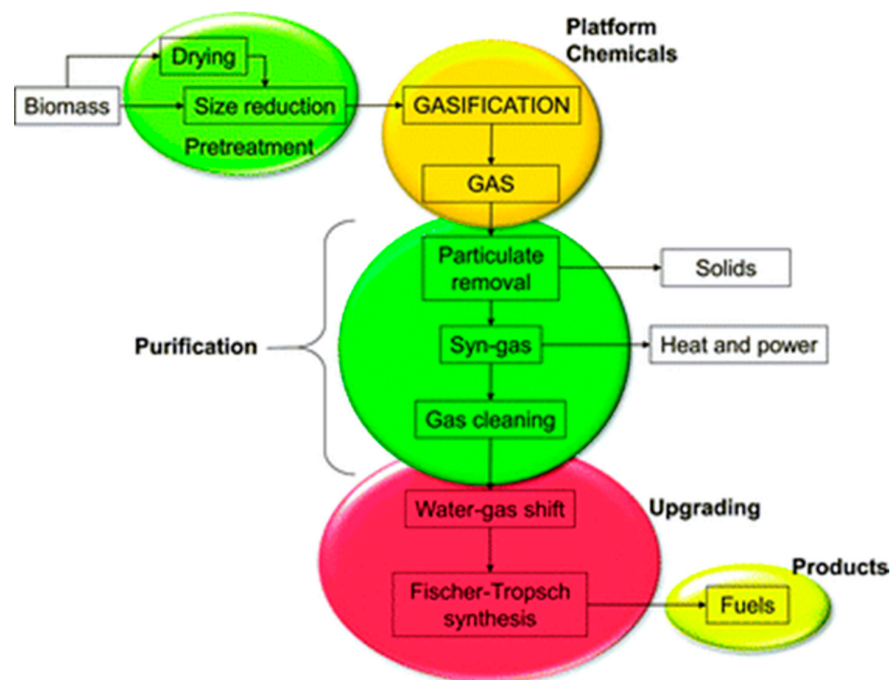


Figure 4. Process schematic: biomass gasification and upgrading [67]. Reprinted with permission from Ref. [67]. Copyright 2010 Royal Society of Chemistry.

In gasification technology, the use of dry biomass is much more effective compared to wet biomass because no further drying is required [71]. The gasification process comprises drying, pyrolysis, combustion, char gasification, and cracking stages (Figure 5) [72].

