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An Overview on the Conversion of Forest Biomass into Bioenergy

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Biomass plays a crucial role in mitigating the concerns associated with increasing fossil fuel combustion. Among various types of biomass, forest biomass has attracted considerable attention given its abundance and variations. In this work, an overview is presented on different pathways available to convert forest biomass into bioenergy. Direct use of forest biomass could reduce carbon dioxide emissions associated with conventional energy production systems. However, there are certain drawbacks to the direct use of forest biomass, such as low energy conversion rate and soot emissions and residues. Also, lack of continuous access to biomass is a severe concern in the long-term sustainability of direct electricity generation by forest biomass. To solve this problem, co-combustion with coal, as well as pelletizing of biomass, are recommended. The co-combustion of forest biomass and coal could reduce carbon monoxide, nitrogen oxides, and sulfide emissions of the process. Forest biomass can also be converted into various liquid and gaseous biofuels through biochemical and thermochemical processes, which are reviewed and discussed herein. Despite the favorable features of forest biomass conversion processes to bioenergy, their long-term sustainability should be more extensively scrutinized by future studies using advanced sustainability assessment tools such as life cycle assessment, exergy, etc.

Keywords: forestry, biomass, biodiesel, biogas, energy

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INTRODUCTION

Greenhouse gases (GHGs) emissions and other harmful gases are among the primary global concern, mainly caused by the increasing use of fossil energy carriers (Jun-jun and Da-rui, 2012). GHGs have been thought of as a critical factor in global warming that plays a crucial role in climate change (Panahi et al., 2020b). Extensive research has shown that using other carbon sources like biomass could reduce these concerns (Hosseinzadeh-Bandbafha et al., 2018). In the literature available on the application of biomass to generate energy, the relative importance of forest biomass is debated (Vassilev et al., 2010; Gustavsson et al., 2015). Generally, the forest biomass is classified into fuelwood and industrial roundwood (Raunikar et al., 2010). Fuelwood is harvested from forestlands and directly combusted for useable heat or converted into bioenergy and biofuel and used to generate

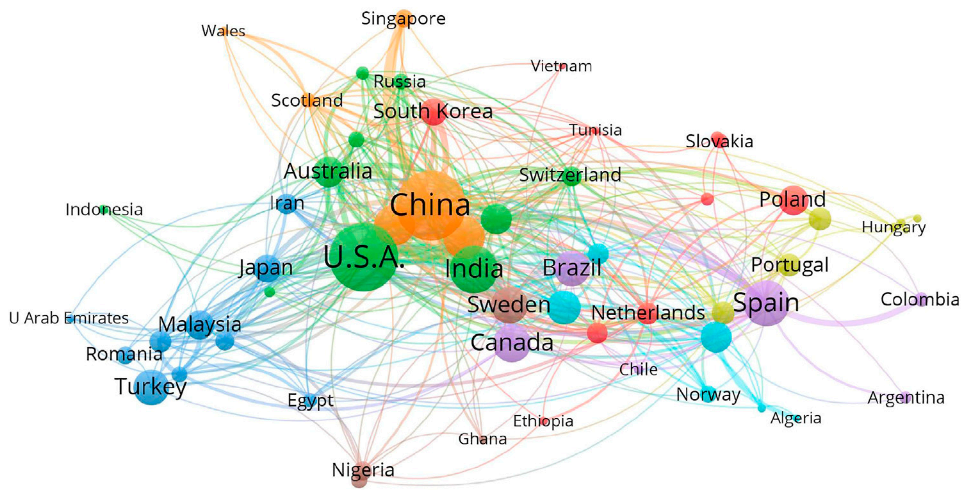

FIGURE 1 | Distribution of research activities on forest biomass to replace fossil-based energy carriers globally and the research interrelations between different countries.

TABLE 1 | Statistics by the EU on energy generation from different types of forest biomass in 2010 and estimated values in 2030.

