JAMIL, F., INAYAT, A., HUSSAIN, M., AKHTER, P., ABIDEEN, Z., GHENAI, C., SHANABLEH, A. and ABDELLATIEF, T.M.M. 2024. Valorization of waste biomass to biofuels for power production and transportation in optimized way: a comprehensive review. *Advanced energy and sustainability research* [online], 5(10), article 2400104. Available from: https://doi.org/10.1002/aesr.202400104

Valorization of waste biomass to biofuels for power production and transportation in optimized way: a comprehensive review.

JAMIL, F., INAYAT, A., HUSSAIN, M., AKHTER, P., ABIDEEN, Z., GHENAI, C., SHANABLEH, A. and ABDELLATIEF, T.M.M.

2024

ADVANCED
ENERGY & SUSTAINABILITY
RESEARCH
Open Access

www.advenergysustres.com

Valorization of Waste Biomass to Biofuels for Power Production and Transportation in Optimized Way: A Comprehensive Review

Farrukh Jamil, Abrar Inayat, Murid Hussain, Parveen Akhter, Zainul Abideen, Chaouki Ghenai, Abdallah Shanableh, and Tamer M. M. Abdellatief*

Fossil fuels are primary sources for energy production. Increased dependence on fossil fuels has resulted in increased environmental issues demanding alternative sources. Bioenergy is becoming a popular alternative energy source due to its positive environmental impact and the availability of renewable sources. However, the availability of renewable energy sources in the energy sector currently contributes to about 14%. Biofuels are preferred due to its sustainability, eco-friendly approach, and low-cost raw materials, making it an efficient technique for energy production. This article provides the fundamental and applied concepts for on conversion processes of biomass to biofuels, such as combustion, pyrolysis, fermentation, gasification, and anaerobic digestion along with their role in the green economy. Different physical characteristics of biomass resources are important and contribute to determining their potential for producing biofuels. Herein, LCA, its techno-economic importance, and the role of biomass in green economy are explained. Varying compositions and properties of different types of biomass resources, including lignocellulosic feedstocks, agriculture and forest residue, municipal solid waste, food waste, and animal manure as potential biomass resources, have been discussed. The article explains the strengths and weaknesses of different thermochemical conversion techniques and their current input toward scalar applications and commercialization.

1. Introduction

1.1. Background and Significance

The agriculture sector is a major contributor toward the generation of large amounts of biodegradable solids and liquid waste.[1] Approximately 26% of the food waste is generated from the drinks industry, which is followed by dairy industries, adding up to 21% of the total waste,[2] production and processing of the fruits and vegetables industry, contributing to about 14.8% and the cereal processing and manufacturing industry which contributes to about 12.9%. About 8% of the total waste is added by the processing and preservation units related to meat, and 3.9% of the waste is added by the manufacturers and processors of vegetable and animal oils.[2] The main characteristics of such waste are its high moisture content, increased biological instability, and high organic loading, which facilitates and promotes bacterial activities and growth, requiring immediate action toward its treatment.[3] Inappropriate disposal practices of kitchen and agricultural waste have also resulted in increased challenges and difficulties for the

---

F. Jamil, C. Ghenai, A. Shanableh
Biomass & Bioenergy Research Group
Center for Sustainable Energy and Power Systems Research
Research Institute of Sciences and Engineering
University of Sharjah
27272 Sharjah, United Arab Emirates

F. Jamil, M. Hussain
Department of Chemical Engineering
COMSATS University Islamabad (CUI)
Lahore, Pakistan

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/aesr.202400104.

DOI: 10.1002/aesr.202400104

A. Inayat
Department of Energy
School of Engineering
Robert Gordon University
Aberdeen, Scotland AB10 7GJ, UK
E-mail: a.inayat@rgu.ac.uk

P. Akhter
Department of Chemistry
The University of Lahore
1-km Defence Road, Off Raiwind Road, Lahore, Pakistan

Z. Abideen
Department of Applied Biology
College of Sciences
University of Sharjah
P.O. Box 2727, Sharjah, United Arab Emirates

Z. Abideen
Dr. Muhammad Ajmal Khan Institute of Sustainable Halophyte Utilization
University of Karachi
75270 Karachi, United Arab Emirates

environment, especially for aquatic life.[4–6] To deal with such issues, different countries across the globe have introduced different legislation to handle waste, its treatment, and appropriate disposal.[2]

The concept of reducing, reuse, and recycling waste can help in mitigating the environmental issues deteriorating environmental conditions.[7] Increased human activity due to rapid urbanization and increase in population has disturbed the balance between nature and man-made activities. As a result, the earth is facing several climatic challenges that need to be addressed appropriately.[8,9] For this purpose, different countries across the world have agreed on the adoption of the concepts of reducing, reusing, and recycling waste in order to produce commercially viable products and energy.[10] For this purpose, bio refineries are being established as they are considered sustainable options. The products obtained from the biorefinery include biofuels, biomass, biofertilizers, and various other secondary chemicals that are obtained by utilizing the waste material as a source. With the help of anaerobic digestion, fermentation, and various other composting techniques, the biotechnological transformation of such waste material results in usable products that are in demand to overcome energy needs.[2]

Rapid industrial growth and development is essential for economic growth of countries; however, this increased activity has also raised the concerns regarding the environment due to drastic increase in the pollution ratio. Air and water contaminations are significant concerns as both have several harmful impacts on the overall environment and human beings.[11] As a result, there has been a rise in the use of conventional and primitive energy resources for electricity generation.[12] Coal, crude oil, and natural gas comprise conventional energy sources that are extensively used for energy production, as about 86% of the total energy production utilizes these actual resources, leading to increased environmental challenges. The significant environmental challenges include the increase in global warming and GHG emissions.[13] The International Energy Agency (IEA) has observed that within the year 2000 in 2010, a 26% increase in energy consumption was observed, which is double the energy consumption between 1970 and 2000. In 2017, about 13.5 million terms of oil were used to get the increasing amount of energy consumption, which showed a 1.7% annual growth.[14] According to an estimation by the year 2040, the overall energy need of the globe is expected to rise by 28%, which, according to the US Energy Administration, is 739 quadrillion BTU.[15] Without the use of these natural resources, the increasing energy demand cannot be catered to; therefore, fossil fuels are dominating energy production sources.[16] The unjust and increased utilization of fossil fuels has fastened its extinction, making it a concerning issue and challenge for the energy sector.[17,18] As a result, the attention is diverted toward the use of environment-friendly alternative sources having low emission ratios and abundance in nature in order to meet the increasing energy demands.[19]

Green economy, including the fundamentals of circular economy and bioeconomy, is now being forced as a new strategy and tool for the generation and implementation of novel environmental policies.[20] The main concept of a green economy revolves around the idea of the reduction of consequential environmental effects due to growth in the development of economic factors by introducing low-carbon economic and renewable energy sources in order to improve eco-efficiency.[21] The green economy is supported and encouraged by policymakers as it promotes sustainable energy, helping the economic sector to flourish while maintaining environmental and social sustainability.[22] The policies under the green economy also comply with the objectives of different environment-related pacts and protocols including “Kyoto Protocol and the Climate and energy package 2020”.[23]

One of the significant and crucial steps in moving to sustainability, especially in the energy sector, is to look for sustainable resources.[24,25] The government and policymakers of the energy sector and industry are aiming to formulate sustainable energy policies that not only cater to the need of increasing energy demand but also contribute toward environment conservation. Sustainable energy is aimed at the exploitation of renewable energy sources that are abundant in nature and help in the production of green energy.[26] The sources can be solar, geothermal, wind, biomass, and hydroelectric, which can be used according to their suitability and availability in respective areas.[27,28]

One of the significant challenges in the utilization of renewable energy resources includes geographical and environmental limitations. Due to these challenges, appropriate and complete utilization of these resources for energy production is limited.[29] Biomass has emerged as a potential substitute to fossil fuels and a powerful energy source.[30] Along with that, it also has the capacity to produce several by-products along with production of energy.[31] Biomass can be efficiently used to replace petroleum and its related products as a potential energy source and can be considered a sustainable energy source that also promote environmental conservation. Lignocellulosic biomass is cheaper and considered sustainable, which majorly depends on cellulose-based biomass and is available to be used in the energy production process.[32] Biomass is organic matter that originates from biogenic sources. Biomass can be regarded as a source of deposited solar energy, in which plants act as a medium to store this energy through photosynthesis and is converted into different forms, including cellulose, hemicellulose, and lignin.[33] However, different cellulosic materials, including vegetable oil,

---

C. Ghenai
Department of Sustainable and Renewable Energy Engineering
University of Sharjah
27272 Sharjah, United Arab Emirates

A. Shanableh
Department of Civil and Environmental Engineering
University of Sharjah
27272 Sharjah, United Arab Emirates

A. Shanableh
Scientific Research Center
Australian University
West Mishref, Kuwait

T. M. M. Abdellatief
Sustainable Energy & Power Systems Research Centre
RISE
University of Sharjah
P.O. Box 27272, Sharjah, United Arab Emirates

T. M. M. Abdellatief
Department of Chemical Engineering
Faculty of Engineering
Minia University
EL-Minia 61519, Egypt

fish oil, agriculture residues, or cellulosic waste and microalgae, are considered volatile thermodynamically and oxidatively in comparison to petroleum-derived fuels.[16,34,35]

The estimated production of lignocellulosic biomass is considered to be 181.5 billion tons across the globe. Energy production by the utilization of lignocellulosic biomass is 10%. The agriculture and forest biomass adds only 30EJ–4500EJ of the total energy utilization per annum.[23] Lignocellulosic biomass has the potential to be used and converted into other products that may include bioethanol, bio-oils, chemicals, biofuels, and gasoline. The use of plant biomass for the production of bioenergy is considered crucial as it needs energy demands and is considered an environment-friendly approach for energy production.[27] There has been an increase in overall waste production, which is majorly due to increased population and urbanization, resulting in increased industrial activity.[36] The use of such waste can help in overcoming the energy demands while also managing the issues of waste management.[37] As a result, the dependence on conventional energy sources like fossil fuels can be lowered and ultimately eliminated, conserving the biofuel resources and the environment.[38] Countries having a wide range of forest and agricultural lands have access to the abundance of forest and agriculture bio waste that can be readily available as a feedstock for biofuel production, making it a potential source for energy production. Industrialized countries utilize various fuels, including agriculture and forestry, building and industrial waste, and municipal solid waste.[39] The biofuels generated from such feedstocks are second-generation biofuels. First-generation biofuels are usually derived from edible food crops, which majorly depend on a wide range of crops. In contrast, second-generation biofuels include lignocellulosic material and residues of agriculture waste.[14,40] The reuse of waste comes with a variety of advantages, including the reduction in the emission of hazardous greenhouse gasses, appropriate waste management, and generation of energy leading toward the development and progress of green markets, generation of employment, increased bioenergy production, and efficient waste management.[41,42]

This review aims to highlight the technological details regarding server conversion techniques that are being applied for the conversion of biomass waste and residues to energy in the form of biofuels and bioelectricity. This review focuses on the current use of existing conversion technology, including gasification liquefaction, anaerobic digestion, alcoholic fermentation, photobiological hydrogen protection, transesterification, pyrolysis, combustion, photosynthetic microbial fuel cells, and supercritical fluid processing. This review focuses on the provision of updated information regarding various processes and conversion techniques related to the production of bioenergy by the treatment of biomass residues and waste in the bioenergy field.

2. Waste Biomass as a Resource

2.1. Types and Sources of Waste Biomass

Using biomass residues and wastes is beneficial because it does not require any preparation for its generation as it is generated as a by-product alongside the desired material. There is no need to take special measures, which in the case of biomass cultivated for energy purposes is required.[43] The residues of biomass can be categorized into different groups, namely primary, secondary, and tertiary. The residues that are generated by cultivating targeted crop are known as primary residues which majorly includes forest products, such as stems, stalks, and leaves.[44] The secondary residues comprise the waste products and material that is derived after the processing of food crops. This may include wood chips, rice house, sugarcane bagasse, and palm kernel cake. These products are obtained from the processing of main crops and are the result of agriculture and food processing waste.[45] The tertiary residues are regarded as the waste obtained from biomass-derived products after their consumption by human beings or animals.[46] The majority of the waste in this category includes sewage or sludge, wastewater, and municipal solid waste. Such biomass includes a variety of residues that can include the combination of primary and secondary master residues, cooking oil waste, and microalgae biomass.[14]

2.1.1. Agricultural Residue

Agriculture waste includes the residues that are generated as a by-product during the harvesting and processing of agricultural products, including crops. These crop residues can be categorized into two major types where the field residue and agro-food processing residues are separated due to their processing.[47] These residues are nonedible parts of the crops; therefore, there is no risk or challenge toward the competition to the food supply or any disturbance to the existing food security issues or fertile lands.[48] Agriculture and forest residues are considered as one of the significant and major sources of environmental wastes. This wastes act as the potential resource for the development and production of biofuels after the conduction pretreatment to the available biomass in relative areas. The agriculture and forest residues include rice husks, straws, wood, and other plant residues rich in lignocellulosic material.[49] The classification of agriculture waste is shown in **Figure 1**.

Composition of Agriculture Waste: The majority of agricultural products are rich in cellulose in comparison to hemicellulose and lignin. Cellulose is considered an essential and integral structural element of lignocellulosic biomass, making plants harder and sturdier, fibrous, and impenetrable polysaccharide, which is arranged in the form of change as the packs of microfibrils for the maintenance of the stability and rigor of the plant structure. The cellulosic characteristics of the plants show the mechanical stability and chemical fingerprints of the biomass.[50] Hemicellulose is insoluble in water; however, they are readily soluble in alkaline, weak acid, and enzymatic media. Hemicellulose is considered weak in comparison to cellulose and is more susceptible to chemical exposure. Therefore, the majority of the biomass that is required to be converted into biofuel depends on the hemicellulose content of the waste material. Lignin is also an important component and integral part of the plants, which is considered second to cellulose.

The agricultural waste and the crop residues comprise dry basis, among which 35–50% is cellulose, 20–35% is hemicellulose, lignin forms 15–20%, and 15–20% comprises extractive compounds, including ash and protein.[38] There is a variation in the ligament content in different crops, which varies from

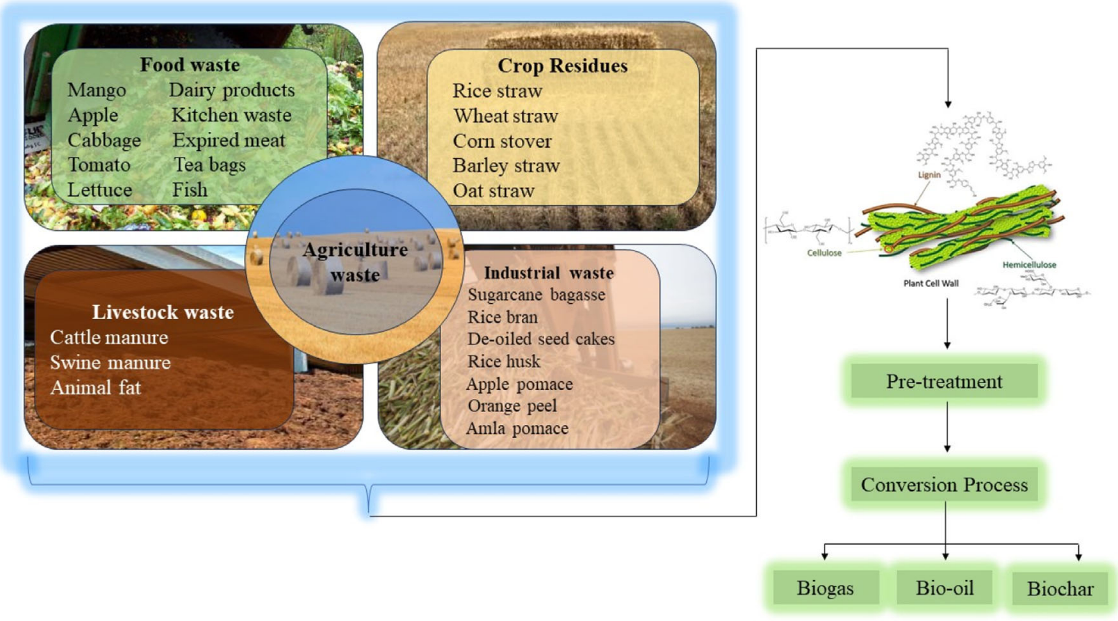

Figure 1. Classification of agriculture waste.[236]

7–21%. The waste obtained from processed agricultural products is considered to have a high ratio ranging between 21% and 45%, with 15–33% hemicellulose and 5–24% lignin. The content ratio is highly dependent on their source of origin. For example, waste rice bran is considered to have a low lignin content of up to 5% and is considered a potential field stock for the production of bioethanol. The waste material having high lignin content, for example, sugarcane bagasse, requires pretreatment for the removal of additional lignin before ethanol production. The preferred raw material for biohydrogen biogas and alcohol production needs certain characteristics, which include carbohydrates, which subtract due to ease in degradation. Structural composition of waste agricultural biomass is depicted in **Table 1**. Industrial waste is usually rich in carbohydrate content, where the carbohydrate comprises 42–85% of the total solids.[51] In general, agricultural waste is categorized into four major groups, which include crop residues, the waste generated from industrial processing, livestock, and food waste.[52]

Crop Residues: In fields, the majority of the waste residues obtained from the agricultural products include crop residues which include straws, seed pods, leaves, and stover.[53] According to the estimation, the annual yield of residues of crops revolves around 2802 million tons.[51] The agricultural wastes collected from the crop waste materials are abundant and low cost.[54] These waste materials can be utilized for the manufacture of different products. Rice straw, wheat straw, and corn stover are considered three major residues that can extensively be used for bioethanol production.[55] The availability of these drops across the year and utilization of a small portion of the crop for food purposes makes these crops suitable to be used as fodder to produce biofuel. In traditional and conventional methods, the rest of the plant is usually burnt which not only enhances the waste material but also deteriorates the environment leading to several environmental issues and problems. The utilization of the raw material obtained from these three major crops to produce biofuel has served dual purposes.[56,57] Among these, rice straw is the most abundant and available biomass with the global production of 731 million tons per annum. Asia is considered as one of the largest producers of rice straws. The other crop residues to be declared as agriculture waste and to be used for biofuel production include barley, sorghum, and oats.[58]

Agro-Industry Wastes: Agro-industry wastes contribute to overall waste making it a second largest waste producing sector. This sector facilitates the production of a variety of by-products obtained from processing food at industrial levels. This waste may consist of fruits and vegetable waste, fruit pomace after juice extraction, the residue generated from starch manufacturing industries, sugar bagasse and molasses from the sugar industry, the oil seed cake from oil manufacturing industries, eggs, meat and animal fat and chicken skin from water houses and other meat processing units.[59] The structural composition of agro-industry waste is explained in **Table 2**. The overall worldwide availability of sugarcane bagasse ranges around 180.73 million tons. The palm oil industry is involved in the production of edible oil and is responsible for the production of about 35.19 million terms to 85.84 million terms of fresh fruit palm bunches. Other industrial waste ranges according to their processes, which may include apple pomace, orange peels, and various other varieties of fruit waste generated from the food processing units.[60]

2.1.2. Forest Residue

The extraction and utilization of residues from the forest for bioenergy and biofuel production have gained immense interest due to its potential to contribute to the economy of forest sector. The use of forest produce for the generation of energy is also facilitated toward the reduction of greenhouse gas connections while

Table 1. Structural composition of biomass (agricultural waste).[52,241–244]

Agricultural and agro-industrial waste	Chemical composition of waste samples			
	Cellulose	Hemicellulose	Lignin	Extractives
Corn cob	37.52	47.47	6.85	25.78 t
Corn cob	31.7	3.4	31.7	N/A
Corn cob	52	32.5	15.5	EF
Rice husk	38.35	11.14	15.5	10.35
Rice husk	32 ± 0.21	19 ± 0.39	26 ± 0.31	NA
Rice husk	37.34 ± 0.14	10.07 ± 0.51	41.08 ± 0.18	11.51 ± 0.28
Wheat straw	45.12	9.16	37.14	8.31
Wheat straw	35 ± 0.29	36 ± 0.65	18 ± 0.38	NA
Wheat straw	32.6	22.6	16.9	NA
Corn straw	43.82 ± 0.36	24.39 ± 0.34	9.03 ± 0,04	22.76 ± 0.25
Rice straw	32.03	8.42	30.34	29.21
Rice straw	40 ± 0.27	26 ± 0.56	19 ± 0.26	NA
Rice straw	31.84 ± 1.82	7.29 ± 1.80	28.39 ± 2,25	32.48 ± 1.96
Olive husk	25.2	24.2	50.6	EF
Olive husk	24	23.6	48.4	9.4
Tea waste	33.2	23.3	43.5	EF
Barley straw	46	23	15	NA
Peanut straw	36.56	20.27	18.36	NA
Soybean straw	42.39	22.05	18.93	NA
Canola stalk	38	29.42	20	NA
Almond shell	50.7	28.9	20.4	2.5
Almond shells	29.8	19.3	50.7	0.2
Almond shell	50.7	28.9	20.4	2.5
Hazelnut shell	26.8	30.4	42.9	3.3
Hazelnut shell	26.8	30.4	42.9	3.3
Walnut shell	25.6	22.1	42.9	3.3
Walnut shell	25.6	22.1	42.9	3.3
Sunflower shell	48.4	34.6	17	2.7
Sunflower shell	48.4	34.6	17	2.7
Sugarcane bagasse	43 ± 0.19	26 ± 0.32	12 ± 0.36	NA
Sugarcane bagasse	42.96 ± 1.22	22.45 ± 0.09	12 ± 0.36	19.20 ± 1.04
Bagasse	43.87	21.49	17.-2	17.62
Jatropha cake	10.08 ± 0.40	48.83 ± 1.73	13.96 ± 0.94	27.13 ± 1.02
Moringa cake	17.97 ± 1.47	1.85 ± 0.16	24.96 ± 1.26	55.27 ± 0.9

helping the forest and its associated community to enhance their energy sources while achieving energy independence[61] The majority of the forest residues include harvesting residues. Different by-products, including the plant residues, are based on the tops, logs, and branches. Other types of residues generated from the forest include sawmill waste, which depends on sawdust, shavings, and barks. The forest residues can efficiently be used for fuel production by passing them through different processes to convert it to different biofuels or other products. Currently, meal waste usually includes the use of forest product mills, including pallets and pulp. The interest in the utilization of

Table 2. Properties of FW, influencing the performance and efficiency of bioconversion process.[245–247]

Physical properties	Moisture content	FW has moisture ranging from 50 to 80%
		Increase in moisture content helps in ✓ enlargement ✓ decreases volume of porosity ✓ pH drops
	Bulk density	FW has 120–480 kg m^{-3}
		High value of BD indicates ✓ low porosity ✓ high FW compaction
Chemical properties	pH	The pH of FW lies in the range of 4.2–5.3
		pH improves microbial activity in bioconversion process
		The microbial activity lies in neutral and slight acidic pH
	Electrical conductivity (EC)	The EC of food waste is directly associated with conc. Of total dissolved solids (TDS) and salinity
		The increase in concentration of TDS and salinity increases EC
Proximate analysis (wt%, dried food)	Moisture content	6.09
	Ash content	1.61
	Volatile matter	80.9
	Fixed carbon	11.4
		Proximate analysis helps in the determination of combustion properties of waste
Ultimate analysis (wt%, dried food)	Carbon	41.53
	Hydrogen	5.76
	Nitrogen	1.55
	Sulfur	0.12
	Oxygen	51.04
	C/N ratio	C/N ratio helps in appropriate mixing of waste which falls in the range of 10–30 for efficient bioconversion
Biopolymers contents	carbohydrates	30–60%
	proteins	5–20%
	lipids	15–40%
	Impact of food source on biopolymer contents	FW rich in rice and vegetables, shows high concentration of carbohydrate. Meats and eggs show high ratio of proteins and lipids.
		Protein is important for bio-methanation
		Increased carbohydrates in FW helps in biohydrogen
		Liquid biofuel can be increased through high lipid content

Table 2. Continued.