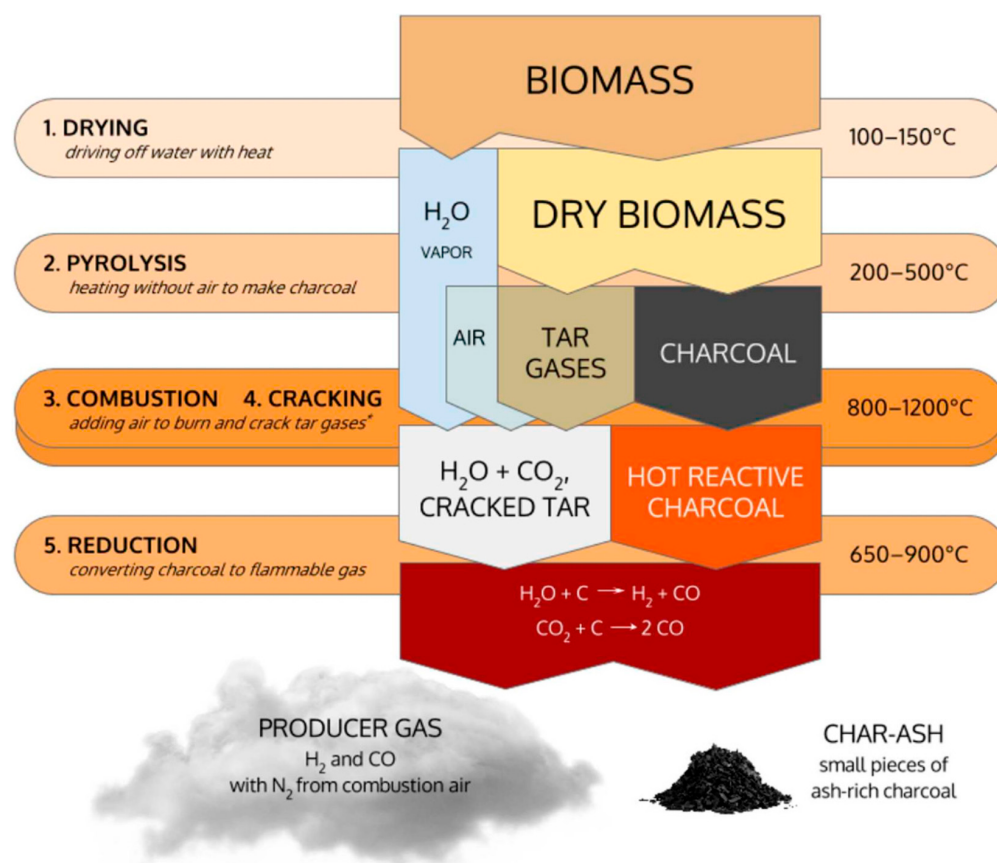


Figure 5. Gasification process steps [72]. Reprinted with permission from Ref. [72]. Copyright 2019 Elsevier.

Biomass gasification could be considered high-temperature gasification (HTG) or low-temperature gasification (LTG), depending on the temperature. In the LTG method, gas and hydrogen can be acquired from biomass of low calorific value. The LGT process has great advantages such as easiness, operation protocol efficiency, and evasion of ash-related complications. [73]. There are various gasification technologies available, which include fluidized bed gasifiers, fixed bed gasifiers, and entrained flow gasifiers. Lately, there have been reports on new gasification technologies to decrease tar quantity, increase hydrogen quantity in the producer gas, and increase biomass gasification energy proficiency [74].

Biomass gasification is a supple technology; it might be employed for the production of electricity, or on the other hand, as a feedstock for chemical methods. Nevertheless, it has shortcomings that limit its flexibility and efficiency. For an installation to successfully operate, a steady and adequate biomass supply and type of biomass should be certain [71].

2.1.4. Combustion

Biomass combustion technology is known to be the ancient and most commonly applied thermochemical conversion process [75].

The combustion method is well known to be the only method to produce electric and heat power. There are three major steps involved during the combustion of biomass: drying, pyrolysis, and reduction; unstable gases; solid char combustion. More than 70% of the total heat generation is contributed by the combustion of unstable gases [76]. Though the combustion process can be used for any form of biomass, it can only be achieved if the moisture volume in the biomass is below 50% [51].

Biomass combustion has great proficiency in the production of heat. As a result, making it economically viable. But the complicated combustion method consists of continuous solid-gas and solid-solid reactions [19]. The combustion process requires air, heat, and fuel.

If one of these three requirements is detached, burning ends. However, when all three are present in precise ratios, combustion is self-sufficient due to the extra heat released from the fuel, which initiates more burning [77].

2.1.5. Torrefaction

Torrefaction, well known as high-temperature drying or roasting, is a thermal treatment method whereby biomass is heated in a 200–300 °C temperature range for a short duration in an inert condition. The torrefaction process, or mild pyrolysis, produces solid char by first heating, pre-drying, post-drying, intermediate heating, torrefaction, and solid cooling of biomass materials [78]. Because torrefaction operates at a lower temperature and for a shorter period of time, it is more appropriate to improve the quality of the solid char [21]. During the torrefaction process, the properties of biomass are reformed into finer fuel characteristics for applications in gasification and combustion [33,34]. Torrefaction on a lab scale is mostly conducted by the use of thermogravimetric analysis (TGA), a small-scale tube reactor, and an oven [79]. Torrefied biomass has great benefits, which include hydrophobic character, closely correlated properties like coal, grindability, and ease of crushing. The products obtained from this process include lactic acid, condensable gases like water vapor, furfural, phenol, methanol, acetic acid, formic acid, and more oxygenates (Figure 6). Non-condensable gases also acquired from this method are carbon dioxide, carbon monoxide, and a small amount of hydrogen and methane [80]. The combustion heat of the non-condensable waste gases released during this process increases with an increase in torrefaction temperature [33]. Regardless of the great benefits of using torrefaction technology, the economic and technical problems need to be resolved for it to be fully commercialized. Moreover, this process is not scientifically elucidated, and further investigation on the impact of the reaction conditions is necessary [81].

