Halophytes: The Nonconventional Crops as Source of Biofuel Production

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Abstract

Biofuels are gaining importance due to high crude oil prices, high energy demands, and global warming issues. According to the world energy council, the biofuel production will be tripled by 2030, with Brazil and the United States contributing to 80% of the total biofuel production. The use of first generation biofuels is connected with food insecurity and increase in food prices, while second generation biofuels used raw cellulosic mass from nonfood crops. The plant-based fuels are considered in renewable sources with easy growing practices and have lesser carbon emission as compared to fossil fuels. This

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inaugurates the possibility of using the neglected and nonconventional plant resources such as halophytes over conventional agriculture crops for biofuel production. Halophytes have great potential in the production of biofuels due to seed oil and energy-rich lignocellulosic biomass. Enzymatic hydrolysis and microbial fermentation are some of the processing techniques which can be used for the production of biodiesel and bioethanol. Along with biodiesel and bioethanol, biochar, a carbonaceous material produced after pyrolysis of *Salicornia*, *Atriplex*, *Achnatherum*, *Kosteletzkya*, and *Sesbania*, has been reported for reclamation of degraded soil and increase in soil fertility. The use of biochar is a safe and economically viable system. A milestone use of these nonconventional crops has been done by Etihad Airways who operated first flight using aviation biofuels made by seed oil of *Salicornia* in February 2018. This review summarized the prospects of halophytic biomass in biofuel production and various application statuses all over the world such as the production of biodiesel, bioethanol, bio-oil, syngas, and some other alternatives. The progressive direction of biofuel production from halophytes should form a trinity with agriculture, biotechnology, and chemistry so as to generate green biomass energy with cost-efficient as well as environmentally friendly aspects.

Keywords

Bioethanol · Biodiesel · Biofuel · Halophytes · GHG

Abbreviations

ASEAN	Association of Southeast Asian Nations
EC	European Commission
EROI	Energy return on investment
GHG	Greenhouse gases
LCA	Life cycle analysis
Mtoe	Millions of tons of oil equivalent

1 Introduction

Ever-increasing energy demands for day-to-day domestic activities, transportation, and industrial sector have depleted the conventional energy sources and caused dramatic climate change. In efforts to mitigate the harmful environmental effects of fossil fuels, the concept of biomass-based fuel generation came and started from first generation biofuels (includes conventional crop's seed oils, sugar beet, and grain processing). The global demand for first generation liquid biofuel tripled between 2000 and 2007 due to advanced technologies and demand generation of palm oil biodiesel in Malaysia, corn ethanol in the United States, rapeseed oil biodiesel in Germany, and sugarcane ethanol in Brazil (Sims et al. 2008). Soon the concept got constraints due to competition with food crops, land, and water insecurities and limited greenhouse gas (GHG) reduction benefits (Harvey and Pilgrim 2011) and led to second generation biofuels which depend on feedstock from lignocellulosic biomass of nonfood crops, agriculture, forest residue, and some energy crop cultivation (Balan 2014). More recently, biomass-based transport fuels including aviation transport have become one of the policy decisions for countries to reduce vehicle emissions and shift to low-carbon fuels (Kovarik 2013; Anonymous 2016). The production of bio-based aviation fuel depends on the availability of cheaper feedstock such as palm oil and its efficiency in low GHG emission (O'Connell et al. 2019). The third generation biofuels are from algal origin and conversion of algal biomass to hydrogen, whereas the fourth generation biofuels include high solar efficiency crop cultivations for biofuel generation (Abdullah et al. 2019; Alalwan et al. 2019). Currently food-energy-water nexus perceptive is being deployed for efficient production of first generation biofuels in a noncompetitive phase with available food, water, and land resources (Moioli et al. 2018; Hejazi et al. 2015), while second generation biofuel energy crops can be developed on degraded land and scarce water resources to minimize the competition with food production (Murphy et al. 2011).

Halophytes, which are able to grow in degraded saline lands, are a good source of food, forage, fodder, oilseed, and cheap lignocellulosic biomass (Joshi et al. 2018; Sharma et al. 2017; Arora and Ramawat 2013). *Crithmum*, *Haloxylon*, *Salicornia*, *Suaeda*, etc. are some of the important halophytes, containing seed oil rich in lipid and fatty acid contents suitable for liquid fuel production. *Salicornia bigelovii*, commonly known as saltwort, is an edible succulent halophyte and has been grown in coastal deserts of Abu Dhabi by Boeing and Etihad Airways for its seed oil content which is being used as biofuel, and the first flight was operated using this biofuel in February 2018. A preliminary, independent analysis found that the use of such biofuel results in 38–68% less GHG emissions than fossil fuels (MacMohan 2019). Presently when various international airlines such as European airline Lufthansa, Airbus, Azul Brazilian airline, Air France/KLM, and British Airways are using different blends of first generation biofuels with the fossil fuels, the use of nonconventional crops mainly halophytes will open new avenues of using cheaper and easily available resources. One of the sections of the present chapter represents a detailed insight of various halophyte representatives for seed oil and its composition. Nevertheless, halophytes are also rich in biomass comprising of cellulose, hemicellulose, lignin, and some other polysaccharides sufficient for bioethanol production. A detailed account of lignocellulosic composition and methods of bioethanol production including microbial fermentation and pyrolysis from different halophytes have also been presented in this chapter. The fatty acid methyl esters from several halophytes have characteristic fuel properties including high cetane number and iodine value for biodiesel production. Biochar, a carbon-rich compound, increased soil fertility, was produced from *S. bigelovii* biomass through pyrolysis (350 °C, 6 h), increased the organic carbon content from 10 to 26 g kg^{-1} in the soil, and did not affect plant available water content (Al Marzooqi and Yousef 2017). The production of biodiesel, biochar, bio-oil, and syngas by various processing methods forming different halophytes has also been presented in this chapter. Along with the economic and social significance of halophytes, the key challenges, logistic issues, techno-economic feasibility, and life cycle analysis have been presented in this overview as the human energy, food, and water demands are inevitable sources of conflict with using food crops for fueling. The need of the present hour is to develop a vision of a sustainable cropping system for most potential such nonfood crops that are halophytes.

2 Current Scenario of the Worldwide Biofuel Production

The first ever commercial concept of using food crops for the generation of biofuels came in 1900 when Rudolf Diesel launched the high-pressure engine driven with clean oil from arachidic peanuts at the World Exhibition in Paris. Twenty years later Henry Ford used the ethanol to power the internal combustion engines. After that in 1929, a mixture of alcohol and gasoline as a fuel (30:70 v/v) was reported in Poland. *Chemical Industry*, a polish journal has published one of the first scientific reports regarding the possibility of using these compounds to power the engines of tractors (Biernat et al. 2013). With the commencement of the concept of biofuels, conventional and advanced biofuels are taking worldwide importance since the last two decades. In European countries there are approximately 5.5 million hectares of agricultural land on which bioenergy cropping takes place. This accounts for 3.2% of total agriculture land of which 82% is being used for oil crops for biodiesel production, 11% for ethanol crops, 7% for biogas, and 1% for perennials for heat and electricity generation (Elbersen et al. 2012). The data represents that despite lots of food, land, and water insecurities, only about 2% of biofuel production are covered by advanced biofuels (Bacovsky et al. 2013). To reduce the pressure on food crops regarding biofuel production, EC has encouraged the use of more diverse feedstock and took some measures like capping the state aid to only 7% for the use of conventional crops for biofuel production and double counting of biofuels produced from certain wastes and residues. Thus there is a requirement of deployment of some new techniques based on advanced feedstock use to minimize the use of conventional production methods (Bacovsky et al. 2017).