Heavy metal contents [mg kg^{-1}]	pb	69
	Zn	57
	Cu	6
	Ni	15
	Properties	High relative density is associated with increased toxication at low concentration Considered as primary pollutants A few of the metals are essential for microbial growth

forest waste is increasing, especially in the energy production sector. The forest residues in Canada are estimated to be between 20 ± 0.6 million oven-dry metric tonnes (odmt) per year.[62,63] The biomass can be transformed into different products, including bio-oil, leading to 61% yield, char, up to 24%, and gasses, up to 15%. The overall final yield of mass based on gasoline or diesel hydrocarbons is 16%, with a 40% energy yield. Therefore, the forest residue can act as a substitute for fossil fuels because the process of pyrolysis char or gasses are used for thermal and hydrogen energy production, leading to a decline in the independence of fossil fuels. Considering these factors, the overall capital investment for the cultivation of grassroots plants was estimated at around US$427 million, with US$154 million in operation costs.[63]

2.1.3. Food Waste

The ratio of municipal solid waste (MSW) is increasing, where the food waste in MSW has reached up to approximately 70%, making it a significant challenge across the globe. The increase in food waste is directly associated with increased environmental pressure for its decomposition. Untreated food waste is linked with the generation of unpleasant odors and smells, emission of toxic gasses, and vermin attraction. The UN highlighted that the food waste material can be used as composting matter, animal feed, and bioenergy. The utilization of food waste not only helps in avoiding food wastage but also reduces the emission and generation of greenhouse gasses, which in other cases occur due to landfill activities.[64] In the absence of appropriate waste management, tonnes of food waste go to landfills without any appropriate usage. For instance, every year, about 1.3 billion tons of food are wasted, which adds to one-third of the total Municipal waste. The overall waste includes spoiled food and other food particles that are associated with the release of bad odor upon decomposition. Food waste is considered rich in several nutrients, including carbohydrates, proteins, and lipid contents, that are highly degradable in comparison to other organic wastes as shown in Table 2. The composition of the food waste differs according to their source.[65,66] However, in general, food waste is collected from different locations and is usually dumped in the land source or is incarcerated without appropriate treatment before its disposal. Improper treatment or directing the food waste to incarceration adds to the cost of waste decomposition and enforces negative impact on the environment, leading to increased air pollution and release of gas and ash in the atmosphere, affecting the respiratory system of the organisms. Similarly, landfilling of food waste is linked with the production of several toxic by-products, including leachates contaminating groundwater and the release of toxic gasses like hydrogen sulfide and methane. Safe disposal of food waste requires technology, which adds to the costs. Therefore, the utilization of food waste as a potential energy source provides an alternative to various existing challenges and overcomes increasing energy demand.[67,68]

Waste Cooking Oil (WCO): Waste cooking oil is regarded as the used vegetable oil, which is not considered appropriate for human use. Such oil can be used to extract low-cost biodiesel, which may require used cooking oils. The waste cooking oil has the capacity to be used as a feedstock for reproduction of biodiesel, which is one of the significant and efficient methods for the reduction of material cost during the production of biodiesel.[69] According to an estimation, biodiesel production cost can be lowered by 60 to 90% if the waste oils are being used as a resource to extract biodiesel. Moreover, the reuse of waste oils is also associated with the disposal of frying oils that are not suitable for edible purposes.[14,70] The conversion of WCO to biodiesel is not sufficient to meet the energy and fuel demands. However, it can contribute significantly toward an environment-friendly approach of energy production while reducing the use of fossil fuels. The use of WCO as a potential fuel source is also celebrated with the reduction of pollution which in other cases would be released to the environment upon its decomposition.[71] Although research is being conducted for the development and introduction of an appropriate system to utilize used cooking oil as a feedstock for the generation of biofuels; however, there is a lack of an appropriate system due to various restrictions that prohibit the use and specifically supplies as a raw material. Different barriers include increased by refined recast, lack of recycling units, inappropriate recycling of the material, nonavailability of stakeholders, lacking technologies for proper degradation or utilization of WCO as biofuel, increased transportation cost, and nonavailability of proper infrastructure to facilitate the production technologies.[72] One of the prime examples of these barriers includes China where the recycling and disposal of WCO are nonsmooth due to demanding policies that require optimization of the system. Restaurants are the potential source providers of WCO, however, due to lack of appropriate attention to this source the majority of the restaurants are neglected which leads to an increase in WCO.[73] Supply chain is considered one of the significant elements for the continuation of biorefineries in order to attain sustainability.[34]

The waste cooking oil used to get disposed of to the environment directly in Japan, before 1997. In 2000, Japan passed a promotion law on efficient resource use and for recycling of food waste 2001 act was introduced in order to support the recycling procedure targeting edible food especially the waste cooking oil. Japan also introduced several tax incentives and subsidies Today's awareness toward recycling of the raw materials. The introduction and implementation of such policies at national level by the government have resulted in increased recycling ratios in the US and Japan.[74] The WCO is being used as a raw material for the generation of cost-efficient biodiesel which not only helps in dealing with the recycling of waste material but also contributes to the energy sector. Currently, WCO can be used as a source of biodiesel production leading to estimated approximately 70–95% of the total cost.[75]

Kitchen Waste: Kitchen waste is an important element of municipal domestic waste. In China, per annum production of kitchen waste revolves around 6.00×10^7–9.24×10^7 tons, whereas globally the production revolves around 1.3×10^9 tons.[75] This organic waste is collected from different sources, including households and restaurants. These sources include certain food industries where the food is created and prepared, including the processing units handling meats, rice, vegetables, or other dairy products. The ratio of kitchen waste is increasing due to the increase in population, especially in Asian countries.[64]

Kitchen waste is problematic as it is associated with the generation of unpleasant smells and leachate, which can occur at any stage from its collection to storage before disposal, leading to the emission of greenhouse gasses up to 6%. The composition of kitchen waste depends on the type of food source it has been using as shown in **Table 3**. The kitchen waste varies according to economic status, time, climate, region, and cultural background. Moreover, it also depends on the content of solids, water, salt, and fat. The knowledge of these contents is necessary for easy deterioration. There is an increased probability of contamination of surface and groundwater along with the soil atmosphere.[76] The probability of the spread of certain diseases is also high as it may contain different contaminants. Food waste is cheap and renewable due to its increased abundance across the world with changes in its content. Kitchen waste is usually high in glucose productivity in comparison to other types of biomasses, specifically agricultural residual. Therefore, it requires pretreatment and enzymatic hydrolysis, especially during the process of the production of bioethanol. These characteristics enable kitchen waste and eco-friendly and economic approaches to be used as a potential source for energy generation, leading toward sustainability.[75]

2.1.4. Municipal Wastewater

The overall global accumulation of municipal waste is around 1.9 billion tonnes per year, where the probability of increased municipal waste is hired due to a rise in population growth and rapid organization. The majority of the municipal waste is collected from different municipalities, including household waste, institutions, different offices, and garden waste. According to their chemical composition and properties, municipal waste can be categorized into three main groups: polymeric, triglycerides, and lignocellulosic waste.[77] The estimation for the increase in overall worldwide waste is about 70% by 2025, where the lower- and middle-income countries are expected to contribute more toward increased waste production.[78] From the total municipal solid waste, only 45% of the waste is created and used through recycling or other procedures, while the rest of the waste goes to landfills or nearby water bodies.[79]

Table 3. Ratio of biopolymer concentration in waste.[246,248]

Waste type	Protein [%]	Carbohydrate [%]	Lipid [%]
Food waste	10–30	40–60	15–40
Synthetic FW	16	62.6	21.3
Kitchen waste	12–20	52–65	15–35
Food waste	27.8	35.1	22.4
Food waste	7	67	10

The increased preference for municipal solid waste is due to its increased degradability at a calorific heat value, which makes it a suitable candidate to be considered as an efficient source for biofuel production in the energy sector despite its increased variability in its composition. One ton of MSW produces approximately 8–12 GJ, which is 1/3 of the calorific value of coal, generating about 600 kWh of electricity.[77,80] Valorization of different types of municipal waste in value-added products is one of the significant uses of waste material that require efficient management, especially when converting MSW into liquid fuels. The management of MSW includes the valorization through different energy sources and the addition of chemicals and activated carbon. In the past, transistor certification has been a prominent way to produce biodiesel from triglyceride oil and fat waste. Biodiesel is involved and provides more benefits in comparison to plant-derived lignocellulose by providing high energy density. The attention is being diverted to the process of valorization with the use of the thermochemical conversion process, especially gasification and pyrolysis, in comparison to transesterification due to limitations. Modern technology including integrated gasification, and Fischer–Tropsch is gaining popularity for the generation and synthesis of gas by using municipal solid waste and garbage as a potential source.[81] The technique of gasification is involved in the production of particulate matter, which majorly includes carbonaceous residues, ash, dust, and tar. It is developed from complex aromatic hydrocarbon compounds. However, for biomass classifiers dependent on tar and particulate matter introduce limitations, which include the falling of downstream equipment, blockage, issues in the engine and the cost of management and maintenance.[77]

2.1.5. Animal Manure

An increase in the global livestock industry has been reported in past years. This has resulted in the increase in the number of anthropogenic land users while employing 1.3 billion people leading to 42–50% of overall agriculture GDP. In the last 50 years, the increase in the maid consumption by twofolds has been observed, where it has risen from 23.1 kg per person per year 24.1 kg from the year 1961 to 2011. The increase in pig and poultry production has also been observed by fivefolds. As a result, there is an increase in the animal manure that can be considered a potential risk to the environment. The decomposition of animal manure is associated with the release of chemical substances with increased chances of the pollution to the soil, underground water, and air.[82] The careful handling of animal manure is required to avoid the contamination. Majorly the nitrate and ammonium ions are formed leading to the release of gaseous ammonia through nitrification and modification.

The process of decomposition includes the production of the soluble compounds and gasses, which upon a proper handling can contaminate soil solutions, air and groundwater. The growth in livestock has resulted in a total of 14.5% of anthropogenic GHG emissions at global levels with the amount of 7.1 GtCO2eq year^{-1}. Untreated and improper handled manure is also a major source of heavy metals and zoonotic pathogens that can be saved in the groundwater through water run off enhancing the ratio and chances of contamination upon consumption. Therefore, appropriate handling of manure is required for which the traditional methods like composting and incineration are being used.[83] Despite increased use of these methods, the viability and practical implementation of these methods are unsuitable for the environment. Anaerobic digestion (AD) can be considered a significant and the most common biochemical process applied to treat solid waste and wastewater. AD has its own drawbacks among which one of the significant is its applicability to large quantities of manure. Other drawbacks include the restriction of this method to high moisture content, for example, sewage sludge and cow manure. Other methods include thermochemical conversion process, which is also known as the depolymerization. This process includes the reforming reactions of lignocellulosic compounds in the biomass with the help of heat and oxygen control and closure under low to relatively high pressure. The main products obtained from this process include bio-oil, syn-ga or product gas and biofertilizers.[84] Thermochemical conversion includes both dry or nonaqueous and hydrothermal or aqueous techniques.

Composition: Livestock, specifically cattle manure, is rich in carbohydrate content having about 50 to 60% carbs, which makes it a significant source and the feedstock for biogas production. The protein and lipid contents are also important for the determination of the potential of biogas in terms of different agricultural waste feedstock.[51]

2.1.6. Industrial Organic Waste

The majority of industrial solid wastes include peelings and scrap of fruits and vegetables. It also includes the scraps from meat and poultry, pulp, and coffee grounds. Current waste management practices involve a waste-to-energy approach, which has introduced the concepts of recovery, reuse, recycling, and reduction.[85] The utilization of these sources for biofuel production has introduced the replacement of fossil fuels along with environmental benefits, saving landfill space and GHG emissions reduction.[80] The majority of industrial waste does not comply with quality control standards and, therefore, is dumped in landfills. Similarly, different liquid wastes from paper and food industries having high sugar starch and other content are disposed of without appropriate treatment or utilization. The inclusion of such industrial organic waste for the production of biogas through aerobic digestion cancels dual purposes by involving it as a potential source for biofuel generation and recycling the material, leading to the conservation of the environment.[79]

2.1.7. Theoretical and Practical Implications of Biomass

Different processes can be used to recycle and reuse the biowaste material. Some of the processes may include chemical conversions, while the others may not depend on its use and need of the time. Theoretically, the woody biomass can be combusted without the need of intense processing, for example, by applying the woody biomass as a few to use it as a low-grade fuel. However, the processes including good size reduction, steam explosion, hydro thermal carbonization, biological treatment, can be considered as significant processing methods to practically convert woody biomass into efficient fuel. Similarly, dehydration is regarded as the seeds horns leaves in stems. The herbaceous biomass is usually generated during post-harvest handling and requires similar procedures. Its rich moisture content is one of its significant and major limitations to be used for the fuel generation. Therefore, different free treatment methods are applied that add to its cost. However, the biomass waste materials also create a variety of opportunities. For example, the by-product is the form of digestate rich in nutrients and can be converted into fertilizers or can be recycled as energy pellets. The practical implementation of the processes by utilizing waste biomass can be considered helpful in handling the current energy crisis.[86]

2.2. Environmental and Economic Importance

With increasing awareness regarding environmental conservation, the environmental and economic effect of every aspect of the energy generation procedure is being considered. The impacts of energy generation activities on the environment and economy are gaining enormous attention. Different forms of combustion have a significant influence on our environment because they are involved in the emission of pollutants in the form of fuel combustion; however, the amount and type of pollution before and after vary according to the combustion process. In comparison to the combustion of fossil fuels, the combustion of forest and agricultural residues involves the emission of similar levels of nitrogen oxides. However, the combustion of plant residues involves less emission of sulfur dioxide. Moreover, waste biomass combustion is observed to have low GHG emissions.[87] The release of carbon during the combustion or utilization fossil fuels by an increase in biomass production as, according to an estimation, after 30 years, only 13% of the carbon will be released from the residue combustion process in the atmosphere it is one of the significant steps to overcome the environmental degradation. There are several limitations in the use of waste biomass as a potential energy source, among which the need for financial assistance to establish and operate plants and units and increased cost to take initiatives can be significant reasons.[88]

The requirement of the preliminary investment cost includes the cost of different components of the power plant along with its installations. The cost of the capital includes the consideration of different technologies that need to be implemented. Along with that, the size and energy of the potential plant are also potential contributors to the determination of the general cost of the plant or the whole procedure. Also, it is difficult to estimate the exact cost because a diverse range of technologies can be applied to obtain biofuel from the waste biomass. However, after initial investment, there is an increased probability of long-term benefits as these technologies are considered economically viable because of their estimated life ranging between 15 and 35 years. The technology also has an increased efficiency by considering the source type and the conversion technology used.[89,90]

3. Biofuels and Their Role in Power Production and Transportation

3.1. Overview of Biofuels

The major sources for biofuels include different types of biological materials, which mainly compressors of plant and animal waste. Biomass comprises organic components that can serve as a potential substitute for the energy sector. Biofuels can be categorized into solid gaseous and liquid fuels, which are being introduced in the energy sector as a potential alternative to the existing energy sources. Solid waste comprises firewood charcoal and fibrous material. These types of solid fields are extensively used to fulfil domestic needs. Methane is a fuel that is usually obtained from the fermentation of the waste of domestic animals.[91] At a commercial level, the process of fire can also be used for commercial extraction of biogas by using a variety of wastes, including food waste, agriculture and forest residues, and municipal solid waste. Different types of liquid biofuels, including organic oils, ethanol and methanol, are generally categorized as biodiesel. Different types of biofuels are recognized for their energy inception because of their efficient cost and environment friendly properties.[92] In recent years, biofuels use instead of fossil fuels has been emphasized because of their environment-friendly approach. Biofuels are also categorized as renewable energy sources. Moreover, the diminishing sources of fossil fuels are also a concern for future generations, demanding the increased use of renewable energy sources to overcome increasing energy demands. Another important aspect of the shift toward biofuels is the environment and climate conservation. Biofuels are regarded as everlasting and renewable sources because of their capacity to be used without getting brained out from the Earth.[93]

3.2. Importance of Biofuels in Energy and Transportation Sectors

Currently, major and critical problems related to the energy and transportation sector include high fuel prices, concerns regarding climate change, and increasing pollution. To fulfill current energy demands, the energy sector relies on fossil fuels, which include petroleum, coal, and natural gas. From the last century, the world has observed a rapid boom in the industrial sector, where different measures have been taken to improve the economy of the world. Among these, the transportation sector has also contributed significantly toward the expansion of economies across the globe. However, the transportation sector demands fuel, which mainly comes from existing natural resources. The outcomes of using such natural resources in the form of climate change are also evidence and cannot be neglected. As a result, the shift to fulfil the fuel demands has been diverted toward the use of biofuel, and fuels are being produced with the help of biomass.[94] Biofuel is considered a potential replacement of existing fuel sources, especially petroleum-based fuels. Biofuels are prioritized due to their contribution toward stability, decrease in GHG emissions, and reuse of renewable sources, especially waste biomass.

Liquid transportation fuels include gasoline and diesel that are replaceable by biomass-based liquid fuels. The introduction of bioethanol and biodiesel has emerged as a potential replacement for gasoline and diesel, respectively. The major potential of biomass-based energy sources includes their potential to be carbon dioxide neutral and recyclability of carbon atoms. Bioethanol is considered a promising fuel because of its environmental benefits. According to an estimation, the European Union is involved in the production of biofuel, which in 2004 was around 2.9 billion litter. The ratio of biofuel generation is increasing with every passing day due to their increased applicability and environmental benefits.[95]

4. Conversion Technologies for Waste Biomass

4.1. Thermochemical Conversion

Thermochemical conversion is regarded as a controlled heating or oxidation system used for the biomass to produce intermediate energy careers or heat. It is considered as one of the simplest examples of the experimental technology to be used by human beings for the generation of liquid fuels for transportation. The technology is associated with thermochemical conversion. The oxidation environment, size of particle, and heating rate are the major determinants of different categories of thermochemical conversion technologies.[96]

4.1.1. Pyrolysis

Pyrolysis has gained attention because of its extensive use in liquid fuel production due to its several advantages in terms of its storage and transportation. This method is versatile and is applied in combustion engines, turbines, and boilers, etc. The treatment and management of solid biomass and waste are costly; therefore, pyrolysis is preferred. The process of pyrolysis is going through the development and is facing several technical and economic challenges to become a potential technique for bioenergy production against conventional fossil fuel energy.[97] Extensive research on the use of pyrolysis for the production of bioliquids has been conducted among which wood bagasse, straws, seed cakes, and MSW, etc. are some known biomass species. Pyrolysis is regarded as thermal decomposition of biomass in the absence of oxygen. The word is derived from Greek word pyro depicting fire and lysis meaning decomposition.[98]

During pyrolysis, the biomass goes through an irreversible thermochemical decomposition reaction for the production of biofuels. The classification of pyrolysis (slow, fast, and intermediate), their operating parameters, and the features of obtained products are shown in **Table 4** and **5**, respectively.

The short vapor residence and fast heating rate are associated with rapid condensation of the volatile hydrocarbon vapors into bio-oil. Slow pyrolysis is associated with increased char production because of slow carbonization of biomass, which occurs due to slow heating rate and longer vapor residence time.[48,99]

Table 4. Operating parameters and products during pyrolysis.[48,98,99]

Pyrolysis process	Solid residence time [s]	Heating rate [K s^{-1}]	Particle size [mm]	Temperature [K]	Yield of product [%]		
					Oil	Char	Gas
Slow	450–550	0.1–1	5–50	550–950	30	35	35
Intermediate pyrolysis	600	278	–	573–723	35–50%	25–40%	20–30%
Fast/Flash	0.5–10	200–1000	0.2–1	850–1300	50–75	12–20	13–30

Table 5. Features of products obtained in pyrolysis.[112]

Temperature	Process reaction	Properties of the products
Below 350 °C	Depolymerization makes free radicals with elimination of water	Forms carbon monoxide and carbon dioxide, carbonyl and carboxyl compounds with char residues
350 to 450 °C	Glycosidic bond is broken	Oligosaccharides, anhydrides, and levoglucosan mix to form tar fraction
Above 450 °C	Sugar units are formed from dehydration	Carbonyl compounds are obtained
Above 500 °C	Mixture of different reactions	Different products are formed
Condensation	Unsaturated products condense	Char residues are formed having trapped free radicals

Pyrolysis is also considered as a thermal cracking method that requires a temperature of 300–700 °C without oxygen for biochar, bio-oil, and noncondensable gasses (H_2, CH_4, CO, and CO_2) production. During this process, thermal decomposition initiates at the temperature of 350–550 °C leading up to700–800 °C. Bio-oil consists of two distinct phases namely water and organic. The organic phase includes tar and hydrocarbons, which are usually upgraded to retrieve clean transportation fuels. An upgrade is required to eliminate oxygen, nitrogen and sulfur through catalytic and noncatalytic processes to lower fuel's heating value. However, during this the ratio of the release of NO_x and SO_x increases. The water phase of bio-oil includes esters, ethers, ketones and aldehydes, phenols and alcohols, acids, and other biochemicals. The gas phase depends on hydrogen and carbon monoxide, which can be converted into hydrocarbons through the catalytic synthesis of Fischer–Tropsch.[48]

Implementation of these in center and regulatory frameworks is focused on reducing the pollution levels in order to mitigate climate change. For this purpose, various climate change conferences have been organized among which the Paris Agreement is currently serving as an international treaty. According to this treaty, there is a need to establish nationality determinant contributions (NDCs) for different countries in accordance with their use of energy and fossil fuel and implement relevant strategies to reduce emissions of GHG and other gasses. Biochar can be considered significant in meeting NDCs in agriculturally diverse countries.[100] Biochar is often obtained through the process of pyrolysis which has been going through by refining in order to make a scalable production.[101] Biochar is usually produced from a variety of biomass materials including agriculture and forest residues which are usually subjected to pyrolysis. The main reason for increasing popularity of biochar and the market is its increasing demand in mitigating the hazardous gas emissions as it is actively being used for the carbon dioxide removal credits which are developed after the generation and utilization of biochar.[102] However, there are several barriers to increasing biochar scale among which expensive processing, limitations in the availability of raw material, and lack of appropriate infrastructure for its white scale production along with volatile markets required efficient strategies. Considering these limitations and barriers, improvement in the pyrolysis process can be considered efficient in achieving the targeted goals regarding biochar production which ultimately can help in achieving carbon credit with the help of NDCs.

Advantages of Pyrolysis: The following are the advantages of pyrolysis: 1) Renewable fuel for turbine, engine, boiler, and several industrial processes; 2) Neutral CO_2 balance with low cost; 3) Uses waste material including municipal industrial and forest residues and second-generation bio-oil feedstocks as a source; 4) Enable the storage and transportation of liquid fuels; 5) High energy density in comparison to atmospheric biomass gasification fuel gasses; 6) High probability of the separation of minerals on the side during liquid feel production and recycling of such minerals as the soil nutrients; 7) Can be converted into motor fuels, special chemicals, or additives; 8) Separation of fractions of lignin and sugars in biomass[98]

Pyrolysis Behavior of Lignocellulose Biomass: Cellulose is the major constituent of lignocellulosic biomass which comprises 60% water and is made up of different glucose molecules linked together by β-(1-4) glycosidic bonds. At the temperature 315–400 °C, the decomposition of cellulose is possible, whereas different ranges of activation energy are required for the breakdown of cellulose which depends on the type, computation process, parameters, and other factors. The most common range for the activation energy revolves around 166–250 kJ mol^{-1}. Different operating conditions including the heating rate, residence time, and temperature have a significant influence on pyrolysis. Levoglucosenone (LGO) is produced at low temperature, while the production of hydroxyacetaldehyde (HAA) is promoted and accelerated at high temperatures, which is a low molecular weight linear compound. LGO is one of essential constituents of pyrolysis oil and is considered thermal stable.

Once the temperature reaches between 430 and 650 °C, deoxygenation and condensation occur. Several oxygenated compounds are produced having different properties, including a variety of compounds having low molecular weight and dehydrated saccharides. These are produced due to several reactions that takes place in cellulosic pyrolysis.[103] There is a wide range of pretreatments that facilitate hemicellulose extraction from biomass. These pretreatments include autohydrolysis, alkali-based solutions, ozonolysis, wet oxidation, enzymatic hydrolysis, microwave-assisted heating. There is a lack of a single successful extraction method to successfully extract hemicellulose from the biomass. However, alkali solutions are considered to be efficient in hemicellulose extraction. This method shows the maintenance of integrity of hemicellulose leading to a sufficient amount of char due to thermal decomposition.[99,104]

4.1.2. Gasification

Gasification is crucial for thermochemical biomass conversion. The conversion of biomass into a multifunctional gaseous mixture, which is also known as syngas in the presence of a gasifying agent, leads to the production of energy, chemicals, and biofuels. Char is usually obtained after biomass conversion, making it a solid residue. A mixture of different gasses makes syngas, which includes CO, H_2, CO_2, and CH_4, also known as primary components and H_2O, H_2S, NH_3, tar, and other trace species known as secondary components. Specification can be divided into four major steps, which include drying (endothermic step), pyrolysis (endothermic step), oxidation (exothermic stage), and reduction (endothermic stage). Tar reforming can also be considered a significant step in the production of light hydrocarbons[105,106]

$$\text{Biomass} \rightarrow CO + H_2 + CO_2 + H_2O + H_2S + NH_3 3 + C_xH_y + \text{Tar} + \text{Char} \tag{1}$$

The process of gasification is based on four major steps: the first step is heating a drawing to reduce moisture content, the second step is per analysis, the third step is known as oxidation or partial combustion, and the fourth step is gasification. About 30–60% of the total measure content is vaporized at 200 °C. Pyrolysis comes with the decomposition of biomass, which includes cellulose, lignin, and hemicellulose in different other solid residues and volatile compounds.[107] The third step, oxidation of partial combustion, leads to resultant volatiles and char residues. This leads to the oxidation of CO, CO_2, and H_2O in the presence of a gasifying agent with a temperature of more than 700 °C. Simultaneous exothermic and endothermic reactions are continuous in this process, where the reactions act as a heat supplier for endothermic reactions. Carbon reactions are the main classification reactions, which may include primary or secondary steam reforming, hydrogasification, shift reaction, mechanization, and steam reaction. Plasma, supercritical, and microwave are being used to improve gasification yields. The plasma precipitation leads to intense plasma thermal processes, which are majorly used for the catalyzation and ionization of the organic compounds, leading to the development of syngas with the help of a plasma torch, which is generally powered by an electric arc having a temperature of more than 2500 °C. Supercritical water gasification includes the availability and presence of water to generate H_2 and CH_4. The process facilitates high yield. However, several factors, including catalyst, biomass/water ratio, and temperature, also play a significant role. Microwave gasification is another transformation technique that includes uniform distribution of temperature, efficiency in handling large particles, and higher heating values. The scrubbers and filters are used to clean syngas.[108]

Parameters: Sikarwar and Molino et al.[106,109] have combined different parameter that can have a significant effect on the feedback and affect the performance of the gasification process.

