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Review

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A R T I C L E I N F O

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A B S T R A C T

Due to increasing anthropogenic activities, especially industry and transport, the fossil fuel demand and consumption have increased proportionally, causing serious environmental issues. This attracted researchers and scientists to develop new alternative energy sources. Therefore, this review covers the biofuel production potential and challenges related to various feedstocks and advances in process technologies. It has been concluded that the biofuels such as biodiesel, ethanol, bio-oil, syngas, Fischer–Tropsch H_2, and methane produced from crop plant residues, micro- and macroalgae and other biomass wastes using thermo-bio-chemical processes are an eco-friendly route for an energy source. Biofuels production and their uses in industries and transportation considerably minimize fossil fuel dependence. Literature analysis showed that biofuels generated from energy crops and microalgae could be the most efficient and attractive process. Recent progress in the field of biofuels using genetic engineering has larger perspectives in commercial-scale production. However, its large-scale production is still challenging; hence, to resolve this problem, it is essential to convert biomass in biofuels by developing novel technology to increase biofuel production to fulfil the current and future energy demand.

1. Introduction

Currently, intensive anthropogenic and industrial activities around the world have led to increased energy demand and environmental protection (Kyriakopoulos et al., 2006a, 2006b; Ambaye et al., 2020). In 2014, coal, natural gas and petroleum satisfied more than 80% world's energy demand (IEA, 2015). According to UN Environment Emission Gap Report (2014), the total greenhouse gases (GHGs) emission from the road transport sector was around 54 gigatons of CO_2 equivalent, which will increase to 87 gigatons of CO_2 equivalent in 2050, and this volume could cause various adverse impacts on natural resources and environments like pollution and global climate change (Prasad et al., 2012; World Oil Outlook, 2015). This pollution needs attention to overcome these problems in the changing scenario. A report of International Energy Agency (2015) projected that petroleum oil and gas reserves and crude oil supply shortages possibly would pose severe energy security emergencies to the world. It was estimated that the growing energy need will outpace the limited oil supply globally from 2020 (IEA, 2015).

Biofuels produced from biomass resources through eco-friendly approaches are getting attention worldwide from researchers and scientists (Uzoejinwaet al., 2018). At present, various gaseous and liquid biofuels (e.g., biodiesel, ethanol, methanol, methane, bio-oil and Fischer–-Tropsch H_2) are produced from biomasses (Demirbas, 2009; Bahadar and Khan, 2013; Voloshin et al., 2016; Joshi et al., 2019; Prasad et al., 2020a, 2020b). These biofuels have shown great potential for future energy supply and to achieve energy security sustainably (Choi et al., 2010). Biofuels use as renewable energy reduces air pollutant emissions including GHGs, especially CO_2 during the combustion process, thus

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minimizing the overall pollution load and other environmental impacts (Prasad et al., 2014a, 2014b, 2020a, 2020b; Anukam et al., 2019). Biofuels production and their use are also reported as a carbon-neutral path because they are produced from biomass, which absorbs the greater amount of CO_2 released to the environment (IEA, 2012; Prasad et al., 2012; Kelsi, 2016).

It is forecasted that about 10–50% of the world's energy consumption would be produced from biomass until the year 2050 (Kumar et al., 2015). This estimation indicates that biomass will be one of the biggest sustainable energy resources worldwide (Moreira, 2006). Several types of biofuels generation technologies are used worldwide, generally known as the 1st, 2nd, 3rd and 4th biofuels generation technologies. Surriya et al. (2015) proved that the biofuel produced from the 1st-generation technology has a certain limitation. However, second and third generations biofuels have greater production potential of biofuels. Hence, the main objective of this review is to analyze and discuss the different technologies for biofuels production using various bioresources on a large scale. This review provides an overview of emerging technologies for biofuel's production. This review will help to contextualize and to address problems associated with current biomass to biofuels conversion technologies. We tried to link the challenges facing biofuels production to its environmental dimensions, especially the outputs and the results of their use in a sustainability context (Kyriakopoulos, 2010; Ambaye et al., 2020). Today, research should be oriented to improve feedstock productivity and boost the efficiency of biomass conversion to biofuels. Plenty of studies on biomass potentials appear in the literature. Technical biomass potential of 150 EJ/year was reported claiming 200–500 EJ/year by 2050 (Elbersen et al., 2012). Within 2030 and concomitant with the sustainable development goals (SDGs), researchers claim the reduction of organic waste (management and valorization of waste) and its conversion to biofuels with a yield of 350 Mtoe (Mega-tons of oil equivalent) compared to the current values of 310 Mtoe.

2. Progress in global energy recovery from biomass resources

Traditionally, the biomass use has remained a major source of energy supply and has influenced the society and environment, locally, regionally and globally (Prasad et al., 2007; BP, 2018; Ebadian et al., 2020). Many conflicts and issues have been noticed with the direct burning of biomass for energy supply. It has significantly contributed to GHGs emissions and climate change. Energy recovery from biomass using modern biofuel production technologies has great potential for global energy security and balancing trade deficits (Dornburg et al., 2008). Worldwide several efforts are going on towards transition from traditional to modern biomass utilization in the current energy supply. According to the comprehensive source data from Renewable Energy Statistics (2020), the total renewable energy production and capacity (CAP) in 2019 reached 2533 GW. Out of which, as shown in Fig. 1, the maximum power output was contributed by hydropower (1308 GW) followed by wind energy (622 GW), solar energy (585 GW), and bioenergy (126 GW).

According to the IRENA-2020 global estimations, the current total bioenergy production was reported to around 115.7 GW. The highest bioenergy production was accessed in the European Union (38.5 GW), followed by Asia (36.27 GW). In Asian countries, China has contributed to the highest bioenergy production (16.54 GW), followed by India (10.23 GW). Leading global bioenergy capacity by country is presented in Fig. 2.

As shown in Fig. 3, the world biofuels production from 2007 to 2017 increased at an annual growth rate of 11.4% (Ebadian et al., 2020). According to the IEA report, worldwide biofuel generation was intensified by 10 billion liters in 2018 to record 154 billion liters. It is forecasted to expand by 25% in 2024, with an expected 3% annual growth rate. However, bioenergy has significant challenges and uncertainties (especially crude oil price uncertainties), including political risks and financial obstacles. Also, the technological obstacles for the commercialization of advanced biofuels have proven to be greater than envisioned. Despite all these, the biofuel industry continues to expand, and its share in global energy consumption continues to increase. Around 2.8 million jobs were created by the bioenergy sector (Kummamuru, 2016), indicating its role in providing job opportunities (Kummamuru, 2016).

Biofuels production in the US reached 16.6 billion gallons in 2016, from 14.1 billion gallons in 2012 (U.S. EPA, 2018). However, as Fig. 4 shows, the production increase was relatively slow, recently likely due to challenges associated with the E10 blend wall (10% ethanol blend with gasoline). Ethanol production from September 2018 to August 2019 was over 16.93 billion gallons (approx. 64 billion liters). Biodiesel production was put at more than 1.724 billion gallons (approx. 6.5 billion liters) (U.S. EPA, 2018).

3. Biomass availability for biofuel production

Biomass is a renewable resource and readily available for either

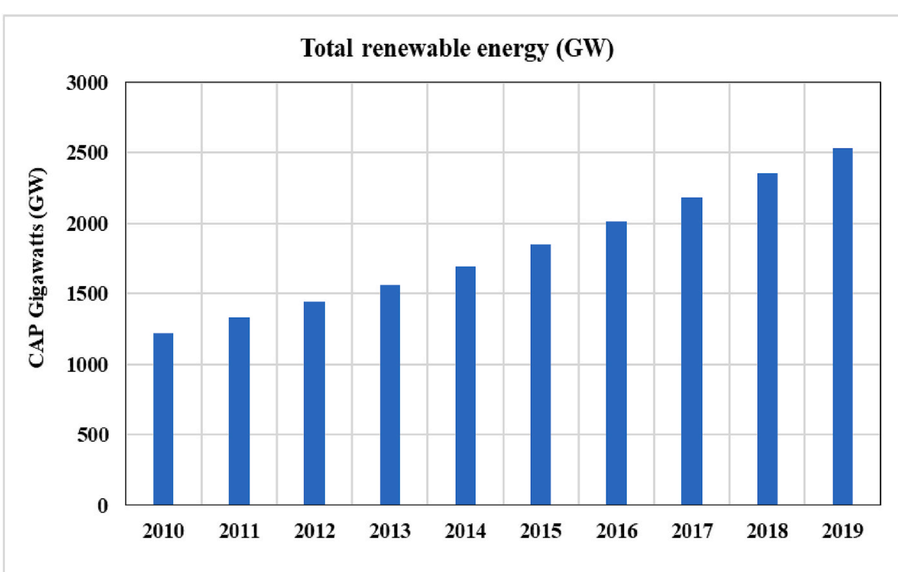

Fig. 1. Global renewable energy production and capacity (CAP); *Source:* IRENA (International Renewable Energy Agency), 2020.

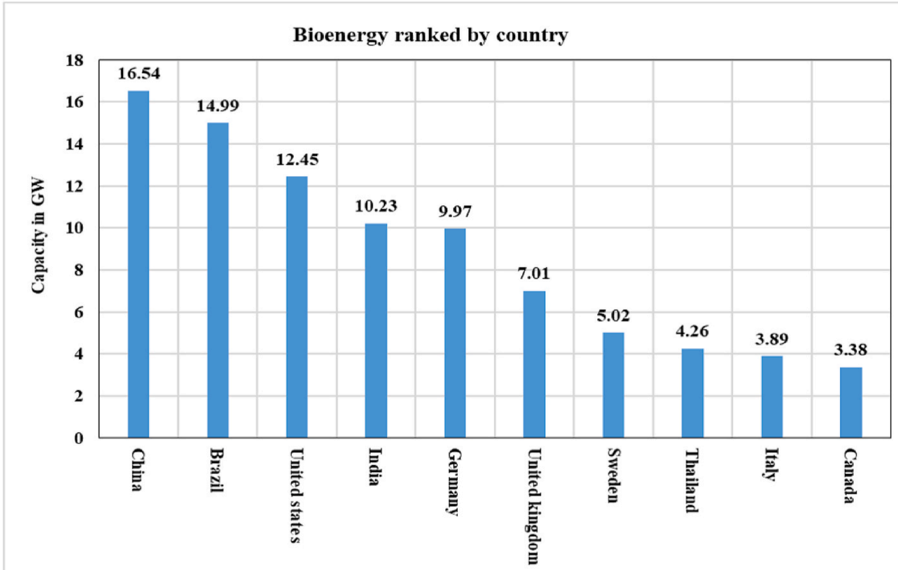

Fig. 2. Worldwide position of bioenergy power ranked by country 2019. Source: https://www.statista.com/statistics/274168/biofuel-production-in-leading-countries-in-oil-equivalent/.