The data of IEA/OECD report (2008) stated that 99% of global ethanol production in 2005 was accounted by Brazil and the United States together, whereas 69% of global biodiesel production was accounted by Germany and France (Sims et al. 2008). Global biofuel production grew with a pace of 7% year on year in 2018 to reach the 152 billion liters Mtoe, but for the next 5 years, only a 3% average growth rate is anticipated which is not appropriate to meet the Sustainable Development Scenario (SDS) demand. There is a need of more biofuel market development and production in China and India, while in the United States (US) and European Union (EU), due to low blending of these biofuels with traditional fossil fuels, the production is low to meet the SDS regarding the use of transport biofuels (Fig. 1, Feuvre et al. 2019). To meet the sustainable bio-jet production by 2020, major European stakeholders set a goal of 2 million metric tons of production under a new program called Biofuel Flight path launched at Paris air show in 2011, but it could not be achieved due to several technical issues. Currently in marine and aviation subsectors, biofuel consumption is minimal, to meet the SDS in 2030, there is an increased consumption of approximately 7% of international shipping and 10% of aviation biofuels, is anticipated.

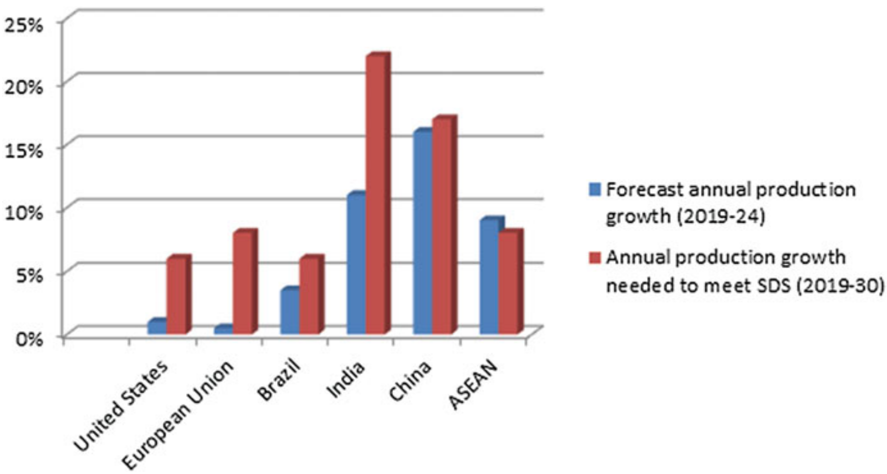

Fig. 1 A forecast production growth versus growth required to meet SDS in 2030 regarding transport biofuels

3 Various Conversion Routes of Halophytic Biomass Feedstocks to Biofuels

Biomass of the halophytes can be used directly or indirectly by converting it into a liquid or gaseous fuel through various thermochemical and biochemical pathways. The thermochemical processes such as pyrolysis and gasification convert the low value biomass to low-carbon transport fuel (Demirbas 2017). Pyrolysis seems to be a simple and proficient method to produce three primary products like char, permanent gases, and vapors. The vapors condense and result in the production of bio-oils or bio-crude composed of a complex mixture of oxygenated compounds with a heating value of 40–50% of that hydrocarbon fuels. However, there are various thermophysical limitations such as phase separation, stability, and fouling of bio-oil during pyrolysis along with the economic viability of the whole process. Bio-oils possess poor volatility, high viscosity, coking, and corrosiveness, which make them less suitable for boilers, turbines, and diesel engines; further they are also used for making resins, fertilizers, flavors, adhesives, and acetic acid. Technological improvement including the pyrolysis process and type of biomass, with modification in engine components, make the complete utilization of bio-oil (Jahirul et al. 2012). Thermal processing of biomass results in 10–35% of a rigid unstructured carbon matrix mainly composed of hydrocarbons, known as biochar. The yield of biochar also depends on the type of biomass, drying process, particle size of feedstock (smaller), flow rate of inert gas, chemical activation, heating rate (higher up to 105–500 °C/s), residence time (shorter), pressure used in the reactor, etc. (Brown 2009). Biogas also known as syngas (synthesis gas), a multifunctional gaseous mixture (up to 10–35%) of CO, H_2, CO_2, and CH_4 produced during slow pyrolysis process and gasification, is used for the production of electricity, heat, ammonia, and biofuels. The quality and quantity of syngas are also dependent on various thermochemical conditions and gasification technology (Molino et al. 2018). Liquefaction is also a thermochemical conversion route of halophytic biomass into primarily liquid oil products in the presence of a catalyzing reagent. Other processing methods include fermenter-based enzymatic methods including lipase enzyme for biodiesel and bioethanol production (Akoh et al. 2007). Enzymatic hydrolysis of the pre-treated samples at 200 °C yielded high glucose up to 90% of glucose in raw *Salicornia bigelovii* corresponding to ethanol yield of 111 kg ethanol/dry ton which is half to ethanol recovery (230 kg/dry ton) obtained from the processing of conventional lignocellulosic residue of corn stover (Brown et al. 2014). This method is more environment-friendly with good biomass utilization. The use of halophytes for the production of bioethanol and biodiesel along with characteristic features of seed oil has also been presented in Tables 1, 2, and 3. Most of the halophytes are rich in salt content in their shoots which impair the enzymatic degradation of lignocellulosic biomass feedstock and enhance the corrosion of rector components. To overcome this problem, a salt-tolerant enzyme can be procured from halophilic bacteria along with adjusting the organic load of the reactor (Debez et al. 2017). Using halophyte as a feedstock, an overview on biofuel production, through various conversion processes, is provided by the authors. Figure 2 shows a systematic representation of the conversion routes of biofuel production.