Biomass species	Biomass potential (TJ × 10^4)		References
	2010	2030	
Forest residues	180	163–301	Moiseyev et al. (2014)
Wood processing	419	427	Searle and Malins (2016)
Forest crops	180–193	427–615	Böttcher and Graichen (2015)
Total	**779–792**	**1,017–1,343**	

heat and power. More specifically, due to the high content of macromolecular sugars such as cellulose and organic matter, fuelwood is a promising feedstock for thermochemical conversion, biological conversion, liquefaction, and gasification (Perez-Garcia et al., 2005; Tan et al., 2015). Forest biomass can be used in co-combustion with fossil fuels or alone in boilers and other equipment of power generation (Scarlat et al., 2011; Calvo et al., 2013). Accordingly, when countries set their macro strategies related to energy development, efficient utilization of forest biomass resources to solve environmental crises is strongly considered (**Figure 1**). For example, among the available energy sources in China, 54.2% of forest biomass is used to generate power and fuel (Liao et al., 2004).

It is reported that the energy generated by forest biomass can support 15.4% of the total human energy consumption (Welfle et al., 2014). During the period 2004–2015, the whole power generation from forest biomass stood at around one million kW/yr, contributing to the elimination of forest residues and achieving ecological-zero carbon dioxide (CO_2) emissions (Ince et al., 2011; Nunes et al., 2018). For instance, forest biomass application as a replacement for fossil energy in Australia reduces atmospheric CO_2 emissions by 25 million tons annually (Zomer et al., 2008; Pour et al., 2018). Furthermore, the European Union (EU) statistics show that there is an increasing trend for total energy that forest waste can provide for human consumption from 2010 to 2030 (**Table 1**) (Urban et al., 2010).

In light of the significance of forest biomass in the global energy market in the future, the present work aims to briefly report on various methods of forest biomass conversion into bioenergy and biofuels.

DIRECT UTILIZATION OF FOREST BIOMASS

Direct Combustion of Wood for Energy Production

A significant advantage of forest biomass is that it could be directly combusted. Direct combustion is a thermochemical process during which biomass burns in the open air, and the photosynthetically stored chemical energy of the biomass is converted into heat (Lam et al., 2019). Although direct combustion of forest biomass leads to the emissions of CO_2, particulates ($PM_{2.5}$), sulfur dioxide (SO_2), and other harmful substances, their amounts are still less than those caused by the combustion of fossil fuels (Karaj et al., 2010; Kacprzak et al., 2016). For example, previous research has established that the direct combustion of forest biomass generates 20% less CO_2 emissions than fossil fuels (Froese et al., 2010). However, there

TABLE 2 | CO_2 emission reduction potentials of biomass-based power plants compared to their fossil fuel-based counterparts.

Types of biomass	Country/Region	Types of power plants	Capacity of power plant	CO_2 emission reduction (t/yr)	References
Forest waste (wood chips, wood pellets, and black pellets)	Japan, Tohoku region	Thermal power plant	500 MW	198,000–252,000	(Furubayashi and Nakata, 2018)
Forest waste	Portugal, Harbor of Sines	Thermal power plant	314 MW	1,000,000	(Nunes et al., 2014)
Palm tree waste	Iran, Bushehr Province	Rankine cycle steam power plant	8 MW	40,500	(Mallaki and Fatehi, 2014)
Forest waste (woody biomass)	Japan	Thermal power plant	5.7 MW	30,934	(Nakano et al., 2015)
Forest waste (wood chips)	United States	Thermal power plant	70 MW	552,032	(Campbell and Mika, 2009)

are certain drawbacks associated with the use of forest biomass. One of these is the low energy conversion rate; moreover, direct combustion leads to soot and residues (Hong-ru and Yi-hu, 2007).

Direct combustion of biomass for power generation has continued since the 1990s (Yin et al., 2008). Biomass-fired combined heat and power (CHP) plants include a vibrating grate boiler, condensing steam turbine, and electric generator (Chen et al., 2021). The vibrating grate boiler is mechanized combustion equipment with a simple structure and small capacity. Its grate surface vibrates under the action of alternating inertial force and prompts biomass to leap forward on it to achieve mechanized combustion. Burning forest biomass produces heat within the boiler that converts water into steam (steam Rankine cycle). After water evaporation in the boiler, steam enters the turbine to expand and perform work, afterward pressure is reduced, and steam is condensed and converted to water (Dote et al., 2001). It should be noted that the steam Rankine cycle is one of the most critical thermodynamic cycles for electricity generation (Dincer and Bicer, 2020).