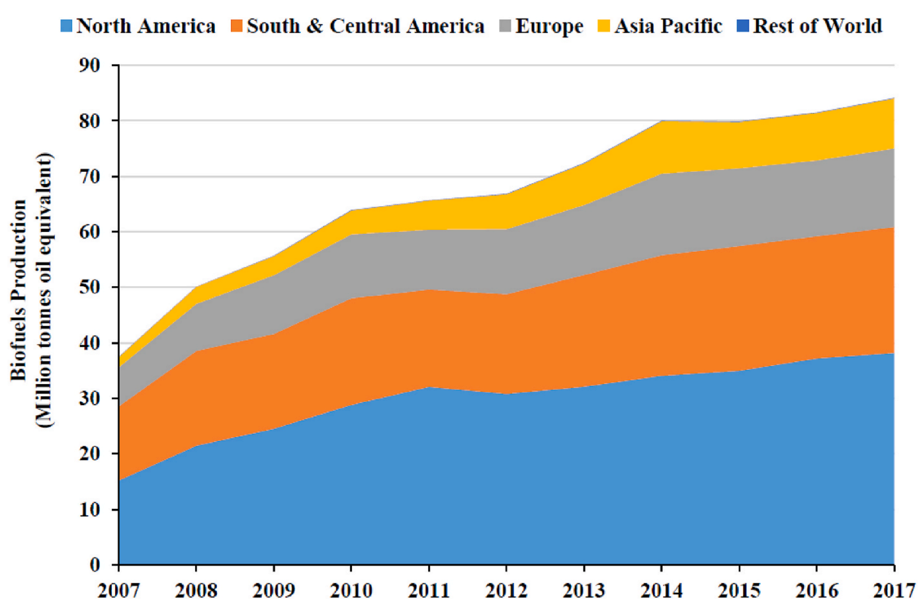

Fig. 3. World biofuels production (adapted from BP, 2018). Source: https://blogs.nottingham.ac.uk/geography/2020/06/25/global-biofuel-production-trend-the-inevitable-energy-bio-future-for-achieving-global-climate-target/.

straight as a biofuel or transformed into another form of bioenergy that is usually introduced as feedstocks. Biomass residues and waste products from agriculture, agro-industries generated waste, forest by-products, and municipal solid waste are the potential and sustainable feedstocks for biofuels production. Popp et al. (2014) reported that agriculture and forestry residues and municipal sewage wastes could provide 50–150 Exajoule (EJ) per year. It is estimated that by 2050, the world's core energy market would be 600–1000 EJ per year. The world potential of biomass may reach 200–500 EJ per year, especially from the forest wastes (80 EJ), agricultural wastes (100 EJ), dedicated energy crops (120 EJ), and intensive residues (140 EJ).

Lal (2005) reported that globally, crop residue production from cereals, legumes, oilseeds, and sugar crops was about 6411 million tons (MT) in 1991, reaching 6973 MT (8.7% higher than 1991) in 2001. According to FAO, in 2016, the agriculture holds nearly one-third of the entire global land area under major cultivated crops like sugarcane, maize, wheat, rice, and potatoes (FAO, 2018). As per OECD (2017) estimate, almost 182 MT of crop-residues (originated from sugarcane, rice, maize, wheat) were burnt in Brazil, China, United States, and India in 2016, and it was equal to 15.77 MT of CO_2 (Prasad et al., 2020a,b).

The world's biggest crop producers, along with the corresponding cereal and straw yields, and useable straw estimates, are shown in Table 1. According to the IRENA estimations (Nakadaet al., 2014), by 2030, the worldwide total biomass supply will be ranged from 97 to 147 EJ/y (in energy terms). By 2050 it is forecasted that the amount of biomass waste will increase, in which agricultural residues will remain the biggest proportion in total biomass supply and will provide up to 550 EJ/y (as shown in Fig. 5). However, energy crop production's stability depends on land availability and impeding factors like water availability, nature stability, biomass production cost, and existing

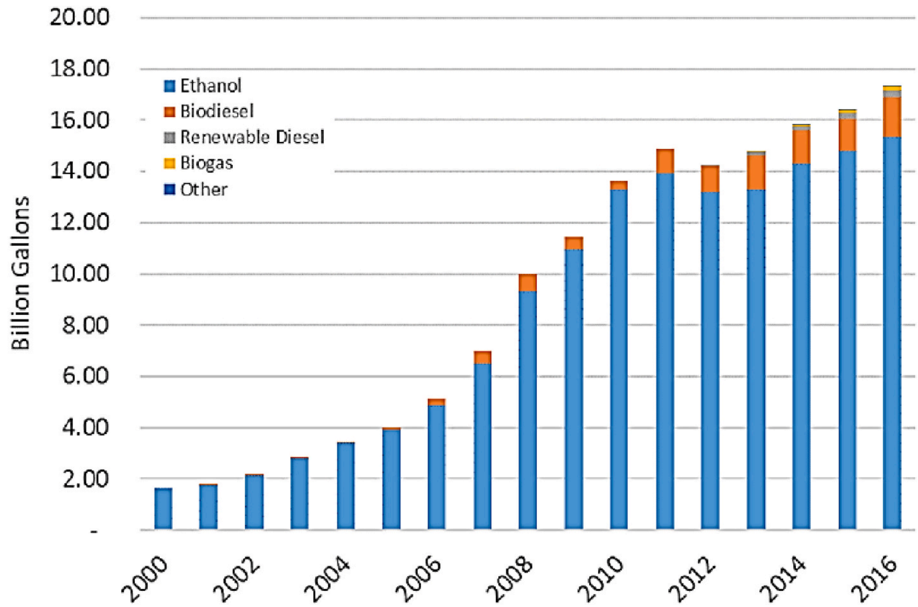

Fig. 4. Global growth of biofuel production from 2000 to 2016, Source: https://www.ers.usda.gov/data-products/us-bioenergy-statistics/.

Table 1
Worldwide cereal grain production and estimated straw residues in 2013 (data expressed in Mt; adapted from Baruya, 2015).

Countries	Wheat grain	Maize grain	Estimated residue/ straw (equal to mass to wheat & maize)	Estimated useable residue/straw (25% of straw residue)
China	122	122	340	85
India	94	94	117	29
USA	58	58	412	103
Brazil	6	81	86	22
Russia	52	12	64	16
Ukraine	23	31	54	13
France	39	15	54	13
Canada	38	14	52	13
Argentina	8	32	40	10
Germany	25	4	29	7
Pakistan	24	5	29	7
Turkey	22	6	28	7
Mexico	3	23	26	7
Australia	23	1	23	6
Romania	7	11	19	5
Indonesia	0	19	19	5
Iran	14	3	17	4
Egypt	10	7	16	4
Kazakhstan	14	1	15	4
South Africa	2	12	14	4
Italy	7	7	14	3
Poland	10	4	14	3
Spain	8	5	13	3
UK	12	0	12	3
Hungary	5	7	12	3
Ethiopia	4	7	11	3
Nigeria	0	10	11	3
Serbia	3	6	9	2
Bulgaria	5	2	7	2
Philippines	0	7	7	2
Rest of the world	200	310	510	128
World Total (Mt)	835	1235	2070	517
World Total (EJ) at 14 MJ/kg	12	17	29	7

supply chain infrastructure. Low-cost residue sourcing can be important since pelletizing wood chips, straw at harvest, and residue originates after post-harvest add further value to the final biomass product.

Fried and cooking wastage oils from hotels, restaurants, and food processing units are alternative sources to obtain additional lipid and fatty acid methyl esters (FAME). Transesterification of waste cooking oil as feedstocks is likely to reduce the biodiesel generation cost up to 60–90% (Talebian-Kiakalaieh et al., 2013). Additionally, the recovery of waste cooking oils for biodiesel production is a better alternative to their disposal, which usually generates environmental impacts (Meng et al., 2008). Another abundantly available promising feedstock of oil due to their high lipid accumulation is macroalgae (seaweeds) and frequently growing microalgae in ponds. Additionally, they do not compete for essentially agricultural land or water resources (Lee et al., 2020). According to the Algae Biomass Organization (ABO, 2016), saltwater algae can potentially yield 86 MT of algal biomass per year. It has been also reported that saltwater algae can capture 211 MT of CO_2 from carbon-intensive industrial sources.

3.1. Composition of crop residues and other biomass wastes

Biomass is a versatile energy resource for biofuels, its biochemical structure and composition greatly affect biofuel productivity, so it is necessary to understand its major chemical structure. Cellulose, hemicellulose, lignin, and small fractions of inorganic matter constitute the plant cell-wall. Thus, it is called lignocellulosic biomass and, however, its mass balance and biochemical composition differ in each plant species. Cellulose, hemicellulose, and lignin contents in agricultural residues, cattle manure, chemical pulps, and sorted wastes are shown in Table 2.