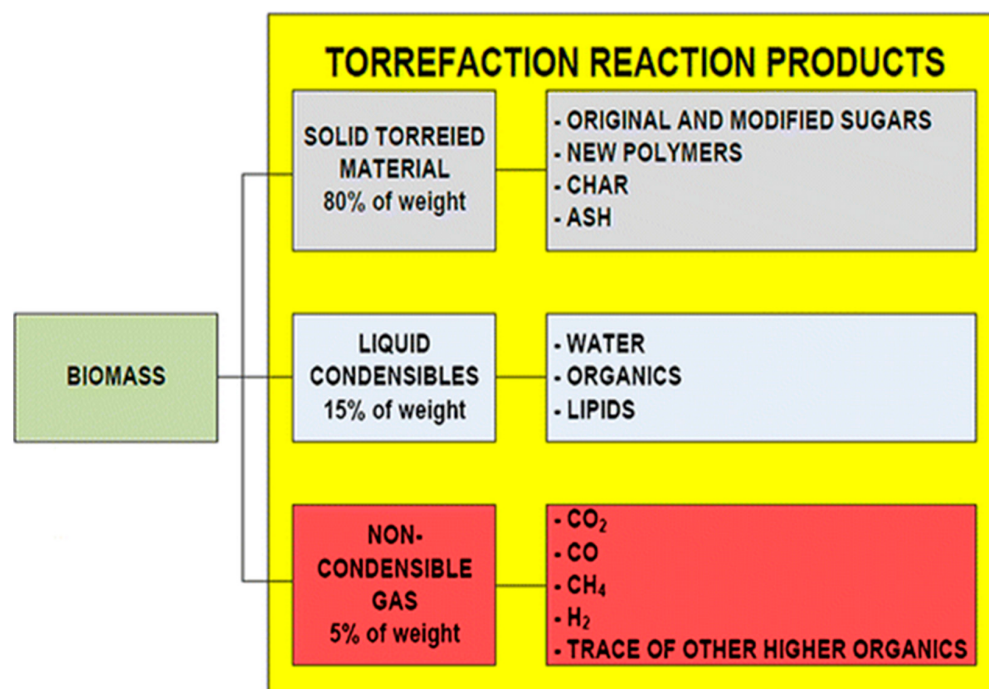


Figure 6. Products formed during the torrefaction process [33]. Reprinted with permission from Ref. [33]. Copyright 2012 Springer Nature.

2.1.6. Incineration

Incineration is the oxidative combustion process under aerobic conditions at high temperatures (900–1100 °C) with the aim of energy recovery and a decrease in volume. The final products from the incineration process are ash, solids, and combustion gas,

which could be applied as heat supplies [8]. The most important steps in the incineration technique are evaporation and degassing, pyrolysis, and gasification [82]. However, the use of incineration generates a lot of chemicals, harmful gases, and greenhouse gas (GHG) emissions, resulting in water and air pollution. Thus, the incineration facility institution in every area will entail effective emission-cleaning innovation together with local community approval [22].

2.2. Biological

Microbial systems such as *Escherichia coli* and *Saccharomyces cerevisiae* are generally used in biological methods. These are enhanced for a specific chemical product by constructing a set of reactions in a metabolic pathway. In this process, there are a few advantages of using biological catalysts, such as the diverse carbohydrate feedstocks' lenience, numerous reactions with no intermediate separations, variety of chemical products, and vastly selective reaction networks [83].