The conversion rate of forest biomass into electricity by Rankine cycle is reported at about 39–44%; therefore, the combustion of each ton of forest biomass generates about 4.4 kWh of electric energy (Van den Broek et al., 1996; Dote et al., 2001). One obvious advantage of using this electric energy is reducing fossil-based CO_2 emissions caused by the power generation industry. **Table 2** tabulates the CO_2 emission reductions of forest biomass-based power plants compared to their fossil-based counterparts.

A significant problem with the direct combustion of forest biomass for energy production is that these waste resources are generally far from industrial and residential areas. Moreover, the forests are vast, and biomass collation is a complex problem; thus, lack of permanent access to biomass is a severe concern in the sustainability of direct electricity generation using forest biomass. Nevertheless, it is recommended that forest biomass-based industries be located within a 120 km radius of forests to solve this concern. Still, they need a lot of financial investment and storage capacity (Hoffmann et al., 2012).

Co-combustion of Forest Biomass and Coal

Co-combustion is a feasible and straightforward option for solving the concerns associated with the direct combustion of forest biomass, such as permanent access to biomass, the area required for storage, and economic problems related to transportation and distribution (Liang et al., 2017). The main advantage of the mixed combustion of biomass and coal vs. coal combustion is that it could reduce carbon monoxide (CO), nitrogen oxides (NOx), and sulfide emissions while ensuring production efficiency (Perea-Moreno et al., 2017). Technically, the co-combustion of forest biomass and coal uses pulverized coal boiler and fluidized bed boiler as the reactor. In the fluidized bed boiler, when forest biomass is added, the generation of nitric oxide (NO) is reduced, and the combustion process is more efficient (Kabir and Kumar, 2012). Also, compared to coal, the volatile content of biomass is higher that is a favorable parameter for rapid ignition. It has been found that 87 tons of CO_2 emission could be reduced by replacing 1 ton of coal with forest biomass during co-combustion (Royo et al., 2012). It is estimated that in 2030 and beyond, biomass utilization will increase by 450,000 t/yr, and relevant CO_2 emission reduction will reach 395,000 t/yr (Kazagic et al., 2016). Furthermore, alkaline ash caused by biomass combustion can block SO_2 emissions from coal and reduce global acidification (Demirba, 2005; Tsalidis et al., 2014).

Due to reducing harmful gases and increased power generation reliability, co-combustion is considered a cheap option to utilize existing biomass resources in power generation (McIlveen-Wright et al., 2011). Given this fact, thermal power plants can use biomass as clean and cost-effective combustion supporting agent to mix with coal (Dai et al., 2008). However, forest biomass suffers from several significant drawbacks despite these desirable features, e.g., poor energy density, high particle emissions, unstable combustion performance, and difficulties in storage and transportation (Kang et al., 2018). Hence, future research should aim at providing solutions to mitigate these obstacles.

FOREST BIOMASS PELLETS

Several techniques have been developed to facilitate the transportation and improve the conversion rate of forest biomass, like mechanical processing of biomass into granular substance (pellet). Pelleting of forest biomass improves its density and reduces water content (Valdés et al., 2018). Density and moisture are two critical properties of biomass affecting combustion efficiency. Hence, direct combustion or co-combustion of pelleted forest biomass with coal could increase combustion efficiency. For instance, it has been reported that the efficiency of pellet-fired boilers ranged between 85 and 90% compared with wood-fired boilers varying from 75 to 85% (Sandro et al., 2019).

Forest biomass can also be mixed with other biomass to enhance the overall properties of the mixture for pellet production (de Souza et al., 2020). For instance, the water content of biomass pellets could affect their durability, a property that could be adjusted by mixing different types of forest biomass. More specifically, when the moisture content of forest biomass is reduced to 1–5%, the average durability reaches 95%, which is convenient for the storage and transportation of the product (Pradhan et al., 2018).