In addition to this composition, the degree of biomass decomposition during pyrolysis and hydrolysis depends on the biomass component's biochemical balance and structural stability (Zhao et al., 2012). For instance, Ahorsu et al. (2018) stated that the pyrolysis of hemicellulose or cellulose could produce a higher yield oil than lignin. In another study, Yang et al. (2007) characterized the pyrolysis of hemicellulose, cellulose, and lignin and found that about 94.5% of loss of weight of cellulose at 400 °C and 80% loss of weight for hemicellulose at 268 °C, while for lignin, only 54% loss weight was identified at pyrolysis temperature of 900 °C. Note that this variation in the pyrolysis temperature and oil yield was due to the biomass components.

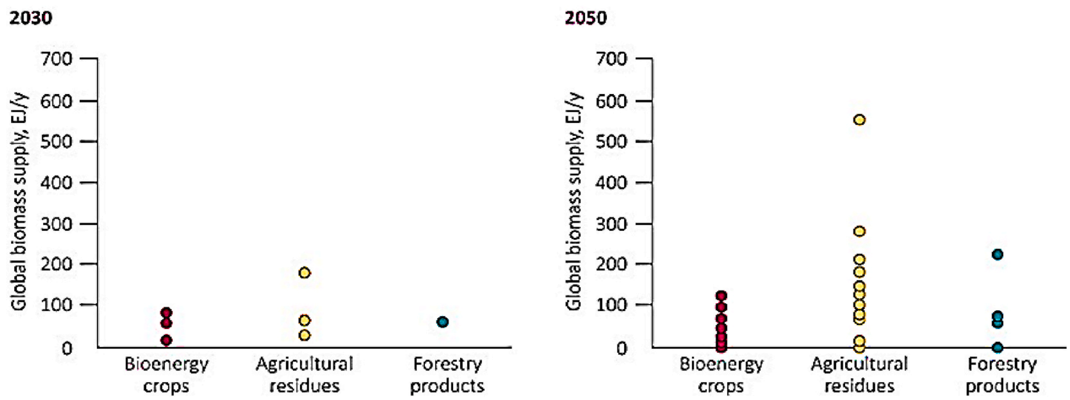

Fig. 5. Global biomass energy supply and estimated potential by 2030 & 2050 (adapted from Slade, 2011).

Table 2
Cellulose, hemicellulose, and lignin content in agricultural residues and wastes (Prasad et al., 2007).

Agricultural residue	Cellulose	Hemicellulose	Lignin
Wheat straw	33–40	20–25	15–20
Rice straw	40	18	55
Corn Cobs	45	35	15
Nutshells	25–30	25–30	30–40
Cottonseed hairs	80–90	5–20	0
Leaves	15–20	80–85	0
Solid cattle manure	1.6–4.7	1.4–3.3	2.7–5.7
Swine waste	6.0	28	
Primary wastewater solids	8–15	–	24–29
Paper	85–99	0	0–15
Newspaper	40–55	25–40	18–30
Sorted refuse	60	20	20
Waste papers (chemical pulps)	60–70	10–20	5–10

Table 3
Composition of carbohydrate–lipid-protein in various microalgae (adapted from Hossain et al., 2019).

Type of microalgae	Total sugars	Protein	Lipids	Others (including ash content)
	On a dry weight basis (%)			
Chlamydomonas reinhardtii	48	17	21	14
Chlorella sp.	56	22	19	3
Spirogyra sp.	20	55	16	9
Porphyridiumcruentum	35	50	11	4
Spirulina platensis	60	12	8	20
Dunaliellasalina	57	32	6	5
Bellerochea sp.	3	24	15	3
Chaetoceros sp.	2	18	18	3
Rhodomonas sp.	9	74	15	2
Scenedesmus sp.	18	56	12	–

Moreover, these authors claimed that from the lignocellulosic biomass pyrolysis, there is a significant amount of biochar can be obtained as a sub-product due to the lignin. Gani et al. (2007) reported the same result in their study where the pyrolysis and combustion characteristics of different biomasses (e.g., corn stalk, cellulose, rice husk, bark, and lignin) showed that those biomasses with a high cellulose content displayed a fast rate of pyrolysis. Biomasses with a high content of lignin showed low pyrolysis rates due to the difference in the material morphology thus causing a variable composition in the pyrolysis products. Another factor that affects the reactivity of the biomass during the pyrolysis is the presence of heteroatoms and oxygen (O_2) contents. For instance, according to Tatterson et al. (1990), the effect of feedstock composition on pyrolysis showed that high heteroatom and O_2 contents in biomasses enhanced their reactivity during the pyrolysis process. In addition to this, biofuel production efficiency and energy output depend upon the feedstock's biochemical composition, which leads to a major challenge to use in the biorefinery processes (McKendry et al., 2002; Hamelinck et al., 2005). In general, developing a strong conversion process of biomass into high-value fuels and chemicals requires an adequate understanding of the biomass originates' source and its biochemical composition variability.

3.2. Microalgae biomass

Microalgae biomass has been widely explored to produce biofuels and value-added materials (Muhammad et al., 2021). The discharge of sludge, wastewater, and huge amounts of CO_2 to the atmosphere has severely threatened the ecosystem. In this situation, algal biomass production using wastewater is considered a green solution for generating renewable energy. As shown in Table 3, algal species contain a large amount of carbohydrate–lipid-protein and many other (including ash content) constituents on a dry weight basis. These components are used to generate various types of biofuels, e.g., bio-oil, biodiesel … Other molecules harvested by adsorption process can be valorized and enter the chain of biofuel production mainstream (Kyriakopoulos, 2005; Kyriakopoulos, 2010). biobutanol, biogas, and biohydrogen (Harun et al., 2011; Hossain et al., 2019). When comparing algae with crops, it has various benefits, like CO_2 fixation with high photosynthetic efficiency, rapid growth, high oil/lipids content, and yield (Chisti, 2007). Algae biomass contains 11–56% carbohydrates, 8–70% lipids, 40–70% proteins, and 3–5% pigments (Roy and Pal, 2015). However, despite these advantages, its cultivation and harvesting have several limitations, especially small cell size (2–20 μm), growth in dilute culture media, cell density close to water, thickening, and dewatering, which alone contribute to 20–30% of the total production cost (Zhang et al., 2019; Rashid et al., 2019).

Efficient harvesting plays a vital part in microalgal biomass production and recovery of lipids content, composition, and extraction (downstream processing). Various innovative harvesting techniques such as flocculation, centrifugation, filtration, and flotation with minimum energy and operational cost expense have been developed. Despite all efforts, the production cost (~$ 2.71/kg) of algal biomass is still higher for commercial applications (Ye et al., 2018). Among all harvesting approaches, downstream processing and designing and process integration are important. They can increase harvesting efficiency and reduce the cost of algal biomass production (Muylaert et al., 2015).

Solvents also play a vital role in the extraction of lipids, mainly triacylglycerols (TAGs) and free fatty acid (FFAs), from algal biomass. The polarity of solvents influences lipids recovery efficiency because polar solvents can extract lipids from a complex protein-lipid mixture by facilitating their dissolution in nonpolar solvents. Wu et al. (2017) used methanol and ethyl acetate combination at a 2:1 ratio and produced a lipid yield of 18.1% from *Chlorella* sp. Vandamme et al. (2017) evaluated the impact of harvesting using flocculants (alum and alkaline) and compared it with centrifugation. They obtained 42% lipid content with alum, 43% using alkali, and 47% using biomass centrifugation. No change in the fatty acids' amount was observed. Crampon et al. (2013) used the supercritical CO_2 technique to extract lipids from *Nannochloropsisoculata* algal species biomass. They extracted 90% triglycerides (TAGs) yield without any phospholipids. Orr and Rehmann (2016) found that ionic liquids can provide lipid extraction yields by 90–100% from dry or wet microalgae. However, the use of ionic liquids for lipids extraction is still expensive due the costs of these compounds thus limiting its commercialization and scale up at industrial level.

4. Progress in emerging technologies for enhancing biofuel production

The production of biofuels from different bioresources using various emerging technologies and biological processes is increasing globally. The use of biomass waste and agricultural crop residues to produce biofuels is likely to reduce environmental burden and solve many environmental issues, including waste disposal problems (Lee et al., 2019; Prasad et al., 2020a, 2020b). Recently, more research is carried out in biofuels production from different plants and microbial originated biomass material because of its eco-friendly nature to the environment and being carbon neutral resources. Moreover, these plants and algae can accumulate biomass due to photosynthesis (Hwang et al., 2016; Voloshin et al., 2015). Due to this, more research takes place in advanced technology for biofuel production as the source of energy. Biofuels are classified based on biomass-based resources used and categorized as 1st, 2nd, 3rd, and 4th generation biofuels, as shown in Fig. 6.

The first generation of biofuels, including biodiesel and bioethanol, were produced from edible food crop resources such as sugarcane, potato, oilseed, corn, barley, wheat, sunflower soybean (Prasad et al., 2007)(Nikolić et al., 2016). In this light, ethanol was the first biofuel chemical energy produced from raw corn and sugarcane using fungal mycelia as an enzyme in fermentation (Hayashida et al., 1982; Qin et al., 2018). The same result reported by Wang et al. (2007) shows that using starch-digesting microbes such as *Rhizopus sp.* and *Saccharomyces cerevisiae* can produce ethanol fermentation with raw corn flour. Thus, a current huge amount of bioethanol was produced at a large scale from starch through initial enzymatic hydrolysis methods in the first generation (Sheldon, 2018). The 2nd-generation refers to creating biofuels from lignocellulosic materials and different organic waste materials (i.e., wood, straw, and switchgrass, including oilseeds bearing trees like jatropha) that are available easily (Prasad et al., 2012; Lee et al., 2019). In the 3rd -generation-biofuels, algae are included as feedstock, yielding an important amount of lipids to produce biodiesel and other biofuels. However, the 4th-generation biofuels production depends on genetically modified organisms and modified metabolism route, the higher ability of fixation of CO_2, and the post-genome technology of the microalgae (Carere et al., 2008; Dragone et al., 2011; Dutta et al., 2014; Lü et al., 2011). The various processes that can be used to produce biofuels from biomass by applying different mechanical, thermo-chemical and biochemical conversion routes, and 1st-generation to the 4th -generation technologies are illustrated in Fig. 7.