4 Halophytes for Biofuel Production

It is well-known that various food crops are the source of tremendous feedstock materials to produce a different form of the biofuel (bioethanol, biodiesel, etc.), and numerous conventional oilseeds (such as canola, mustard, etc.) and food crops (sugarcane, maize, etc.) have already been explored for this purpose (Blackshaw et al. 2011). Halophytes, the nonconventional plants, provide two valuable harvests (seed oil and lignocellulosic biomass or straw) to produce biofuel, separately. Various studies have demonstrated that halophytes produce high oil yield, and their oil contains a huge amount of long-chain fatty acids. However, the yield of oil and composition of the fatty acids varies in diverse species, i.e., *Suaeda aralocaspica* yielded more than 25% oil, while *Suaeda acuminata* yielded only 14% oil. Similarly, *Crithmum maritimum* seeds contain up to 45% oil with an abundance of oleic acid, while *Salicornia brachiata* seeds contain 35% oil with the dominance of linoleic acid (Table 1). The oil produced from the oilseed halophyte has been found to be potentially useful to produced biofuel, mainly biodiesel. Primarily, biodiesel is composed of monoalkyl esters of long-chain fatty acid where fatty acid configuration provides reaction sites for the addition or cracking of the functional group to produce liquid fuel with miscellaneous properties (Kinder and Rahmes 2009).

Usually, oil ingredients do not affect fuel production routs, but at the same time, oil containing four double bonds and a high level of linolenic acid (more than 12%) is not suitable for biodiesel production at the industrial level (Abideen et al. 2015).

Table 1 Investigation on halophytes for oil yields and fatty acid content

Name of halophyte	Seed oil %	Fatty acid content (% of total content)	Reference
Aeluropus lagopoides	[a]	Palmitic acid (20.97), linoleic acid (22.48), stearic acid (0.89)	Patel et al. (2019)
Arthrocnemum macrostachyum	22–25	Linoleic acid (63.02), palmitic (26.93), stearic acid (3.17)	Weber et al. (2007)
Arthrocnemum indicum	[a]	Palmitic acid (17.81), linoleic acid (40.53), stearic acid (5.89), oleic acid (3.83)	Patel et al. (2019)
Cakile maritima	42	Erucic acid (25)	Zarrouk et al. (2003)
Cressa cretica	22–25	Linoleic acid (62.67), palmitic (25.75), stearic acid (8.26)	Weber et al. (2007)
Crithmum maritimum	44.4	Oleic acid (78.6), palmitic acid (4.8), linoleic acid (15.4)	Atia et al. (2010)
Halostachys caspica	11.97	Linoleic acid (64.67), oleic acid (18.28), palmitic acid (9.21)	Firouzabadi et al. (2015)
Haloxylon stocksii	22–25	Linoleic acid (66.24), palmitic acid (21.79), stearic acid (3.64), gadoleic acid (1.53)	Weber et al. (2007)
Kosteletzkya pentacarpos	19.3	Palmitic acid (24.2), malvalic acid (4.4), dihydrosterculic acid (1.4)	Moser et al. (2013) and Knothe and Moser (2015)
Salicornia brachiata	29.30–34.43	Linoleic acid (77.93), palmitic acid (15.95), stearic acid (4.46), and lauric acid (3.23)	Rathod et al. (2013)
	[a]	Linoleic acid (25.70), palmitic acid (25.82), oleic acid (6.13)	Patel et al. (2019)
Salicornia fruticosa	28.5	Oleic acid (56.58), linoleic acid (17.40), linolenic acid (3.98)	Elsebaie et al. (2013)
Salicornia herbaciea	29.4	Linoleic acid (43.73), oleic acid (19.81), arachidic acid (13.52), and palmitic acid (11.84)	Choi et al. (2014)
Sarcocornia ambigua	13	Oleic acid (18.5), palmitic acid (20.4), stearic acid (4.5), linoleic acid (42)	D'Oca et al. (2012)
Suaeda acuminate	14.3–14.5	Linoleic acid (65–68), oleic acid (14–18), palmitic acid (4.55–6.14)	Wang et al. (2011)
Suaeda aegyptiaca	32.99	Linoleic acid (73.14), oleic acid (14.49), palmitic acid (7.44), stearic acid (2.35)	Firouzabadi et al. (2015)
Suaeda aralocaspica	29	Linoleic acid (68–69.5), oleic acid (20–22)	Wang et al. (2012)
Suaeda fruticosa	22–25	Linoleic acid (72.8), palmitic (17.4), stearic acid (4.61)	Weber et al. (2007)
	[a]	Linoleic acid (36.33), palmitic acid (29.75), oleic acid (1.2), stearic acid (3.29)	Patel et al. (2019)

(continued)

Table 1 (continued)

Name of halophyte	Seed oil %	Fatty acid content (% of total content)	Reference
Suaeda maritima	[a]	Linoleic acid (14.26), palmitic acid (41.93), oleic acid (3.90)	Chandrasekaran et al. (2008)
Suaeda monoica	[a]	Linoleic acid (14.01), palmitic acid (19.74), oleic acid (4.71)	Patel et al. (2019)
	[a]	Linoleic acid (22.17), palmitic acid (43.12), oleic acid (5.31)	Chandrasekaran et al. (2008)
Zygophyllum album	6	Linoleic acid (64), oleic acid (19)	Zarrouk et al. (2003)

[a]Not determined

A number of studies have confirmed that fatty acid methyl esters (FAME) of halophytes superlatively meet fuel character recommended by international biodiesel standard (ASTM D6751-07b, EN 14,214) and become a technically viable diesel alternative in compression-ignition engines (Table 2).

The lignocellulosic biomass (comprising of the cellulose, hemicellulose, and lignin) is one of the fastest growing feedstocks especially for bio-alcohol production and presents one of the most exciting possibilities as a future resolution to our energy teething troubles (Mood et al. 2013). However, the net energy balances of lignocellulosic bio-alcohol has significantly lower than bio-alcohols produced from sugarcane or starch feedstock, but it could provide a means of substantial demand for bio-alcohol without pressurizing the food supply (Zhu and Zhuang 2012). It has also acclaimed that the lignin or their derivatives possess numerous challenges for the conversion of biomass to Bioethanol. Hence, species with less lignin in their cell wall is more appropriate and can reduce the cost involved in bio-alcohol production (Abideen et al. 2015). Various studies have demonstrated that halophytes contain a significant amount of cellulose and hemicellulose in their cell wall and are extensively used to produce bioethanol through various biochemical pathways (Table 3). Similarly, bio-butanol, one more compassionate of the bio-alcohols, can be produced from both the cellulosic and lignocellulosic feedstock. Studies show that lignocellulosic biomass of the halophyte has great potential to produce a substantial amount of butanol. A substantial yield of butanol has been obtained from *switchgrass* (Wang et al. 2019) and *Suaeda salsa* biomass (Zhao et al. 2011). Similarly, Gao et al. (2014) obtained 146 g kg^{-1} and 150 g kg^{-1} ABE yield from *Panicum virgatum* and *Phragmites australis*, respectively.