Biomass Type: 1) The yield of syngas is associated with the cellulose and hemicellulose proportion, whereas the residue yield is associated with lignin; 2) The yield of syngas can increase by increasing the ratio of cellulose and hemicellulose to lignin.

Particle Size: 1) The surface area can be increased by the reduction of particle size, which leads to a decrease in diffusion resistance; 2) The heat of syngas can be increased by the improvement of heat and mass transfer between different particles, increase in reaction rates, and improvement in fuel conversion and gasification efficiency; 3) The reduction in the size of the particles can enhance the cost of pretreatment of the feedstock; 4) The particles larger in size are associated with decreased cost; however, they make the feeding and devolatilization complicated, leading to a reduction in gasification performance; 5) The higher temperatures can have a significant impact on the gasification process, whereas the particle size can also produce the performance at high temperatures; 6) The particle size varies between 0.15 and 51 mm for conventional gasifiers, whereas the particle sizes up to 51 mm is facilitated by fixed bed reactors that are considered less sensitive to the size of the particle because of longer residence time; 7) The smaller side particles up to 6 mm can be facilitated in bubbling bed reactors.

Moisture Content: 1) The reduction in moisture content can help in increasing energy efficiency leading to the improvement in the quality of syngas. It is also associated with higher heating values and decrease in conversion emission; 2) The dark content can be increased by enhancing the moisture content more than 30–40% w/w; 3) Convention classification demands a moisture content ring between 10% and 20% w/w; 4) The moisture content up to 60% w/w can be operated by the updraft fixed bed gasifiers.

Ash Content: 1) Fixed bed updraft gasifiers usually prefer the biomass having low as content (lower than 2% w/w); 2) Slag can be formed when the biomass having high content, which is usually more than 10% w/w is treated. This may include the use of cereal crops, oil seed, and route cross and flowers. The slag formation is more common in down draft classification; 3) Slagging can be reduced when the gasifier is operated below ash flow temperature or above its melting point.

Bed Material: 1) The material used for the beds usually acts as an energy transfer medium and can be inert; 2) The bed material has the capacity to show catalytic activity leading to improved syngas quality, captures CO_2, leading to reaction reforming and tar cracking; 3) Different types of catalyst for bad materials that may include olivine, limestone, silica, dolomite, and various other metal oxide and Ni and K-based catalysts.

Operating Parameters: 1) The increase in heating rate can enhance the yield of syngas leading to the reduction in tar formation; 2) High conversion rates of carbon to char with increased CO and H_2 contents can be obtained by a printing specification process at elevated temperature; 3) 750–850, 800–900, and 850–950 °C are considered as a temperature range for the gasification of agriculture waste, RFD, and woody biomass, respectively; 4) Increase temperatures, especially more than 1000 °C, are associated with two drawbacks including the melting of air and the requirement of rigor reactor; 5) Atmospheric and higher pressures both can be used in the gasification.

Steam to Biomass Ratio (SB): 1) 0.3 to 1 is considered as SB optimal value; 2) The range of 1.35–4.04 for SB values can lead to increased H_2 and CO_2 concentrations; 3) The increased SB is directly associated with the increased heating value of syngas, H_2, and CO_2; 4) However, during the procedure, increased steam formation can reduce the temperature that facilitates the formation of tar. In other cases, higher SB is required.[109]

Syngas Processing: Syngas cleaning technology is divided into hot and cold gas cleanup according to the condensation temperatures of different species. This includes the use of water sprays that also allow the contaminants to get absorbed in the water droplets and condense at low temperatures (300 °C). At this temperature, various alkalis condense. While hot gas technologies require a very high temperature of thousand degrees or more. Different syngas transformation routes to synthesize fuels and chemical are shown in **Figure 2**.

4.1.3. Combustion

Biomass combustion is considered as a series of reactions that involves CO_2 and H_2O formation which results after the transformation of carbon and hydrogen during oxidation reactions. The lack of appropriate quality of oxygen can leads to incomplete combustion, which can be associated with the release of several atmospheric pollutants that may include the traces of carbon monoxide, nitrogen oxides, and sulfur oxides along with particulate matter.[108,110] The flame temperatures can exceed the temperature of 1650 °C majorly relying on the moisture content and heating value of the fuel, the air used for burning the fuel, and the construction of the furnace.[111]

The biomass combustion constitutes to the 11% of current demands of energy of the globe which highlights its usefulness. other uses of combustion include the fulfilment of daily heat consumption, heating applications at community level, requirement to full fill the industrial energy demand along with electricity production, extensive use in paper industry, and required for the processing of sugarcane.[112,113]

Combustion is important as it is one of the highly reliable technologies in the energy sector that is also commercially available. The combustion includes three main stages named drying, pyrolysis, and reduction and combustion of volatile gasses and solid char. The volatile gas combustion adds to 70% of the overall

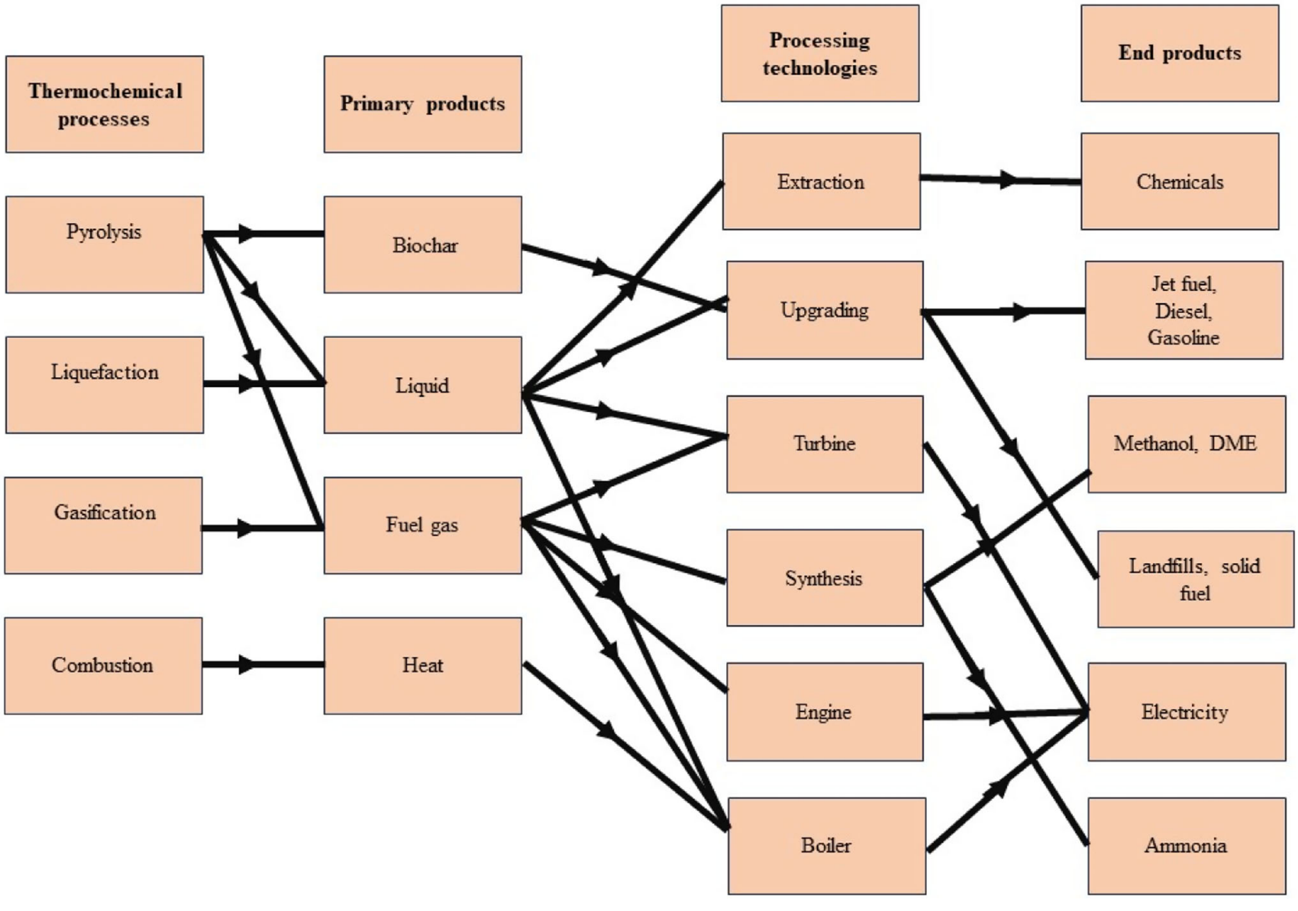

Figure 2. Thermochemical conversion processes products and its applications.[237]

generated heat, which usually took place above the fuel bed and is evident due to the presence of yellow flames. Fluid bed chamber is combusted and is evidenced from its small blue flames. The combustion of biomass at the largest scale is complex due to several technical challenges which may include different characteristics and traits of biomass, types of combustors, and the challenges of co-firing processes.[114] It has been observed that about 418 kJ of heat energy is required for per mole combustion reaction of oxygen molecules. A few of the industries incinerate or combust biomass waste.[112]

The moisture content of about 65% is required to support the self-supporting combustion process. The heating value is negative with the relevant amount of water despite the availability of moisture content in its maximum acceptable limit. During biomass combustion, the significant issues that a combustor can face include fouling and corrosion.[115] Fouling occurs due to availability of alkali metals and other elements including chlorine, calcium, silicon, sulfur, and iron in the biomass ash. Due to a series of chemical reactions, there are increased chances of the deposition of such elements in the forms of silicates sulfates and chloride alongside the walls of the combustor or on the surface of the heat transfer elements. The herbaceous material including straws and grass are considered to have a great potential to have high content of alkali sulfur and chlorine leading to the corrosion in comparison to woody biomass.[114] A comparison of different parameters of both gasification and combustion is given in **Table 6**.

4.1.4. Liquefaction

The hydrothermal liquefaction (HTL) is well known for its available at water which is crucial and essential in thermochemical processes earning its name.[52] Liquefaction can be linked with liquid biofuel production from biomass, and the reactions occur in the presence of water or organic solvents. The process of hydrothermal liquefaction is related to the generation of bio-oil with low temperatures and elevated pressures with or without a catalyst in the presence of hydrogen.[14] In this procedure, the temperature ranges between 200 and 400 °C, and the pressure is between 4 and 20 MPa. The use of alkaline catalyst is common, and the reactants including CO or H_2 are often known to improve the process performance. The hydrolysis of macromolecules in the biomass (lignin and cellulose) is hydrolyzed into smaller molecules under decarboxylation, dehydrogenation, dehydration, and various other reactions leading to the production of smaller compounds. If the water acts as a solvent, then the process is known as hydrothermal process, which is known for its use of wet biomass. However, the limitations in its use include the lower yield of bio-oil in comparison to pyrolysis, decreased quality, and high cost as it requires increased temperature and pressure, catalyst, and reactants.[116] This has resulted in the shift toward other methods including moderate acid catalyzed liquification or MACL, which can be conducted at atmospheric pressure and lower temperature with the use of organic solvent and catalyst. The increase in lignin content of biomass leads to probability of reduced yield of bio-oil and increases challenges regarding lignin degradation. Upon combustion in the majority of the part of the solid waste and ash content. In hydrothermal liquefaction, different catalysts either acid or alkaline are used, whereas alkaline catalysts are considered more efficient however are also more corrosive. Water is used as the solvent, which comes with several drawbacks. For example, water and soluble leading to low yield. The bio-oil comprises increased oxygen content and low heating values, which demands the use of organic solvent. The process of hydrothermal liquefaction can be efficiently in compliance with other processes to improve the performance of gasification.[117]

4.2. Biochemical Conversion

The organic waste and energy products are correlated with each other in order to extract energy from waste. A variety of products

Table 6. Gasification and combustion; a comparison.[114]

Characteristics/Features	Combustion	Gasification
Aim	Heat generation	Production of eco-friendly and usable products from waste
Type of process	Use of excess oxygen to facilitate complete combustion	Conversion (thermally or chemically) without or little oxygen
Raw gas	CO_2, H_2O, SO_2, NO_x, and particulates	H_2, H_2S, NH_3, CO, and particulates
Gas cleanup	Cleanup of flue gas at atmospheric pressure Discharge of treated flue gas in atmosphere	Cleanup of syngas at atmospheric and high pressure
	Treatment of sulfur if present in the gas	Use of treated syngas for various uses (chemical, fuel, or power generation)
		Recovery of sulfur species
Solid by-products	Ashes	Char or slag
Handling of ash and slag/char	Collection, treatment, and disposal of bottom and fly ash	Processes at low temperature produce char
		High temperature produces slag or other materials
Pressure	Atmospheric	Atmospheric to high
Economic benefits	Facilitates the reactions require high temperature	Reduces cost waste handling
		Facilitates less emissions
	New combustion techniques are being introduced in energy sector for sustainable energy production.	Transform low-priced feedstock into valuable products

and various other value-added compounds related to energy can be extracted from liquid and solid waste with the help of aerobic or anaerobic digestion.[118] Aerobic digestion requires the availability of specialized specifiers to obtain gaseous fuels. Anaerobic digestion also known as dark fermentation is considered a crucial biological process for the extraction of gaseous fuels from waste.[79]

4.2.1. Fermentation

The use of faculty or obligate anaerobes can promote the process of dark fermentation, which is used for the production of biohydrogen. During this process, the breakdown of complex organic polymers occurs leading to the formation of monomers using fermentative bacteria to obtain organic acids and alcohols by using acidogenic bacteria. Dark fermentation is facilitated by a variety of bacteria which continues with a series of biochemical reactions demanding similar steps to anaerobic digestion process.[119] The waste biomass service for the production of hydrogen by fermentative bacteria is considered an optimum source in terms of its availability, cost, and biodegradability. The inclusion of waste from diverse industries as a substrate provides efficient waste management and contributes to the production of hydrogen facilitating the energy sector to utilize the waste in a sustainable manner.[120]

4.2.2. Anaerobic Digestion (AD)

AD occurs in the absence of oxygen, where the organic waste is degraded with the help of microbes, which results in the generation of gas mixtures including methane (50–75%), CO_2 (25–50%), hydrogen (5–10%), nitrogen (1–2%), and traces of H_2S. The anaerobic digestion consists of four stages named: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These four steps occur with the sequence to convert ways into biogas in the presence of a diversity of bacteria.[121] The anaerobic digestion process includes its first step, which is known as hydrolysis, followed by acidogenesis of the products. During this process, waste material is converted into several other components, including organic acids, carbon dioxide, hydrogen, alcohol, ammonia, sugars, and proteins.[122] Organic acids are then converted into acetic acid hydrogen carbon in the presence of acetogenic bacteria. In the last stage, methanogenic bacteria are used to convert the abovementioned products into biogas, precious hydrogen sulfide, and nitrogen. The transformational route of biomass into biofuel is described in **Figure 3**.

Different types of lignocellulosic biomass are used as a potential source in the biodigesters.[123] Lignocellulose is a complex material that requires a print treatment for its conversion into biogas. The breakage of the barriers of biopolymers can be considered an efficient free treatment that can open the lignocellulosic structure, leading to increased probability of biodegradation and biogas production.[124] Different studies have depicted the pilot scale pressing system depicting the pretreatment of biomass for biogas production, among which the autoclave and microwave strategy for improved hydrolysis is considered efficient. However, there are several drawbacks to these strategies as they require increased financial assistance to improve their efficiency and application at a large scale to make it commercially feasible.[79] Different mechanisms involved in biogas production through waste biomass are shown in **Table 7**.

4.3. Hybrid Conversion Technologies

4.3.1. Solar Thermal Pyrolysis

The increasing energy demand has diverted the world's attention toward utilizing several renewable material sources, among

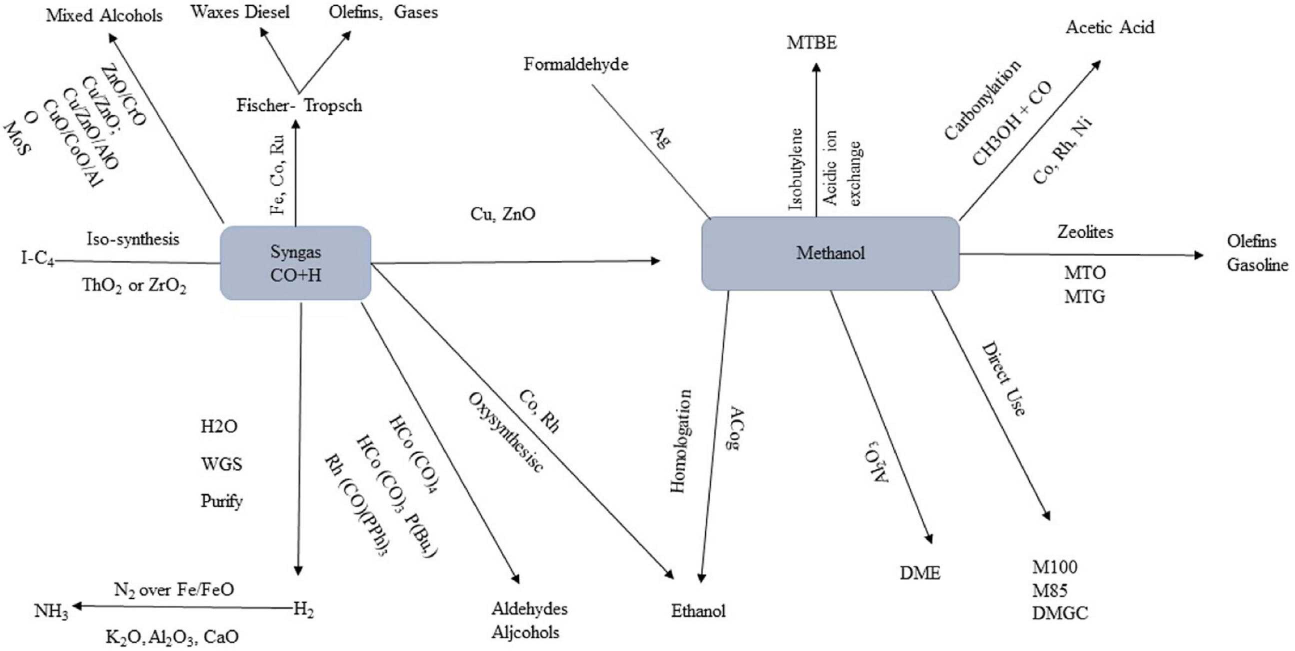

Figure 3. Different syngas transformation routes to synthesize fuels and chemical.[106]

Table 7. Typical comparison of thermochemical conversion technologies for bioenergy production.[249–252]

Parameters	Conversion technologies			
	Combustion	Gasification	Pyrolysis	Hydrothermal liquefaction
Process temperature	Up to 1400 °C	Up to 1600 °C	Up to 900 °C	Up to 400 °C
Products	Heat, electricity	Syngas, bio-oil, electricity	Biogas, biofuel, biochar	Biofuels, biochar, valuable biochemicals, gas
Emissions	Produces GHG emissions causing air pollution Flue gas cleaning Ash	Extensive gas cleaning Ash content	Cleaning of biogas Heavy metals in biochar	Biocrude needs to be processed to remove oxygen and heteroatoms like nitrogen[253]
Feedstock pre-treatment	Drying is needed to directly burn biomass feedstock	Low moisture content and tolerance in feedstock	Pretreatment is needed to achieve high efficiency	High moisture content feedstock is used. Drying is not needed
Capital cost	High	High	High	High
Operating cost	High (drying of feedstock requires extensive energy. Achieving high temperatures increases energy capitals)	High (drying of feedstock requires extensive energy. Achieving high temperatures increases energy capitals)	High (pretreatment of feedstock requires extensive energy)	Zero to low pretreatment cost Less energy intensive interms of process temperature
Feedstock quality	Feedstock quality is not required	Low sensitivity toward feedstock quality	Sensitive to feedstock quality while producing valuable chemicals	Sensitive to feedstock quality while producing valuable chemicals
Commercial use	Heat and electricity	Syngas, electricity and methanol	Valuable chemicals mainly, electricity and waste management	Valuable chemicals, upgrading gasification fuels
Status	Commercial/mature technology	Commercial/mature technology	Immature	Immature
Product cost	High compared to gasification	Low	High	High
Atmosphere	Oxidizing atmosphere	Partial oxidizing	No oxidant	High pressure
Pollutants	SO_x, NO_x, dust, polycyclic aromatic hydrocarbons (PAH)	H_2S, CO_2, and tar	H_2S, NH_3, and dust	HTL biocrude contains sulfur and nitrogen
Maintenance	Ash fouling and slagging	Blockage of downstream processes due to tar	Clogging or corrosion can occur in reactor and cooling system	High pressure conditions can lead to corrosion

which solar thermal pyrolysis has emerged as a promising choice to fulfil increasing energy demands **Table 8–10**. The rise in energy demands revolves around the transportation and industrial sectors, demanding increased availability with low cost. For this purpose, solar energy can be considered a potential substitute that not only provides an abundance of energy with low-cost efficiency but is also a renewable source.[125] Solar energy is cost efficient because it only demands an initial investment, for which the payback period toward its financial efficiency can be compared with the cost of energy provided through the conventional system. In solar thermal power, the radiations reflected from the concentrator are directed to the pyrolysis reactor. When the temperature goes up to 300–350 °C, thermochemical reactions occur, directing toward pyrolysis-related products.[126] This process reduces the efficiency of energy conversion due to certain problems associated with the loss of radiation and heat transfer.[127]

This methodology and technique are most appropriate for remote and hilly areas where access to energy is difficult. As a result, solar thermal pyrolysis emerged as a productive

Table 8. Mechanisms involved in energy production through waste biomass.[79,254]

Energy product	Type of feedstock	Bioprocesses	Involved processes	Lab scale production
Biogas	Agriculture waste, food waste, MSW	Aerobic digestion of glucose producing methane and CO_2	Hydrolysis, acidogenesis, acetogenesis, methanogenesis	0.211 $m^3\,kg^{-1}$ by using MSW
Biohydrogen	FW, kitchen waste	Fermentation of glucose into acetic acid, butyric acid, and acetic acid	Catalytic methane conversion Catalytic gas-shift fraction	Increase in hexose by 23% 14.27% H_2 using kitchen waste
Biomethane	FW, sugarcane bagasse, rice straw, food waste, algal biomass	Hydrogenotrophic methanogenesis Acetoclastic methanogenesis	Glucose to methane conversion	0.54–1.62 L CH_4/L^{-d} from algal biomass
Biohythane	Wheat bran, MSW, FW	2-stage anaerobic digestion		H_2 and CH_4 (334.7) $L\,kg^{-1}$

Table 9. Hybrid conversion techniques for waste biomass to electricity generation.

Biomass type	Biomass/ plant capacity	Catalyst/pretreatment	Hybrid technology	Capital cost	Annual electricity production	Electricity cost	software	Location	References
Red oak biomass	2000 MTPD	Drying and grinding	Fast Pyrolysis-bio-oil fuel cell	16.74 \$MM (15.02 for bio-oil, 1.72 for fuel cell stacks)	1.50×10^7 kWh	5.36 \$ kWh^{-1}	Aspen	–	[255]
Forest biomass	22.5 MWe	–	Concentrated solar power (CSP)—direct combustion	\$210 million	98 GWh	0.42 \$ kWh^{-1}	–	Spain	[256]
Municipal solid waste (MSW)	500 t day^{-1}	–	Waste to Energy (WtE) plant—biomass fired power plant	\$2.24 Million	64.52 GWh	–	EBSILON	–	[257]
Forest biomass	2.1 MWe	–	Solar-biomass combined heat system (CHP)	4.3–9.5 million Eur	–	100–220 Eur MWh^{-1}	–	Italy	[258]
Animal manure	Expected to meet 60 kW day^{-1}	Directly fed to the anaerobic digestor without any pretreatment	Wind energy-diesel-anaerobic digestion	\$183 850	–	0.202 \$ kWh^{-1}	Homer	Pakistan	[259]

Table 10. Different parameters and techno-economic analysis of thermochemical technologies.