In the manufacturing process of forest biomass pellets, the biomass needs to be dehydrated in advance (Civitarese et al., 2018). A rotary dryer could be used to remove the moisture in poplar wood chips, with a moisture removal rate of about 17%. In comparison, the moisture removal rate for *Robinia pseudoacacia* sawdust stands at a higher rate of 31%. These differences are ascribed to the differences in the density of various types of forest biomass (Prokkola et al., 2014; Del Giudice et al., 2019). Notably, if the rotary dryer cannot remove the moisture effectively, the pneumatic dryer would be a good choice, also increasing the drying rate by 22% (Frodeson et al., 2013).

From an environmental point of view, it is reported that if biomass pellets are used instead of coal for power generation, CO_2 emissions will be reduced by 205 Mt annually (Purohit and Chaturvedi, 2018). Sikkema et al. (2011) reported that through the consumption of 8.2 million tons of wood pellets, 12.6 million tons of CO_2 emissions were avoided in all EU countries in 2008.

Compared with sawdust, coal, and other traditional fuels, mixing forest biomass pellets with coal causes less harm to the environment. For example, co-combustion of forest biomass pellets and coal reportedly led to a 50% reduction in CO_2 emission, and the ash formed in the combustion process only accounted for about 1%, 15–20 times less than coal combustion (Palšauskas and Petkevičius, 2013; Morrison et al., 2018). Ehrig and Behrendt (2013) also showed that co-firing wood pellets with coal resulted in lower CO_2 than other renewables. It is also claimed that adding eggshells in the combustion of forest biomass pellets could also absorb CO_2 through the calcium carbonate present in eggshells, further reducing GHG emissions (Yuan et al., 2019). Molina-Moreno et al. (2016) also reported that CO and NO_x emissions levels caused by pellets combustion were very satisfactory. Tamura et al. (2014) claimed that co-firing wood pellets with coal when wood pellets were burnt in lower row burners could prevent CO emissions.

Despite these promising results, power plants relying on forest biomass pellets also face several problems such as high energy consumption, labor-intensive process, higher prices than other solid biofuels, need for higher storage space in comparison with oil, need for ash removal, and susceptibility of pellets to moisture exposure (Abdoli et al., 2018).

CONVERSION OF FOREST BIOMASS INTO LIQUID BIOFUELS

The pollution caused by diesel combustion in diesel engines is one of the main contributors to global air pollution (Aghbashlo et al., 2017b; 2018b). The most crucial emissions released from diesel combustion are CO_2, NO_X, sulfur oxides (SO_X), CO, and PM emissions (Aghbashlo et al., 2021b). There is evidence that these emissions play a crucial role in damage to the environment and human health (Hosseinzadeh-Bandbafha et al., 2020). To solve the problem associated with diesel exhaust emissions and to mitigate the existing environmental pressure, cleaner alternatives to diesel are widely sought (Khalife et al., 2017; Aghbashlo et al., 2018a).

Biodiesel, long-chain fatty acid methyl or ethyl esters (FAME or FAEE, respectively) is produced mainly *via* the transesterification reaction using short-chain alcohols, i.e., methanol or ethanol, and in the presence of a base or acid catalyst (Chuah et al., 2017; Hajjari et al., 2017). Compared with diesel, biodiesel combustion leads to lower smoke, PM CO, and unburned hydrocarbon (HC) emissions (Amid et al., 2020). Also, it contributes much less to global warming than diesel because the carbon contained in biodiesel is mainly of biogenic CO_2 origin (Hosseinzadeh-Bandbafha et al., 2018). The research on biodiesel production has already reached maturity, resulting in replacing diesel with various biodiesel blends in many parts of the world. It should be quoted that neat biodiesel and its blends (up to 20%) with diesel can be used in diesel engines without requiring engine modifications (Narasimharao et al., 2007).