Biological conversion processes are considered environmentally friendly. But their fermentation period, use of costly hydrolytic enzymes, and the sensitivity of microorganisms to various aspects like growth settings, impurities, sugar substrates, nutrients, and inhibitors render them time-consuming [21]. Some of the biological methods include fermentation, anaerobic digestion, and aerobic composting (Table 3).

Table 3. Biological technologies.

Technology	Biomass Type	Product	Advantages	Disadvantages	References
Fermentation	Microalgae biomass	Grain alcohol	Lower cost, high ethanol yield, and short processing time	Cannot use commonly used yeasts, recombinant microorganism instability, and techno-economic limitations	[18,84]
Anaerobic digestion	Sewage sludge, livestock manure	Methane, CO ₂ , digestate	Economic costs and the safe disposal of digestate	Complex products require additional processing to become refined products; storage and processing problems	[85–87]
Aerobic composting	Organic waste	Heat	Minimizes animal manure quantity and kills microorganisms	Causes secondary environmental pollution	[8,88]

2.2.1. Fermentation

The fermentation method transforms biomass into desirable bio-products such as bioethanol, bio-hydrogen, and biogas in the presence of microorganisms (i.e., bacteria, fungi, and yeast) [89]. Biomass fermentation comes with great challenges. This is attributed to the obligation to convert many hexose sugars and pentose to ethanol in a simultaneous saccharification co-fermentation (SSCF) step. *Pichia* and *Saccharomyces* yeast species, along with *Klebsiella*, *Zymomonas*, and *Escherichia coli* bacteria, have been natively arranged to ferment arabinose sugars, glucose, and xylose [90].

The fermentation method is known to have the following benefits:

- Regardless of the quality of the biomass, the whole biomass could be used, together with lignin.
- Costly enzyme removal and challenging pretreatment steps.
- Higher biocatalyst selectivity.
- The H₂:CO proportion for bioconversion independence
- Aseptic process of the fermentation of syngas due to the production of syngas at elevated temperatures
- Bioreactor operation under normal conditions.
- There are no noble issues with metal poisoning [91].

2.2.2. Anaerobic Digestion

Anaerobic Digestion (AD) is a sequence of interrelated biological reactions whereby organic material is converted into methane (CH_4), carbon dioxide (CO_2), and anaerobic biomass in the absence of oxygen (Figure 7) [92]. The CH_4 yield per unit area is mostly applied to govern the energy efficiency of a given feedstock. It considerably differs across organisms, with growth, geographical setting, and inputs (i.e., water, manure) among identical species [93].

Anaerobic digestion occurs in three stages:

1. The complex organic macromolecules are hydrolyzed into simpler, solvable molecules.
2. Acid-forming microbes convert molecules into basic organic acids, hydrogen, and carbon dioxide. The main acids produced include ethanol, butyric acid, propionic acid, and acetic acid.
3. Formation of methane by the methanogenic microbe. This is formed by disintegrating acids into methane and carbon dioxide or by reducing carbon dioxide reduction with hydrogen [94,95].

Different factors, such as the population of microbes employed during the procedure and its source, pH, temperature, redox potential, and harmful elements existence (cyanide, unstable fatty acids, heavy metals, and ammonium) in the digester, together with the carbon to nitrogen volume proportion of the feedstock, affect the efficiency of the AD process [96].

The AD method is highly recommended for encouraging renewable energy as compared to other technology processes because it does not require oxygen, has lesser nutrient requirements, generates energy carriers via harmless methods, and allows residual biomass reuse in agriculture [97,98]. Nevertheless, it has shown some disadvantages, such as difficulties in storing biogas and the fact that the quality of the biogas produced is mostly substandard and contains hydrogen sulfide (H_2S), which is expensive to remove [99].