Thermochemical technique	Working temp	Working pressure	Type of feed stock /biomass	Moisture content	Product/ biofuel	Byproducts	Cost	Status	Ref
Direct combustion	1650 °C	1 atm	Wood, agriculture residuals, and municipal solid waste	20%	Heat, ethanol, and biodiesel	Ash and exhaust gases	68–78 \$ MWh^{-1}	Mature (commercial level production)	[112,212,260]
Gasification	700–1000 °C	Atm/ pressurized	Municipal solid waste, wood chips, agricultural waste	10–20%	Bio-oil and Syngas	Ash/char, slag, and metals	49–54\$ MWh^{-1}	Mature (commercial level production)	[209,261]
Pyrolysis	350– 900 °C	1 atm	Agriculture and municipal waste and wood chips	15–30%	Bio-oil and biochar	Char, heavy metals, and gases	88.78–177.56 \$ MWh^{-1}	Immature	[262,263]
Hydrothermal liquefaction	200–374 °C	15–220 bar	Algae, municipal sludge, lignocellulose, or an organic component of municipal solid waste	High moisture content	Bio-oil	Solid residue, aqueous phase, and gas phase products	–	Immature	[260]

alternative technology with the potential to meet global energy demands. However, it also faces several challenges and difficulties, which are as follows. This required an appropriate solar concentrator with a reactor-integrated system. This system currently attains lower reactor temperatures at off times. There are also several issues associated with the solar energy storage that can be used in the absence of solar radiation. Another important challenge associated with solid thermal power is the low ratio of energy conversion efficiency. Irregular distribution of heat energy in the pyrolysis reactor system and the loss of heat due to air convection on the surface of a reactor are also notable challenges. The compatibility issues of the reactor material are also a concerning challenge of this emerging technology.[128]

4.3.2. Upgrading of Pyrolysis Oil

Olefins comprising gas fraction and aromatic hydrocarbons are some of the notable and essential products that are usually obtained from catalytic cracking of biomass. The process of oligomerization facilitates the production of olefins-rich fuel gas that can be upgraded to C5-C12 iso-olefins and iso-alkanes, contributing to increased gasoline production.[129] Oligomerization process involving a mixture of low carbon olefins over an amorphous silica-alumina (ASA) catalyst in the temperature of 280 with 3–4 MPa leads to the conversion of ethylene, propylene, and butylene reaching 19.2, 37.3, and 58.7 c-mol%, respectively. The yield obtained was 23.43 c-mol%, and the gasoline-producing species was C6 to C10 olefins and alkanes. The outcomes of the study have depicted that the coupling of olefins oligomerization to gasoline and biomass catalytic pyrolysis can give high efficiency.[130]

4.3.3. Combined Hydrothermal Carbonization and Anaerobic Digestion System

Heidari et al.[131] conducted the study to observe biomass conversion to fuel with the help of two methods named hydrogen carbonization (HTC) and anaerobic digestion (AD). The study focused on the design and analysis of two scenarios for the production of undervalued biomass, mainly sawdust. In one of the scenarios, the combustion or burning of raw biomass was conducted by the provision of heat, which is required by the Rankine cycle for electricity generation. In anaerobic digestion, the raw biomass initially underwent HTC treatment. The solid product is used for the production of power by the Rankine cycle, in which the liquid by-product undergoes an AD process.

It has been observed that a $16\,\mathrm{g\,s^{-1}}$ sawdust biomass stream with 10% moisture content has the capacity to produce 95.79 kW power for the HTC-AD scenario. In comparison to this, direct combustion (DC) can produce 101 kW. The HTC-AD scenario, despite its complexity and potential capital cost, can be efficient if it undergoes direct use of biomass. The increased moisture content enhances efficiency and production power. In an integrated system, different parameters can have a significant influence. It has been observed that when the initial HHV of biomass is lower, with a low water-to-biomass ratio, then the benefits of the HTC-AD scenario are greater. It also depends on the type of biomass that generates acid like HMF (levulinic acid).[131]

4.3.4. Lignocellulosic Biomass-Based Bio-Refinery

A bio-refinery is a facility or unit that is used for the integration of the processes and equipment to generate or produce chemicals or biofuels by utilizing a variety of sources. Different conversion techniques and their combinations are used to produce value-added products to be used in the transportation and energy sector by the use of biomass feedstock through the process of gasification or fermentations.[132] The categorization of biorefineries is based on the nature and the type of biomass used. For example, crop-based materials, e.g., cereals, are usually employed in crop bio-refineries, and the cellulosic biomass is directed to lignocellulosic biorefinery. A biorefinery is like a petroleum refinery, where the input of the feedstock can lead to diverse outputs. However, there is a difference in the input material that leads to the variation in the properties of biomass, leading to a diverse range of products.[133] Different mills, including pulp and paper mills, are categorized under biorefineries because of their ability to reuse different products to formulate or produce a usable product. Research is underway to establish large-scale production of different products to strengthen the biorefineries with the aim of producing high-value products, including chemicals and biofuels, to overcome energy requirements while strengthening the economy.

The significant challenges of biorefineries include the efficient and economic transformation of 5 and 6 carbon sugars present in lignocellulosic feedstock into value-added products that can be used in the energy and transportation sector. Different thermochemical platforms used for biorefineries are involved in providing a diverse range of options in which processes like liquefaction, combustion, gasification, and pyrolysis are conducted. This unit has the capacity to convert biomass into different products, e.g., chemicals, liquid, heat electricity, and syngas. These versatile and renewable energy sources are obtained due to the diversity of raw materials. However, these processes come up with several limitations, which may include reduced energy density, high fiber content, ash in certain types of feedstocks, and diverse composition of the material used in these refineries.[134] The potential of nonedible crops, especially waste materials rich in lignocellulose, is one of the main reasons for the successful installation and operability of these biorefineries as they are involved in the production of integrated biofuel and renewable chemicals. However, there is a need to tackle different technical challenges that are involved in the increased cost and reduced efficiency of these biorefineries.[106]

4.4. Emerging and Innovative Conversion Techniques

4.4.1. Nanomaterial for Dark Fermentative Biohydrogen Production

Nanomaterials are considered efficient for their catalytic activity in dark fermentative biohydrogen reactions. Nanomaterials or nanoparticles are efficient due to their large surface area and biocompatibility.[135] In dark fermentation, a wide range of microbes because of the availability of hydrogen is enzymes, which is essential for the degradation of organic subtracts in the absence of light under the conditions. According to the presence of metal on its active sites' dehydrogenase enzymes can be grouped into two categories. Fe—Fe hydrogenase and Ni—Fe hydrogenase. Nanomaterials act as cofactors including iron and nickel (also known as magnetic nanoparticles) and therefore lead to improve the efficiency of the process as they are involved in altering enzymatic activity and stability. Nanoparticles are also known to facilitate the transfer of electrons to their respective electronics sectors, which is necessary for the reduction of hydrogen to biohydrogen leading to improved yield. Nanoparticles also have a significant impact on the microbes morphology during biohydrogen production leading to improved yield.[136]

4.4.2. Biomass-Based Catalyst

Modern technology is promoting innovative heterogeneous catalysts that are majorly extracted and derived from agricultural waste. The use of biomass is efficient as it is involved in the provision of effective catalysts that can be used for the production of high-quality, cost-efficient, and lasting biofuels, which can vary in their structure and usage. Different carbon-based catalysts are distinctive because of their lower cost as they are usually extracted and derived from low-value biomass with a large surface area and porosity.[137] The majority of the catalysts that are derived from biomass usually exhibit a large surface area and increased porosity. The method of chemical activation by the use of H_2SO_4, H_3PO_4, and KOH to improve the acidity and textile properties of reactivated carbon catalysts is being used, leading to the promotion of esterification and transesterification reactions.[138]

4.4.3. *Energy-Saving Techniques*

In order to produce and manufacture biodiesel to meet current energy demands, especially in the transportation sector, different robust and innovative methods for biodiesel production have been introduced. These methods mainly include ultrasonic irradiations, a motionless mixer, microwave heating, a membrane reactor, and reactive distillation. All of these methods are involved in improving the reaction rate and the production of biodiesel. Although the fact that these technologies are still in the early stages and require more research cannot be denied.[138]

5. Optimization Techniques for Biofuel Production

5.1. Process Optimization

5.1.1. *Design and Operation Parameters*

Gasification: The gasification reactions can take place at both high and low temperatures. Operation parameters for gasification are discussed in Section 4.1.2. Summary and comparison of different reactors for gasification are given in **Figure 4**:

Pyrolysis: Pyrolysis is divisible into three main categories: slow or conventional, fast, and flash pyrolysis. The type of pyrolysis to be used depends on the condition of the reactive, with the main focus on the operating temperature, heating rate, particle size of the field stock, and solid/vapor residence time. Table 5 shows operating conditions for all three types of pyrolysis. Fast pyrolysis produces increased numbers of bio-oils, whereas slow pyrolysis leads to the production of biochar.

Fast pyrolysis prefers particle sizes less than 0.2 and 1 mm. The particle size of 5–50 mm is preferred in slow pyrolysis. A fraction of noncondensable gasses is observed in both slow and fast pyrolysis. This is because of secondary reactions that occur during the process of mass transfer and are catalyzed by char fines and other particulate matter. The noncondensable gasses can be recycled during the process of pyrolysis for heat recovery. Organic vapor is a complex mixture of different elements, including aerosols, particulate matter, noncondensable gasses, and mist. In order to extract bio-oil, different reactor technologies, including circulating fluidized beds, ablative reactors, rotating cones, transported beds, and vacuum moving beds, are being used as shown in **Figure 5**. The bio-oil that is obtained from the majority of the reactor systems changes between 65 and 75 wt%.[139]

Combustion: The combustion of biomass is referred to a series of chemical reactions that can result in carbon dioxide and water formation during oxidative reactions. The availability of oxygen affects the combustion as the release of atmospheric pollutants in the air **Figure 6**.

Types of Combustion: Following are the types of combustion:[112] 1) Complete combustion; 2) Incomplete combustion; 3) Smoldering combustion; 4) Rapid combustion; 5) Spontaneous combustion; 6) Turbulence; 7) Microgravity

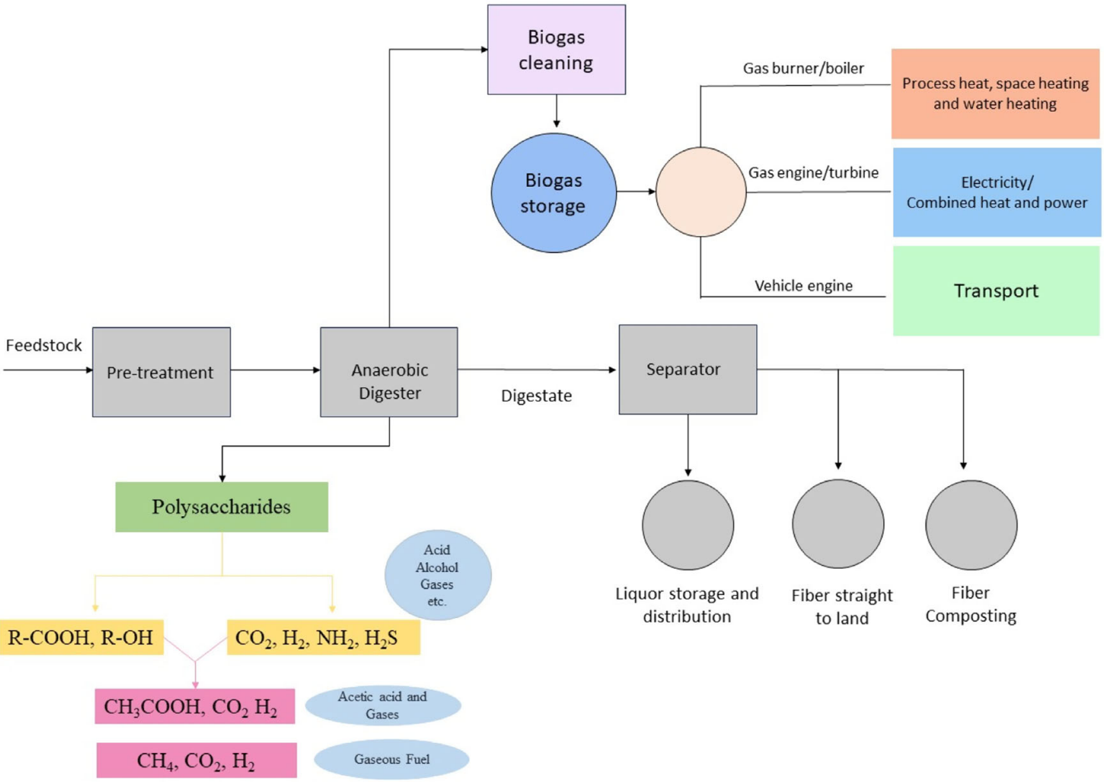

Figure 4. Process of energy production through anaerobic digester.[79,238]

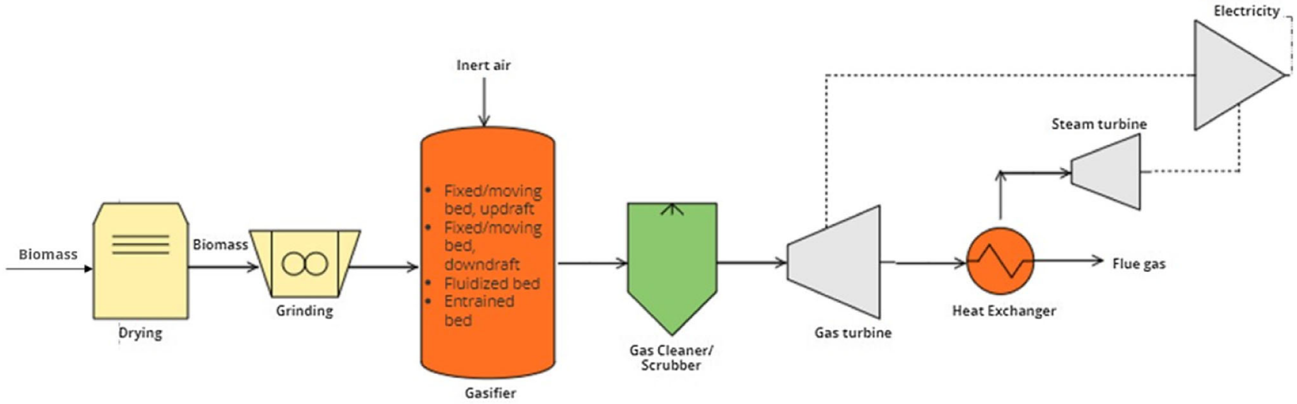

Figure 5. Advantages and Disadvantages of Gasifiers.[48,114]

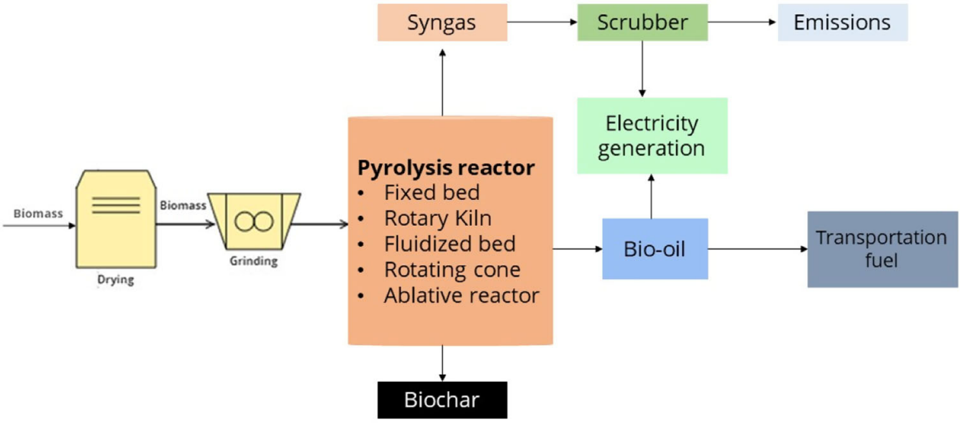

Figure 6. General depiction of electricity production.[48,239]

Liquefaction: The slowdown of the reactions has been observed after the addition of solvent as it reduces the undesirable condensation reactions that are required for the formation of char. The catalysts are involved in the reduction of the reaction temperature, improve kinetics, and enhance the yield of bio-oil.[140] The addition of alkali catalysts during the reaction improves oil yield and reduces charge formation, whereas acid catalysts are involved in reducing the reaction temperature and time. For the process of liquefaction, the temperature ranges between 250 and 350 °C, and the pressure changes between 5 and 20 MPa. However, the process of liquidation demands the availability of the catalyst in which different alkali metal catalysts at supplemental reactants facilitate the overall process.

5.1.2. Reaction Kinetics

Pyrolysis: The cleavage of the macro polymeric bond of demerits demands immense heat as the thermal degeneration of lignocellulose in the feedstock needs heat to be broken down into smaller fragments. When the temperature is raised to about 400 °C, the oxygen becomes unstable leading to chemical changes until they are quenched thermally.[141] There is a need to maintain the heat flux of the biomass during the transfer of heat from one particle to another which usually takes minimum time. This depicts that there is a need for a short resistance time during the reaction which is necessary to terminate the cooling of waffles and introduce cracking severity. In case of improper condensation, there is a probability of the production of smaller fragments or particles of the compounds. In certain cases, the procedure can also polymerize to large particles. The actual value of the heat transfer is debatable; however; it is observed that 600 to 100 W cm^{-2} is considered an optimum rate of heat transfer. The value depends on this applied energy to the reaction vessel, the quality and quantity of the by-product, and the time of reaction.[112]

Tahir et al.[142] demonstrated that the canola residues are suitable to be used as a biomass to convert it into biofuel via pyrolysis. This included reaction kinetics, evolved gas analysis, and thermodynamics. Different thermodynamic parameters and the measurements of kinetics depict that the conversion activation energy is below 70 wt%, and enthalpies lead to similar outcomes in terms of biomass residues. However, if thermodynamic parameters and activation energies increase from 154.3 to 400 kJ mol^{-1}, then a conversion of 65 to 80% is observed that is thermodynamically unsuitable. This is because of increased elemental carbon content, which leads to increased carbonization.

When the temperature is high, the entropic forces combine with other high activation energy and cause diminishing returns for the biorefinery. However, if the temperature is below 450 °C, the process of slow pyrolysis is used for the recovery of biofuels leading to an increased yield of ethanol, methane, and condensable bio-oil.

Kinetics of Gasification: Biomass classification involves complex overlapping steps with highly variable physical and chemical properties of biomass feedback. The thermodynamic predictions do not need the type of reactor, the time, and network of reaction. Practically, the outcomes of thermodynamics are appropriate for gasification depicting longer reaction turning because of the key role of kinetics. Practically, chemical reactions occur in a gasifier for a nighttime; therefore, the equilibrium models predicted mixed suggestions regarding the success ratio which depended on the reaction temperature and residence time. According to these predictions equilibrium models are more efficient at high temperatures because of their entrainment for the flow gasifiers in comparison to the fluidized bed systems. Lopez et al.[143] have suggested that the rise in temperature from 800 to 900 °C is efficient in reducing the time that is required for the conversion of charge to one-sixth. The impact of steam pressure was insignificant and did not show any influence on the particle size below 2 mm on the reaction rate.

Gao et al.[144] have conducted the gasification of by the implementation of carbon dioxide as the justifying agent to observe intrinsic kinetic parameters. The activation energy and reaction order were » 226–232 kJ mol^{-1} and 0.28–0.35, respectively. The pre-exponential factor was observed to be 2.38×10^5–$2.82 \times 10^5\ \text{s}^{-1}$ at the temperature of 700–900 °C. Enhancement rate constant bringing between 7.36 and 7.64 was observed when the temperature increases from 850 to 950 °C. The rate constant increased 1.48 to 1.63 times when the concentration of carbon dioxide was increased from 25 to 100%.

5.2. Feedstock Selection

5.2.1. Composition of Biomass Feedstock for Pyrolysis

Lignocellulose is considered as an efficient biomass used in pyrolysis which majorly comprises cellulose, hemicellulose, and lignin which upon decomposition at different temperatures give satisfactory outcomes due to thermometer reactions. During pyrolysis, the three components are decomposed at different times and temperatures. Hemicellulose is pyrolyzed in the beginning that is followed by cellulose and lignin. Lignin has a significant influence on cellulosic decomposition; however, it does not affect the overall process of pyrolysis. Cellulose is considered as the main source of bio-oil obtained from the biomass, whereas linen is responsible for the provision of solid residue or biochar.[112]

5.2.2. Feedstock Composition for Gasification

Biomass with low ash content is used for the production of syngas. The availability or increased concentration of ash results in slagging. Syngas is used for various purposes that are as follows. Synthesis of mixed alcohol, by Fischer–Tropsch which is based on catalytic procedure for the production of liquid fuel from syngas and coal-derived natural gas, fermentation of same gas which involves farewell biological procedure based on anaerobic microbes for the fermentation of syngas to produce alcohol and methanol synthesis.[112]

5.2.3. Feedstock for Combustion

A wide range of biomass is used according to their availability and the purpose. Lignocellulosic fibers that includes wood, nutshells, straws, and stalks are extensively used as the main source of biomass.[112]

5.2.4. Pretreatment Methods

Single Pretreatment: The subtract quality can be improved by using different pretreatment methods subscribed easily available for the enzymes facilitating the conversion to the biofuel. The following are the single pretreatments.

Physical: In physical pretreatment, the reduced particle size by the removal of lignocellulose can be efficient. It includes thermal and microwave treatments. In microwave pretreatment, the molecular collision due to dielectric polarization helps in the disruption of lignocellulosic biomass.[145] The thermal treatment occurs between the temperature of 150 and 240 °C and the pressure of up to 35 bar, leading to reduced particle size and increased surface area for enzymatic hydrolysis. It also facilitates reduced crystallinity.[146] The yield of thermally pretreated wheat straw can be enhanced by 53% by adding 180 °C.

Chemical: In chemical pretreatment, hydrolysis depends on the pH. At low pH, hemicellulose solubilizes in comparison to cellulose and lignin. Higher pH dissolved lignin, however, increases the overall cost. The commonly used agents include sodium hydroxide, along with the cheapest alkali agent, calcium hydroxide. For acidic pretreatment, dilute acids at height and bridges are used. Highly concentrated sulfuric acid, which converts crystalline cellulose into an amorphous form, is common for acid hydrolysis. Sulfuric acid reacts with cellulose, breaking hydrogen bonds and leading to amorphous cell loss, forming a gel-like consistency in acid solution.[147]

Mechanical: Mechanical pretreatment demands high force for the degradation of the components in lignocellulosic biomass. Ultrasonication and dispersal are efficient mechanical techniques. Ultrasonication follows the cavitation principle, which facilitates the implication of ultrasonic radiation. It also provides physical and chemical effects while helping in the modification of the structure. During the process, cavitation bubbles allow the disruption of cellulose and hemicellulose, leading to enzymatic hydrolysis. The dispersal pretreatment helps reduce particle size, destroys the structure, and changes its crystallinity, leading to increased surface area for anaerobic hydrolysis.

Biological: It is one of the cost-efficient treatment methods that do not demand high energy, reagents, or equipment. In this procedure, the living organisms are involved that are direct to the bracket and cleavage of the components. These microbes include a variety of bacteria and fungi that release different enzymes to degrade the biomass. However, it is important to consider the cost and environmental impacts during the build-up of microbes.

For example, different types of fungus, including white rot, brown rot, and soft fungi, can be used for the alteration of lignins as they are involved in the release of lignin peroxides, manganese peroxidase, and laccase that leads to the degradation of lignin. Other enzymes, including endocellulase and β-glucosidases, are involved in the hydrolysis of cellulose and convert it to sugars.[148] Similarly, the enzymes αarabinofuranosidases and esterases hydrolyze xylan to sugar.

5.3. Catalysts

Heterogeneous and enzymatic agents are the two catalysts having hypertension instead of homogeneous catalysts. Heterogeneous catalysts are preferred because of several properties, including their segregation and recycling, which allow efficient and easy reactions that lead to a reduction in manufacturing costs. Enzymatic agents are preferred in less extreme processing conditions, for example, cheap oil. Both of these enzymes have significant contributions toward the development and processing of biodiesel.[138] The typical catalysts that are used for gasification are usually active metals and provide support. For example, nickel was used in methanation. Even after 100 years of its discovery, it is still preferred because of its high activity and sea activity along with produce, making it one of the primary choices for commercial-scale bio-methane production. Ru is another important catalyst that is extensively used for methanation; however, its increased cost, which is almost 120 times that of nickel, restricts its large-scale commercial application. Other catalysts used for methanation include Co, Fe, and Mo. The choice of support for active metals depends on the choice of the catalyst. Metal oxides (Al_2O_3, SiO_2, TiO_2) having a lot of surface areas are responsible for making the primary choices for the supports.[106]

Zeolite is considered a complex and three-dimensional porous structure having different elemental compositions, which are used for the upgradation of paralysis bio-oils. Zeolites exhibit catalytic activity exceeding up to 50% of their volume. Zeolites are involved in the production of aromatic atmospheric pressure without hydrogen. The final product obtained usually has a low heating value because of its low hydrogen–carbon ratio and high oxygen–carbon ratio in comparison to hydrodeoxygenated oils. In the presence of nitrogen gas, catalytic tracking is conducted, which is necessary to stabilize the product. Amorphous silica alumina (ASA) is also used for oligomerization.[130]

5.4. Sustainability

Biofuels have emerged as sustainable and renewable energy sources due to their potential to reduce pollution, which mainly comprises increased levels of greenhouse gasses, especially carbon dioxide.[34] The increased use of biofuels promotes a carbon-neutral path as waves of carbon dioxide during their production from their environment. Sustainability has a significant influence on the resources in their long-term use. There are several factors that can affect sustainability, which may include energy return on investment (EROI) and efficiency in resource use. The EROI for fossil fuels is 20, while for biofuels, it is five, which makes biofuels closer to the needed EROI, providing an efficient energy source to fulfil energy demands. A significant limiting factor is the high energy demand, which requires the production of energy at a large scale, leading to the large-scale conversion of biomass into biofuel. This may lead to an increase in the utility of water and an increase in the collection, extraction, and separation of raw materials by implementing different techniques and methods. Despite these limitations, biofuels are considered to be eco-friendly because of their low impact. However, their large-scale implementation is limited by several factors which require intensive research and study.[149,150]

All types of biofuels cannot be categorized as sustainable. For example, the biofuel generated from edible food crops is not acceptable due to its competition with the food shortage. Similarly, the use of oil seed crops, including palm and canola, for biofuel generation as a feedstock is not acceptable due to their use as a food crop. The main criterion for sustainable biofuel generation is that the sources used as feedstock do not compete with food or any other basic requirement. Therefore, the preferences are more diverted toward the use of nonedible food as a potential feedstock, which serves dual purposes.[151,152]

The second generation of biofuel production is an energy-intensive process. However, microwave reactors facilitate several chemical processes, which reduce energy consumption and the length of the reaction.[5] Several factors, including the use of land, probability of disease, and transportation of lignocellulosic biomass, are responsible for determining the price of second-generation fuel. Biofuels are majorly criticized for their economic and energy-intensive approach, which can be mitigated only through their large-scale production.[153–156]

6. Power Production from Biofuels

6.1. Electricity Generation

The use of biomass for electricity goes through different steps and stages.[157] The process depends on different physical characteristics along with the chemical composition of the solid by a fuel that is being used for the conversion to electricity. These characteristics and properties of the fuels are important, especially in terms of biomass combustion. For example, the heating value, which is known as the amount of heat released during oxidation, is important as this heat is used to stay in the water in the flue gas. There is a variation in the gross calorific value (GCV) of biomass, mainly lignocellulosic biomass. The variation in GCV is in a small bandwidth, around 18.5 MJ kg^{-1}.[158] Along with that, the water or the moisture content varies according to the season of the year and the harvesting time. The moisture of the biomass depends on the weight of water in the lignocellulosic biomass, which is usually expressed as the weight of the oven-dry biomass. The water content of the biomass differs between 10% and 50%. The ash content of the biomass fuel is observed to be 0.5%. However, the ash content is affected by de-ashing and combustion technology.[159] The transportation and storage of the ash are also dependent on the ash content of the fuel. Low-content fuel is considered better and optimum for thermal utilization in comparison to high-content fuel. The reduced levels of low fuel content are facilitated by de-ashing and its utilization and disposal. Fuels with higher ash content are involved in increased estimation, which affects the heat exchanger design, cleaning system, and dust precipitation technology.[160,161] The increase in the process temperature reserves in the melting of ash, solid deposition, loss of efficiency, and breakdown of the plant require high maintenance. Therefore, the sources and the fuse having low content are preferred.