Recently, there is an enormous research interest to produce some other energy alternative in form of biochar, bio-oil, and syngas using lignocellulosic biomass of the various halophytes (Table 4). A study conducted on *Salsola collina* revealed that halophyte-derived biochar had higher aromaticity and cation exchange capacity and provides more energy gratified in comparison to glycophyte-derived biochars (Yue et al. 2016). Evaluating the specific energy content of char and bio-oil derived from

Table 2 Investigations on halophytes for biodiesel production and their fuel characteristics

Name of species	Fuel properties						Reference
	KN	CN	IV	SN	HHVs	FP	
Aeluropus lagopoides	1.13	29.91	191.83	203.89	39.12	[a]	Patel et al. (2019)
Arthrocnemum indicum	1.20	25.71	151.87	198.55	38.54	[a]	Patel et al. (2019)
Atriplex griffithii	1.13	27.89	201.27	203.09	39.17	[a]	Patel et al. (2019)
Atriplex nummularia	1.17	34.32	173.69	201.42	38.96	[a]	Patel et al. (2019)
Heleochloa setulosa	1.14	29.09	196.73	201.76	39.03	[a]	Patel et al. (2019)
Kosteletzkya pentacarpos	2.31	59.9	[a]	[a]	45.2	[a]	Moser et al. (2013)
Kosteletzkya virginica	[a]	47.37	113.14	205.99	[a]	[a]	Abideen et al. (2015)
Porteresia coarctata	1.21	39.72	147.61	204.90	39.27		Patel et al. (2019)
Salicornia bigelovii	31.60	38.93	154.05	201	39.40	152	Folayan et al. (2019)
	[a]	38.78	154.32	200.86	[a]	[a]	Abideen et al. (2015)
	1.22	44.1	132.02	199.13	38.44	[a]	Patel et al. (2019)
Salicornia brachiate	29.30	50	81.77	247.66	38.75	137	Folayan et al. (2019)
	[a]	81.67	29.7	129.89	[a]	[a]	Abideen et al. (2015)
Salicornia europaea	[a]	38.19	155.96	202.5	[a]	[a]	Abideen et al. (2015)
Salvadora persica	1.10	25.71	210.45	203.92	39.14	[a]	Patel et al. (2019)
	5.51	61	[a]	[a]	35.26	178.5	Ali et al. (2018)
Sesuvium portulacastrum	1.12	26.99	205.75	202.28	39.13	[a]	Patel et al. (2019)
Sporobolus virginicus	1.09	23.35	220.75	204.25	39.22	[a]	Patel et al. (2019)
Suaeda fruticosa	1.21	40.74	143.43	204.35	39.11	[a]	Patel et al. (2019)
Suaeda monica	1.14	30.91	187.06	204.46	39.14	[a]	Patel et al. (2019)

KN kinematic viscosity (mm^2/S), *CN* cetane number, *IV* iodine value, *SN* saponification number, *HHVs* higher heating values, *FP* flash point (°C)
[a]Not determined

switchgrass, Daniel et al. (2018) revealed that the specific energy of the biochar and bio-oil is approximately twofold higher than the raw biomass.

Table 3 Investigations on halophytes for bio-alcohol production

Name of species	Content in biomass	Production/process/methods	Reference
Achnatherum splendens	35.04% cellulose + 28.73% hemicellulose + 8.10% lignin	Bioethanol	Irfan et al. (2016)
Aeluropus lagopoides	26.67% cellulose + 29.33% hemicellulose + 7.67% lignin	Bioethanol	Abideen et al. (2011)
Atriplex nummularia	32.65% cellulose + 23.55% hemicelluloses + 8.02% lignin	Bioethanol	Tawfik et al. (2015)
Chenopodium formosanum	41.82% glucan + 24.15% xylan + 1.87% arabinan + 20.46% lignin	Bioethanol via pre-treatment (sulfite and acid steam explosion), enzymatic hydrolysis from *Escherichia coli*	Yang et al. (2014)
Cyperus imbricatus	35.6% cellulose + 32.3% hemicellulose + 4.7% lignin	Bioenergy and ethanol production	Premjet et al. (2013)
Cyperus iria	33.4% cellulose + 31% hemicelluloses + 6.3% lignin	Bioenergy and bioethanol	Premjet et al. (2013)
Cyperus rotundus	20–22% carbohydrate	Bioethanol via enzymatic hydrolysis	Kumar et al. (2014)
Cyperus spp.	20.76–30.07% cellulose + 12.93–15.87% hemicellulose + 4.03–11.88% lignin	Bioethanol via enzymatic saccharification from *Trichoderma reesei*	Vishwakarma and Banerjee (2016)
Euphorbia geniculate	24.9% cellulose + 8.4% hemicelluloses + 5% lignin	Bioenergy and ethanol	Premjet et al. (2013)
Halodule uninervis	11.3% glucan + 1.3% xylan + 0.5% arabinan + 17.5% lignin	Bioethanol and biomethane	Ashraf et al. (2016)
Halophila ovalis	11.4% glucan + 3.5% xylan, 2.8% arabinan + 4.5% lignin	Bioethanol and biomethane	Ashraf et al. (2016)
Halophila stipulacea	17.4% glucan + 2.3% xylan + 2.9% arabinan + 7.6% lignin	Bioethanol and biomethane	Ashraf et al. (2016)
Halopyrum mucronatum	37.00% cellulose + 28.67% hemicellulose + 5.0% lignin	Bioethanol	Abideen et al. (2011)
Heliotropium indicum	26.7% cellulose + 19.3% hemicellulose + 12.3% lignin	Bioenergy and ethanol	Premjet et al. (2013)

(continued)

Table 3 (continued)

Name of species	Content in biomass	Production/process/methods	Reference
Juncus maritimus	41.5% cellulose + 31.34% hemicellulose	Bioethanol via using freezing and thawing biomass pre-treatment	Smichi et al. (2016)
Kochia scoparia	27.36% cellulose + 24.71% hemicelluloses + 9.52% lignin	Bioethanol	Tawfik et al. (2015)
Leptochloa fusca	27.32% cellulose + 23.65% hemicellulose + 10.36 lignin	Bioethanol	Tawfik et al. (2013)
Leucaena leucocephala	21.54% cellulose + 18.56% hemicelluloses + 12.65% lignin	Bioethanol	Tawfik et al. (2015)
Lasiurus scindicus	24.67% cellulose + 29.67% hemicellulose + 6.00% lignin	Bioethanol	Abideen et al. (2011)
Miscanthus spp.	40–60% Cellulose + 20–40% Hemicellulose + 10–30% lignin	Bioethanol	Brosse et al. (2012)
Myoporum serratum	22.36% cellulose + 19.65% hemicelluloses + 13.54% lignin	Bioethanol	Tawfik et al. (2015)
Panicum turgidum	28.00% cellulose + 27.97% hemicellulose + 6.0% lignin	Bioethanol	Abideen et al. (2011)
Panicum virgatum	45% cellulose + 31% hemicellulose + 12% lignin	Biofuel	McLaughlin and Kszos (2005)
Phragmites karka	26.00% cellulose + 29.00 hemicellulose + 10.33% lignin	Bioethanol	Abideen et al. (2011)
Phragmites australis	50% cellulose + 17% lignin	Bioethanol	Yan et al. (2010)
Salicornia bigelovii	46.22% cellulose + 14.93% hemicelluloses + 1.96% lignin	Bioethanol via saccharification and fermentation using *Saccharomyces cerevisiae*	Bañuelos et al. (2018)
	9.1% glucan + 7.7% xylan + 5.5% arabinan + 6.8% lignin	Bioethanol and biomethane	Ashraf et al. (2016)
	25.7% glucan + 21.57% xylan + 5.73% arabinan + 7.69% lignin	Bioethanol and biomethane via pre-treatment	Chaturvedi et al. (2013)