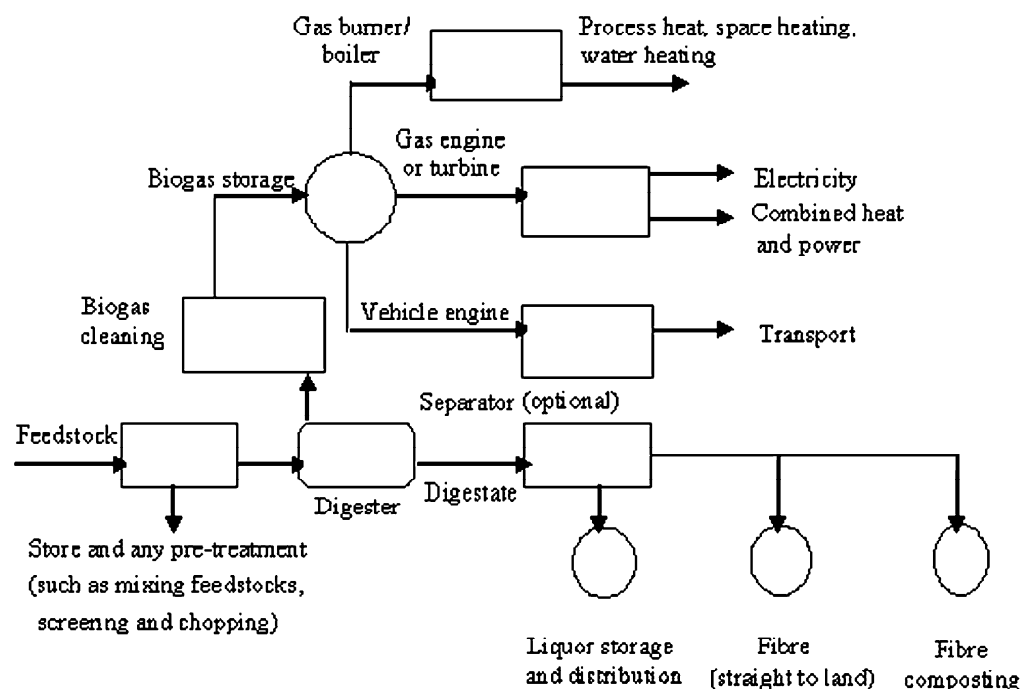


Figure 7. Overview of the anaerobic digestion process [100]. Reprinted with permission from Ref. [100]. Copyright 2006 Taylor & Francis.

2.2.3. Aerobic Composting

In aerobic composting/degradation, microorganisms use oxygen from the air to disintegrate biomass into heat, CO_2 , and a solid product [75]. It alters organic waste

biomass into steady humus using microorganisms in specific external environments and is often used in the treatment of biomass waste [101,102]. Compounds of carbon and nitrogen are easily converted and used as energy and protein sources by the microbes during the composting procedure, producing heat, CO₂, H₂O, NH₃, organic acids, and fully developed compost products at the final phase [103]. Aerobic composting has many benefits, notably reducing animal manure quantity, destroying pathogens, and turning manure waste into nutritious, steady organic matter (e.g., compost) that could enhance the fertility of soil. However, the excess release of various greenhouse gases (GHGs) such as N₂O, CH₄, and CO₂ from composting procedures reduces the agronomic value and contributes to additional environmental pollution [88].

2.3. Biochemical

Biochemical conversion technologies such as hydrolysis, transesterification, and supercritical water gasification are a blend of biological and chemical pathways (Table 4). This process uses microbes and biological catalysts to convert biomass into gas (CO₂/CH₄), waste (compost or manure), and H₂O [104]. It provides great selectivity in transforming biomass into the final ideal products [105].

Table 4. Biochemical technologies.

Technology	Biomass Type	Product	Advantages	Disadvantages	References
Hydrolysis	lignocellulosic biomass	Sugars-ethanol	Moderate process temperature and does not need expensive enzymes	Toxic, hazardous, and corrosive	[18,106]
Transesterification	Microalgal biomass	Liquid fuel, biodiesel	Environmentally friendly, low process temperature, and high ester yield	Long process and high purification product costs	[27,107]
SCWG	Waste plastics	Hydrogen	High reaction efficiency, H ₂ selectivity, and rapid reaction	High-pressure operation	[4,108]

2.3.1. Hydrolysis

Hydrolysis is a technique that involves the breakdown of β -1,4 glycosidic cellulose linkages into simple sugars, which are thereafter hydrolyzed to ethanol [109]. Biomass hydrolysis technologies, including acid and enzymatic hydrolysis, are applied to break down feedstock into simple sugars [110,111].