6.1.1. Combustion-Based Power Plants

Almost all types of solid biomass can be used when it comes to the combustion of biomass for electricity generation. A similar strategy is applied for the plant residues, where almost all types of plant material in the form of residues after harvesting are collected. After the collection of the plant-based residual biomass, it is transported to its location, where it is subjected to a pretreatment facility or the combustion plant. After combusting, the residual heat is generated, which is transferred to run the turbines or engines, which ultimately produce and generate electricity. The efficient use of biomass with the help of the combustion process includes the combination of electricity and heat in parallel, which leads to combined heat and power plants (CHP). According to an estimation, the overall MSW combustion plants have the capacity to consume about 67% of collected MSW adding to about 3% towards electricity.[162,163]

Energy Conversion Technology: The following energy conversion phases take place in a typical facility used for the combustion of biomass to generate electricity. 1) Conversion from chemical to thermal energy; 2) Conversion from thermal to mechanical energy; 3) Conversion from mechanical to electrical energy

Biomass Preprocessing: Before the arrival to the combustion site, the biomass fuel is preprocessed and becomes ready to get burnt. The treatment is required for various purposes that may include homogenization for improved handling and can be fed directly to the combustion chamber for better combustion. preprocessing is also required to reduce the same purity which enhances the combustion quality. All these steps ensure the improved efficiency of the biomass to avoid any technical issues or mishaps and also improve environmental impacts. The steps are also necessary to lower the investment cost along with the maintenance of the power plant.[164]

Storage Facilities: Different types of storage facilities can be used to store biofuels that may include ground storage or in buildings. Both types of facilities are available in the electricity generation plants; therefore, the biofuels consisting of food or wood chips are often directly stored on the ground. However, the ground storage facilities do not use any protection devices to protect the biomass from snow, rain, or any other environmental change. On the other hand, on-plant storage facilities reduce the transportation cost and save time.[165]

Conversion of Chemical Energy into Thermal Energy: In biomass to electricity plants, the combustion facilitates the conversion of chemical energy to thermal energy. These reactions usually take place in boilers, which are mostly a combination of a steam generator and a combustion device. The conversion of solid biomass into gaseous or liquid energy carriers can be burnt in the boiler. However, in the majority of the scenarios, such carriers are burnt in other devices, which can be either internal combustion engines (ICEs) or combustion chambers of gas turbines.[166] Combustion is explained as deoxidation of the fuel, which is an exothermic chemical reaction involving any type of fuel or the oxidant releasing heat. This release of heat leads to the light production producing a glow or a flame, which can be explained by the sum formula. Biomass consists of carbon, oxygen, and hydrogen, which reacts with oxygen to produce carbon dioxide and water.[167]

$$\mathrm{C_nH_mO_p} + \left(n + \frac{\mathrm{m}}{4} - \frac{\mathrm{p}}{2}\right)\mathrm{O_2} \rightarrow n\mathrm{CO_2} + \frac{\mathrm{m}}{2}\mathrm{H_2O} \tag{2}$$

The following is the categorization of combustion process, which includes drying, pyrolytic decomposition, gasification, and complete oxidation. During the drying phase, the moisture content available in the biofuel evaporates at temperatures less than 150 °C. Pyrolytic decomposition is regarded as thermal degradation, which occurs at a temperature between 150 and 500 °C without any oxidizing agent with zero excess air oxidation.[168] Gasification is considered the conversion of solids, which in the majority of cases is which are coal and the remains of the wire after pyrolytic decomposition in two gaseous fuels. This is an endothermic process that occurs in the presence of an oxidizing agent. The excessive coefficient lies between zero and one, which is reserved for partial oxidation.[169] For gasification, the temperature range usually lies between 400 and 1000 °C. At this stage, different products are obtained, among which combustible product gasses have traces and components of carbon monoxide, carbon dioxide, hydrogen, methane, and water. The last step in the combustion process is oxidation, which is the process of complete oxidation.

Combustion efficiency explains the overall efficiency of the combustion process, which is also described as the ratio of heat energy produced during the combustion and the heating value of fuel. Incomplete oxidation results in losses, which can be due to unoxidized components. Currently, modern combustion processes or CHPs have improved their efficiency to more than 95%. The performance is not expressed in terms of efficiency; however, it is controlled by the analysis of ash, which explains unburned matter and flue gas.[170]

Thermal Cycle: The organic Rankine cycle (ORC) is a closed cycle that is used in biomass combustion facilities which is like Rankine cycle. The only difference is the use of organic fluid instead of water having a low-boiling temperature.[171] This allows the operation to be conducted at relatively low temperatures ranging between 90 and 150 °C making the cycle more efficient to be used to generate electricity from geothermal energy. In the biomass sector, usually ORC processes are added after the Clausius Rankine cycle in order to utilize residual heat at low temperatures for electricity generation. The thermal efficiency of the ORC is less in comparison to the Clausius Rankine process which lies between 12% and 17%. The reason for lower efficiency can be the low temperature of the driving heat source.[172]

Reactors: The boilers are commonly used to carry out the combustion procedures to produce electricity from biomass. Different types of combustors including fixed bed, fluidized bed, and pulverized fuel combustors are being used. These combustors are commonly used for burning the biomass from which thermal heat is generated, which is used to heat the water in the pipes. After preheating, the water is heated until its evaporation point. Biomass boilers or combustors are energy efficient, and their energy efficiency is associated with net calorific value.[173]

Conversion from Thermal to Mechanical Energy: Different devices are used for the conversion of thermal energy into mechanical energy and are generally divided on the basis of turbine type (steam turbines and engine types (steam engines and Stirling engines). Steam turbine is most commonly used in the process of the conversion of biomass to electricity.[167]

Conversion from Mechanical to Electrical Energy: The generator is used to convert mechanical energy into electrical energy with the help of the basic conversion principle of electromagnetic induction. A variety of generators are used in different processes; however, in thermal power plants, synchronous single-fed generators are used to convert biomass to electricity. Other generators include asynchronous or induction single-fed generators, doubly-fed generators, or brushless wound rotor doubly fed generators.[174] The voltage levels for the biomass combustion plants of 20 MW are up to 400 V. Several losses can occur in different forms including heat, wire resistance, and mechanical losses in the bearings of rotors. The efficiency of modern synchronous generators is between 96% and 98%.[172]

6.1.2. Gasification-Based Power Plants

The process of gasification involves different steps, for example, drying, devolatilization, and gasification of the remaining char. The gasification of the remaining charge is an endothermic reaction for which the heat is supplied to continue the process.[175] The design of the gasification reactors also needs consideration. About 80% of a total weight of the biomass is released during the process of devolatilization and the remaining 20% is char. During pyrolysis, after devolatilization, the reaction is ceased with three available products, i.e., char, condensable volatiles, and gasses. Such a type of pyrolysis is well known as a thermal conversion process but also acts as a pretreatment for gasification. Other types include the mixture of steam and oxygen, which is used to obtain nitrogen-free producer gas in order to apply it at a large scale.

6.2. Cogeneration and Combined Heat and Power (CHP)

Combined heat and power generation is normally applied if there is a need and requirement for high energy utilization. The increased electrical output is equivalent to the improved economic performance of a plant. The processes that use gasification results in improved electrical output and high energy utilization. For CHP, the producer gas is fed in gas engines and turbines.[176] These types of plants consist of gasification, gas cooling, gas cleaning including tar and particle separation, and use of the clean and cold gas in gas engines. From these plants, the overall electrical efficiency ranging between 20% and 30% and overall energy utilization degrees between 75% and 80% can be achieved.

In current scenarios, the majority of the installations apply cold gas or wet gas cleaning. Fixed bed or fluidized bed gasifiers are used for the generation of producer gas in the presence of atmospheric air or steam gasification. On the discharge from the gasifier, the temperatures are dropped from 180 to 200 °C to cool down the producer gas which results in the selection of cooler construction and cooler operation. This is necessary to avoid tar condensation that can result in plugging of the pipes and heat exchangers.[172] This temperature allows the separation of the particles from the producer gas with the use of fabric filters or electrostatic precipitators. In some situations, the fabric cloth is protected from that dust or tar mixture with the help of precoated materials. Dust to tar ratio is also an important parameter for smooth continuation of the operations that requires a certain ratio of the heat exchanger or tubes clean. This ratio can be controlled by the recycling of ash and feeding it back to the gasifier with the fuel. The tar components can be removed by scrubbing the producer gas. There have been advances in the cleaning procedures and processes in the last decade where different traditional cleaning tools and chemicals have been replaced by the modern one. For example, water scrubbers have been replaced by solvent scrubbers. The catalytic cracking of tar is followed by the procedure of cooling down without any issues related to tar condensation. In a conventional particle separation system, the particles will be removed at a low temperature making the energy in the flu gas to be utilize the game to fulfill heat-demanding processes.[172] An example of CHP is given in **Figure 7** for sustainable production of biomethane **Figure 8** and **9**.

7. Biofuels for Transportation

7.1. Bioethanol

Biomass-based ethanol is considered one of the main candidates for the adoption of a sustainable choice of fuel, especially for the transportation sector. The increased use of ethanol as a potential biofuel, especially E85 for mid-sized passenger vehicles, can equal about 32% of global gasoline consumption. These alternative choices can help us reduce the use of nonrenewable resources, especially fossil fuels, which will not only lead us towards the conservation of these natural resources but also help in reducing the drastic effects of climate change.[177]

The shift toward the utilization of renewable energy sources can help in reducing the concentration of carbon dioxide in the atmosphere. This will also help us reduce our reliance on fossil fuels for the generation of energy and electricity. The dependence and increased use of bioethanol can lead toward the efficient utilization of carbon dioxide as similar carbonate can be consumed by the crops during the development of stages that serve as potential feedstock. Bioethanol has the potential to reduce the amount of highly obtained additives in gasoline. Therefore, the fuel spills containing ethanol are considered to be biodegradable as they are involved in the revolution of the substances to nontoxic levels.[178] For example, the blend of 10% bioethanol and gasoline can result in the production of E10. Additional uses of bioethanol include the synthesis of ethyl tertiary butyl ether, which is usually mixed with gasoline to enhance the oxygen content and reduce pollution. However, biotechnology comes with a few disadvantages; the significance includes the huge intake of large quantities of energy and increased land utilization. Other drawbacks include the ferrous deterioration of the fuel containing more than 10% ethanol content until it is prepared to be used as E85. These conditions can lead to a negative

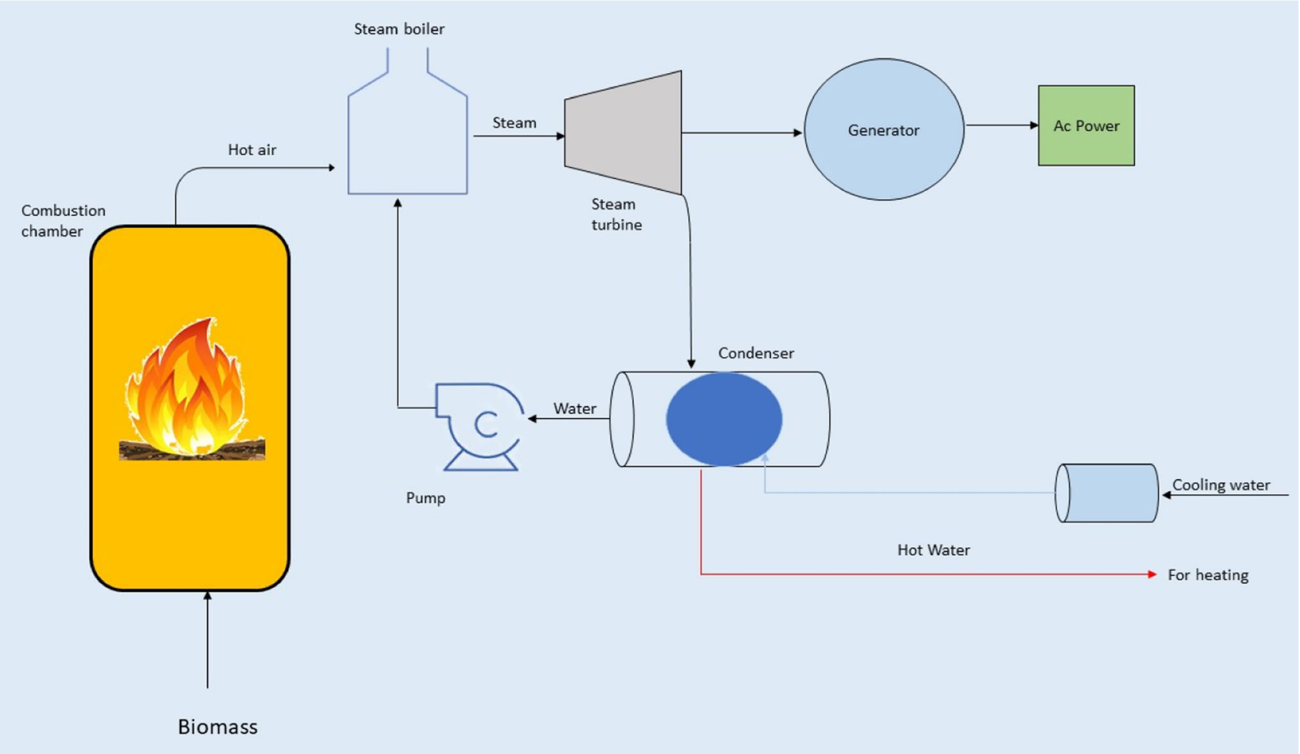

Figure 7. Process flow diagram of combustion of biomass to electricity production.[172,240]

impact on the electric fuel pump as these factors accelerate internal deterioration.[179]

7.2. Biodiesel

Biodiesel is often used as a blank with regular diesel fuel and can be used in different diesel vehicles without any modifications to the engine. These properties of biodiesel make it suitable for use with conventional diesel vehicles. B20 is one of the most common biodiesel blends, having 20% diesel and 80% petroleum diesel. B20 is famous because of its cost efficiency, improved performance in cold weather, material compatibility, and capacity to act as a solvent. The engines that can be operated on v20 include similar fuel consumption, horsepower, and torque to run the Engines on petroleum diesel. b20 is also important because it has a higher seating number, which is regarded as the measure of the ignition value of diesel fuel and higher lubricity, the capacity to lubricate fuel pumps, fuels, and injectors. The efficiency of biodiesel can be measured by the variability of its energy, which is less than 8% per gallon.[180]

7.3. Biogas

The growing market for renewable energy can greatly benefit from biogas because of its protection and contribution to the global energy demand. According to an estimation, the consumption of biogas will double over the next several years from 14.5 to 29.5 GW. The combustion or burning of fossil fuels for energy purposes has various drawbacks, among which the generation and release of greenhouse gasses in the atmosphere is a significant environmental concern that is demanding renewable energy sources for power generation. Purified biogas has various potential uses, including the production of heat and staying to be used for domestic and business processes, the injection of the gas into natural gas grids, and fueling automobiles.[181] Sweden is facing an increase in the demand for biogas to be used as a fuel for vehicles. Other than Sweden, various countries, including Germany, Austria, and France, are also making progress toward the production and utilization of biogas as a potential fuel for automobiles.[182]

In order to be competitive in the market, biogas is expected to be at least 20 to 30% less expensive in comparison to bioethanol and biodiesel. The production and utilization of biogas are still in their early phases; therefore, there are certain barriers to their adoption and spread across the globe. The significant barrier is the limited number of gas stations, which serves as a potential obstacle to the use of biogas, leading to an increased infrastructure cost. The use of the mixture of liquid in the kitchen acts as a potential field stroke contributes toward the cost of the production of commercial biogas, which may range from USD 0.45 to USD 0.55 per liter. This commercial value is also dependent on the utilization of the technology, which is used to develop and produce biogas. Therefore, upon drawing the comparison between the economic value of the production systems of bioethanol and biodiesel, the production value of biogas and its utilization as a potential fuel is limited.[183] Despite the availability of government support in the form of subsidies, the biogas generation system, which is dependent on the organic waste in liquid manure, can be considered more competitive than wheat-based ethanol production.

7.4. Hydrogen from Biofuels

Hydrogen depicts the highest energy content per unit weight of known fuel leading to high energy density in comparison to other biofuels including methanol, ethanol, and methane. These characteristics make it a potential fuel to be used for direct combustion in ICE or as a fuel for a fuel cell. Moreover, hydrogen gas is also considered to be an efficient agent to be used as environment-friendly fuel to generate energy.[184]

7.5. Challenges of Biohydrogen Production

Hydrogen is considered as one of the simplest elements in the world playing an important role as an energy carrier in the energy systems. Hydrogen has emerged as a potential renewable and low-carbon energy source named as green hydrogen. Green hydrogen has the capacity to limit less carbon in comparison to the hydrogen obtained from the steam reforming of natural gas. Green hydrogen is being implemented in several industries, and it is considered as a significant energy source for transportation, i.e., green energy product.[185] The biohydrogen production with the help of biological methods including dark fermentation has the capacity to produce hydrogen without light along with photo fermentation and where the photosensitive bacteria have the capacity to use a wide range of spectral energy. The energy conversion efficiency is low for dark and photo fermentation methods achieving 4.3 and 5.11% efficiency, respectively.[186,187] One of the major challenges includes the limited rate and efficiency of biohydrogen protection along with an increased cost of raw feedstock. Overall, hydrogen production may include different sources including renewable electricity, nuclear power, and lignocellulosic biomass. Currently, the sector is dominated with the use of fossil fuels. Therefore, biohydrogen

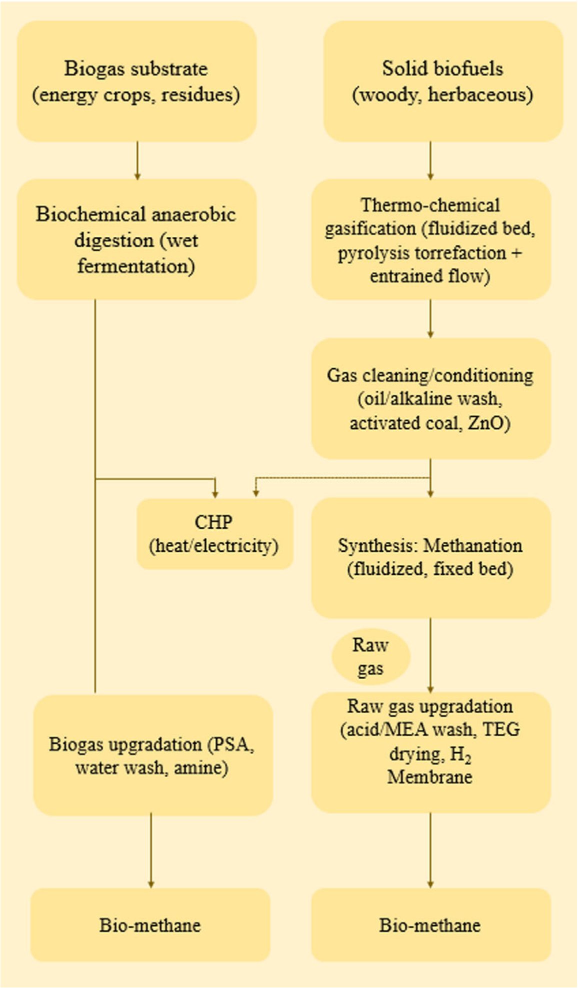

Figure 8. Biomethane from anaerobic processes combined with gasification.[172]

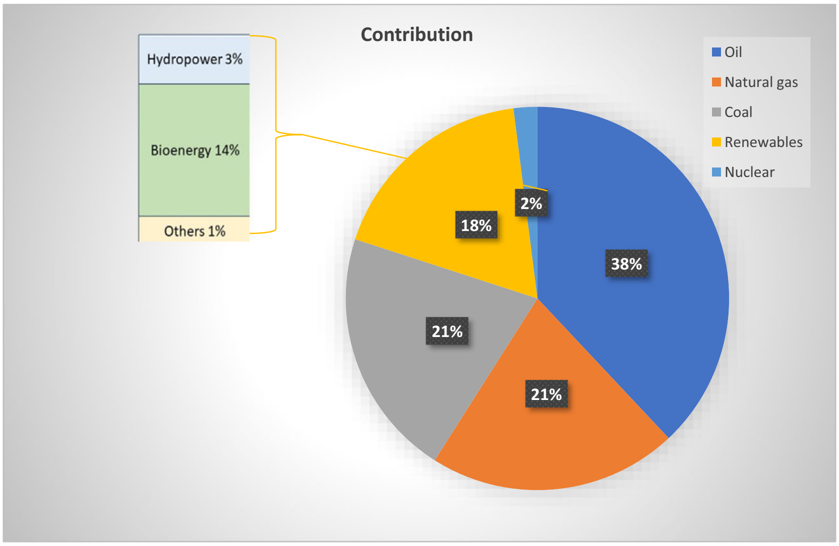

Figure 9. Fuel contribution to total energy consumption.[110]

production faces various challenges including barriers in fermentation due to increasing cost of raw material, lack of suitable industrial support for efficient production, and lack of appropriate design to continue and improve its production at a large scale.[188] On the other hand, hydrogen production occurs through anaerobic digestion, fermentation, or gasification. Hydrogen production is based on different sources, i.e., natural gas and coal; however, during this process, huge amounts of CO_2 are released into the atmosphere. Advanced technological systems have resulted in the production of both low and high-carbon hydrogen, which may include the development of solar photovoltaic and wind renewable energy technologies. The production of hydrogen from natural gas is one of the cheapest methods across the world with an average cost of 1$ kg^{-1}, while the electrolysis can cost up to 10–40 \$ MWh^{-1}.[189]

8. Environmental and Economic Assessment

8.1. Environmental Impact

8.1.1. Greenhouse Gas Emissions

Low energy inputs are dissipated and expected from biofuel production because it is considered to be a sustainable approach from the very first step of growing crops to the processing until its production. The biofuels are also considered to have better performance in terms of providing an energy balance to the engine while releasing very few greenhouse gasses in the atmosphere.[190]

Different studies regarding the effect of the environment on the synthesis of methanol have been conducted that are directed toward the use of different types of feedstocks including corn, sugarcane bagasse, and food waste. The amount of the release of greenhouse gasses of methanol varies from 20/9 to 45.5 kg CO2/GJ. This amount is also dependent on the raw material used to produce biofuel. It has been observed that the methanol and ethanol produced from corn have less effect on the environment. The lignocellulosic biomass (LCB) including rice husk, barley, pinewood, or coffee pulp is considered to be beneficial for the environment in terms of ethanol production. It was observed that the ratio of greenhouse gas emissions is lower in the fuels produced by LCB in comparison to conventional fossil fuels.[191]

The worldwide aviation sector aims to reduce emissions by 50% by 2050 by introducing aircraft designs, streamlining air traffic control, and encouraging the use of biomass-based fuels at commercial levels. The life cycle missions of renewable fuel production from sugarcane bagasse are 21 g CO_2 eq./MJ in comparison to the emission range of fossil fuels which is observed to be 8095 g CO2 eq./MJ. The production of biogas is more energy efficient in comparison to the combination of biogas and bioethanol production. It has been observed that the biofuel generated from the biomass is still in its early phases and requires more research work to become efficient in terms of cost and energy utilization.[190]

8.1.2. Air and Water Quality

The transesterification process uses an acid/base catalyst and methanol as a reactant. The use of these compounds increases acidification and human toxicity. Hydrogen is used in the hydrotreatment, and the reaction is conducted at high temperatures and pressures. The carbon dioxide and carbon monoxide are collected as by-products. One of the major factors of concern is the contribution of the transportation sector to the increased emissions of GHG, which are often transported from the side of production to the processing units.[190]

The treatment stage of wood biomass is considered to have a greater influence on the potential for land usage. Land use, human carcinogenic toxicity, and global warming are some of the significant factors that affect the production of Na_2CO_3 for pretreatment. The method of manufacturing also causes certain effects on the environment, which may introduce acidification, eutrophication, global warming, photochemical oxidation demands, and increased probability of marine and human ecotoxicity due to the increase in the use of chemical pretreatment processes. The reduction in greenhouse gases is one of the significant roles in stabilizing the climate and reducing climate change and its impacts. The production and utilization of fire fields such as ethanol, along with the use of these as fuel for electricity generation, is an eco-friendly approach serving dual purposes, i.e., fulfilling energy and electricity demands and conserving the environment.[191] Meanwhile, food waste valorization into biofuel is efficient due to its rich content of nutrients that prefer microbial growth, which is necessary for bioconversion processes. Currently, there is a lack of propagated management of food waste because of the increased probability of its hazards to the environment due to the release of toxic components that can run off in nearby water bodies and pollute them. Appropriate management of the waste and the recycling of food waste can not only prevent the above-mentioned situations but also help the energy and transport sector.