(continued)

Table 3 (continued)

Name of species	Content in biomass	Production/process/methods	Reference
Salicornia sinus-persica	15.6% glucan + 10.7% xylan + 11.1% arabinan + 14.6% lignin	Bioethanol and biomethane	Ashraf et al. (2016)
Salsola imbricate	9.00% cellulose + 18.33% hemicellulose + 2.67% lignin	Bioethanol	Abideen et al. (2011)
Salvadora persica	22.00% cellulose + 13.33% hemicellulose + 7.00% lignin	Bioethanol	Abideen et al. (2011)
Spartina patens	24.69% cellulose + 21.65% hemicellulose + 10.2% lignin	Bioethanol	Tawfik et al. (2013)
Sporobolus indicus	35.6% cellulose + 29.9% hemicellulose + 6.6% lignin	Bioenergy and ethanol	Premjet et al. (2013)
Sporobolus virginicus	28.64% cellulose + 24.87% hemicellulose + 9.36% lignin	Bioethanol	Tawfik et al. (2013)
Sueada fruticosa	28.15% cellulose + 23.15% hemicelluloses + 7.21% lignin	Bioethanol	Tawfik et al. (2015)
Suaeda fruticosa	8.67% cellulose + 21.00% hemicellulose + 4.67 lignin	Bioethanol	Abideen et al. (2011)
Suaeda salsa	31.12% glucan + 24.91% xylan + 1.66% arabinan + 22.4% lignin	Bioethanol via enzymatic scarification	Li et al. (2013)
Tamarix indica	12.17% cellulose + 24.67% hemicellulose + 3.33% lignin	Bioethanol	Abideen et al. (2011)
Typha angustifolia	47.1% cellulose + 16.9% hemicellulose + 10% lignin	Bioenergy and ethanol	Premjet et al. (2013)

5 Socioeconomic Impacts of Biofuel Production from Halophyte Biomass

Replacing petroleum fuels with halophyte-based fuels, especially bioethanol and biodiesel, has huge potential to generate a number of impacts on both human beings and the environment (Fig. 3). These liquid biofuels provide economic sustainability in terms of investments, revenues, and employments, not only for the producer country but also to the whole global economy (Ingle et al. 2019). Consequently, the global biofuel market was valued at USD 168 billion in 2016 and is expected to extend to USD 218.7 billion in 2022. Similarly, the employments in the biofuels industries are at close to providing two million jobs in 2018 and will expand by 12% in the forthcoming years (Anonymous 2018). This industry is also subjected to enhance producer nation's revenue by diverse fiscal policies that are reliant on the

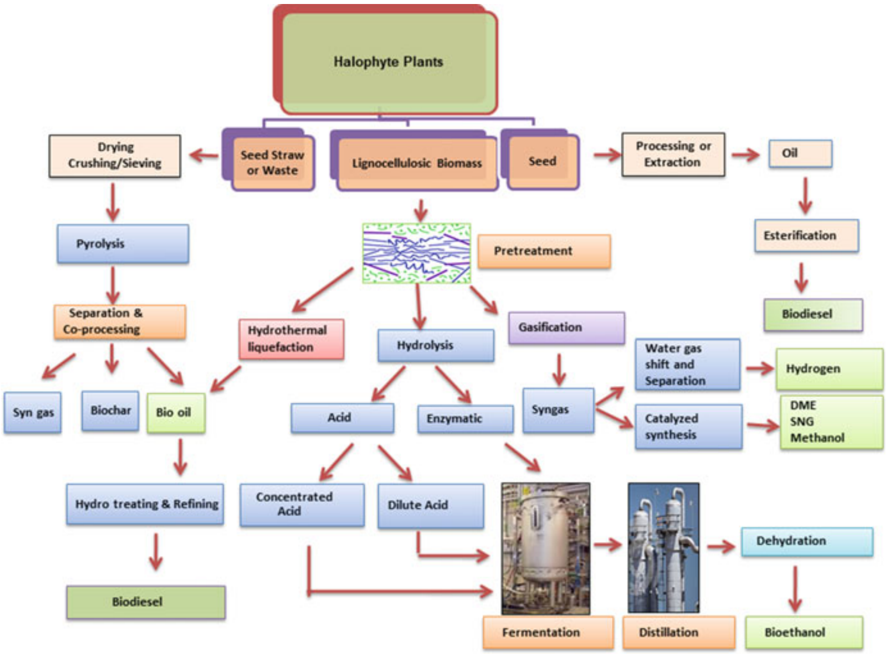

Fig. 2 Conversion processes of halophytes biomass feedstocks to biofuels

types of fuel, supply, and transaction places. Indeed, biofuel from halophytic biomass may reduce the reliance of the producer country on fuel import and save their foreign currency (Demırbas 2017). For instance, US reliance on petroleum imports has declined greatly in the last 5 years due to the increased production of biofuels (Anonymous 2019b). Similarly, India has successfully replaced 3.95 million metric tons of diesel by biodiesel and would save their foreign currency of approx. $1.47 billion in 2019 (Anonymous 2019a). Such types of biofuel contain a lesser amount of sulfur and aromatic content than fossil fuels and reduce the emission of hazardous GHG like CO_2, methane, and SO_2. It has been estimated that the use of 1 kg of biodiesel would lead to a reduction of approx. 3 kg of CO_2. Using biofuel in transportation and industrial sector, several developing and developed countries (like the European Union, the United States, Denmark, etc.) amazingly reduced their overall CO_2 emission in the last few years. Biofuel production practices can also contribute to support the rural diversification, traditional industries, as well as social development of rural societies (Demırbas 2017).