4.1. Mechanical transformation of biomass to biofuels

Low bulk density (BD) of biomass is an important aspect limiting biomass use for bioenergy generation efficiently and cost-effectively (Rentzelas et al., 2009; Lei et al., 2013; Thurber et al., 2014; Vaccari et al., 2017). In this situation, briquetting technology, which mechanically converts or densifies biomass into solid biofuel, could be useful (Lei et al., 2013). During the procedure, biomass wastes are compacted under high compression to make dense briquettes (with moisture contents 12–18%) and pellets (with moisture contents 15–30%) (Thurber et al., 2014). Usually, the BD of grasses is around 40–150 kg/m^3, while it is nearly 150–200 kg/m^3 for woodchips (Larson, 2008; Stelte et al., 2012). Biomass pelletization increases the BD of around 700 kg/m^3 and gives proper shape and structure (Sokhansanj and Turhollow, 2004). Apart from these advantages, briquettes and pellets have shown encouraging results during the automated feeding into boiler systems. However, due to an insufficient reserve availability of wood, alternative raw materials are being searched presently. Countries like Europe, North America, and Asia use wood pellets and briquettes in co-firing to produce electricity and quality premium fuels. They are very useful substitutes for coal in co-firing coal-based power plants. Currently,

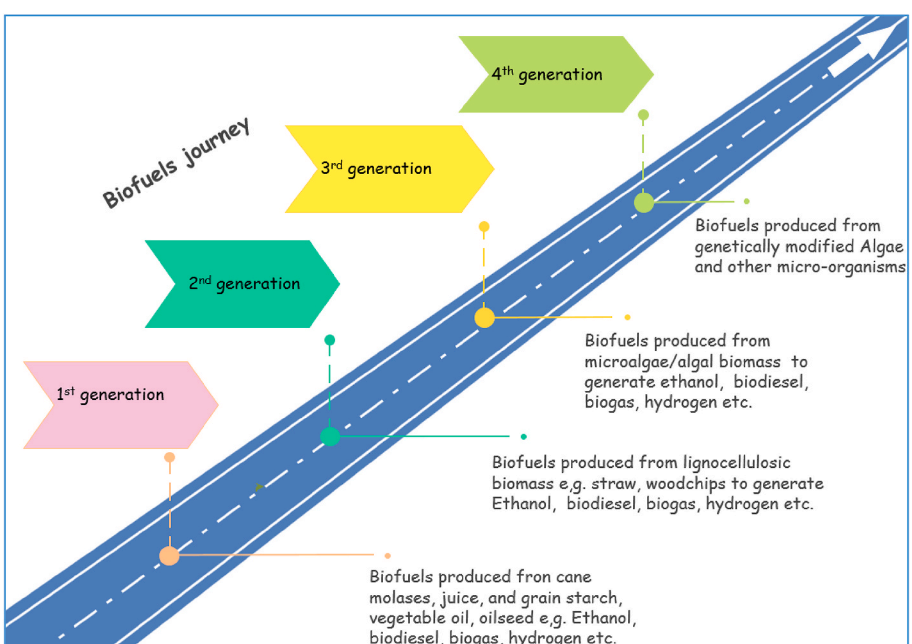

Fig. 6. Graphically demonstration in the advancement of biofuel production.(adapted from Dutta et al., 2014).

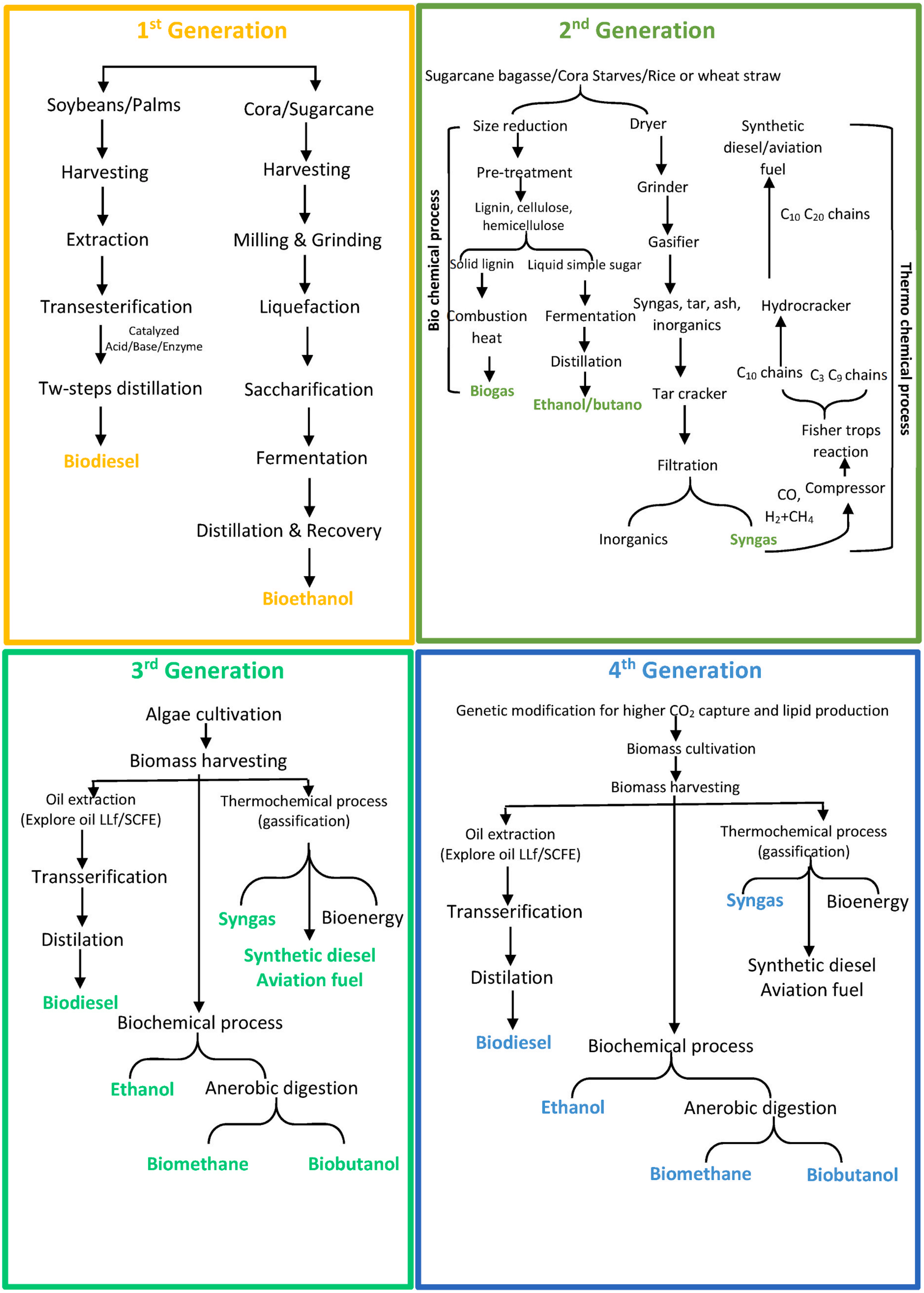

Fig. 7. Graphical representation of biofuel production technologies (adapted from Dutta et al., 2014).

torrefaction and pelletization are combined to create torrefied pellets with low moisture content and high heating value. Brachi et al. (2017) reported conventional torrefied wood pellets to give better energy storage properties.

4.2. Thermo-chemical transformation of biomass to biofuels

Several thermo-chemical processes can be utilized to generate power from lignocellulosic biomasses and also to obtain other energy products such as heat, syngas, oxygenated bio-oil (liquid biofuels), biochar (solid) and chemicals (Lee et al., 2019). The common thermal energy production route has five broad pathways: combustion, torrefaction, pyrolysis, liquefaction, and gasification based on temperature, pressure, and heating (Demirbas, 2009). Recent studies on various thermo-chemical paths for lignocellulosic biomass transformation into bioenergy are presented in Table 4.

The chemical makeup and energy stored in biomass differ from coal by the high O_2 concentration captured in crop/plant carbohydrate polymers. Biomass is the form of a complex polymer of glucose and is composed of 3–11% inorganic minerals, organic extracts, 35% lignin, and usually 60–80% of celluloses and hemicellulose (Brown et al., 2019). Natural chemical extractives such as fats, acids, alcohols, phenols, terpenes, resin, waxes, and other organic components are also present in biomass. These chemical extractives, carbohydrate polymers constituents and moisture content present in biomass can be transformed into various thermal energy products such as producer gas, bio-oil, and biochar (Ayiania et al., 2019).

Combustion is a proven and mature technology of biomass utilization (Kumar et al., 2015). It is an exothermic redox reaction process where biomass is burned at a higher temperature within 800–1000 °C in the optimal amount of O_2. During the procedure, the temperature could reach 1400 °C (Demirbas, 2009). More than 90% of energy expenditure comes from biomass combustion (Brown et al., 2019). Generally, the size of the combustion plants starts at small-scale (domestic, 100–MW) to the extent with a large-scale (3000–MW) industrial application (Kumar et al., 2015). One disadvantage of this process is the generation of by-products such as soot, dust, ash, NOx, CO, and CO_2. Research indicates that biomass co-combustion, particularly in those power plants running with coal-fired technologies, is an attractive alternative to achieve the sustainable energy transition. Internationally, co-combustion is the preferred technology for biomass to biofuel conversion due to its rapid conversion efficiency; currently, European countries like the Netherlands, Spain, and Germany are leading place in harnessing biomass co-combustion with coal-fired technologies (Boumanchar et al., 2019). Studies have proven that if very dense quality pellets are utilized as feedstock in co-combustion with coal-fired technologies, around 40% greater electrical energy efficiency was achieved. It also helped to reduce investment costs and direct emission avoidance.