Enzymatic hydrolysis employs enzymes to disintegrate the lignocellulose carbohydrate polymer's complicated chemical composition [112]. The enzymes denote a green approach to reducing waste production and energy consumption. A green method is a necessity for the setup of cheap and sustainable biorefineries [113]. Enzymatic hydrolysis solely depends on the accessibility and potency of enzymes, which are completely connected to the structural features of biomass [114].

Lignocellulosic biomass enzymatic hydrolysis is one of the significant stages in the production of sugar, leading to the transformation of sugars into biofuels and chemicals [115,116]. Several aspects, including lignin dosage, lignin dispersion and structure, polymerization rate, fiber sizes, accessible surface area and pore size, crystallinity, and others, have a substantial effect on enzymatic hydrolysis [117]. The benefits of the enzymatic hydrolysis method encompass low utility usage, minor corrosion problems, minimal toxicity of hydrolysis products, and higher sugar recovery with smaller inhibitor production. However, there is a cost of cellulases for the bioethanol production of cellulosic materials [118,119].

Acid-based hydrolytic methods have been applied to many feedstocks, namely soft and hardwoods and agricultural residues, in the existence of acid catalysts like sulfuric

acid (H_2SO_4), hydrochloric acid (HCl), and nitric acid (HNO_3) [43,120]. Acid hydrolysis is carried out in three steps:

- (1) The acid proton interacts with the glycosidic oxygen, binding two sugar molecules, resulting in a conjugated acid.
- (2) The cleavage C-O linkage and the conjugate acid breakdown to cyclic carbonium ions.
- (3) After the addition of water, there is a release of free sugar and a proton [121].

This process has the advantages of operating at a milder temperature and pressure, having greater sugar retrieval efficacy that might exceed 90% of theoretical output for both glucose and xylose, and having a low cost of ethanol production. But it has greater toxic effects and corrosivity, and reactors that are resistant to corrosion are essential [122].

2.3.2. Transesterification

Transesterification involves a number of successive reversible reactions whereby lipids/triglycerides react with alcohol, mostly methanol, to yield monoglycerides, diglycerides, glycerol, and moieties of fatty acid methyl ester (FAME) biodiesel at each step [89,123,124]. The transesterification efficiency process is affected by factors such as alcohol-to-oil molar fraction, temperature, stirring speed, moisture, microalgal cell wall, reaction period, and the kind of catalyst [123].

This process may be accelerated by different catalysts, which are acidic or alkaline (homogeneous or heterogeneous), enzymes, ionic liquids, and carbon-based catalysts. Homogeneous alkaline catalysis is the most used process for the production of biodiesel. This is attributed to the fact that it accelerates the reaction at low temperatures and atmospheric pressure and can rapidly achieve a significant conversion yield. Potassium hydroxide (KOH) and sodium hydroxide (NaOH) are the most commonly utilized alkaline catalysts for this method [125].

The challenge with the use of these alkaline catalysts is that they can cause the formation of soap-free fatty acids in oils, which is not suitable for microalgal biodiesel production due to the significant concentration of free fatty acids found in microalgal oils. To solve this challenge, acid catalysts are usually used once the concentration of free fatty acids exceeds 1%. Currently, the commercial methods applied depend on triglyceride transesterification with homogeneous alkaline and methanol [126].

2.3.3. Supercritical Water Gasification

The world's most available biomass is mainly wet, with a moisture level of more than 70%. The probable solution for the energy valorization of wet biomass is using the supercritical water gasification (SCWG) method [127]. Water, the most common element on the surface of the planet, occurs in three states: solid, liquid, and gas. In the hydrothermal vents on the deep sea floor called supercritical water (SCW), water also occurs in a supercritical state ($p > 22.064$ MPa, $T > 373.946$ °C) [128]. Biomass treatment in supercritical water might convert it into fuel gases that are enriched with hydrogen [129]. SCW has a unique capacity to break down materials that are typically not soluble in ambient liquid water or steam and has full compatibility with liquid/vapor products from the procedures. This creates a one-step environment for reactions that might require a multi-phase arrangement under normal circumstances. This leads to inter-phase mass transit routes, which might delay reaction rates [76].