Despite its advantages, some physicochemical properties of biodiesel limit its widespread application, including higher viscosity of biodiesel than fossil diesel and poor cold flow properties (Aghbashlo et al., 2015; Pang, 2019). Moreover, biodiesel production from first-generation feedstock (edible vegetable oils) has led to high production costs and triggered competition between fuel and food over arable land water resources (Aghbashlo et al., 2017a). Fuels derived from waste biomass are classified as second-generation biofuels and are regarded as a solution to overcome the mentioned competition between food and fuel (Laesecke et al., 2017). High oil content tree species are suitable raw materials for biodiesel production (Patel et al., 2019).

Pyrolysis is also a promising thermochemical valorization technique for producing biofuels from forest waste at moderate temperatures (typically between 300 and 1,300°C) (Aghbashlo et al., 2019; Yek et al., 2020) During this process, the feedstock's chemical structure faces fundamental changes (Foong et al., 2020; Ge et al., 2021). Generally, pyrolysis is known as the method with the ability to produce a variety of solid, liquid, and gaseous products depending on pyrolysis conditions (Aghbashlo et al., 2021a). Slow pyrolysis produces solid products such as biochar or charcoal, while fast pyrolysis results in the production of liquid products (bio-oil). It is reported that forest biomass is an ideal feedstock for pyrolysis (Chireshe et al., 2020), and different researchers have successfully conducted pyrolysis of forest biomass to produce bio-oil (Oasmaa et al., 2010; Puy et al., 2011; Stefanidis et al., 2015;

TABLE 3 | Potential of different types of forest biomass for second-generation bioethanol production.

Biomass species	Convertible materials (%)	Convertible materials yield (t/ha/yr)	Potential bioethanol yield (L/ha)	References
Manihot esculenta	35 (Sugar)	30	4,500–4,901	Zabed et al. (2016)
Miscanthus spp.	56–73.5 (Holocellulose)	5–43	4,600–12,400	Ho et al. (2014)
Panicum virgatum	35–70 (Holocellulose)	5–25	555–3,871	Zabed et al. (2016)
Populus spp.	56 (Holocellulose)	2–10	1,500–3,400	Ho et al. (2014)
Saccharum spp.	12–17.6 (Sugar) 61–73 (Holocellulose)	70–122.9 (Sugar) 19.6–34.4 (Holocellulose)	5,345–9,950	Lebaka (2013)
Salix spp.	69.9 (Holocellulose)	5–11	769–4,026	Zamora et al. (2014)
Triticum aestivum	65.3–76 (Sugar) 59–70 (Holocellulose)	1.8–6.4 (Sugar) 6.5–11 (Holocellulose)	1,001–1700	Lebaka (2013)

Luo et al., 2017). It should be noted that the bio-oil produced by the pyrolysis process typically has a high oxygen and water content, and thus, it should be upgraded (van Schalkwyk et al., 2020).

Another conversion pathway to valorize forest biomass is gasification. González and García (2015) converted wood biomass into bio-oil through the gasification process and subsequent liquefaction (Fischer-Tropsch). Natarajan et al. (2014) reported that the installation of five Fischer-Tropsch plants could contribute to achieving Finland's various 2020 targets, i.e., using up to 58% of the available forest biomass for energy production, total emission reduction of 4%, and powering the transportation sector with 100% biofuel. Sunde et al. (2011) also estimated that converting forest biomass and woody wastes into liquid biofuel by the Fischer-Tropsch process as a replacement for fossil diesel could reduce the overall environmental impacts of the transportation sector in Norway. GHG savings and reductions in greenhouse impacts by production and use of Fischer-Tropsch biofuel from forest residues are estimated to amount to roughly 20–90% on a 100-year timescale (Jäppinen et al., 2014). It should also be noted that in addition to reducing CO_2 emissions, biofuel production from forest biomass could also offer economic opportunities, including creating new jobs (Natarajan et al., 2014).