Pyrolysis technology is an old practice to breakdown the biomass thermochemical into solid fuel (charcoal), liquid fuel (py-oil/bio-oil), and gas (syngas/fuel gas) that happens in a vacuum or absence of air or O_2 with heating in the temperature range of 350–550 °C, which can go up to 700 °C (Basu et al., 2018; Lee et al., 2019). Pyrolysis can be performed using different operating conditions and categorized in slow, fast, and flash pyrolysis. The pyrolytic product composition is significantly affected by heating rate, residence time, and temperature. Operating parameters, such as lower temperature, slow heating rate, and long residence time, enhance char yield. In comparison, high temperatures and low residence time increase syngas yield. It has also realized that intermediate temperature, high heating rate with short residence time, maximize pyrolysis oil/bio-oil yield. In the slow pyrolysis process, volatiles from biomass partly evaporate, and 80% char remains. Fast pyrolysis is performed with biomass particle size <1 mm in a controlled temperature range of 300–700 °C at a more rapid heating rate of 10–200 °C with a short residence time of 0.5–10 s in the absence of air (O_2) where producer gas is generated with Pyrolysis oil. Flash pyrolysis is performed at extremely high temperatures for short residence times (100–10,000 °C per second), and bio-oil is obtained with 80% higher efficiency. More attention is currently given to py-oil due to its cost-effective production, increased energy efficiency, and eco-friendly substitute for crude oil (Bridgwater, 2012). Py-oil can be utilized to drive turbines, automobiles, electric generators, and to produce various chemicals. However, some limitations, especially thermal stability and corrosion, are major concerns. Advancements in

Table 4
Recent studies on thermochemical conversion of biomass to bioenergy.

Thermochemical technologies	Feedstock, bioenergy produced, compositions, yield, and energy recovery	Specific operating conditions	Reference
Torrefactions	Olive tree waste, 5830 cal/g HHV (higher heating values)	Temperature approximately 275 °C and 30 min of residence time	Martín-Pascual et al. (2020)
	Sorghum straw powder and pellets HHV energy yield above 85%	280 °C, 5 °C/min	Liu et al. (2020)
Gasification	Pine wood-chips, syngas composition: H_2: 26–42%, CH_4: 8–11%, CO: 25–37%, and CO_2: 16–19%	Modern fluidized-bed gasifier, temperature 700–900 °C, steam/fuel ratio 0.3 kg/kg	Ngo et al. (2011)
	Solid waste and hazardous waste, electrical efficiency 41%, energy generation 81 MW	Plasma gasifier co-gasification using MSW, composition 90%wt and O_2 volume 95%	Mazzoni et al. (2017)
	Rice straw, fuel gas efficiency around 34%, fuel composition CO2.0%, H_2 5.5%, CH_4 0.5%	Temperature range 600–800 °C, O_2 ratio 33%, airflow 0.6 Nm^3/hr, biomass feeding rate 1.12 kg/h	Liu et al. (2018)
Liquefaction	Algal biomass (microalgae), crude bio-oil yield 60.0%	Temperature 350 °C, and duration of reaction time 15 min	López et al. (2015)
	Jatropha curcas seed, crude bio-oil yield 41.5 with energy recovery of 54.8%	Temperature 250 °C, and duration of reaction time 40 min	Lu et al. (2017)
	Domestic sewage from ponds, crude bio-oil yield 44.4%,	Temperature 300 °C, reaction time 15 min, water/biomass ratio kept at 10/1	Couto et al. (2018)
Pyrolysis	Sugarcane leaves and tops, bio-oil yield 52.5 and 59.0 by wt% from leaves and tops, respectively	Temperature for leaves 429 °C and tops 403 °C, the flow rate of N_2 gas 7 L/min, biomass feeding rate 300 g/h	Pattiya and Suttibak (2017)
	Waste biomass from coffee Syngas compositional yield: CO 4.7 mol %, H_2 1.6 mol%,	Temperature 700 °C, co-biochar as a catalyst, reaction time duration 110 min	Cho et al. (2018)
	Pinyon wood chips, HDO bio-oil recovery 48 wt%	Temperature 350 °C catalyst Ni/red mud, feedstock feeding rate 0.9 kg/h	Jahromi Agblevor (2018)

bioprocessing up-gradation and efficient routes are required to improve py-oil production and properties through hydrogenation and physical, chemical, and catalytic cracking approaches (Dhyani et al., 2018).

Gasification of biomass waste is an endothermic reaction. In this process, biomass is converted into syngas at 800–1000 °C under partial oxidation with oxygen or steam (Hirano et al., 1998; Vitali et al., 2013; Parmigiani et al., 2014; Basu et al., 2018). The gasification mechanism starts with the reaction of biomass and steam, O_2-enriched air, and thermochemically degraded into CH_4, H_2, CO, CO_2, C_2H_4, and C_2H_6, along with water and tar. The gasification reaction is described with the following Eq. (1):

$$\text{Biomass} \rightarrow CO + H_2 + CO_2 + CH_4 + \text{Tar} + H_2O + H_2S + NH_3 + C(\text{char}) + \text{traces} \quad (1)$$

Gasifying media plays a substantial role in enhancing the syngas quality and energy content (Brown et al., 2019). Several researchers have stated that organic waste and biomass with a low moisture content of <30 wt% are suitable for gasification. Some of the unwanted products, such as tar and other trace impurities, are also produced during gasification, creating operational difficulties for downstream gas utilization. However, the use of catalysts and modifications in gasifier design has shown promising results in reducing tar. That way, they can be managed effectively. Currently, integrated biomass gasification/combined cycle has been seen as a promising alternative to convert syngas to electricity through gas turbines. Syngas collected after gasification normally has an unfavorable CO to H_2 ratio if the following biomass processing step is Fischer–Tropsch synthesis, which operates at H_2:CO ratio of 2. Hence, water–gas shift reaction is carried out before Fischer–Tropsch synthesis, where this typical reaction as $CO + H_2O \rightarrow CO_2 + H_2$ purifies syngas. Syngas can be converted into H_2 gas, an excellent substitute for transport fuel (Yao et al., 2018). However, when syngas is utilized in automobiles or other machinery, it must pass through the dry-cleaning system before its use. Currently, Integrated Gasification Combined Cycle (IGCC) is considered as an emerging technology which combines modern coal gasification with syngas and steam turbine to improves the efficiencies of coal power plants and reduce toxic emissions (Ani, 2015).

The liquefaction has historically been used in many countries. Thermochemically, biomass can be transformed into liquid biofuel at 250–350 °C under high H_2 partial pressure, generally 100–200 bar. Biomass liquefaction products, referred to as bio-oil, are an improved quality fuel over py-oil (Liu et al., 2017; Gollakota et al., 2018). In this technique, the pre-drying of the biomass step is eliminated. Therefore, it is the best-suited technique for those feedstocks with high moisture content (Ruiz et al., 2013; Liu et al., 2017). Liquefaction can be put into two categories: (i) hydrothermal liquefaction (HTL)-water based, and (ii) solvent liquefaction (SL)- organic acids based. HTL is the thermal depolymerization of wet biomass utilized to transform it into crude like bio-oil. It is a synonym of hydrous pyrolysis. HTL is performed under pressurized hot-water conditions for a defined period, where biomass bio-polymeric structure breakdown in liquid ingredients to produce bio-oil (Gollakota et al., 2018). Solvent liquefaction (SL), organic acid-based biomass liquefaction, is a promising technology, where solvent helps to promote the dissolution of biomass fragments for efficient biomass conversion to bio-oil. However, this method also has some limitations, higher solvent and biomass ratio found creating fewer molecules interaction and suppressing components dissolution. If the ratio is very high, the liquefaction is inclined to behave like the pyrolysis. Consequently, a low ratio enhances the biomass component's dissolution. It provides a high yield of bio-oil, but it results in a low bio-oil yield if the ratio is too low.

4.3. Biochemical transformation of biomass to biofuels

Biochemical transformation of biomass to biofuel is primarily based on anaerobic digestion, fermentation, esterification, and photo-fermentation. Biochemical conversion involves the use of bacteria, fungi, and yeast. Here, the enzymes produced by these microbes play a significant role in breaking down the biomass structural biopolymers to gaseous or liquid biofuels such as biogas, hydrogen, and ethanol. A known biochemical process called transesterification is used to produce biodiesel (Khan et al., 2018). Recent studies on various biochemical paths for lignocellulosic biomass conversion into biofuel are presented in Table 5. Anaerobic digestion (AD) is a traditionally well-adopted method to generate biogas. The stepwise orders of the AD method are displayed here. In the first step, cellulose ($C_6H_{10}O_5$), a biopolymer of simple sugars, is hydrolyzed by the addition of H_2O to produce glucose as the primary product or feedstock for hydrolytic bacteria and they convert it to soluble organic compounds. In the second step, soluble compounds ($C_6H_{12}O_6$) produced during the hydrolysis (in the first step) are transformed into CO_2 and H_2 by specific bacteria called acidogenic bacteria. The CH_3COOH is also produced, which is utilized by CH_4-generating microbes as a substrate.

In the third step, called acetogenesis, organic acids produced in the 2nd step are transformed into acetate (CH_3COOH) and hydrogen (H_2). Here acetogenic bacteria play an important role. In the fourth stage of the anaerobic digestion process (methanogenesis), methanogenic bacteria play an essential role in transforming CH_3COOH and H_2 into CO_2 and CH_4 (Anukam et al., 2019). In AD, organic matter with 80–90% moisture content is a highly suitable feedstock for biogas production (Prasad et al., 2017; Zehnsordf et al., 2018). Organic waste material such as agriculture-horticultural waste, urban municipal sludge, and sewage can be utilized along with animal and cow dung. Biogas is a mixture of about 60% CH_4 and 40% CO_2 gas (Prasad et al., 2017). CH_4 is a combustible constituent of biogas. Biogas can be utilized for lighting gas/petromax, directly combusted for heat and cooking. Considerable research has been shown to use biogas to run internal combustion engines to generate mechanical or electrical energy, even for running machinery and agriculture tools. Leftover slurry from the biogas plant can be continuously utilized in manuring crops as organic fertilizer (Kumar et al., 2015), and this makes AD a promising technology for wide applications to the farming society (Prasad et al., 2017; Zehnsordf et al., 2018).