8.2. Life Cycle Assessment of Bioenergy Produced from Lignocellulosic Biomass

Bioenergy has emerged as a significant alternative to fossil fuels because of its efficiency and potential to limit and reduce greenhouse gas emissions. It is considered as a renewable energy source that utilizes carbon as the main supply making it an essential element of renewable energy mix. Atmospheric carbon dioxide can serve as the main element and source of the carbon used in bioenergy, which is generally absorbed during the process of photosynthesis by the plants. Bioenergy can serve as carbon emission neutral leading to negative when the captured carbon is combined with the stored carbon. The potential to reduce greenhouse gas and the availability of biomass are considered important factors for determining the development of bio energy chains during the transition towards low carbon.[189]

Life cycle assessment (LCA) is considered as an evaluation that aims to measure environmental effects during the production of biofuels.[108,192] LCA focuses on the provision of comprehensive insights toward human activities and the environment, which is essential for successful strategic planning. Renewable bioenergy synthesis is a significant and intriguing source for the production of low-carbon energy, which is currently the need of time to reduce environmental toxicity. Efficient use of lignocellulosic biomass for bioenergy production is an optimum alternative to achieve a carbon zero footprint. The growth stage of the plants from their germination till the conversion of the obtained biomass into biofuels and their utilization as potential energy sources is considered as life cycle assessment of biofuel production. One of the significant potentials of the biofuels obtained from lignocellulose derived materials is eco-friendly nature which is currently the necessity of the time to reduce GHG emissions and achieve zero carbon footprint.[193]

Among different physicochemical treatments based on steam, liquid hot water, organosolvent and dilute acid, and liquid hot water are promising when used as pressurized deionized water for the reduction of GHG leading to increased sugar yield for fermentative production of biofuels. According to the research, methanol has a limited impact on eutrophication, acidity, and global warming. However, the inclusion of NaOH demonstrated an adverse impact on the ecosystem. The application of combined methods including the combination of mechanical, chemical, and enzyme-mediated treatments can efficiently reduce energy consumption and lower the generation of waste in comparison to the primitive processes which mainly relied on chemicals.[194]

According to Prasad et al. (2015), 385 kg of CO_2 is being produced. The overall production of electricity through dilute acid pretreatment produces about 54.6 kg of CO_2 is produced, while the line treatment that involves the alternation of living structure and swelling of cellulose surface leads to 85% CO_2 emissions. The process for the implementation of a water bath is usually maintained at 60 °C for 12 h. The huge difference is due to the difference in operation time which is combined with increased temperature in comparison with other treatments. Irrespective of the choice of the treatment (i.e., stream expulsion or dilute acid), the produced electricity is the major shareholder toward CO_2 emissions accounting for 88% and 99%, respectively. This is one of the significant representations of the efforts being made to reduce CO_2 emissions by adopting green and renewable energy sources during the process of production.[132]

Soleymani Angili 2023 et al. focused on an early-stage LCA for catalytic intermediate pyrolysis for the valorization of rapid neem with the help of ZSM-5 and zeolite Y catalysts. Catalysts are important and play a significant role in the emissions from the products; therefore, catalyst cars are considered important for LCAs. The application of ZSM-5 to pyrolysis increases Burden in nonrenewable energy, respiratory in organic and ecotoxicity by 140.88 MJ 8.83×10^{-3} kg PM2.5 eq. and 125.63 kg TEG soil, respectively. The natural gas and relevant chemicals including phosphorus trichloride, sodium hydroxide, and sodium silicate can be used as a driving factor for the manufacturing of ZMS-5.[195]

According to Isabel Quispe et al. (2019), the outcomes of a study based on the rice husk depicted that the environmental effects of obtaining 1 MJ of rice husk are less than 1 MJ from coal including global warming acidification and eutrophication. In the case of water depletion, the environmental impacts are 98% better with the use of coal in comparison to the rice husk. Other potentials include global warming potential to upto 1.96 kg CO_2 eq, water depletion potential equal to 2.3 m^3, eutrophication = 12.5 g PO_4 eq, and acidification potential = 50.3 g SO_2 eq. Similarly, for coal systems, the potential of global warming equals to 61 kgCO_2 eq, water depletion 23 m^3, eutrophication potential 63 g, PO_4, and acidification potential 462 g SO_2.[196]

Santoyo-Castelazo et al. (2023) conducted the study by considering cradle-to-grave perspective for the quantification of major environmental concerns. Aspen Plus v11 software was used for the simulation of bioethanol production with a yield of 0.42 L bioethanol per kg of bagasse for the production of 100 L h^{-1} with the purity of 98.6%. The biofuel used in the vehicle and production stages have different highest contributions which in total can be quantified as approximately 26.7 kg CO_2 eq/L. after the implementation of cradle-to-gate perspective the amount was reduced to approximately 8.4 kg CO_2 eq/L.[197]

Winjobi et al. (2016) conducted the LCA two bio-oil obtained from woody biomass with the help of two pathways including one-step pathway of fast pyrolysis and two-step pathways of torrefaction prior to fast pyrolysis. Both have a collective potential of about 6 g CO_2 equivalent per MJ of bio-oil in comparison to 39 g CO_2 equivalent per MJ of bio-oil for one-step pathway with the help of energy allocation-based analysis. The use of a two-step pathway against the one-step password has the capacity to save up to 80% GHG in comparison to heavy fuel oil (HFO). The increase in the temperature of torrefaction prior to fast pyrolysis is effective in reducing environmental burnt burdens associated with global warming. The utilization of renewable energy in the form of char burning or torrefaction of low-quality liquid fuel leads to satisfying heat energy requirements while reducing GHG emissions in comparison to natural gas use for process heat.[198]

8.3. Economic Viability

The utilization of cellulosic feedstock, mainly consisting of waste and leftover material that can be used as a potential feedstock for biofuel production, can be considered an economically viable option for the energy sector. The majority of the waste materials that serve as the potential source usually do not cost much; however, the cost of the technology that is required for its preprocessing and conversion of these materials into biofuels can be higher, adding to the cost of the process and the energy produced.[199] Treatment has become a necessary measure prior to hydrolysis, especially for second-generation biofuels because of the strong crystalline structure of cellulose.[149,200] The overall cost of the feedstock accounts for between 35% and 50% of the entire production cost of second-generation bioethanol. However, in order to produce large-scale commercial second-generation biofuels, it is necessary to cogenerate chemicals and biofuels.

Third-generation biofuels are not being commercially produced due to several biological and technical issues leading to the imitation of the scale-up of personalities, making them incompatible with the market. Microbial growth and development contribute majorly to the overall cost of the procedure because the day watering and harvesting accounts for 20 to 30% of the production cost. Water is also necessary for microbial growth, which acts as a medium to provide nutrients to the microbes, along with maintaining temperature and other conditions.[201] This requirement of water for microbial growth can compete with human water needs, leading to the generation of controversy. Although the concept of recycling water is suggested, there are increased chances of competition, which can add to the cost of the procedure. Another argument is generated regarding the utilization of bioproducts to mitigate the cost of microbial growth.[201,202] For this purpose, the utilization of lipid content is emphasized; however, the limit content only contributes to 30% of the total harvested biomass. Therefore, the procedure requires more economic viability to make it a cost-efficient and commercially available process for power generation.

8.3.1. Techno-Economics of Sustainable Bioenergy Production

Lignocellulosic biomass is considered less expensive and does not affect the food supply as it is mainly made up of food waste material.[16] The butanol derived from starch is being sold for \$1.41 per kg, while for wheat stover, it is \$1.25, and for corn stover, it is \$1.10/kg. Therefore, the feedstock reaction has a significant influence over the determination of the price. The yield and the trend of the resources that are used for the production of lignocellulosic biomass can vary in quality and quantity.[203] The cost and the technology used for the conversion of lignocellulosic biomass to the fuel outweigh the cost of the final product (biofuel). However, the current cost of technology is higher than the overall production of the biofuels in comparison to the first-generation biofuels, which make the second-generation biofuels economically unfeasible. Another important barrier is the storage of the biofuel field stock. The majority of the feedstock is high in water moisture content, which affects the cost of supply as increased moisture content increases the volume and the number of vehicles used for transportation.[204]

The location of the bio refinery, along with its proximity to the source of the stock, is also a major and leading concern. The majority of resources (feedstock) are at a distance, which requires transportation, adding to its production cost. Transportation contributes to about 10 to 25% of the total cost, and in certain conditions, it can go up to 65%, making the generation of biofuel more expensive. Moreover, the pretreatment processes cannot be overlooked in terms of the addition of cost. All of these factors together increase the overall price of buyer fuel in comparison to fossil fuels, making it a nonviable option.[205]

Feedstock: The estimated cost of lignocellulosic biomass (LCB) Is between \$22 and 85/t. The cost depends on the category and accessibility of LCB. A constructive relation can be observed between the biomass and biofuel cost. With an increase in the related factors including labor, fertilizer inflation, and transportation costs, the overall cost of biomass also increases. Jung and Choi (2018) conducting the study use concentrated acid preparation of LCB in order to produce but an all and conduct a technical economic analysis. The analysis is based on the plant capacity of 40 000 t/y with the feed cost of 60 \$/t. There has been a decrease in the price of butanol from 2668 to 2139 \$/t with double the capacity of the plant. With the reduction in production cost by 55%, commercial feasibility can be achieved[206]

Pretreatment Cost: Acid and alkali treatment results in the yield of 56.1- and 48.9-MM gallons per year. The techno economic analysis for acid and alkali treatment indicates the cost of 25 \$MM and 22.3 \$MM with the capital cost of 208.6 and 163.6 \$MM.[191] The operational cost depends on energy production and integration of processes. In case of chemical-free treatment, the increase in the chemical cost is usually compensated with the increased yield of the product. Unique material is required for the storage of chemicals along with their transportation that adds to its increased cost. The general operational cost of pretreatment involving chemicals is usually high; however, it can be reduced by the implementation of different technology involved in the chemical retrieval.[207]

Production Cost: Operating and capital cost constitutes the production cost, whereas the investment cost is considered independent of yield of the biomass where this cost can largely depend on the degree of pretreatment. In order to produce biogas, different parameters have a significant impact on the operational and implementation cost. These factors were analyzed and studied by ref. [191]. High temperature and atmospheric pressure can be maintained for the gasifiers. The production cost of the biochemicals including methanol, ethanol, and dimethylether can vary in accordance to their availability and the conditions they are exposed to. The methanol production through gasification leads to minimum selling unit price from 92 to 117 $\$\,kg^{-1}$.[208] For example, methanol production costs produced from atmospheric and pressurized gasifiers within the same capacity at 2000 dry tons per day are \$0.2 and $\$0.45\,kg^{-1}$.[209] The capital cost of pressurized equipment is higher in comparison to atmospheric equipment which is the main cause of the price difference. The pressurized gasification system can be four times costlier in comparison to the atmospheric system for a power plant having the capacity of 20 MWe. The majority of the feedback used for gasification includes woody and agriculture biomass along with the energy crops. Biomass feedstock can be considered a responsible element for the determination of the economics of classification for example the use of woody biomass including forest residues whole trees for hydrogen production has a lower production cost around 1.17–1.3 $\$\,kg^{-1}$ in comparison to agriculture biomass with the overall cost of $\$1.29–1.33\,kg^{-1}$.[209]

Different types of boilers can be used for the combustion of biomass required in the power generation. With time, modern combustion techniques are being introduced which are efficiently being used due to their increased efficiency.[210] Other methods to remove environmental pollutants include the use of polymer microgels that are aimed at encapsulating different enzymes.[211] In general, pulverized coal-fired boilers dependent on biomass feedstock cofired with the coal as the capacity to give a lower cost of electricity in comparison to the fluidized bed boilers. Circulating fluidized bed boilers are usually involved in generating low-cost electricity in comparison to bubbling circulating bed boilers. Moreover, supercritical boilers are considered to have low cost of electricity compared to subcritical boilers. A solely biomass fuel power plant system has higher electricity cost than a coal power plant because of increased prices of biomass in comparison to coal leading to the effect of cost on electricity production.[209]

In comparison to co-generation plants, conventional biomass power generation systems have increased selling price in terms of break-even electricity due to increased installation cost of cogeneration plants. The use of wood biomass and coal in a supercritical pulverized coal fired boiler leads to the production of 500MVe costing to about 86.91–133.3 $\$\,MWh^{-1}$.[209] The capital costs for necessary modifications to co-fire woody biomass with the help of PC boilers range between \$250 kW and

\$1000 kW.[212] On the other hand, the use of wood even as in subcritical circulating fluidized bed boilers, the electricity production is halved, i.e., 250 MVe within the price range of 173.82–318.68 $\$\,\text{MWh}^{-1}$ with the inflation factor of 2%. The co-generation of heat with power is associated with a better economic solution.[209]

Brigagão et al. (2019) reported that in the corncob-fired Rankine cycle, the biomass combustion route is dependent on the electricity generation. In the furnace radiation zone, heat recovery is involved in generating superheated steam for the turbine. This results in an estimated net efficiency of 30.2% LHV with the ability to export 114.10 MW electricity.[213] Rhenals-Julio et al. (2023) stated that overall efficiency of Rankine cycle is 24.4%with a net specific power of about 2.790 MW kg^{-1}.[214] Fast pyrolysis of different energy crops during the production of bio-oil has an estimated cost of around 12–26 $\$\,\text{GJ}^{-1}$. Surplus char selling and electricity consumption are the significant important factors that affect the cost of bio-oils generated from pyrolysis. According to the estimation, about 18% of the generated bio-oil can be consumed if the bio-oils are to be used in diesel engines for power generation in order to generate internal electricity for pyrolysis plants. The sale of the by-product produced during the process of pyrolysis, i.e., char can be helpful in reducing the cost to up to 18%; however, this depends on the market value of char in different regions.

Wright et al. (2010) concluded that the production of naphtha and diesel from bio-oil can lower the transportation fuel cost to up to 0.56–0.82 per liters in the year 2007 with a capacity of 2000 dry tonnes per day. Diesel engine systems and fast pyrolysis can be considered suitable options for power generation. 1–20 MVe with an estimated cost of 88.78–177.56 $\$\,\text{MWh}^{-1}$ is generated with the help of pyrolysis of biomass.[215] The electricity generated is higher than the combustion system and lower than other biomass power generation systems. Diesel systems and fast pyrolysis are considered inefficient due to low energy rate of feedstock and production costs.[209] If the operations can be carried out in two or three shifts for the production of efficient biofuels, then it can lead to an increase in return of investment from 4.19 to 116.63%.[191]

8.3.2. Policy and Incentives

In Europe, cellulosic ethanol production could not attract much attention as there was a decline in the demand for biofuel due to different policies. Technical issues, increased cost, challenges associated with supplier change, and delayed commercialization of second-generation biofuel are a few of the barriers that contribute to reduced demand. The ideal locations for biofuel generation are landfills, which can be upgraded for the production of biogas or the areas that can reach the corn stover or cornstarch for ethanol production. Third-generation biofuels are facing various biological and technical issues, while first-generation biofuels are still in their experimental stages.[216] There is a need to implement rules and regulations to avoid generation of waste. One of the significant examples can be found in South Korea where the government has implemented the same "pay as you throw" to avoid or reduce the overall waste generation. In 1994, South Korea implemented this game by allowing the waste 1.3 kg per person per day. However, in the year 2014, it has been reduced to 0.95 kg per person per day. This policy has resulted in overall reduction of the waste from 97% in 1994 to 2% in 2014. Moreover, there has been increased interest in the recycling of food waste for the recovery of biofuels and other value added products which has increased up to 59% from 15.4% in the similar years.[67]

In the energy sector, the need for sustainable economic growth is not dependent on fossil-based resources. However, these are the major drivers toward economic growth. However, current environmental concerns have highlighted the need for alternatives that has introduced biofuel as a potential economy.[217] Similar to other economic sources, biofuels have the capacity to generate important social and economic benefits for rural and local economies. Significant elements of biofuels include the environmental compatibility that makes them an eco-friendly fuel and overall economic importance. Although biofuel production in OECD countries is higher than conventional fuels, however, for developing countries the first of biofuel production is close to conventional fuels. The developing countries are usually rich in raw materials that are required for biomass, reduced consumption per capita, and low labor cost.[218]

Different countries have their own policies, regulations, and standards toward the production and utilization of biofuels. The Europe framework is based on EU's laws and member state's law where the biofuels are regulated by establishing general goals to achieve the aim of maintaining environmental sustainability. A general framework is established, which is modified and implemented by member states in accordance with their own legal and administrative systems. Similarly different support schemes including the RED directive which focus is on the utilization of the minimum of 10% of the final energy consumption from renewable sources. The US framework is based on the energy policy act 2005 and energy independence and security act 2007.[218] These acts are responsible for setting renewable fuel standards making the use of biofuels essential. Different support mechanisms and schemes introduced by the US promote the use of biofuels. For example, the renewable fuel standard (RFS) necessitates use of a certain share of renewable fuel along with the conventional fuels.[219] The establishment and implementations of the standard and promotion of schemes for the use of biofuels can be considered a promising step to mitigate environmental effects of conventional source and attain sustainability.

Along with the above-mentioned issues, there is also a need to resolve social compliance with biodiesel, which is majorly connected to people's beliefs. The community cannot be forcefully made to accept biodiesel as a fuel as they might consider it unworthy to be used in their vehicles. In this regard, there is a need for the government and industries to take serious measures and efforts to encourage people to switch their fuel preferences, which can be possible through awareness campaigns. Along with social compliance, there is also a need to discover new feedstock sources that are not only cost efficient but also do not pose a threat or competition to the food industry. There is also a need to improve existing methods for biodiesel synthesis and to promote the use and efficiency of biodiesel.[138]
1) Interference of government is also important, especially for

policy making and its implementation at the national level. For this purpose, awareness campaigns and incentives can be beneficial to promote biofuel production. Following are some of the recommendations that can promote biofuels. 2) The introduction of a rural development strategy is efficient in increasing the social acceptability of biofuels. For this purpose, NGOs can be efficient and, in coordination with another institute, can launch public awareness campaigns to spread awareness and enhance the acceptance of biofuels. 3) The market value of agricultural goods varies over time, for which biofuels can act as a buffer because they can be swapped for fossil fuels. During the time of surplus production of agricultural products, the access can be used for the production of biofuels. Modifications in the global framework can contribute to the utilization and acceptance of biofuels. 4) The storage facility and supply chain are required, which can contribute to the capital cost. There is also a need to build facilities that can ensure the availability of the feedstock throughout the year. 5) The supply system of the feedstock at the commodity scale is required in order to connect the standardized infrastructure of the supply system and biorefineries.

Different biofuel strategies and policies are being implemented in different countries according to their goals for trade and commerce and policies related to environmental conservation and issues related to food security.[220] Biofuel policies are considered an efficient component of environmental policies in industrialized countries. South Korea, Japan, and China are aiming to reduce the impact of global warming by reducing their greenhouse gas emissions and air pollution levels. Along with various national benefits and advantages of the production and utilization of biofuels, it is also significant for the development of rural areas or areas generating feedstock. These benefits are integrated with each other, promoting local production. Different nations and countries have developed legislative frameworks for the establishment of sustainable development.

8.3.3. Socioeconomic Benefits of Biofuels

Production has several social economic benefits that can contribute significantly toward the development of rural areas. The important benefit includes the availability of the potential market for the biomass, increased transportation, and installation of new plants providing different employment opportunities.[221] The farmers can also have the opportunity to improve their income levels by utilizing the agriculture and forest residues as the potential biofuel feedstock. Biofuels can also add to the environmental and landscape benefits by revitalizing the degraded land through the initiation of forestation along with the utilization of excessive water for energy production. As a result, the rural areas that are the main providers of the primary sources or raw material of biofuels can have various positive implications leading toward increased rural diversification, availability of electricity supply, and employment opportunities.[218]

Biomass and its practical implications in the form of energy generation are actively contributing to upgrading the living styles of the adjacent community. It involves the associated farmers creating the supply chain to the industry from where it is processed and is actively used as an efficient form of bio energy. During the process, the areas from where the raw material is accessed are involved as it creates another employment of opportunities for the native including vulnerable communities. However, due to lack of appropriate knowledge and awareness regarding the practical and positive implications of renewable energy, there is a need to initiate campaigns to inform adjacent communities and the general public.[222]

8.4. Green Economy

Rapid economic expansion across the globe has increased the consumption of fossil fuels, which has resulted in increasing emissions which are actively contributing toward global warming. Different types of energy sources including gas, coal, and oil are the major contributors toward GHG emissions.[223] In order to mitigate the impacts of these emissions, different countries are contributing to achieve net zero by 2030 through sustainable development goals. Green energy transition (GETR) has now become a necessity for the attainment of sustainable growth while utilizing renewable alternative energy sources. GETR includes the production of clean energy with the help of different renewable sources including hydrowave, tidal, solar, wind, geothermal, and bioenergy. GETR can be challenging for developing nations due to the lack of required technology and a strong economy to support the import of technology. Economic globalization can be considered important in this regard as it facilitates imports with the help of international trade. Foreign direct investment can also contribute toward the goal of net zero by encouraging investments along with supportive and eco-friendly regulations. Direct import and export of green technology in order to promote green energy not only solve the issues of green energy but also facilitate the economy of different countries.[224] The environmental issues in economic development are complex and multifaceted with each other because the increase in economic growth leads to increased industrialization and consumption causing increased pollution and resource depletion.[225] However, this increase in economic growth is associated with uplifting different social and economic elements that are necessary to uplift the lifestyle of adjacent areas and populations.[226] However, considering current environmental issues, it has become the necessity to implement environmental protection measures along with sustainable resource management which can have a negative impact on overall economic development. The green economy revolves around the establishment of environmental regulations in policies that not only promote clean energy production and consumption practices but also create a balance towards sustainable economic growth. Saudi Arabia is actively pursuing clean energy through hydrogen production for a clean environment and economy.[227] The CO_2 level in every country varies as it depends on their industrial activity or in other terms their carbon footprint. Therefore, there is a need to implement relevant policies and strategies that not only depend on their current carbon footprint but also ensure their economic development. The implementation of legal reforms in accordance with the Paris agreement can help the countries to achieve net zero by reducing the global warming below 2 °C.[228]

9. Case Studies and Examples

In different countries, the use of agricultural residues for the production of energy is being prioritized. Currently, almost all countries are dependent on conventional energy production methods, which include the use of fossil fuels for power and electricity generation. However, the concerns regarding the environment and the threat of the declining ratio of fossil fuels have diverted attention toward the use of renewable energy sources. Among several available options, the utilization of agriculture residues or food waste as a potential biomass or feedstock for power generation is being introduced because of its several benefits. Bolivia is one of the promising countries to use agricultural residues as a source of energy. Bolivia is also aiming to increase its share of renewable energy sources to support its power sector by considering agricultural residues as a potential source for power and electricity generation. The promising biomass feedstock in the form of residues included harvested sugarcane, soybean, corn, sorghum, rice, and sunflower. The availability of residues of the above-mentioned crops depends on the season. For this purpose, the government has supported the whole procedure by providing a novel framework to geographically locate different biomass collection points, which were used for the collection and storage of the residues. Although there is a diverse range of convergent technology available, Bolivia focused on grate-firing and fluidized wet combustion. This integration was named Energy from Biomass Techno Economic Model (ENBIOTEM), which led to the generation of energy, which caused about 71.6 $ MWh^{-1} for the plant capacity of 300 MW.[229]

There has been an increase in energy demand along with the growing economies that are the major consumers of energy across the world. The rise in industrial development in developing countries has resulted in an increase in the demand for energy. Along with this, it has also led to increased pollution due to the emission of carbon dioxide and other greenhouse gasses.[230] Brazil is also a country involved in increased industrial development. Along with that, Brazil is also blessed with various agricultural products, which results in increased biomass residues every year. According to an estimation, Brazil produces about 330 million metric tons of biomass every year, which demands increased efforts to manage the waste appropriately. However, the utilization of crop residues in the energy sector not only fulfills the energy demands but also conserves the environment by producing sustainable energy and managing the waste in a sustainable way. Brazilian agroindustrial biomass sources and residues are being valorized for the production of biofuel change as a way to introduce renewable and sustainable energy sources. Brazil is rich in its residual production, which is subject to pyrolysis. For specific purposes, a combination of different sources is subjected to flow gasification to produce syngas. This combination provides a unique arrangement which allows the use of low-value lignocellulosic biomass as an available energy source, which often goes through catalytic synthesis to fulfill energy demands.[231]

Developing nations like Uganda are facing several challenges, including the lowest electricity access levels. However, the country is rich in banana farming, which can serve as a potential biowaste source for energy production. Several banana farmers have limited financial capacity and are therefore unable to access modern solid technology, leading to a great loss and lack of access to energy and electricity. The utilization and implementation of potential ways to energy technology can be efficiently used in the valorization of banana waste. The three main technologies include thermal (consisting of direct combustion and incineration), thermochemical (torrefaction, plasma treatment, gasification, and pyrolysis), and biochemical (ethanol fermentation and anaerobic digestion). However, despite the availability of these potential techniques and technologies for the utilization of waste biomass in energy generation and production, Uganda is lacking due to several technical limitations and low economic capacity to build up the setups that can promote conversions of biowaste to energy.[232]

The energy need is increasing due to several reasons, among which increased population and rapid urbanization are the main drivers for high energy demand. Different technologies are being developed to fulfill current energy demands among which the management of agriculture biomass and waste and its utilization for power and electricity production is a significant solution which not only provides sustainability but also helps in achieving financially feasible with abundance of raw material.[233] One significant example is the use of banana waste as a potential source of energy production in Turkey with a specific emphasis on Mersin and Antalya. Although several types of thermochemical biomass conversion processes are being used, among which combustion, gasification, pyrolysis, and liquefaction are significant. The most abundantly used method for the conversion of biomass is the combustion process. The outcome of the study has revealed that the conversion of banana waste material into biogas and then to electricity is one of the significant methods to efficiently utilize energy and employ the principles of circular economy.[234] In the past 5 years, the electrical energy generated from banana waste is about 2218.26 MWh in Antalya and in Mersin it was 2884.43 MWh. The electricity generated was being used for household uses, emphasizing the use of agricultural waste for energy production.[235]

10. Conclusions and Future Recommendations

The need for alternative energy production sources has resulted in the development and introduction of sustainable fuels. These fuels are generated through the waste biomass making it a potential reliable and sustainable solution to increasing energy demands and environmental concerns. The use of biomass or other organic waste material has resulted in the development and production of a useful solution to introduce sustainable and green energy for our future generations. Although new technologies are facing several challenges especially in terms of technician; however, progress is being made to utilize the food waste or other organic waste materials. The technology requires appropriate analysis and optimization in order to completely utilize the waste. The optimization is based on several factors, which include the selection of feedstock, different methods used for pretreatment, reaction and separation processes, recycling of water and waste, integration of energy, and the utilization of the products obtained from the biomass for economic gains. Thermochemical processing has gained more popularity as it is considered an efficient technology to convert biomass into valuable products. Combustion is one of the most conventional technologies that has been used for the processing of biomass; however, other technologies including pyrolysis and gasification are also being evolved. The study also considered LCA, cost analysis, and techno-economic assessment along with socioeconomic importance of biofuels and their roles in society. The process is efficient in promoting the power generation while incising the specificity of different forms of biology. The product of these thermochemical conversions is being used as a substitute for conventional methods providing a sustainable way to meet current energy demand.