The SCWG procedure has great reaction efficacy with the specificity of H_2 , and the reactions progress rapidly. Furthermore, this method yields high solid conversion (minimal char quantity and tar production) [4]. However, there are disadvantages related to this process, such as the fact that it is essential to operate at high pressure and that corrosion difficulties can happen [108].

2.4. Physical Conversion

Physical or mechanical biomass conversion entails the alteration of biomass via pre-processing operations, reduction/comminution of size, drying, and densification. This

process transforms biomass into forms with improved properties such as higher mass density, higher density of energy, and hydrophobicity than raw biomass [130]. Briquetting, extraction, and distillation are the commonly used biomass conversion technologies (Table 5).

Table 5. Physical technologies.

Technology	Biomass Type	Product	Advantages	Disadvantages	References
Briquetting	Agricultural and forestry waste	Fuel briquettes	Extended transportation distances, reliable energy, and storage possibilities	Expensive technology and high energy consumption	[131,132]
Extraction	Seeds	Oil	Environmentally friendly, safe, and low energy consumption	Large-scale application challenges	[133]
Distillation	Seeds	Bio-oil	Separates components effectively and maximum yield is obtained	A large amount of energy consumption	[134]

2.4.1. Briquetting

Briquetting is a procedure (Figure 8) that converts agricultural and forestry waste into biomass briquettes/bio coal (Figure 9), which are combustible in typical burners. Briquetting is a technology that might provide several socio-economic and environmental benefits, specifically in developing countries where traditional biomass is the main source of energy [131,135,136]. The biomass briquette not only supports the economy of the developing country's progress but also assists in preserving the environment [137].

Briquettes have various uses in both households and small industrial cottages:

- Household and heating of water;
- Heating productive operations, including drying tobacco, fruits, drying tea, and chicken breeding;
- Heating ceramics and clay products like better cook stoves, pottery, and bricks;
- Fuel for electricity-generating gasifiers;
- Operating boilers for steam generation [138,139].

Some of the advantages of briquettes from biomass are that they may be conveyed for prolonged distances with reliable energy storage choices, ensure proper size and density, and are easily affordable [140]. In terms of production, briquettes can be developed using different organic waste constituents. However, the application of the technology itself is costly due to the briquetting press's elevated pressure, excessive energy usage, and the need for trained personnel [141]. The primary aspect that greatly impacts the briquetting process is the briquette binder. Various briquette binders such as sewage sludge, cow dung, microalgae, molasses, waste paper pulp, starch, and okra stem gum have been tested. The standard and burning efficiency of briquettes are influenced by the binders and the agricultural biomass chosen [142,143].

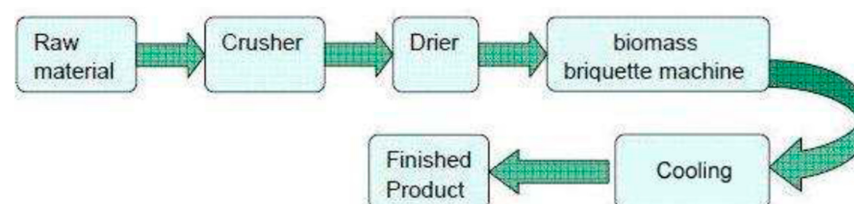


Figure 8. Briquetting production method [131].



Figure 9. Example of briquettes made with a manual piston press [144].

2.4.2. Extraction

Extraction is a mechanical conversion procedure whereby oil is generated from the seeds of different biomass crops like cotton, groundnuts, and so forth. This procedure not only yields oil but also excess solid/“cake”, which is appropriate for livestock food [145]. It is important to disintegrate the cell walls for complete oil extraction by using different mechanical or non-mechanical methods [107]. The oil recovery process efficiency is influenced by the extraction parameter optimization steps, whereby the optimization is dependent on the oil accumulation in the vegetable fractions, the oil’s physical-chemical properties, and potential applications [133].