Intensive studies have been carried out in past decades to generate H_2 from a wide range of resources. Various bio-based emerging technologies such as direct biophotolysis, photo-fermentation, dark-fermentation, and hybrid systems, including water–gas shift reactions are currently being used to produce bio-H_2 efficiently (Holladay et al., 2009; Chaubey et al., 2013). Some important bio-based H_2 production processes are summarized with overall reactions involved (as shown in Eqs. 2 to 6) in Table 6.

In the light-dependent process, H_2 production includes the direct and indirect biophotolysis process that occurs through cyanobacteria and green algae and is further mediated via photosynthetic bacteria. Various microbes, such as *Bacteroidetes, Firmicutes, and Actinobacteria,* belong to multiple classes and species, have a crucial enzyme of hydrogenase that regulated the production of H_2. Bio-H_2 can also be produced, especially from the refining of syngas generated through biomass's thermochemical transformation.

Biomass materials providing sugars, or transformed into sugars, can be used to ferment ethanol. Bioethanol fermentation by yeast is a metabolic process that includes a set of biochemical reactions. Sugar crop products, especially sugar cane juice, molasses, sugar beet pulp, are used to generate ethanol worldwide at commercial levels (Prasad et al., 2007; Farinas et al., 2018). Usually, biomass materials are classified into two groups (i) direct fermentable sugar-containing sucrose, glucose, and fructose, and (ii) biomass materials-containing starch, cellulose, hemicellulose that need a pretreatment to convert into fermentable sugars (Prasad et al., 2012). These materials are first hydrolyzed and saccharified into monomeric sugars (glucose), then utilized as a substrate for fermentation to produce ethanol (Prasad et al., 2007, 2020; Prasad et al.,

Table 5
Recent studies on the biochemical conversion of biomass to bioenergy.

Biochemical technologies	Feedstock, bioenergy produced, compositions, yield, and energy recovery	Specific operating conditions	Reference
Anaerobic digestion	Sewage sludge, methane recovery 181 mL CH_4/g VS	Anaerobic incubation temperature 35 °C, pH of 7.0, reaction time 10 h	Passos et al. (2015)
	Microalgae and bacterial co-cultured biomass, methane recovery 325 mL CH_4 per g of volatile solids	Anaerobic incubation temperature 35 °C, pretreatment of biomass by CaO at temperature 72 °C, duration of reaction time 24 h	Solé-Bundó et al. (2017)
	Algal biomass from a mixed culture, methane recovery 146 to 171 mL CH_4 per g of COD	Temperature for anaerobic digestion of sludge 35 °C, NH_4 level 250 mg/L, reaction time 14 h	Molinuevo-Salces et al. (2016)
Alcoholic fermentation	Pretreated and saccharified rice straw, maximum ethanol recovery 25.3 g L^{-1}	Microwave-assisted alkali pretreatment of rice straw by 2% v/w NaOH, fermentation by *P. stipitis* NCIM 3499, fermentation time 72 h	Prasad et al., 2020a, 2020b)
	Microalgae biomass, ethanol recovery 0.18 kg/kg of biomass	Temperature 37 °C, pH 5.5, biomass pretreatment by thermal and enzymatic hydrolysis, hydraulic retention time 2.5 days	Hwang et al. (2016)
	Microalgae biomass (*Chlorella*), a mixture of acetone butanol, recovery 0.32 g/L/h, and 0.35 g/L/h	Acid hydrolysis with 2% H_2SO_4 and detoxification of residue by resin L-493, fermentation by yeast under anaerobic condition	Gao et al. (2016)
	Pine needle, ethanol yield (0.148 g/g)	*Schizosaccharomyces pombe CHFY0201*	Vaid et al. (2018)
Biological H_2-production	Microalgae (*Chlorella* sp.), H_2-recovery 11.65 mL/L	Temperature 30 °C, pH 6.8, anaerobic condition, light intensity 48 μmol per m^2/second, and duration of photo-fermentation 24 h	Sengmee et al. (2017)
	Microalgae (*Chlamydomonas* sp.), H_2-recovery 1.05 mL/L/h and 1.3 mL/L/h	Anaerobic condition, duration of photo-fermentation 120 h, Sulfur-free media, light intensity 50 μE/m^2/second	Oncel et al. (2014)
	Microalgae biomass (*Chlamydomonas reinhardtii* CC124), H_2-recovery 0.6 mL/L/h	Sulfur-free medium, nanoparticle 40 mg/L, anaerobic condition, duration of reaction time 72 h	Giannelli et al. (2012)
Transesterification	*Jatropha curcas oil,* biodiesel recovery 90%	Temperature 60 °C, transesterification reaction time 3 h, and catalyst used in oil with methanol mixture	Yunus et al. (2018)
	Recycled waste cooking oil, biodiesel recovery: 98.9%	Temperature 55 °C for heating of mixture up to 20 min, MgO + CaO added with methanol and warmed to 75 °C, total transesterification reaction time 4–6 h	Tahvildari et al. (2015)

Table 6
Summary of important bio-based H_2 production processes and overall reactions.

Process	Reactions	Notes
Direct biophotolysis	$2H_2O + light \rightarrow 2H_2 + O_2$ (2)	It is a water-splitting process happening in biological systems to produce H_2
Water-gas shift reaction	$CO + H_2O \rightarrow CO_2 + H_2$ … … (3)	It enables direct converting syngas into H_2
Indirect biophotolysis	$(C_6H_{12}O_6)_n + 12H_2O + light \rightarrow 12H_2 + 6CO_2$ (4)	In this process electrons are derived from stored starch in algae and H_2 is produced
Photo-fermentation	$CH_3COOH + 2H_2O + light \rightarrow 4H_2 + 2CO_2$ (5)	In presence of light, H_2 produced from hydrolyzed biomass (saccharified sugars).
Dark-fermentation	$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2$ (6)	In absence of light, H_2 produced from hydrolyzed biomass (saccharified sugars).

2018). Sugar from cane, beet, and sweet sorghum can be directly used to produce ethanol. The overall biochemical reactions and processes involved in hydrolysis and fermentation are given in Eqs. (7) and (8) (Prasad et al., 2007).

$$\text{Hydrolysis of polysaccharide: } (C_6H_{10}O_5)_n + nH_2O \rightarrow nC_6H_{12}O_6 \quad (7)$$

$$\text{Ethanol fermentation: } C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 + \text{energy (ATP)} \quad (8)$$

Since the prime aim of agriculture is to satisfy the food necessities of the world ever-increasing population, collectively searching opportunities for meeting the transport sector's ethanol demands is also a need of time (Prasad et al., 2014a, 2014b). Lignocellulosic biomass has a huge potential to provide fuel and chemicals to society. It was estimated that worldwide 73.9 Tg dry biomass waste and crop residues are generated; if they are scientifically used on a commercial basis, they could provide 49.1 GL ethanol annually, which is nearly 16 times more than the current worldwide ethanol generation, which can replace 353 GL of gasoline (32% of the worldwide petroleum consumption).

Biochemically biodiesel is derived from biomass resources that contain lipids through transesterification (e.g., seed oil, vegetable oil, rapeseed methyl ester (RME), animal fat, and other lipids-containing feedstocks) (Fig. 8). It is a monoalkyl ester of long-chain fatty acids, a most suitable substitute for fossil fuel, especially diesel. The chemical reactions and processes involved in transesterification are shown below. In this process, triglycerides (oil, lipids, and free fatty acids) are transformed into biodiesel, chemically called monoalkyl ester. The feedstock is added to alcohol, such as methanol, a catalyst such as liquid acid (H_2SO_4), and a base NaOH or KOH can be also used. The reaction between the triglycerides and the alcohol is reversible. Therefore,

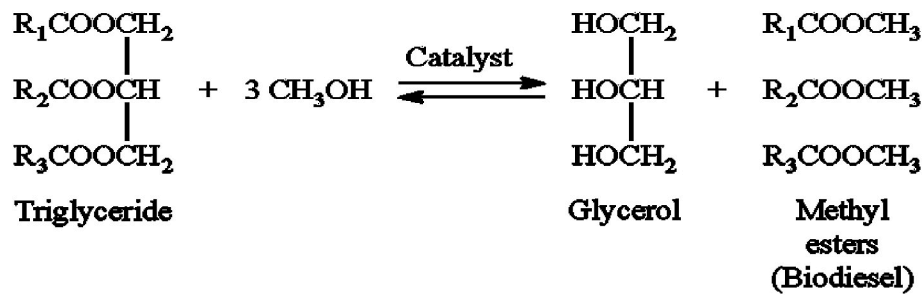

Fig. 8. Process of transesterification to produce biodiesel from triglycerides.

methanol can be added in excess to drive the transesterification reaction and to ensure complete transformation (Wallace et al., 2017; Yunus et al., 2018).

Substantial developmental activities have been carried out about biodiesel production through the transesterification of non-edible oil resources (e.g., microalgae) and waste raw materials (e.g., waste oils and fats). Over the past few decades, various microalgal strains have been selected for high lipid content, which has great potential for biodiesel making. Hotels and various commercial enterprises and industries, pumping a huge amount of waste cooking oil, are also economically viable sources to obtain biofuels feedstock because this biomass is almost freely available. Their proper utilization for biodiesel production can resolve the severe disposal concern of this residual biomass. However, waste cooking oil normally contains <15% FFA (free fatty acid), which increases during heating and frying processes; high FFA can create challenges to generating high-quality biodiesel (Wallace et al., 2017). This condition implies the application of a pre-treatment stage to improve the quality of this feedstock before its transformation to biofuels.