Several methods have been explained where this method has its advantages and disadvantages; however, implication in industrial production is limited. The main challenge for the industrial implication is the lack of appropriate knowledge, cost efficiency, and technical complexity affecting their performance at a larger scale. Therefore, inappropriate extensive research is required to identify the efficiency of existing processes and two observe their suitability. Current energy demand and concerns toward the environment are also in demand for cheaper fuse and energy sources along with environment sustainability. Therefore, there is a need to pay more attention toward green energy and sustainable approaches. This demand probed research for the selection of wisdom, preprocessing procedures, identification of a different parameter and their impact on the process, design of the reactors, separation of a product, value-added product, and their complete utilization to make them viable and economical for the industrial and social use. The co-gasification of biomass with coal is a viable alternative because of the availability of volatile matter in biomass that helps in achieving auto thermal gasification. Decoupling is regarded as the use of a single, high-speed pyrolysis plant to supply diesel engines. The decoupled system is significant in reducing the cost of electricity production in comparison to close-coupled systems. The use of a decoupling system allows for efficient power management during peak and off-peak periods during the time of independent operation of pyrolysis.

This study focuses on the valorization of biomass potential alternatives toward the energy production to be used as a fuel for electricity and transportation. The study also highlights the role of biomass in the green economy. However, the study lacks and represents experimental work that can be extended to the experimentation of relevant models highlighting the importance of biomass as an alternative renewable fuel energy source while considering its role in the green economy. The study can further be extended to the determination of biomass as a potential source to mitigate environmental challenges while maximizing the value of biomass by analyzing its practical participation in the circular and green economy.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

biofuels, biomass valorization, modern conversation technologies, pretreatment methods, sustainable energy

Received: April 7, 2024
Revised: May 29, 2024

[1] K. Harshwardhan, K. Upadhyay, *J. Fundam. Renewable Energy Appl.* **2017**, *7*, 237.
[2] A. Nayak, B. Bhushan, *Environ. Manage.* **2019**, *233*, 352.
[3] M. Danish, M. Naqvi, U. Farooq, S. Naqvi, *Energy Procedia* **2015**, *75*, 2974.
[4] B. Grizzetti, U. Pretato, L. Lassaletta, G. Billen, J. Garnier, *Environ. Sci. Policy* **2013**, *33*, 186.
[5] F. Xu, Y. Li, X. Ge, L. Yang, Y. Li, *Bioresour. Technol.* **2018**, *247*, 1047.
[6] H. Huang, V. Singh, N. Qureshi, *Biotechnol. Biofuels* **2015**, *8*, 147.
[7] D. Pleissner, *Curr. Opin. Green Sustainable Chem.* **2018**, *13*, 39.
[8] M. Mourad, *J. Cleaner Prod.* **2016**, *126*, 461.
[9] L. Pinotti, M. Manoni, F. Fumagalli, N. Rovere, A. Luciano, M. Ottoboni, L. Ferrari, F. Cheli, O. Djuragic, *Animals* **2020**, *10*, 1082.
[10] P. Garrone, M. Melacini, A. Perego, S. Sert, *J. Cleaner Prod.* **2016**, *137*, 1076.
[11] J. Aravind Kumar, S. Sathish, T. Krithiga, T. R. Praveenkumar, S. Lokesh, D. Prabu, A. Annam Renita, P. Prakash, M. Rajasimman, *Fuel* **2022**, *319*, 123594.
[12] R. Singh, B. B. Krishna, J. Kumar, T. Bhaskar, *Bioresour. Technol.* **2016**, *199*, 398.
[13] C. Magazzino, G. Cerulli, U. Shahzad, S. Khan, *Atmos. Pollut. Res.* **2023**, *14*, 101846.
[14] S. Y. Lee, R. Sankaran, K. W. Chew, C. H. Tan, R. Krishnamoorthy, D.-T. Chu, P.-L. Show, *BMC Energy* **2019**, *1*, 4.
[15] M. D. Leonard, E. E. Michaelides, D. N. Michaelides, *Renewable Energy* **2020**, *145*, 951.
[16] G. Velvizhi, P. J. Jacqueline, N. P. Shetti, L. K. G. Mohanakrishna, T. M. Aminabhavi, *J. Environ. Manage.* **2023**, *345*, 118527.
[17] J. Kotcher, E. Maibach, W.-T. Choi, *BMC Public Health* **2019**, *19*, 1079.
[18] T. Rasheed, A. Naveed, F. Nabeel, M. S. Ahmed, J. Ali, S. U.-D. Khan, *Mater. Chem. Phys.* **2020**, *242*, 122543.
[19] S. Kaniapan, S. Hassan, H. Ya, K. Patma Nesan, M. Azeem, *Sustainability* **2021**, *13*, 3110.
[20] E. Loiseau, L. Saikku, R. Antikainen, N. Droste, B. Hansjürgens, K. Pitkänen, P. Leskinen, P. Kuikman, M. Thomsen, *J. Cleaner Prod.* **2016**, *139*, 361.
[21] L. Georgeson, M. Maslin, M. Poessinouw, *Geo: Geogr. Environ.* **2017**, *4*, e00036.
[22] A. Sulich, *Vision* **2020**, IBIMA, Wroclaw, pp. 6861–6869.
[23] I. U. Haq, K. Qaisar, A. Nawaz, F. Akram, H. Mukhtar, Y. Xu, M. W. Mumtaz, U. Rashid, W. A. K. Ghani, T. S. Y. Choong, *Catalysts* **2021**, *11*, 309.
[24] S. E. Hosseini, M. A. Wahid, *Int. J. Energy Res.* **2020**, *44*, 4110.
[25] M. A. Salam, S. A. Khan, *Energy Explor. Exploit.* **2017**, *36*, 3.
[26] D. Sangroya, J. K. Nayak, *J. Cleaner Prod.* **2017**, *151*, 393.
[27] M. Grifoni, F. Pedron, M. Barbafieri, I. Rosellini, G. Petruzzelli, E. Franchi, *Handbook of Assisted and Amendment: Enhanced Sustainable Remediation Technology* Wiley, Chichester **2021**, pp. 29–51.
[28] R. Kothari, V. V. Tyagi, A. Pathak, *Renewable Sustainable Energy Rev.* **2010**, *14*, 3164.
[29] G. E. Halkos, E.-C. Gkampoura, *Energies* **2020**, *13*, 2906.
[30] J. Ben-Iwo, V. Manovic, P. Longhurst, *Renewable Sustainable Energy Rev.* **2016**, *63*, 172.
[31] M. K. Awasthi, S. Sarsaiya, A. Patel, A. Juneja, R. P. Singh, B. Yan, S. K. Awasthi, A. Jain, T. Liu, Y. Duan, A. Pandey, Z. Zhang, M. J. Taherzadeh, *Renewable Sustainable Energy Rev.* **2020**, *127*, 109876.

[32] N. Verma, V. Kumar, M. C. Bansal, *Waste Biomass Valorization* **2021**, *12*, 613.
[33] W. Dessie, X. Luo, M. Wang, L. Feng, Y. Liao, Z. Wang, Z. Yong, Z. Qin, *Appl. Microbiol. Biotechnol.* **2020**, *104*, 4757.
[34] A. Sarwer, M. Hussain, A. A. H. Al-Muhtaseb, A. Inayat, S. Rafiq, M. S. Khurram, N. Ul-Haq, N. S. Shah, A. Alaud Din, I. Ahmad, F. Jamil, *ChemBioEng Rev.* **2022**, *9*, 423.
[35] A. A. H. Al-Muhtaseb, F. Jamil, A. Sarwer, S. Al-Maawali, in *Valorization of Microalgal Biomass and Wastewater Treatment* (Eds: S. A. Bandh, F. A. Malla), Elsevier, Amsterdam **2023**, pp. 81–112.
[36] F. Jamil, I. Shafiq, A. Sarwer, M. Ahmad, P. Akhter, A. Inayat, S. Shafique, Y.-K. Park, M. Hussain, *Energy Environ.* **2024**, *35*, 438.
[37] S. Mishra, P. K. Singh, S. Dash, R. Pattnaik, *3 Biotech* **2018**, *8*, 458.
[38] O. Awogbemi, D. V. V. Kallon, *Heliyon* **2022**, *8*, e11117.
[39] A. Bhatnagar, M. Sillanpää, A. Witek-Krowiak, *Chem. Eng. J.* **2015**, *270*, 244.
[40] J. Sherwood, *Bioresour. Technol.* **2020**, *300*, 122755.
[41] T. T. Van Nguyen, A. N. Phan, T.-A. Nguyen, T. K. Nguyen, S. T. Nguyen, A. Pugazhendhi, H. H. Ky Phuong, *Chemosphere* **2022**, *307*, 135834.
[42] S. El Kourdi, A. Chaabane, S. Abderafi, M. A. Abbassi, *Results Eng.* **2024**, *21*, 101659.
[43] Z. Al-Hamamre, M. Saidan, M. Hararah, K. Rawajfeh, H. E. Alkhasawneh, M. Al-Shannag, *Renewable Sustainable Energy Rev.* **2017**, *67*, 295.
[44] N. S. Mat Aron, K. S. Khoo, K. W. Chew, P. L. Show, W.-H. Chen, T. H. P. Nguyen, *Int. J. Energy Res.* **2020**, *44*, 9266.
[45] H. K. Jeswani, A. Chilvers, A. Azapagic, *Proc. R. Soc. A* **2020**, *476*, 20200351.
[46] H. Chowdhury, B. Loganathan, *Curr. Opin. Green Sustainable Chem.* **2019**, *20*, 39.
[47] B. Koul, M. Yakoob, M. P. Shah, *Environ. Res.* **2022**, *206*, 112285.
[48] S. Jha, S. Nanda, B. Acharya, A. K. Dalai, *Energies* **2022**, *15*, 6352.
[49] J. A. Kumar, S. Sathish, D. Prabu, A. A. Renita, A. Saravanan, V. C. Deivayanai, M. Anish, J. Jayaprabakar, O. Baigenzhenov, A. Hosseini-Bandegharaei, *Chemosphere* **2023**, *331*, 138680.
[50] S. Padhi, A. Singh, W. Routray, *Rev. Environ. Sci. Bio/Technol.* **2023**, *22*, 1.
[51] L. Pattanaik, F. Pattnaik, D. K. Saxena, S. N. Naik, *Second and Third Generation of Feedstocks* (Eds: A. Basile, F. Dalena), Elsevier, Amsterdam **2019**, pp. 103–142.
[52] Z. Rahimi, A. Anand, S. Gautam, *Energy Nexus* **2022**, *7*, 100125.
[53] C. Huang, B. Jeuck, Q. Yong, *Waste Biomass Management – A Holistic Approach* (Eds: L. Singh, V. C. Kalia), Springer International Publishing, Cham **2017**, pp. 15–38.
[54] S. Saha, A. Mondal, M. B. Kurade, Y. Ahn, P. Banerjee, H.-K. Park, A. Pandey, T. H. Kim, B.-H. Jeon, *Rev. Environ. Sci. Bio/Technol.* **2023**, *22*, 397.
[55] M. I. Miskat, A. Ahmed, H. Chowdhury, T. Chowdhury, P. Chowdhury, S. M. Sait, Y.-K. Park, *Sustainability* **2020**, *12*, 8583.
[56] S. Heo, J. W. Choi, *Sustainability* **2019**, *11*, 1502.
[57] B. Holmatov, J. F. Schyns, M. S. Krol, P. W. Gerbens-Leenes, A. Y. Hoekstra, *Renewable Sustainable Energy Rev.* **2021**, *149*, 111417.
[58] P. K. Sarangi, M. M. Nayak, *Liquid Biofuels* Scrivener Publishing Hoboken, USA **2021**, pp. 697–709.
[59] M. Ali, M. Saleem, Z. Khan, I. A. Watson, *Biomass, Biopolymer-Based Materials, and Bioenergy* (Eds: D. Verma, E. Fortunati, S. Jain, X. Zhang), Woodhead Publishing Duxford, UK **2019**, pp. 369–395.
[60] J. K. Saini, R. Saini, L. Tewari, *3 Biotech* **2015**, *5*, 337.
[61] J. Gupta, M. Kumari, A. Mishra, . Swati, M. Akram, I. S. Thakur, *Chemosphere* **2022**, *287*, 132321.
[62] C. Cambero, T. Sowlati, M. Marinescu, D. Röser, *Int. J. Energy Res.* **2015**, *39*, 439.
[63] J. L. Carrasco, S. Gunukula, A. A. Boateng, C. A. Mullen, W. J. DeSisto, M. C. Wheeler, *Fuel* **2017**, *193*, 477.
[64] H. S. Hafid, F. N. Omar, N. A. Abdul Rahman, M. Wakisaka, *Crit. Rev. Environ. Sci. Technol.* **2022**, *52*, 3453.
[65] A. Sridhar, A. Kapoor, P. Senthil Kumar, M. Ponnuchamy, S. Balasubramanian, S. Prabhakar, *Fuel* **2021**, *302*, 121069.
[66] S. Dutta, M. He, X. Xiong, D. C. W. Tsang, *Bioresour. Technol.* **2021**, *341*, 125915.
[67] R. Yukesh Kannah, J. Merrylin, T. Poornima Devi, S. Kavitha, P. Sivashanmugam, G. Kumar, J. Rajesh Banu, *Bioresour. Technol. Rep.* **2020**, *11*, 100524.
[68] M. V. L. Chhandama, A. C. Chetia, K. B. Satyan, A. Supongsenla, J. V. L. Ruatpuia, S. L. Rokhum, *Bioresour. Technol. Rep.* **2022**, *17*, 100945.
[69] M. R. Khodadadi, I. Malpartida, C.-W. Tsang, C. S. K. Lin, C. Len, *Mol. Catal.* **2020**, *494*, 111128.
[70] A. Gouran, B. Aghel, F. Nasirmanesh, *Fuel* **2021**, *295*, 120542.
[71] A. B. Avagyan, B. Singh, in *Biodiesel: Feedstocks, Technologies, Economics and Barriers: Assessment of Environmental Impact in Producing and Using Chains* (Eds: A. B. Avagyan, B. Singh), Springer Singapore, Singapore **2019**, pp. 15–75.
[72] A. Orjuela, J. Clark, *Curr. Opin. Green Sustainable Chem.* **2020**, *26*, 100369.
[73] Y. Wang, J. Fang, F. Lü, H. Zhang, P. He, *Sci. Total Environ.* **2023**, *903*, 166143.
[74] B. H. H. Goh, C. T. Chong, Y. Ge, H. C. Ong, J.-H. Ng, B. Tian, V. Ashokkumar, S. Lim, T. Seljak, V. Józsa, *Energy Convers. Manage.* **2020**, *223*, 113296.
[75] X. Xiong, W. Zhang, X. Ha, N. Li, S. Chen, H. Xing, J. Yang, *Fermentation* **2023**, *9*, 247.
[76] A. Iravanian, S. O. Ravari, *IOP Conf. Ser.: Earth Environ. Sci.* **2020**, *614*, 012083.
[77] W. A. Wan Mahari, E. Azwar, S. Y. Foong, A. Ahmed, W. Peng, M. Tabatabaei, M. Aghbashlo, Y.-K. Park, C. Sonne, S. S. Lam, *Chem. Eng. J.* **2021**, *421*, 129749.
[78] Z. Kowalski, J. Kulczycka, R. Verhé, L. Desender, G. De Clercq, A. Makara, N. Generowicz, P. Harazin, *Front. Energy Res.* **2022**, *10*, 919415.
[79] R. K. Bhatia, G. Ramadoss, A. K. Jain, R. K. Dhiman, S. K. Bhatia, A. K. Bhatt, *BioEnergy Res.* **2020**, *13*, 1046.
[80] D. P. Ho, H. H. Ngo, W. Guo, *Bioresour. Technol.* **2014**, *169*, 742.
[81] A. Cesaro, *J. Environ. Manage.* **2021**, *280*, 111742.
[82] G. Su, H. C. Ong, N. W. Mohd Zulkifli, S. Ibrahim, W. H. Chen, C. T. Chong, Y. S. Ok, *J. Cleaner Prod.* **2022**, *343*, 130965.
[83] M. Lin, A. Wang, L. Ren, W. Qiao, S. M. Wandera, R. Dong, *Bioengineered* **2022**, *13*, 1149.
[84] F. Ameen, J. Ranjitha, N. Ahsan, V. Shankar, *Fuel* **2021**, *306*, 121746.
[85] R. Permal, W. Leong Chang, B. Seale, N. Hamid, R. Kam, *Food Chem.* **2020**, *306*, 125635.
[86] A. I. Osman, A. Abdelkader, C. Farrell, D. Rooney, K. Morgan, *Fuel Process. Technol.* **2019**, *192*, 179.
[87] M. K. Shahid, A. Batool, A. Kashif, M. H. Nawaz, M. Aslam, N. Iqbal, Y. Choi, *J. Environ. Manage.* **2021**, *297*, 113268.
[88] P. Carneiro, P. Ferreira, *Renewable Energy* **2012**, *44*, 17.
[89] F. H. Pour, Y. T. Makkawi, *Energy Rep.* **2021**, *7*, 7759.
[90] J. Escalante, W.-H. Chen, M. Tabatabaei, A. T. Hoang, E. E. Kwon, K.-Y. Andrew Lin, A. Saravanakumar, *Renewable Sustainable Energy Rev.* **2022**, *169*, 112914.
[91] J. J. Hoyos-Sebá, N. P. Arias, J. Salcedo-Mendoza, V. Aristizábal-Marulanda, *Chem. Eng. Process.* **2024**, *196*, 109660.
[92] S. V. Vassilev, C. G. Vassileva, *Fuel* **2016**, *181*, 1.
[93] A. Datta, A. Hossain, S. Roy, *Res. J. Pharm. Technol.* **2019**, *12*, 6187.