6 Techno-economic Feasibility of Biofuel Production

Biofuel productions using both cellulosic and lignocellulosic feedstock are technologically feasible and being tested on a demonstration scale in several producing countries (Dao et al. 2018). Techno-economic study of biofuel production technologies enables us to compare technical as well as economic output of the substitute

Table 4 Investigation on halophytes for the production of other bioenergy alternatives

Name of species	Biochar, bio-oil, and syngas production (% yield)	Process/methods/remarks	Reference
Achnatherum splendens	Biochar (24–28), bio-oil (18–27), syngas (34–54)	Using paralyzer under different pyrolysis temperatures	Irfan et al. (2016)
Arundo donax	Biochar (29–45), bio-oil (16.65–26.18), biogas (28.74–45.16)	Using pyrolysis in a fixed-bed reactor at temperature (350–650 °C), heating rate (10 °C and 40 °C min^{-1}), and sweeping gas flow rate (50–250 ml min^{-1})	Saikia et al. (2015)
Panicum virgatum	Biochar (27–41.3), bio-oil (30.8–34.1), syngas (26.3–40.9)	Via slow pyrolysis in a fixed-bed slow pyrolysis	Yue et al. (2017)
	Biochar (28–30), bio-oil (31–33), syngas (33–38)	Pyrolitic conversion using inductively heated reactor system	Daniel et al. (2018)
	Biochar (29), bio-oil (50–54), non-condensable gas (17–21)	Pyrolitic conversion using semi-pilot scale auger pyrolyzer	Ren et al. (2014)
	Biochar (25–48), bio-oil (22–37), syngas (8–26)	Via pyrolitic conversion at various temperatures	Imam and Capareda (2012)
Phragmites australis	Biochar (23.29–38.16), bio-oil (29.35–34.67), syngas (33.66–44.14)	Using fixed-bed tubular reactor with catalyst (tincal, colemanite, and ulexite) at different temperatures	Aysu (2014)
Tamarix chinensis	Biochar (38–41), bio-oil (20–35), syngas (30–41)	Using fixed-bed pyrolysis system	Irfan et al. (2016)
Salsola collina	Biochar (26.83–47.54), bio-oil (26–30), syngas (26.07–46.37)	Using fixed-bed slow pyrolysis system	Yue et al. (2016)

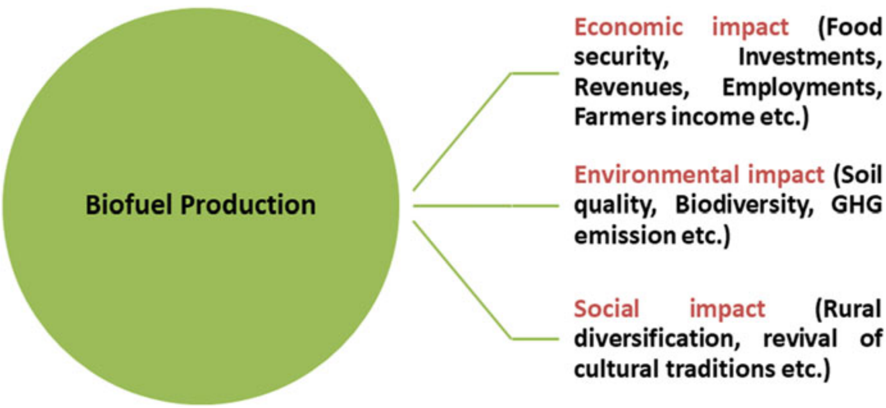

Fig. 3 Schematic representation of various impacts of biofuel production

technologies to choose some value-added options. Technical performances are generally determined using energy and material constancies of the whole production procedure including the total yield, quality, and performance. This assessment can also be done through evaluation of the processing steps, technical benefits, as well as limitations of alternative technologies (Patel et al. 2016). In the same way, the economic performance was generally determined through different economic parameters in which total investment cost and the total manufacturing cost are the main parameters. Such parameters give a clue to determine the cost-effectiveness of the whole biofuel production technologies and set a resolute market scenario (Zabed et al. 2017; Brown 2015). However, it is obvious that some market variable parameters (such as price break, tax alteration) show a crucial impact on the techno-economic feasibility of the whole production process (Campbell et al. 2018). Despite the large extent of research that has been carried out in this field, the economic outlook of commercial-scale production of biofuels from the halophyte biomass still remains unclear. There are only a few techno-economic models in the literature for halophytic biomass. Tao et al. (2011) compared techno-economic feasibility of six pre-treatment processes for converting *switchgrass* biomass into ethanol. They analyzed the overall ethanol production, total capital investment, and minimum ethanol selling price and concluded that pre-treatment process shows narrow differences among the projected economic performances, except the process which exhibits lower ethanol yield. In order to understand the economic feasibility of *Salicornia bigelovii*-based biorefinery, Alassali et al. (2013) took a number of economic parameters and compares it in three proposed technological scenarios (Table 5). Accordingly, it was concluded that *Salicornia*-based biorefinery is economically feasible and showed comparable EROI values to first generation-based biorefineries, despite the energy-intensive pre-treatment processes involved. It is

Table 5 Economic assessment of a *Salicornia*-based biorefinery on three technological scenarios

Technological scenario	Economic parameters					
	Total investment ($)	Total revenues ($/year)	Operating cost ($/year)	Gross margin (%)	Payback period (Year)	IRR before taxes (%)
Scenario 1 (Whole biomass to biodiesel, bioethanol, and biogas)	45,659,000	36,730,000	31,536,000	17.3	4.3	25.55
Scenario 2 (Whole biomass to biodiesel and biogas)	39,300,000	27,131,000	18,298,000	36.4	2.9	46.48
Scenario 3 (Seed to biodiesel and biogas)	24,943,000	8,149,000	9,565,000	−17.4	26.6	–

also precarious to optimize the bioethanol process mainly reducing the capital and operating costs in order to minimize the economic risk associated with running a biorefinery with biogas as the core product. Similarly, Dzidzienyo et al. (2018) studied the pyrolysis kinetics of *Salicornia bigelovii* and *Phoenix dactylifera* using thermo-gravimetric analysis and concluded that values of the activation energy during pyrolysis are more comparable with values which are obtained by various researchers using different biomasses.

7 Life Cycle Analysis

Life cycle analysis (LCA) is a universally distinguished approach for appraising the environmental performance of a product throughout its partial or whole life cycle including the acquisition of raw material, production, transportation, and usages (Muench and Guenther 2013). A wide range of feedstock material and its conversion process to biofuel alternatives have been analyzed by a number of researchers in a mean of life cycle analysis as well as assessments (Ubando et al. 2019; Righi 2019; Khoo et al. 2016). Morales et al. (2015) reviewed a number of studies which exhibit lignocellulosic ethanol production from miscellaneous feedstock. As a result, they conclude that most of the LCA studies focus on the global warming perspective and a clear reduction potential was observed if fossil feedstock is used instead of lignocellulosic feedstock. Furthermore, certain studies perceived the lower impacts on ozone depletion and toxicities related to heavy metal emission. However, some other impacts such as acidification, eutrophication, as well as ecotoxicity trends are less clear and depend on feedstock categories (Daylan and Ciliz 2016; Morales et al. 2015). Despite the fact that a wide variety of feedstock has been analyzed, only a few studies have focused on the environmental performances of the halophyte-based biofuels. LCA of a *switchgrass*-based biorefinery producing bioethanol, biomethane, and chemicals suggested that switchgrass extensively increases the GHG savings of the system for the first 20 years after crop establishment because it enhances carbon sequestration in soils when established on set-aside land (Cherubini and Jungmeier 2010). This biorefinery system exhibits reduced CO_2 and CH_4 emissions, ozone layer depletion, as well as marine, terrestrial, and freshwater ecotoxicity in comparison to fossil reference system (Tables 6 and 7).