Bioethanol production from forest biomass has also been investigated since the early 1990s (Mabee and Saddler, 2010). The lignocellulosic nature of forest biomass (such as *PopulusL.*, *Salix babylonica*, and *Saccharum officinarum*) and its abundance mark it as a suitable feedstock for second-generation bioethanol production (Limayem and Ricke, 2012; Ko et al., 2020). International Energy Agency (IEA) estimates that the potential use of 10% of global forest and agricultural biomass in 2030 can provide 233 billion L of bioethanol, equivalent to 155 billion L of gasoline (Morales et al., 2021). The bioethanol production potentials of several forest biomass are shown in **Table 3**.

Bioethanol is well known as a promising substitute for petroleum-based gasoline (Huang et al., 2020; Amid et al., 2021), with considerably lower emissions throughout its life cycle (Mabee and Saddler, 2010). For example, Becerra-Ruiz et al. (2019) reported a decrease of 99, 93, and 67% in CO, HC, and NOx, respectively, when a 5500 W portable engine generator of alternating current burned bioethanol instead of gasoline. Compared to first-generation bioethanol such as corn and sugarcane-based bioethanol, second-generation bioethanol (i.e., bioethanol produced from lignocellulosic feedstocks) has significantly lower life cycle GHG emissions (Wang et al., 2020). Moreover, bioethanol yields of forest biomass are relatively higher than those of other types of biomass. In a study investigating bioethanol yields, Mabee and Saddler (2010) reported that bioethanol yields of forest biomass ranged between 0.12 and 0.3 m^3/t (dry basis) vs. 0.11 and 0.27 m^3/t (dry basis) for bioethanol production from agricultural residues.

The biochemical or thermochemical conversion are two primary methods used to process lignocellulosic feedstocks into bioethanol (Soltanian et al., 2020). The biochemical conversion starts with pretreatment to separate hemicellulose and lignin from cellulose and is followed by hydrolysis of cellulose to obtain fermentable sugars (Panahi et al., 2020a). Finally, sugars are fermented into ethanol (Anyanwu et al., 2018). Pretreatment is an instrumental stage of the process, and hence, its type and conditions play important roles in the overall technical viability of the whole process (Negro et al., 2020; Morales et al., 2021). The various pretreatment methods include chemical, physical, physicochemical, and biological (Sharma et al., 2020).

It should be noted that forest biomass, due to the presence of bark and juvenile wood, tends to have higher lignin contents (Zhu et al., 2015). As a result, forest biomass is more recalcitrant to bioconversion into sugars than other biomass types such as agricultural residues (Yamamoto et al., 2014). Although there are pretreatment processes to overcome such a high level of recalcitrance for efficient sugar/biofuel production, they are more time-consuming and costlier. One of these methods is steam explosion treatment which has been reported to increase bioethanol production of *Hemp fiber* by upto 70% (Zhao et al., 2020). It has also been claimed that the application of surfactants, owing to their unique structure and functional properties, could improve the solubility, fluidity, bioavailability, and biodegradability of forest biomass, thereby increasing the production of bioethanol. Zheng et al. (2020) argued that tween, polyethylene glycol (PEG), and sulfonate-based surfactants could increase the conversion rate of lignocellulose by 10–20%.

Compared to the biochemical conversion, thermochemical conversion, particularly gasification, can be applied to a broader range of forest biomass (Wang et al., 2020). During gasification of the lignocellulosic biomass at high pressure and in the absence of inert gases, lignocellulosic biomass is converted into syngas, which will then be converted into bioethanol through the Fischer-Tropsch process (Laesecke et al., 2017). Also, syngas can be utilized by the microorganism *Clostridium ljungdahlii* to generate bioethanol in the presence of catalysts (Limayem and Ricke, 2012).

CONVERSION OF FOREST BIOMASS INTO GASEOUS BIOFUELS

The gasification process of forest biomass leads to syngas production through a series of thermal cracking reactions (Burbano et al., 2011). Forest biomass, including seeds, leaves, tree trunks, and fruit shells, could be pyrolyzed in a fixed bed gasifier for a long time at high temperatures (above 1,200°C) to produce hydrogen-rich syngas (Brachi et al., 2014; Ozbas et al., 2019), which has been highlighted as one of the most promising alternative sources of energy (Shih and Hsu, 2011). It is claimed that 1.3 Gt/yr of biomass can produce 100 Mt/yr of hydrogen (Duan et al., 2020).