[94] M. Millinger, L. Reichenberg, F. Hedenus, G. Berndes, E. Zeyen, T. Brown, *Appl. Energy* **2022**, *326*, 120016.
[95] A. Demırbas, *Energy Sources, Part B* **2017**, *12*, 47.
[96] P. Tanger, J. Field, C. Jahn, M. DeFoort, J. Leach, *Front. Plant Sci.* **2013**, *4*, 218.
[97] A. Patel, B. Agrawal, B. R. Rawal, *Energy Sources, Part A* **2020**, *42*, 1649.
[98] M. I. Jahirul, M. G. Rasul, A. A. Chowdhury, N. Ashwath, *Energies* **2012**, *5*, 4952.
[99] A. T. Hoang, H. C. Ong, I. M. R. Fattah, C. T. Chong, C. K. Cheng, R. Sakthivel, Y. S. Ok, *Fuel Process. Technol.* **2021**, *223*, 106997.
[100] D. Lefebvre, S. Fawzy, C. Aquije, A. Osman, K. Draper, T. Trabold, *Biochar* **2023**, *5*, 65.
[101] A. Salma, L. Fryda, H. Djelal, *Resources* **2024**, *13*, 31.
[102] M. Elias, D. L. Sanchez, P. Saksa, J. Hunt, J. Remucal, *Biofuels, Bioproducts And Biorefining* Society of Industrial Chemistry and John Wiley & Sons Ltd., London, UK **2024**.
[103] H. C. Ong, W.-H. Chen, A. Farooq, Y. Y. Gan, K. T. Lee, V. Ashokkumar, *Renewable Sustainable Energy Rev.* **2019**, *113*, 109266.
[104] S. Wang, G. Dai, H. Yang, Z. Luo, *Prog. Energy Combust. Sci.* **2017**, *62*, 33.
[105] R. Muthu Dinesh Kumar, R. Anand, in *Advanced Biofuels* (Eds: A. K. Azad, M. Rasul), Woodhead Publishing, UK **2019**, pp. 129–151.
[106] V. S. Sikarwar, M. Zhao, P. S. Fennell, N. Shah, E. J. Anthony, *Prog. Energy Combust. Sci.* **2017**, *61*, 189.
[107] V. Dhyani, T. Bhaskar, in *Biofuels: Alternative Feedstocks and Conversion Processes for the Production of Liquid and Gaseous Biofuels*, 2nd ed. (Eds: A. Pandey, C. Larroche, C.-G. Dussap, E. Gnansounou, S. K. Khanal, S. Ricke), Academic Press **2019**, pp. 217–244.
[108] A. I. Osman, N. Mehta, A. M. Elgarahy, A. Al-Hinai, A. A. H. Al-Muhtaseb, D. W. Rooney, *Environ. Chem. Lett.* **2021**, *19*, 4075.
[109] A. Molino, V. Larocca, S. Chianese, D. Musmarra, *Energies* **2018**, *11*, 811.
[110] K. Sivabalan, S. Hassan, H. Ya, J. Pasupuleti, in *Journal of Physics: Conf. Series*, IOP Publishing **2021**, p. 012033.
[111] R. Brown, T. Brown, *Biorenewable Resources*, Wiley Blackwell Ames, Iowa **2014**, pp. 195–236.
[112] K. Kundu, A. Chatterjee, T. Bhattacharyya, M. Roy, A. Kaur, in *Prospects of Alternative Transportation Fuels* (Eds: A. P. Singh, R. A. Agarwal, A. K. Agarwal, A. Dhar, M. K. Shukla), Springer Singapore, Singapore **2018**, pp. 235–268.
[113] J. L. Míguez, J. Porteiro, F. Behrendt, D. Blanco, D. Patiño, A. Dieguez-Alonso, *Renewable Sustainable Energy Rev.* **2021**, *141*, 110502.
[114] L. Zhang, C. Xu, P. Champagne, *Energy Convers. Manage.* **2010**, *51*, 969.
[115] M. Hupa, O. Karlström, E. Vainio, *Proc. Combust. Inst.* **2017**, *36*, 113.
[116] W. Jiang, A. Kumar, S. Adamopoulos, *Ind. Crops Prod.* **2018**, *124*, 325.
[117] C. J. Durán-Valle, *Process Systems Engineering for Biofuels Development* Wiley-Blackwell **2020**, pp. 285–310.
[118] L. Gouveia, P. C. Passarinho, in *Biorefineries: Targeting Energy, High Value Products and Waste Valorisation* (Eds: M. Rabaçal, A. F. Ferreira, C. A. M. Silva, M. Costa), Springer International Publishing, Cham **2017**, pp. 99–111.
[119] R. Łukajtis, I. Hołowacz, K. Kucharska, M. Glinka, P. Rybarczyk, A. Przyjazny, M. Kamiński, *Renewable Sustainable Energy Rev.* **2018**, *91*, 665.
[120] G. Kumar, S. Shobana, D. Nagarajan, D.-J. Lee, K.-S. Lee, C.-Y. Lin, C.-Y. Chen, J.-S. Chang, *Curr. Opin. Biotechnol.* **2018**, *50*, 136.
[121] K. Rajendran, D. Mahapatra, A. V. Venkatraman, S. Muthuswamy, A. Pugazhendhi, *Renewable Sustainable Energy Rev.* **2020**, *123*, 109746.
[122] P. A. Cremonez, J. G. Teleken, T. R. Weiser Meier, H. J. Alves, *J. Environ. Manage.* **2021**, *281*, 111854.
[123] A. R. Mankar, A. Pandey, A. Modak, K. K. Pant, *Bioresour. Technol.* **2021**, *334*, 125235.
[124] K. N. Yogalakshmi, P. Sivashanmugam, S. Kavitha, Y. Kannah, S. Varjani, S. AdishKumar, G. Kumar, *Chemosphere* **2022**, *286*, 131824.
[125] M. C. Ndukwu, I. T. Horsfall, E. A. Ubouh, F. N. Orji, I. E. Ekop, N. R. Ezejiofor, *J. King Saud Univ., Eng. Sci.* **2021**, *33*, 413.
[126] S. S. Qiang, W.-C. Wang, *J. Cleaner Prod.* **2020**, *277*, 124136.
[127] S. Sobek, S. Werle, *Renewable Energy* **2019**, *143*, 1939.
[128] S. Mondal, A. K. Mondal, V. Chintala, S. M. Tauseef, S. Kumar, J. K. Pandey, *Biofuels* **2021**, *12*, 125.
[129] M. Mencigar, **2020**.
[130] P. Ibarra-Gonzalez, B.-G. Rong, *Chin. J. Chem. Eng.* **2019**, *27*, 1523.
[131] M. Heidari, S. Salaudeen, O. Norouzi, B. Acharya, A. Dutta, *Processes* **2020**, *8*, 43.
[132] J. Rajesh Banu, . Preethi, S. Kavitha, V. K. Tyagi, M. Gunasekaran, O. P. Karthikeyan, G. Kumar, *Fuel* **2021**, *302*, 121086.
[133] L. Goswami, R. Kayalvizhi, P. K. Dikshit, K. C. Sherpa, S. Roy, A. Kushwaha, B. S. Kim, R. Banerjee, S. Jacob, R. C. Rajak, *Chem. Eng. J.* **2022**, *448*, 137677.
[134] Z. Usmani, M. Sharma, A. K. Awasthi, T. Lukk, M. G. Tuohy, L. Gong, P. Nguyen-Tri, A. D. Goddard, R. M. Bill, S. C. Nayak, V. K. Gupta, *Renewable Sustainable Energy Rev.* **2021**, *148*, 111258.
[135] R. Nawaz, N. T. Sahrin, S. Haider, H. Ullah, M. Junaid, M. S. Akhtar, S. Khan, *Appl. Nanosci.* **2022**, *12*, 3499.
[136] N. Srivastava, M. Srivastava, P. K. Mishra, M. A. Kausar, M. Saeed, V. K. Gupta, R. Singh, P. W. Ramteke, *Bioresour. Technol.* **2020**, *307*, 123094.
[137] S. De, A. M. Balu, J. C. van der Waal, R. Luque, *ChemCatChem* **2015**, *7*, 1608.
[138] A. G. Alsultan, N. Asikin-Mijan, Z. Ibrahim, R. Yunus, S. Z. Razali, N. Mansir, A. Islam, S. Seenivasagam, Y. H. Taufiq-Yap, *Catalysts* **2021**, *11*, 1261.
[139] S. Nanda, J. Mohammad, S. N. Reddy, J. A. Kozinski, A. K. Dalai, *Biomass Convers. Biorefin.* **2014**, *4*, 157.
[140] A. Dahdouh, Y. Le Brech, I. Khay, A. El Maakoul, M. Bakhouya, *Ind. Crops Prod.* **2023**, *205*, 117519.
[141] N. Pannucharoenwong, K. Duanguppama, S. Echaroj, C. Turakarn, K. Chaiphet, P. Rattanadecho, *Energy Rep.* **2023**, *9*, 125.
[142] M. H. Tahir, G. Çakman, J. L. Goldfarb, Y. Topcu, S. R. Naqvi, S. Ceylan, *Bioresour. Technol.* **2019**, *279*, 67.
[143] G. Lopez, J. Alvarez, M. Amutio, A. Arregi, J. Bilbao, M. Olazar, *Energy* **2016**, *107*, 493.
[144] X. Gao, Y. Zhang, B. Li, Y. Zhao, B. Jiang, *Bioresour. Technol.* **2016**, *218*, 1073.
[145] L. Gouveia, in *Microalgae as a Feedstock for Biofuels* (Ed: L. Gouveia), Springer Berlin Heidelberg, Berlin, Heidelberg **2011**, pp. 1–69.
[146] K. Karimi, M. Shafiei, R. Kumar, in *Biofuel Technologies: Recent Developments* (Eds: V. K. Gupta, M. G. Tuohy), Springer Berlin Heidelberg, Berlin, Heidelberg **2013**, pp. 53–96.
[147] S. Behera, R. Arora, N. Nandhagopal, S. Kumar, *Renewable Sustainable Energy Rev.* **2014**, *36*, 91.
[148] T. Roukas, P. Kotzekidou, *Rev. Environ. Sci. Bio/Technol.* **2022**, *21*, 299.
[149] G. Perin, P. R. Jones, *Curr. Opin. Biotechnol.* **2019**, *57*, 175.
[150] J. Dumas, A. Dubois, P. Thiran, P. Jacques, F. Contino, B. Cornélusse, G. Limpens, *Biophys. Econ. Sustainability* **2022**, *7*, 12.
[151] Y. Demirel, *Int. J. Energy Res.* **2018**, *42*, 881.

[152] U. Lucia, G. Grisolia, *Energies* **2018**, *11*, 156.
[153] M. Rizwan, G. Mujtaba, S. A. Memon, K. Lee, N. Rashid, *Renewable Sustainable Energy Rev.* **2018**, *92*, 394.
[154] M. Bhattacharya, S. Goswami, *Biocatal. Agric. Biotechnol.* **2020**, *25*, 101580.
[155] L. Moreno García, Y. Gariépy, S. Barnabé, V. Raghavan, in *Refining Biomass Residues for Sustainable Energy and Bioproducts* (Eds: R. P. Kumar, E. Gnansounou, J.K. Raman, G. Baskar), Academic Press, Amsterdam **2020**, pp. 149–180.
[156] R. Sankaran, P. L. Show, D. Nagarajan, J.-S. Chang, in *Waste Biorefinery* (Eds: T. Bhaskar, A. Pandey, S. V. Mohan, D.-J. Lee, S. K. Khanal), Elsevier Amsterdam, Netherlands **2018**, pp. 571–601.
[157] D. Parlevliet, N. R. Moheimani, *Aquat. Biosyst.* **2014**, *10*, 4.
[158] N. A. Sadiku, A. O. Oluyegem, I. B. Sadiku, *Lignocellulose* **2016**, *5*, 34.
[159] C. D. Everard, K. P. McDonnell, C. C. Fagan, *Biomass Bioenergy* **2012**, *45*, 203.
[160] E. Čubars, L. Poiša, in *Proc. Int. Scientific and Practical Conf.* Environ. Technol. Latvia **2017**, pp. 31–36.
[161] D. Cudjoe, E. Nketiah, B. Obuobi, G. Adu-Gyamfi, M. Adjei, B. Zhu, *Energy* **2021**, *226*, 120342.
[162] J. Wang, S. You, Y. Zong, C. Træholt, Z. Y. Dong, Y. Zhou, *Appl. Energy* **2019**, *252*, 113445.
[163] A. I. Osman, Z. Y. Lai, M. Farghali, C. L. Yiin, A. M. Elgarahy, A. Hammad, I. Ihara, A. S. Al-Fatesh, D. W. Rooney, P.-S. Yap, *Environ. Chem. Lett.* **2023**, *21*, 2639.
[164] Q. A. Nguyen, W. A. Smith, B. D. Wahlen, L. M. Wendt, *Front. Bioeng. Biotechnol.* **2020**, *8*, 546.
[165] A. A. Rentizelas, A. J. Tolis, I. P. Tatsiopoulos, *Renewable Sustainable Energy Rev.* **2009**, *13*, 887.
[166] P. Adams, T. Bridgwater, A. Lea-Langton, A. Ross, I. Watson, in *Greenhouse Gas Balances of Bioenergy Systems* (Eds: P. Thornley, P. Adams), Elsevier, Academic Press Inc., London, UK **2018**, pp. 107–139.
[167] W. M. Lewandowski, M. Ryms, W. Kosakowski, *Processes* **2020**, *8*, 516.
[168] T. Kan, V. Strezov, T. J. Evans, *Renewable Sustainable Energy Rev.* **2016**, *57*, 1126.
[169] C. Yang, S. Wang, J. Yang, D. Xu, Y. Li, J. Li, Y. Zhang, *Green Chem.* **2020**, *22*, 8210.
[170] A. Briones-Hidrovo, J. Copa, L. A. C. Tarelho, C. Gonçalves, T. Pacheco da Costa, A. C. Dias, *J. Cleaner Prod.* **2021**, *289*, 125680.
[171] S. Quoilin, M. V. D. Broek, S. Declaye, P. Dewallef, V. Lemort, *Renewable Sustainable Energy Rev.* **2013**, *22*, 168.
[172] A. Wiese, *Renewable Energy Systems*, Springer, New York **2013**, pp. 290–327.
[173] T. T. Al-Shemmeri, R. Yedla, D. Wardle, *Appl. Therm. Eng.* **2015**, *85*, 243.
[174] A. Beainy, C. Maatouk, N. Moubayed, F. Kaddah, in *2016 3rd Int. Conf. Renewable Energies for Developing Countries (REDEC)*, July **2016**, pp. 1–6.
[175] U. Arena, F. Di Gregorio, *Waste Manage.* **2013**, *33*, 1142.
[176] M. Casisi, P. Pinamonti, M. Reini, *Energy* **2009**, *34*, 2175.
[177] H. von Blottnitz, M. A. Curran, *J. Cleaner Prod.* **2007**, *15*, 607.
[178] S. K. Thangavelu, A. S. Ahmed, F. N. Ani, *Renewable Sustainable Energy Rev.* **2016**, *56*, 820.
[179] W. Tutak, *Energy Convers. Manage.* **2014**, *86*, 39.
[180] W.-R. Chang, J.-J. Hwang, W. Wu, *Renewable Sustainable Energy Rev.* **2017**, *67*, 277.
[181] I. Ullah Khan, M. Hafiz Dzarfan Othman, H. Hashim, T. Matsuura, A. F. Ismail, M. Rezaei-DashtArzhandi, I. Wan Azelee, *Energy Convers. Manage.* **2017**, *150*, 277.
[182] M. Ottosson, T. Magnusson, H. Andersson, *Environ. Innovation Societal Transitions* **2020**, *36*, 303.
[183] R. Dimitrov, P. Zlateva, in *2019 11th Electrical Engineering Faculty Conf. (BulEF)*, September 2019, pp. 1–4.
[184] S. N. A. Rahman, M. S. Masdar, M. I. Rosli, E. H. Majlan, T. Husaini, S. K. Kamarudin, W. R. W. Daud, *Renewable Sustainable Energy Rev.* **2016**, *66*, 137.
[185] J. Jayaprabakar, N. S. Sri Hari, M. Badreenath, M. Anish, N. Joy, A. Prabhu, M. Rajasimman, J. A. Kumar, *Int. J. Hydrogen Energy* **2024**, *52*, 674.
[186] Z. Zhang, Y. Li, H. Zhang, C. He, Q. Zhang, *Bioresour. Technol.* **2017**, *245*, 884.
[187] H. Zhang, J. Li, Q. Zhang, S. Zhu, S. Yang, Z. Zhang, *Sustainability* **2020**, *12*, 2700.
[188] M. Kamaraj, K. K. Ramachandran, J. Aravind, *Int. J. Environ. Sci. Technol.* **2020**, *17*, 559.
[189] A. I. Osman, T. J. Deka, D. C. Baruah, D. W. Rooney, *Biomass Convers. Biorefin.* **2023**, *13*, 8383.
[190] N. Arun, A. K. Dalai, in *Lignocellulosic Biomass to Liquid Biofuels* (Eds: A. Yousuf, D. Pirozzi, F. Sannino), Academic Press, London, UK **2020**, pp. 283–299.
[191] G. M. Preethi, G. Kumar, O. P. Karthikeyan, S. Varjani, *Environ. Technol. Innovation* **2021**, *24*, 102080.
[192] A. I. Osman, M. Farghali, I. Ihara, A. M. Elgarahy, A. Ayyad, N. Mehta, K. H. Ng, E. M. Abd El-Monaem, A. S. Eltaweil, M. Hosny, S. M. Hamed, S. Fawzy, P.-S. Yap, D. W. Rooney, *Environ. Chem. Lett.* **2023**, *21*, 1419.
[193] S. Sharma, M.-L. Tsai, V. Sharma, P.-P. Sun, P. Nargotra, B. K. Bajaj, C.-W. Chen, C.-D. Dong, *Environments* **2023**, *10*, 6.
[194] M. Bilal, H. M. N. Iqbal, *Curr. Sustainable/Renewable Energy Rep.* **2020**, *7*, 100.
[195] T. Soleymani Angili, K. Grzesik, W. Jerzak, *Energies* **2023**, *16*, 2004.
[196] I. Quispe, R. Navia, R. Kahhat, *J. Cleaner Prod.* **2019**, *209*, 1235.
[197] E. Santoyo-Castelazo, E. Santoyo, L. Zurita-García, D. A. Camacho Luengas, K. Solano-Olivares, *Appl. Therm. Eng.* **2023**, *219*, 119414.
[198] O. Winjobi, D. R. Shonnard, E. Bar-Ziv, W. Zhou, *Biofuels, Bioprod. Biorefin.* **2016**, *10*, 576.
[199] S. Nanda, R. Rana, P. K. Sarangi, A. K. Dalai, J. A. Kozinski, in *Recent Advancements in Biofuels and Bioenergy Utilization* (Eds: P. K. Sarangi, S. Nanda, P. Mohanty), Springer Singapore, Singapore **2018**, pp. 1–25.
[200] R. D. Perlack, A. F. Turhollow, *Energy* **2003**, *28*, 1395.
[201] D. Debnath, in *Biofuels, Bioenergy and Food Security* (Eds: D. Debnath, S. C. Babu), Elsevier Academic Press, London, UK **2019**, pp. 45–60.
[202] S. F. Ahmed, J. C. Debnath, F. Mehejabin, N. Islam, R. Tripura, M. Mofijur, A. T. Hoang, M. G. Rasul, D.-V. N. Vo, *Sustainable Energy Technol. Assess.* **2023**, *55*, 102894.
[203] Z. Anwar, M. Gulfraz, M. Irshad, *J. Radiat. Res. Appl. Sci.* **2014**, *7*, 163.
[204] R. Saini, C. S. Osorio-Gonzalez, K. Hegde, S. K. Brar, S. Magdouli, P. Vezina, A. Avalos-Ramirez, *Curr. Sustainable/Renewable Energy Rep.* **2020**, *7*, 122.
[205] W. A. Marvin, L. D. Schmidt, P. Daoutidis, *Ind. Eng. Chem. Res.* **2013**, *52*, 3192.
[206] M.-O. Jang, G. Choi, *Biochem. Eng. J.* **2018**, *134*, 30.
[207] N. R. Baral, O. Kavvada, D. Mendez-Perez, A. Mukhopadhyay, T. S. Lee, B. A. Simmons, C. D. Scown, *Energy Environ. Sci.* **2019**, *12*, 807.
[208] G. Butera, S. H. Jensen, J. Ahrenfeldt, L. R. Clausen, *Fuel Process. Technol.* **2021**, *215*, 106718.
[209] M. Patel, X. Zhang, A. Kumar, *Renewable Sustainable Energy Rev.* **2016**, *53*, 1486.
[210] A. Bala-Litwiniak, D. Musiał, *Materials* **2022**, *15*, 4826.

[211] K. Naseem, M. Arif, A. Ahmad Haral, M. H. Tahir, A. Khurshid, K. Ahmed, H. Majeed, S. Haider, S. U.-D. Khan, M. F. Nazar, A. Aziz, *Int. J. Polym. Mater. Polym. Biomater.* **2024**, *73*, 785.
[212] L. M. Raatikka, in *ASME 2011 Power Conf. collocated with JSME ICOPE 2011* EBSCO, Denver, Colorado USA **2011**, pp. 339–350.
[213] G. V. Brigagão, O. de Queiroz Fernandes Araújo, J. L. de Medeiros, H. Mikulcic, N. Duic, *Fuel Process. Technol.* **2019**, *193*, 102.
[214] J. D. Rhenals-Julio, J. G. Castellar, C. A. Camargo, J. M. Mendoza, *Int. J. Energy Econ. Policy* **2023**, *13*, 126.
[215] M. M. Wright, D. E. Daugaard, J. A. Satrio, R. C. Brown, *Fuel* **2010**, *89*, S2.
[216] J. R. Ziolkowska, in *Biofuels for a More Sustainable Future* (Eds: J. Ren, A. Scipioni, A. Manzardo, H. Liang), Elsevier, Amsterdam, Netherlands **2020**, pp. 1–19.
[217] Z. Tsitrouli, *Bioethica* **2021**, *7*, 46.
[218] P. Morone, A. Strzałkowski, A. Tani, in *Biofuels for a More Sustainable Future* (Eds: J. Ren, A. Scipioni, A. Manzardo, H. Liang), Elsevier, Amsterdam, Netherlands **2020**, pp. 21–46.
[219] T. J. Lark, N. P. Hendricks, A. Smith, N. Pates, S. A. Spawn-Lee, M. Bougie, E. G. Booth, C. J. Kucharik, H. K. Gibbs, *Proc. Natl. Acad. Sci.* **2022**, *119*, e2101084119.
[220] H. L. Breetz, *Energy Res. Social Sci.* **2020**, *69*, 101755.
[221] N. Pryshliak, D. Tokarchuk, H. Shevchuk, *Polityka Energetyczna* **2021**, *24*, 133.
[222] K. Löhr, C. E. Matavel, S. Tadesse, M. Yazdanpanah, S. Sieber, N. Komendantova, *Land* **2022**, *11*, 2193.
[223] Y. Zhang, . Danish, S. U. D. D. Khan, *Resour. Policy* **2023**, *85*, 103838.
[224] J. Han, D. Xie, Z. Ahmed, S. Khan, D. Kirikkaleli, *Environ. Sci. Pollut. Res.* **2023**, *30*, 92255.
[225] S. Deng, S. Tiwari, S. Khan, M. Razib Hossain, R. Chen, *Gondwana Res.* **2024**, *128*, 283.
[226] K. Pi, S. Khan, S. A. Raza, I. Shahzadi, *Geol. J.* **2024**, *59*, 301.
[227] S. U.-D. Khan, A. Al-Hamdan, Z. Almutairi, *Nucl. Eng. Des.* **2022**, *399*, 112018.
[228] A. Emre Caglar, *J. Cleaner Prod.* **2020**, *264*, 121663.
[229] T. Morató, M. Vaezi, A. Kumar, *Renewable Sustainable Energy Rev.* **2020**, *134*, 110154.
[230] J. Wang, W. Azam, *Geosci. Front.* **2024**, *15*, 101757.
[231] E. Virmond, J. Rocha, R. Moreira, H. José, *Braz. J. Chem. Eng.* **2013**, *30*, 197.
[232] R. Gumisiriza, J. F. Hawumba, M. Okure, O. Hensel, *Biotechnol. Biofuels* **2017**, *10*, 11.
[233] M. Kaur, R. Kaur, S. Sharma, G. S. Kocher, in *Paddy Straw Waste for Biorefinery Applications* (Eds: N. Srivastava, B. Verma, P. K. Mishra), Springer Nature Singapore, Singapore **2024**, pp. 71–85.
[234] A. Romaní, P. G. Del-Río, A. Rubira, M. J. Pérez, G. Garrote, *Ind. Crops Prod.* **2024**, *209*, 117992.
[235] A. Atilgan, A. Krakowiak-Bal, H. Ertop, B. Saltuk, M. Malinowski, *Energies* **2023**, *16*, 5244.
[236] A. Omojola, D. Kallon, *Heliyon* **2022**, *8*, e11117.
[237] M. Guida, B. Rebbah, N. Anter, A. Medaghri-Alaoui, R. El Mostapha, A. Hannioui, *Prog. Agric. Eng. Sci.* **2021**, *17*, 15.
[238] G. Abdurrahman, in *Biotechnological Applications of Biomass* (Eds: B. Thalita Peixoto, B. Thiago Olitta, B. Luiz Carlos), IntechOpen, Rijeka **2020**, Ch. 1.
[239] U. Campos, H. Zamenian, D. Koo, D. Goodman, *Int. J. Emerging Technol. Adv. Eng.* **2015**, *5*, 504.
[240] M. Shahbaz, A. Alnouss, I. Ghiat, G. McKay, H. Mackey, S. Elkhalifa, T. Al-Ansari, *Resour., Conserv. Recycl.* **2021**, *173*, 105734.
[241] J. Yanik, C. Kornmayer, M. Saglam, M. Yüksel, *Fuel Process. Technol.* **2007**, *88*, 942.
[242] D. Mu, T. Seager, P. S. Rao, F. Zhao, *Environ. Manage.* **2010**, *46*, 565.
[243] M. Pointner, P. Kuttner, T. Obrlik, A. Jäger, H. Kahr, *Agron. Res.* **2014**, *12*, 391.
[244] X. Li, Y. Liu, J. Hao, W. Wang, *Materials* **2018**, *11*, 1782.
[245] G. Trif-Tordai, I. Ionel, *Alternative Fuel* InTech Open, Rijeka **2011**, p. 304.
[246] J. Chen, Y. Fan, J. E. W. Cao, F. Zhang, J. Gong, G. Liu, W. Xu, *Fuel* **2019**, *241*, 94.
[247] A. Selvam, P. Ilamathi, M. Udayakumar, K. Murugesan, R. Banu, Y. Khanna, J. Wong, *Food Waste Properties* Elsevier **2021**, pp. 11–41.
[248] N. U. Saqib, S. Baroutian, A. K. Sarmah, *Bioresour. Technol.* **2018**, *266*, 357.
[249] M. Zhou, N. Hu, M. Liu, Y. Deng, L. He, C. Guo, X. Zhao, Y. Li, *Biomed Res. Int.* **2020**, *2020*, 5462063.
[250] M. W. Seo, S. H. Lee, H. Nam, D. Lee, D. Tokmurzin, S. Wang, Y.-K. Park, *Bioresour. Technol.* **2022**, *343*, 126109.
[251] E. Walling, A. Babin, C. Vaneeckhaute, *Nutrient and Carbon Recovery From Organic Wastes*, Springer Cham, Switzerland **2019**, pp. 351–373.
[252] C. Xia, A. Pathy, B. Paramasivan, P. Ganeshan, K. Dhamodharan, A. Juneja, D. Kumar, K. Brindhadevi, S.-H. Kim, K. Rajendran, *Fuel* **2022**, *311*, 121932.
[253] S. Khare, K. O. P. Bjørgen, K. Kohansal, M. S. Haider, D. Castello, T. H. Pedersen, T. Løvås, D. R. Emberson, *Energies* **2023**, *16*, 6754.
[254] M. Alam, M. B. Sultan, M. Mehnaz, C. S. U. Fahim, S. Hossain, A. H. Anik, *Energy Nexus* **2022**, *7*, 100126.
[255] Q. Dang, W. Li, M. Wright, *Energy Technol.* **2017**, *6*, 178.
[256] M. R. Mohaghegh, M. Heidari, S. Tasnim, A. Dutta, S. Mahmud, *Energy Sources, Part A* **2021**, 1.
[257] P. Pan, M. Zhang, G. Xu, H. Chen, X. Song, T. Liu, *Energies* **2020**, *13*, 4345.
[258] A. M. Pantaleo, S. M. Camporeale, A. Miliozzi, V. Russo, N. Shah, C. N. Markides, *Appl. Energy* **2017**, *204*, 994.
[259] A. Raheem, M. Y. Hassan, R. Shakoor, N. Rasheed, *Int. J. Integr. Eng.* **2014**, *06*, 1.
[260] A. I. Osman, B. Fang, Y. Zhang, Y. Liu, J. Yu, M. Farghali, A. K. Rashwan, Z. Chen, L. Chen, I. Ihara, D. W. Rooney, P.-S. Yap, *Environ. Chem. Lett.* **2024**, *22*, 1115.
[261] H. Morita, F. Yoshiba, N. Woudstra, K. Hemmes, H. Spliethoff, *J. Power Sources* **2004**, *138*, 31.
[262] I. M. Maafa, *Polymers* **2021**, *13*, 225.
[263] P. Liu, A. Bridgwater, *Effect of Feedstock Moisture Content on the Quality of Liquids From Fast Pyrolysis of Spruce Wood*, Citeseer Bio-Energy Research Group, Chemical Engineering and Applied Chemistry, Aston University Brimingham **2001**.

Farrukh Jamil received his B.S. (Hons) in Chemical Engineering from COMSATS Institute of Information Technology (CIIT), Pakistan and did his MS Chemical Engineering from Universiti Teknologi PETRONAS (UTP), Malaysia and Ph.D. from Sultan Qaboos University (SQU), Oman. His research interest includes biofuels, catalysis, and materials.

Abrar Inayat is a Lecturer at the Department of Energy, School of Engineering, Robert Gordon University, Aberdeen AB10 7GJ, Scotland, UK. His area of research is heterogeneous catalysis, chemical reaction engineering, biomass and bioenergy, solid waste management, and energy for next generation.