Similarly, Alassali et al. (2013) analyzed a *Salicornia*-based biorefinery in terms of GHG and EROI. After evaluating the values of the different considerations (such as energy content and CO_2-eq emission of the materials, utilities, and energy sources), they conclude that *Salicornia*-based biorefinery is environmentally sustainable and showed comparable EROI values to first generation-based biorefineries (Fig. 4). Belasari et al. (2015) analyzed EROI values of a bioethanol process plant based on *Salicornia* biomass and obtained 2.40 EROI value, where 2,519 kWh/ha is the energy input and 6,050 kWh/ha is the energy output. Also, a study has resolved that switchgrass production on marginal land would reduce GHG emissions by 29.49 million ton CO_2-eq/year (Liu et al. 2017). Moreover, LCA of *Miscanthus*-derived ethanol showed that it holds potential for the reduction of GHG emissions in the transportation sector in comparison with the fossil reference petrol (Lask et al. 2019).

Table 6 A comparative account of total GHG emissions and savings of *switchgrass*-based biorefinery system with fossil reference system (Cherubini and Jungmeier 2010)

Systems	GHG emissions (kt CO_2-eq)				GHG savings		
	CO_2	N_2O	CH_4	Total	Per year (kt CO_2-eq)	Per t_{dry} feedstock (t CO_2-eq/t_{dry})	Per hectare (t CO_2-eq/ha)
Biorefinery 1–20 year (with soil CO_2 sequestration)	−8.6	64.2	4.86	60.5	221	0.46	7.41
Biorefinery >20 years (without soil CO_2 sequestration)	58.2	64.2	4.86	126	155	0.33	5.21
Fossil reference system	266	6.56	8.91	281	–	–	–

Table 7 A comparative account of various environmental impacts of *switchgrass*-based biorefinery with comparison to fossil reference system (Cherubini and Jungmeier 2010)

Sl. no.	Environmental impacts	Biorefinery	Fossil reference system
1	Abiotic depletion (ktSbeq)	0.42	1.94
2	Global warming (kt CO_2-eq)	60.5	281
3	Ozone layer depletion (kg CFC-11 eq)	10.5	31.2
4	Human toxicity (kt 1,4-DB eq)	34.2	187
5	Freshwater aquatic ecotoxicity (kt 1,4-DB eq)	4.08	16.8
6	Marine aquatic ecotoxicity (Mt 1,4-DB eq)	22.8	50.1
8	Terrestrial ecotoxicity (kt 1,4-DB eq)	0.35	0.62
9	Photochemical oxidation (kt C_2H_4)	0.06	0.28

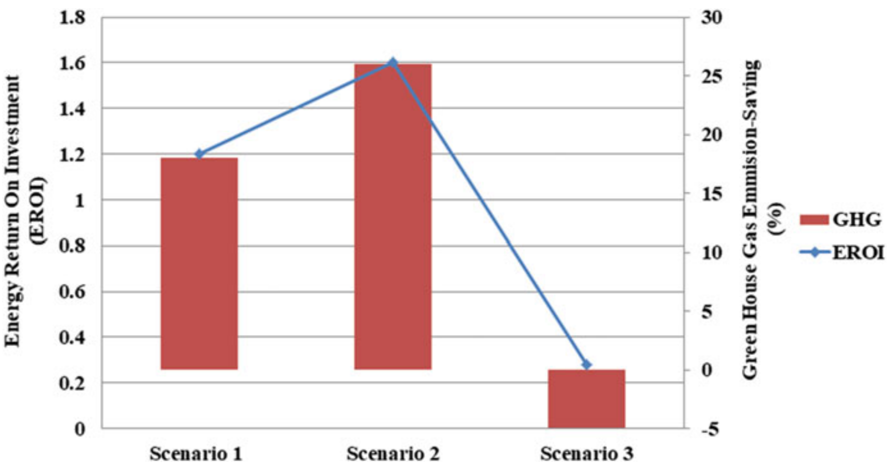

Fig. 4 EROI and GHG emission savings for the three different scenarios (Scenario 1, whole biomass to biodiesel, bioethanol, and biogas; Scenario 2, whole biomass to biodiesel and biogas; Scenario 3, seed to biodiesel and biogas) of a *Salicornia*-based biorefinery

8 Policy Considerations in the Main Biofuel Producing Countries

Policy concern has played a crucial role towards fruitfulness of the biofuels across the globe. It will likely continue for the foreseeable future by reducing barriers, highlighting the funding needs as well as encouraging sustainable approaches. Therefore, in this section we summarized policy considerations in the main biofuel producing countries along with their unsustainable issues related to policy trade activity.

8.1 United States

The United States is the leader among major biofuel producer countries. In the United States, national energy security with reduced fossil fuel import and development of a sustainable economy with low carbon release are the main driving forces behind the growth of biofuel. In order to guarantee the national energy security, the United States put forward the renewable fuel standard (RFS) that was established with the Energy Policy Act of 2005 and later enlarged with the Energy Independence and Security Act (EISA) 2007. EISA2007 distinct the advanced biofuel from non-corn feedstock and set a strict limit on the total amount of the greenhouse gas emission during its processing steps. The United States Environmental Protection Agency (EPA) regulates compliance with a tradable credit system as well as waiver capabilities. In 2019, EPA proposed regulatory changes to allow gasoline blended with up to 15% ethanol (E15) to take advantage of the 1-psi Reid vapor pressure (RVP) waiver that currently applies to E10 during the summer months. Similarly, a consent decree program has also announced for completing the anti-backsliding study required by Clean Air Act Section 211(v)(1) by March 2020. Also, the US biofuel policy supports the R&D as well as industrialization of bioethanol and biodiesel. To provide sustained industrialization and decreasing subsidies for the whole process, the US government has launched several projects such as Biomass Research and Development Initiative (BDRI), Small Business Innovation Research (SBIR), and Small Business Technology Transfer (STTR). Also, the US Senate Finance Committee announced to provide tax credits of $1.00 per gallon for renewable diesel like biodiesel and agri-biodiesel. However, such tax credits exist for delivery of 100% biodiesel as on road fuel (Meng and McKechnie 2019; Araújo et al. 2017).

8.2 Brazil

Brazil is the world's leader particularly for bioethanol production and trades. As early as the 1970s, the Brazilian government launched the National Ethanol Fuel Program (the Programa Nacional do Alcool) to improve ethanol production using sugarcane feedstock and decrease the country's reliance on petroleum fuel import. After the successful implementation of such program, sugarcane industry accounts for 3.5% of total GDP and provides approx. 3.6 million jobs. In recent years, the blending requirement of ethanol and biodiesel has been resining 27% and 10% in the country. To maintain its leading position and gratifying the blending requirement, Brazil encourages different policies and feedstock alternatives for biofuel production. In this regard, the Brazilian Socio-economic Development Bank (BNDES) has been established that could provide financial support to biofuel manufactures for establishing projects. A couple of incentive polices has also been launched by the Brazilian government to enhance the production of bioethanol via tax exemption practices, and a total 0.12 reais/l tax exemption was given on PIS and CONFIN taxes. Also, the government will also deposit an additional $340 million subsidies for farmers to expand the feedstock planting for bioethanol especially sugarcane. In recent years, the Brazilian government has made lots of efforts to seek international cooperation for the improvement of biofuels especially aviation biofuel. In that context, Embraer a leading Brazilian company has developed the first sugarcane fuel-based aircraft in association with the two US-based companies (General Electric and the Amyris). Also, Sao Paulo Research Foundation and US Boeing Company signed an agreement for the development of aviation biofuels (Cicogna et al. 2017; Araújo et al. 2017).