During gasification, the reaction rate can be controlled by adjusting the gas flow. Using this strategy, the decomposition rate of forest biomass into hydrogen could reach 60% (Solar et al., 2018). The cost of hydrogen production from forest biomass through gasification is about 1.18 USD/kg H2 (Sarkar and Kumar, 2009), almost half of the other processes (Sarkar and Kumar, 2010). It should be noted that industrial gasification devices are usually connected with power generation equipment to generate electricity while providing gas; the former can be supplied to nearby households (Sasujit et al., 2017; Schulzke, 2019).

Adding appropriate catalysts to the gasification process can improve the gas content (Pang, 2019). In the catalytic gasification experiment of *Eucalyptus* residue with NiO as the catalyst, the total gas production increased by 30%. Corujo et al (2010) also reported that through catalytic gasification, the biochar and ash contents were decreased, and the utilization rate of biomass was improved. It has been argued that catalytic cracking is more economical than traditional biofuel production methods such as pyrolysis and fermentation (Meerman and Larson, 2017).

In addition to producing hydrogen-rich syngas, forest biomass can also be used to produce biogas through anaerobic digestion (Tabatabaei et al., 2020a). The technology of converting forest biomass into CH_4 is relatively mature and has been used for practical production for many years (González et al., 2006; Tabatabaei et al., 2020b). The production of biogas, whose main components are CH_4 and CO_2, is largely affected by the composition of raw materials (Dehhaghi et al., 2019). It should be noted that in addition to species, the composition of forest biomass could also be affected by variations in geographical location and growth environment.

One of the main challenges of anaerobic digestion is the non-degradability of lignin under anaerobic conditions (Dehhaghi et al., 2019). In better words, lignocellulose-rich organic materials such as forest biomass suffer from the disadvantage of low availability of cellulose and hemicellulose as biodegradable components for microorganisms and their enzymes (Lópe et al., 2013). Nevertheless, similar to other types of lignocellulosic biomass, chemical (hydrolysis with acids, alkali, or oxidants), physical (irradiation, shredding, thermal, and pressure shocks), and biological (fungi, actinobacteria, or their enzymes) pretreatments could also be employed to improve the anaerobic biodegradation of forest biomass (Chang and Holtzapple, 2000; Taherzadeh and Karimi, 2008; Hendriks and Zeeman, 2009).

CONCLUSION

It was shown that forest biomass could, directly and indirectly, be used as an energy resource. More specifically, forest biomass can be directly combusted to reduce CO_2 emissions associated with conventional energy production processes. However, the energy conversion rate of forest biomass is low, and it also leads to emissions of soot and residues. Also, the lack of continuous access to biomass and the need for lots of financial investment and storage capacity are among the severe concerns in the sustainability of direct electricity generation using forest biomass.

In comparison, co-combustion of biomass and coal vs. combustion of coal alone could be regarded as a promising strategy to reduce emissions while ensuring production efficiency. It also partly solves issues related to biomass availability, the area required for storage, and economic problems related to transportation and distribution. Despite these desirable features, forest biomass suffers from poor energy density and high moisture, which could be addressed by pelleting forest biomass. Due to the improved density and moisture, direct combustion of pelleted forest biomass or its co-combustion with coal accelerates the combustion rate. Nevertheless, power plants relying on forest biomass pellets also face several problems such as high energy consumption, labor-intensive process, and higher prices than other solid biofuels. Forest biomass also can be converted into bio-oil, bioethanol, and biogas by biochemical and thermochemical methods, which are critically explained in the present work.

Given the growing awareness about the environmental consequences of burning fossil fuels, the future will undoubtedly shift toward the use of more biomass and biofuels. Although forest biomass conversion processes to bioenergy are well known, as mentioned, their long-term sustainability should be more extensively scrutinized by future studies using advanced sustainability assessment tools such as life cycle assessment, exergy, etc.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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