5. Recent progress in the field of biofuels using genetic engineering

According to Larson (2008), the National Renewable Energy Laboratory (NREL) of the US-Department of Energy has emphasized developing biomass feedstocks with lower lignin content through lignin bioengineering. Generally, high lignin contents reduced the sugars yield during saccharification and hydrolysis, and also act as inhibitors in ethanol fermentation. The higher amount of polysaccharides present in lignocellulosic biomass like cellulose, callose, galactan, and mixed-linkage glucans and their content in cell plant walls are also important because, after processing, they give more ethanol and other biofuel yields. Improving the efficiency of cellulolytic enzymes through genetic engineering to facilitate hydrolysis is equally important (Prasad et al., 2007; Brandon and Scheller, 2020). Traditionally, ethanol fermenting yeast has some limitations. They can ferment 6-carbon or hexose sugars only. Therefore, the development of new strains that can ferment multiple types of sugars (6-carbon and 5-carbon) can also tolerate high-temperature and ethanol concentration.

Significant improvements in achieving these goals may be facilitated by suppressing or eliminating the expression of various genes related to biosynthesis through genetic engineering (Jeffries, 2006; Stricklen, 2006; Li et al., 2019; Brandon and Scheller, 2020). The quality of biomass can be enhanced by transgenic expression of enzymes that modify the cell wall's polysaccharides before its full maturation. Crop plants express many glycosyl hydrolases (GH) to build and remodel tissues' cell walls and growth (Barnes and Anderson, 2018). In rice crops, native gene GH9Bs (*OsGH9B1* and *OsGH9B3*) were found to increase biomass quality without affecting its growth and development (Huang et al., 2019). However, the transgenic lines exhibited a 23% reduction in degree of polymerization (DP) of cellulose and 11–23% reduction in the crystalline index (CrI). After biomass pretreatment, both transgenic lines, *GH9B1* and *GH9B3*, were released 63% more, reducing sugars over the control line. In another study, overexpressing genes OsAT10 in rice had the supplementary effect of enhancing cell wall glucose by 8–19% compared to wild-type rice. Using this gene in transgenic rice and switchgrass lines demonstrated around 40% boost in total sugar yield after enzymatic saccharification (Marcia, 2009; Bartley et al., 2013; Brandon et al., 2020). Overexpression of *Aspergillus aculeatus* xyloglucanase gene (*AaXEG2*) in *Populusalba* led to enhanced growth and cellulose deposition, and up to 81% more glucose released after enzymatic hydrolysis (Park et al., 2004; Kaida et al., 2009). Fonseca et al. (2020) used T. reesei RUT-C30 strain and genetically modified for efficient cellulase enzyme production. They achieved a cellulase titer of 80.6 g L^{-1} (0.24 g/L/h). The saccharification efficiency of the produced enzyme was found very good. It can be commercialized to produce various liquid and gaseous biofuels. Genetic engineering also plays an important role in biodiesel production (Hegde et al., 2015). Janβen and Chel (2014) reported that triglyceride (TAG) production by engineered *E. coli* was found to 530 mg/L in fed-batch fermentation.

6. Challenges and perspectives in biofuels production

The promise of advanced biofuels depends on socio-economically and environmentally sound technologies. Globally, biofuels demand is increasing rapidly due to its ecologically sustainable and attractive benefits like: (i) being renewable, (ii) indirectly help to reduce carbon dioxide and enhancing carbon fixation, (iii) enabling local economic growth, (iv) reducing air pollution from burning of biomass in fields and biomass rotting in fields, (v) bringing energy security and reducing dependence on imported oil, and (v) creating jobs for farmers and high technology employment for engineers, specialists, process bioengineers, and scientists. However, some of the important constraints imposed by economics, limited resources, food security conflicts, health and safety, water demand, and land use challenges, and different environmental impacts that could affect local communities must be addressed properly. A life-cycle assessment (LCA) can typically respond to these challenges (Prasad et al., 2020a, 2020b). LCA can help evaluate biofuel production's potential impact on the environment over the entire cradle-to-grave life cycle. Applying the LCA approach to advanced biofuels, the first point is understanding farmers' needs, feedstock type and options, and land-use change.

6.1. Major technological challenges in biofuels production

Currently, several opportunities exist for biofuel production, as discussed above. As the world's economic and social development depends on energy, this demand will grow to about 37% in 2040. More than 80% of the energy demand source in the world is getting from petroleum and related field (Joshi et al, 2017a, b). However, depleting and limiting petroleum fuels' natural resources has forced scientists to examine more efficient alternative and sustainable renewable energy sources such as biofuels to fill the world's energy demand (Tomes et al., 2010; Joshi et al, 2017a, b; Rodionova et al., 2017). The major technological challenges in biofuels production are (i) non-edible feedstock such as lignocellulosic biomass and other organic waste feedstock utilization, (ii) production logistics, (iii) energy-efficient pretreatment, enzyme hydrolysis, and fermentation technologies, (iv) efficient co-products utilization, (v) establishment of biofuel standards, (vi) distribution logistics, (vii) social and economic benefits and its acceptance and (viii) minimization of its effect on the environment. These challenging areas require financial support, infrastructure, and expertise in science and related specific fields.

An important factor that affects the conversion of biomass to biofuels is the biomass physical properties like its moisture content, particle size, microstructure, elastic properties, and bulk density. For this reason, to have high conversion through the biochemical process, it needs a high degree of size reduction and the final volume to be accepted will be depending upon the utilization of the processing system (Van Walsum et al., 1996; Prasad et al., 2007; Li et al., 2019). Simultaneously, the particle size of the biomass has less effect on biomass conversion through the thermochemical method because of the high heating rate of liquid media. This leads to the particle size being less insensitive (Akhtar and Amin, 2011). However, while pumping the biomass sludge into a continuous system, it needs a significant size reduction (Jazrawi et al., 2013). In another research, Demirbas (2004) showed that particle size smaller than 0.5 mmm is convenient for the conversion of the biomass through pyrolysis because the smaller size of the particle can have a high rate of heating and decrease the yield of the char. Spliethoff et al. (1998) reported that the optimal size for combustion biomass differs from feedstock type. In general, any kind of conversion method needs some reduction in particle size.

The other physical and most problematic property that affects biomass waste conversion into biofuel is the moisture content (Kenney et al., 2013), directly or indirectly affecting the bio-refining operations and feedstock supply. For instance, few studies reported that moisture content that increases during the pretreatment in the biological process could decrease the thermochemical conversion and bio-oil quality and lead to low thermal efficiency during the combustion (Brownell et al., 1986; Bridgwater et al., 1999; Jenkins et al., 1998). Besides the moisture content and particle size, other physical properties like microstructure, elastic properties, and bulk density (BD) affect biomass conversion to biofuels. For instance, Weiss et al. (2010) reported that the biomass conversion into fuels and biochemicals is profoundly impacted by the biomass's microstructure and elastic properties. These properties can increase the interparticle interaction and compressibility of the biomass.

Moreover, they claimed that bulk density also affects the transportation and handling of feedstock supply. The lower the bulk density the higher the cost for the transportation of the feedstock supply. Biomass chemical properties also affect the biofuel quality and composition of high-value chemicals produced during the conversion process. The biomass's main chemical properties that affect biomass conversion into biofuels are lignin, volatile, and ash content (Li et al., 2019). For example, Toor et al. (2014) and Tumuluru et al. (2012) described that the ash content that increases during the pretreatment of the biological process leads to growth in the yield of the char as well as fouling of the biomass transformation processes like combustion, pyrolysis, gasification, and liquefaction. However, ash content can be removed by developing air classification and leaching (Lacey et al., 2015).

The other chemical properties that affect biomass conversion into biofuel include volatile organics such as acetic acid and volatile organic fractions of furan. For example, Palmqvist et al. (2000) observed that the presence of furan organic fraction could reduce the fermentation's efficiency during the biological process to convert biomass into biofuel. Another research conducted by Carpenter et al. (2014) also reported that having high volatile organic matter can lower the bio-oils stability and energy content produced through the thermochemical process. Lignin content in biomass also affects the biofuels conversion process. However, its effect varies based on the type of process selected. For instance, Sun et al. (2002) reported that the lignin content could reduce the production of ethanol during the fermentation process by inhabiting enzymes not to react with cellulose, while during the conversion process such as pyrolysis and combustion process, it escalates bio-oil yield and heating values respectively (Kim et al., 2006; Wang et al., 2015).

Another important challenge is removing lignin and toxic substances like short-chain aliphatic acids as acetic acid, levulinic acid, formic acid, furfural, and 5-hydroxymethylfurfural (HMF) produced through the biomass pretreatment (Prasad et al., 2018; Wang et al., 2015). They act as inhibitors for the microorganism and negatively impact the saccharification and fermentation (Zhang et al., 2019; Wang et al., 2015). To solve the problem of inhibitors generated during biofuel production, some researchers have adopted the techniques to reduce these inhibitors from pretreated hydrolysates before fermentation (Prasad et al., 2018). Screening of efficient microorganism that tolerates the effects of inhibitors may be an effective strategy to enhance biofuels. Genetic engineering tools and techniques can also play an important role in developing genetically improved microbial strains in situ detoxification of pretreated hydrolysates, and efficient enzymatic saccharification and fermentation to produce liquid and gaseous biofuels. Adaptation of these approaches can help to enhance overall biofuel production on a large scale (Wang et al., 2015; Prasad et al., 2020a, 2020b). However, more research is necessary to optimize biofuel production by developing novel strains by integrating the different genetic engineering methods.

6.2. Environmental challenges in biofuels production

Biofuels offer several benefits over fossil fuels. However, environmental issues and related challenges such as sustainability, greenhouse gas emissions, air pollution, soil and water resources, biodiversity, and land use are the important factors that should be considered while designing guidelines for assessing biofuel sector impacts. LCA is often used to evaluate these environmental impacts (Prasad et al., 2020a,b). Currently, most of the biofuel production enterprises taking LCA very seriously assesses the ecological impact to make decisions to adjust the process that needed, which should be focused on reducing the emissions during biofuel production. It is extremely important to take the benefits of opportunities and finding a sustainable solution for environmental challenges to enhance socio-economic developments.