2.4.3. Distillation

The distillation process involves the crushing of oilseeds for the extraction of oil. It also consists of steam distillation of the oil mixture and essential oil vaporization. The vaporized oils are then captured and condensed or cooled to get bio-oil [104]. One drawback of the distillation method is the significant energy demand. Distillation needs a lot of energy to heat liquid, change it to vapor, and finally condense the vapor back into liquid at the condenser [146].

3. Hybrid Technologies

Hybrid or combined systems are also under research using blends of different technologies, like thermochemical and biochemical technologies. However, based on the kind and accessibility of the feedstock, every bio-refinery method can yield a particular fuel. Consequently, if these methods could be merged under an integrated waste bio-refinery notion, heterogeneous and several feedstocks may be processed to yield many supplies in the form of fodder, fuel, electricity, heat, and valuable chemicals [22]. Hybrid configuration systems result in the maximum feasible generation efficiency of electricity and minimal hazardous emissions [147].

4. Challenges, Sustainability, and Environmental Benefits

More research is required for the developments in the advanced, affordable methods for production, detoxification, biofuels, and platform chemical analysis [43].

Economic problems may be influenced by technical challenges like poor technology implementation, resulting in high technical risk that could increase operational expenses [148]. Also, the economic aspects significantly rely on the costs related to the collection, trans-

portation, storage, and processing of biomass residues. Therefore, a decrease in the feed value of biomass should be established, which consists of reducing the cost of shipping, enhancing biomass collection systems, and establishing collection systems [149]. Though these biomass technologies are certified environmentally benign, they still have some challenges. Traditional biomass sources like wood result in many environmental consequences, such as the deforestation and degradation of land, the decline of biodiversity, indoor and outdoor contamination, and climate change [150]. To maintain sustainability standards, environmental authorization has become a crucial instrument for enhancing the image of biofuel products on the market [30]. Due to the seasonal nature and annual biomass variability, proper planning is needed to ensure sufficient quality and quantities of the biomass feedstocks. Moreover, biomass pretreatment such as drying and pyrolysis is required to reduce its moisture content and improve energy density, which leads to an increase in cost and production time [12].

Currently, the major challenge of biomass energy is that it is not economically competitive compared to petroleum [151]. To overcome this challenge, the commercialization of biomass products and environmental certification will bring out their economic relevance and create a supply chain that will readily sustain the production of biomass products, as well as improve the image of biofuel products in the market [30,132]. Moreover, biofuel production may be combined with nitrogen-rich municipal wastewater and CO₂-rich flue gas treatment to be considered sustainable and economical [152]. Lastly, these biomass conversion technologies are mostly carried out on a small or lab scale. It has been a great challenge to develop a conversion technology that could successfully convert biomass into biofuel on an industrial scale. Currently, researchers are trying to find methods that can improve the existing technologies for large-scale conversions [153].

5. Conclusions

The utility of biomass for the fabrication of various biofuels using biological, thermochemical, physical, biochemical, and hybrid system conversion technologies has been reviewed. It can be concluded that these biomass technologies have great benefits and limitations. Thermochemical technologies are the most commonly used and have proven to be the most efficient in biofuel production. They are deemed commercially feasible. Biological and biochemical technologies exhibit potential that is environmentally benign and economically feasible due to their low energy consumption and greenhouse emission characteristics. Physical conversion technologies are known to be beneficial for different domestic uses, making them a great option in developing countries, particularly in rural areas and regions where traditional biomass is the primary source of energy. More work is still needed on hybrid systems to acquire more information about their benefits and limitations. The recycling of biomass can solve a lot of current energy challenges. However, the conversion technologies employed have shown significant challenges in upscaling and commercialization. This is caused by their operational and investment expenses and high energy usage. More research is required in this area for these conversion technologies to meet certain economic standards and conditions.

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