8.3 China

China will require strategic bioenergy planning because it has ranked first in the consequences of population and total energy consumption in the world. Also, it becomes the world's largest in terms of total oil import as well as CO_2 emission. China has formulated a series of policies to encourage the development as well as utilization of the bioenergy. The biofuel development program has implemented in China since early 2000, and in 2011 it become the world's sixth largest producer of biofuel. In 2012, the renewable energy program has been launched by the national energy bureau to support renewable energy via industrial development guidance and management approach. In terms of policy support, the Chinese Government projected approx. 973 programs which gave strong support to the research and development of the biomass energy for the period of upcoming 5-year programs. Such projects also include a scientific basis for microalgae energy-scale preparation and efficient transformation of lignocellulose in bioenergy. Most of the Chinese legislation, policies, and supporting programs give primary emphasis on the cultivation of feedstock and promotion of the technology for liquid biofuel and advocate the use of nonfood substitutes to produce bioenergy in form of bio-oil, biochar, and syngas. Furthermore, China taking an active role in decreasing CO_2 emission, some additional policies will require (Hao et al. 2018).

8.4 European Union Bioenergy Policy

The European Union predominantly initiated a bioenergy development program after the assignation of Kyoto Protocol in 1997. Since then the mitigation of climate change has become an important driving factor for the making of policies in

EU. In order to accomplish the objectives of bioenergy development and environmental sustainability, the EU Council launched a couple of directives such as the promotion of renewable energy (2009/28/EC), the use of renewable fuels for transport (2003/30/EC), and fuel quality (2009/30/EC). Such directives set broad-spectrum targets to reduce greenhouse gas emission by the use of biofuels and other renewable fuels. Also, EU released a roadmap for a competitive low-carbon economy in 2050 in which EU should reduce greenhouse gas emission by up to 60% by 2040 and up to 80% by 2050 in comparison to 1990. In addition, EU Framework Programmes for Research and Technological Development (EU-FP) and Horizon 2020 have been launched to directing R&D efforts of capital and Member States to actively promote the innovation and development of bioenergy technologies through large-scale R&D projects (Drabik and Venus 2019).

8.5 India

India is the fourth largest petroleum consumer across the globe and spends 45% of its export earnings on importing petroleum. As a consequence, biofuels have received considerable attention in India to reduce its reliance on petroleum imports. The first legislation on biofuel has been made through the Indian Power Alcohol Act (1948) with a vision of establishing power alcohol industry and was further repealed by Indian Power Alcohol Act (2000). In 2003, the Indian government introduced ethanol blended petrol program (EBPP) to promote the blending ethanol with petrol. In 2009, the National Biofuel Policy has been launched by the Ministry of New and Renewable Energy (MNRE) to endorse the biofuel blending (at least 20%) with diesel and petrol by 2017. This blending will increase the bioethanol requirement by up to 3.4 billion liters by 2020. As of June 2018, the government of India has set a resolute target of achieving 225 Giga Watt (GW) of renewable energy capacity by 2022 via renewable energy sources including the biomass power (Joshi et al. 2019). In addition, a minimum support price (MSP) has been announced for farmers to promote the production of nonedible oilseeds for biodiesel. Similarly, a minimum purchase price (MPP) has been announced for the purchase of bioethanol by the oil marketing companies (OMCs). The Ministry of Agriculture and the Ministry of Science and Technology has provided support for the production of biofuel feedstock crops and biotechnological research in biofuel crops, respectively. Also, the National Biofuel Coordination Committee (NBCC) was formulated to provide high-level coordination of various agencies and departments and review the different aspects of biofuels such as development, promotion, as well as utilization (Prasad et al. 2020).

8.6 Association of Southeast Asian Nations (ASEAN)

Governments of ASEAN countries have set target to use biofuel in diesel engines to reduce dependency on fossil fuel and harmful gas emission to the environment. In this regard, Malaysia and Thailand launched a national biofuel policy and successfully introduce B7 and B10 mandate across the country, respectively. Similarly, the Vietnam government targets renewable energy to reach 5% of primary commercial energy in 2020 and 11% by 2050. Indonesia targeted biofuel share to reach 5% of total energy share and 15% bioethanol and 20% biodiesel to replace gasoline and diesel, respectively, within 2025 (Mamat et al. 2019).

9 Key Challenge and Logistic Issues Related to Biofuel Production

Biofuel production from halophytes is more challenging than the glycophytes as the halophytic feedstock required some additional processing steps due to the composite nature of their biomass. The halophytic feedstock contains a large amount of inorganic salts and lignin substances and, therefore, possess a major challenge for the thermochemical and biochemical conversion process and increase the cost involved in biofuel production. In the fields, their harvesting requires additional mechanical or manual labor support for cutting, raking, as well as balling of feedstock material. Their supply chain possibly boosts the production cost, as it requires various dispensation steps, such as collection and storage, preprocessing (at the field), and postprocessing (at the refinery) as well as transportation. According to the NASA research laboratory working on halophyte-based biofuel production, it has been estimated that the cost of per gallon halophyte-based biofuel is approx. 1.3-fold higher than petroleum fuels where only feedstock harvesting takes account for 30–35% of the total production cost.

10 Conclusion and Future Perspectives

With the ever-increasing population and higher food demand, a conventional cropping system is not suitable to cope with the situation, where soil's salinity is adversely affecting the agricultural productivity. One of the major challenges is either to remediate the degraded soil or to cultivate the plant species that could tolerate and withstand salinity with good agricultural production yields along with market value products such as biofuels. In the last years, biomass from various agriculture crops has been used for biofuel production due to their CO_2 mitigation effects and less GHG emissions. The use of such agriculture crops limited the food availability, and the use of nonconventional crops such as halophytes had been increased for biomass, biodiesel, bioethanol, and many other energy-generating secondary products. The proper cultivation practices with proper selection of suitable halophytes will result in improved feedstock, along with the improvement in various technical processes of thermochemical conversion of cellulosic and lignocellulosic biomass used for the production of such biofuels with proper regulation of temperature, pressure, residence time, heating rate, etc. The use of halophytes with a crop diversification system is judicious to reclaim saline soils because these plants can accumulate high amounts of heavy metals and various inorganic salts present in the soil.

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