6.2.1. Biofuel production and GHGs emissions challenges

Another point is characterizing tailpipe emissions and their consequences. Recently, US-EPA and the California Air Resources Board (CARB) found that biofuel use is enough in decreasing tailpipe GHG emissions by 50% equivalents to fossil fuel (Sacramento, 2019). Blending of 20% biodiesel and 80% Low-Sulfur Diesel fuel (ULSD) can reduce GHGs by 50–85% without any investments. According to the latest data obtained, CARB indicated that blends of ULSD in biodiesel could significantly decrease transport-related GHG emissions (Sacramento, 2019). For example, under California's Low Carbon Fuel Standard (LCFS) program until now, biodiesel has avoided more than 18 Mt of CO_2 (Fig. 9).

Domestically generated biodiesel offers a cost-effective fuel to buyers enabling them to fleets without any change in current vehicle models. It can assist in reducing GHG emissions widely. According to recent reports, the blends of ULSD in biodiesel decreases around 20 Mt CO_2 in California yearly. That implies a win-win position for a society to protect its environment and reduce dependency on crude fossil fuel (Sacramento, 2019).

These biofuels have great potential to mitigate GHGs emissions and many other environmental problems. Indeed, plants absorb CO_2 from the air to begin photosynthesis to produce energy and biomass. During the combustion of biofuel from biomass, some amount of CO_2 is also emitted, which is again used by the crop plants of the next growth and developmental period. Thus, biofuel produced from lignocellulosic biomass resources and other waste organic material is now considered carbon neutral. The carbon present in various biofuels is a part of the

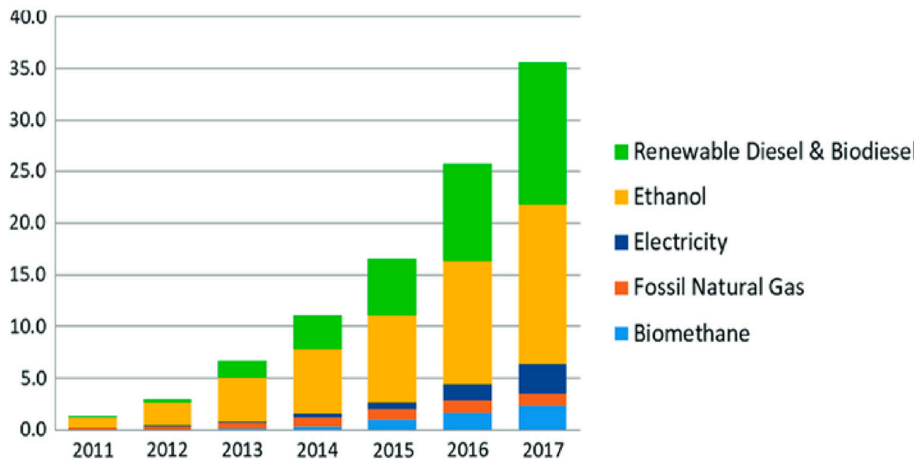

Fig. 9. Cumulative CO_2 reductions in million tons (Mt) (Sacramento, 2019). source Source California Energy Commission, Low Carbon Fuel Standard Dashboard Diesel Technology Forum (https://www.globenewswire.com/news-release/2019/05/28/1851185/0/en/Bio-based-Diesel-Fuels-Deliver-the-Biggest-Reductions-in-Transportation-Related-Greenhouse-Gas-Emissions-in-California-Ever.html)

ongoing C-cycle, in which it is continuously moved, recycled, and exchanged from the atmosphere to the biosphere (Morris, 2008).

The impact of various biofuels on GHGs emissions is presented in Table 7. The evidence shows that bioethanol produced from sugarcane crops and cellulosic biomass lessens GHG emissions by 88 and 91%, while corn bioethanol-fueled with natural gas can decrease GHGs emissions from 28 to 39%. Furthermore, if lignocellulosic biomass resources and other waste organic material are utilized, they can mitigate GHG emissions by 39–52% (Wang et al., 2007).

Biofuels' contribution to GHGs emissions mitigation is currently not valued due to the absence of a specific decarbonization market through which biofuels' environmental benefits could be recognized (GAIN Report, 2019). It could be obvious that there is a need for market formalization, considering bioenergy is still a significant renewable energy source globally. All renewable options are needed to realize the long-term decarbonization of end-use sectors. Policy support and innovation to cut the cost are essentially required. According to the proposals adopted by the International Civil Aviation Organization (ICAO), carbon offsetting will be voluntary from 2020 to 2027 and mandatory afterward. The offset's goal is to cover the projected 65% emissions growth above 2020 levels in the optional and 80% range from 2027 to 2035 (Revill and Harris, 2017). They suggested that the access to biofuels should be line-up ahead of other aviation industry sectors because currently, there is no any alternative pathway to reach near-zero-emissions. It is expected that the share of the global emissions of the marine industry doubles by 2050. Further, by 2050, three-quarters of peoples will live in the megacity of the world. Adjusting the energy mix will be essential to living sustainably and protecting the environment.

6.2.2. Biofuel production and land use challenges

The major challenge in biofuels production is to manage efficient land use and lowering GHGs emissions to ensure it does not lead to food vs. energy conflict, climate change, and other ecological destruction. However, using various land types to grow crops raises environmental issues that are the same, whether the crops are cultivated for food or industrial and fuel applications. Land use for monocultures in forestry or field crop production can pose risks to biodiversity, pests, and pathogens. Simultaneously, land use for cultivating mixed crop and woody species, such as perennial grasses or trees could be used in preference to enhance biodiversity, without compromising yield (Tilman et al., 2006). Certain land types, such as peatlands and tropical forests, represent large carbon sinks. The conversion of these land to grow crops has been reported to emit higher carbon from the soil. The synthetic fertilizer application to increase crop yield must be strictly reduced to mitigate emissions of N_2O and potent greenhouse gases from agricultural land (Lewandowski and Schmidt, 2006). Input efficient agronomic practices play a key role in mitigating negative environmental impacts. Managing microbial diversity of soils and rhizosphere is beneficial for sustainable crop production.

Table 7
GHGs reduction from various biofuels use (Wang et al., 2007).

Biofuel with feedstock	GHG reductions relative to petrol/diesel vehicles
Cellulosic ethanol	86–88%
Sugarcane ethanol	28–39%
Ethanol	14%
Corn ethanol	28–39%
Biodiesel (soya)	40%
Biodiesel (rape)	50%

The use of fossil fuels and their burning in automobiles raise GHGs emissions and contribute seriously to climate change and air pollution. Therefore, alternative energy sources, especially oxygenated biofuels, must be produced from lignocellulosic biomass waste and various left out residues to resolve land use issues. Energy crops, especially *Miscanthus* (*Miscanthus x giganteus*) and willows (*Salix*spp) are also used to treat high nitrates polluted water, such as sewage plants, animal waste, and drainage ditches. That way, it can help grow more biomass and reduce GHGs emissions (Arneth et al., 2007). However, according to some experts, crop production for biofuels could displace existing products from land currently being used for food, forage, and fiber. It may increase food prices in the market. GHG emissions need to be carefully assessed. However, the variations in land-use change patterns in totality and its share are nearly 15% of the global carbon emission, and the generation of biofuel crops share is <1% of the world's total land utilized. Land-use changes related to biofuel serve as a small portion of overall land use (IEA, bioenergy, 2009).

6.3. Socio-economic issues

Energy is a very crucial input for social and economic growth (Demırbas, 2017), especially biomass to bioenergy resources are very important because they offer additional value derived from products already in the economy. Biofuels' social and economic aspects are associated with future liquid fuel demand proposed to encourage wealth and earnings and socio-economic benefits. Many countries diversify their energy mix to ensure the rural and regional service from domestic biofuel production and its use. Biofuel is providing many job opportunities that arise in growing and harvesting biomass, transport and handling, plant operation, equipment manufacturing, and maintenance. According to Statista (2020) estimates, 2,063,000 biofuels-related jobs were created worldwide in 2018. The maximum employment was created in Brazil (832,000), followed by United States (311,000), the European Union (208,000), China (51,000), and India (35,000). Biofuel production and its use contribute to local and national energy security, economic growth through business earnings and employment, rural economy diversification, import substitution with direct and indirect effects on the trade balance, energy supply, and diversification through establishing new industries.

7. Conclusions and future perspectives

In this review, biofuel production potential and challenges related to various feedstocks and advances in process technologies are addressed. Biomass is the energy-rich feedstock for biofuels production; however, its conversion process is restricted by many operational conditions, type of chosen conversion process, and cost of benefits. The cost-effective biofuels production from biomass depends on the efficiency of cellulolytic fungal enzymes and biofuel fermenting strains that can ferment multiple types of sugars (6-carbon and 5-carbon). Therefore, the development of advanced technologies and such novel strains through genetic engineering needs to be further refined and developed to facilitate and addressed these problems. Admittedly, biofuels produced from energy crops and microalgae seem to be the most efficient and attractive solution. It must be studied or developed further to improve biofuel production using genetic engineering on a larger commercial-scale. Biofuels offer several environmental benefits over fossil fuels. Blends of biodiesel in Low-Sulfur Diesel fuel (ULSD) could significantly reduce transport-related carbon dioxide and GHG emissions and air pollution. However, issues related to land use, water, and biodiversity should be considered while designing guidelines for assessing biofuel sector impacts. This review shows that the biofuels-related social and economic aspects are extremely important. Biofuels production and its use provide opportunities and find a sustainable solution to contribute to local and national energy security, economic growth, rural economy diversification and employment, import substitution with direct and indirect effects on the trade balance, energy supply, and diversification through establishing new industries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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