

REVIEW ARTICLE

Sustainable biofuel production from non-food sources – An overview

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Abstract

Increasing human population demands more fuel supply causing the release of hazardous greenhouse gases that could be compensated by supplementing with renewable and environment-friendly alternatives such as biofuels. The argument against the use of food crops for biofuel production that it may cause food shortages can be countered by using feedstock outside the human food chain. This opens up the possibility of using halophytes, algae and photosynthetic bacteria as sources of the carbon neutral biofuel which can be produced sustainably without compromising conventional agriculture. In this review we assess the suitability of these non-food resources as bio-fuel alternates.

Key words: Algae, Biofuels, Halophytes, Photosynthetic bacteria, Renewable energy, Salinity

Introduction

Burgeoning world population needs food security for sustenance and energy supplies for industry, transportation and domestic purposes. Agriculture has so far managed to keep pace with the demand however food is not available to everyone due to uneven distribution and capacity to purchase (Raven et al., 2013). Energy requirement increased in some order of magnitude (~2.4-fold) from 5000 million tons of oil equivalent (Mtoe) in 1971 to 11700 Mtoe in 2010; 70% of this increase was recorded in Asia (Van Lienden et al., 2010). The trend of increasing energy demand will continue and is expected to rise 1.5 fold worldwide and almost double in Asia by the year 2035 (Matsuo et al., 2013). Fossil fuel is not going to last long given the rate of its utilization. It is projected that at the current rate of utilization, oil and gas will be exhausted in 2050 (British Petroleum, 2010) while coal may be available for about 100 years (Shafiee and Topal, 2009). The world hence desperately needs alternate energy sources preferably those

which are renewable and carbon neutral.

Severe water shortage, desertification and soil salinization have been forecast in the near future for many parts of the world (Bayram and Ozturk, 2014). Therefore, ensuring availability of inexpensive and clean water appears an overriding global challenge (Wessman et al., 2014). Demands for biomass-derived energy production through biofuels may lead to competition with food crops for farmland and water (Wessman et al., 2014) hence; innovative alternatives for biofuel production are needed. Biomass produced using saline land and saline water which can be used for biofuel production may supplement fuel requirement without compromising food security (Beccles, 2013). This will also decrease the dependence of many countries on fuel imports as well as reduce their foreign exchange bills (Moller et al., 2014; Prakasham et al., 2014). Moreover, biofuels release almost the same amount of CO₂ which was fixed during photosynthesis hence, they hold great potential to fulfill/supplement future energy requirements with minimum hazards for the environment provided their production is carefully regulated and planned (Gul et al., 2013). The aim of this paper is to provide an overview of utilizing different non-food sources for the production of various types of biofuels.

Biofuels classification

Biofuels, on the basis of type of feedstock used, are divided into three categories (Figure 1). First

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generation biofuels are prepared directly from food crops such as sugarcane, corn, sunflower and wheat etc. Second generation biofuels are obtained from non-edible biomass such as crop byproducts, plant litter and organic waste etc., while, third generation biofuels are obtained from non-food resource which are grown using land or water unsuitable for crop production (Chisti, 2007). On the basis of chemical nature, biofuels can be categorized into bioethanol and biodiesel (Figure 1). Bioethanol used to supplement gasoline (10-15%) can be produced either by digestion of cellulosic biomass into sugars or direct extraction of sugars, followed by their conversion into ethanol (van derlaaka et al., 2007). About 20% of car fuel in Brazil, is obtained from bioethanol (Eshel et al., 2010) while it is the most widely used renewable transportation biofuel in the US with the production of 13.3 billion gallons in 2012 (Westpheling, 2014). Sugar cane is the dominant raw material in Brazil while many other crop plants such as cassava, sugar-beet, wheat, rice, corn, barley, potato, and sorghum are also being utilized for bioethanol production in different parts of the world (Rajagopal et al., 2007; Lee and Lavoie, 2013).

Biodiesel which can either be used directly in diesel engines or blended with conventional diesel, is produced by esterification of oil extracted from different oilseed crops such as soybean, sunflower, oil-palm, canola and rapeseed (Lee and Lavoie, 2013). The concerned countries have allocated areas with limits of coverage for cultivating crops meant for bio-diesel production (Avinash et al., 2014). However, use of algae and many non-crop

seed oil plants such as *Jatropha curcas*, *Pongamia pinnata*, and many halophytes is also being advised for this purpose (Singh and Ahalavat, 2014). At present, USA uses 50 million gallons and European countries use 350 million gallons of bio-diesel annually. France is the country which uses 50% of bio-diesel mixed with diesel fuel (Murugesan et al., 2014). Many other forms of biofuels such as bio-methanol (Yusuf et al., 2011), syngas (Munasinghe and Khanal, 2010), biochar (Clarke and Preto, 2011), and bio-hydrogen (Mckinlay et al., 2014) are also emerging as biofuel alternative.

Use of first generation biofuels has penalties

At present sugarcane, cassava, sugar-beet, wheat, rice, corn, and sorghum occupy about 42% of the world's cropping area (Rajagopal et al., 2007), which if directed towards bioethanol production to compensate increasing demand for fast growing human population, could have drastic effects on food security. Same is true for edible oil crops such as sunflower, rapeseed, canola and soybeans, which are common choices for biodiesel production. This concern has sparked the "food versus fuel" debate among scientists and policy-makers of the world. Furthermore, first generation biofuels not only threaten food security but also have many environmental issues. For, instance, cultivation of Oil-Palm for biodiesel in many parts of Indonesia is encroaching upon virgin rain forest; similarly soybean cultivation is damaging the Amazon in South America (Teoh, 2010). Hence, second and third generation biofuels obtained from non-food sources is receiving more attention.

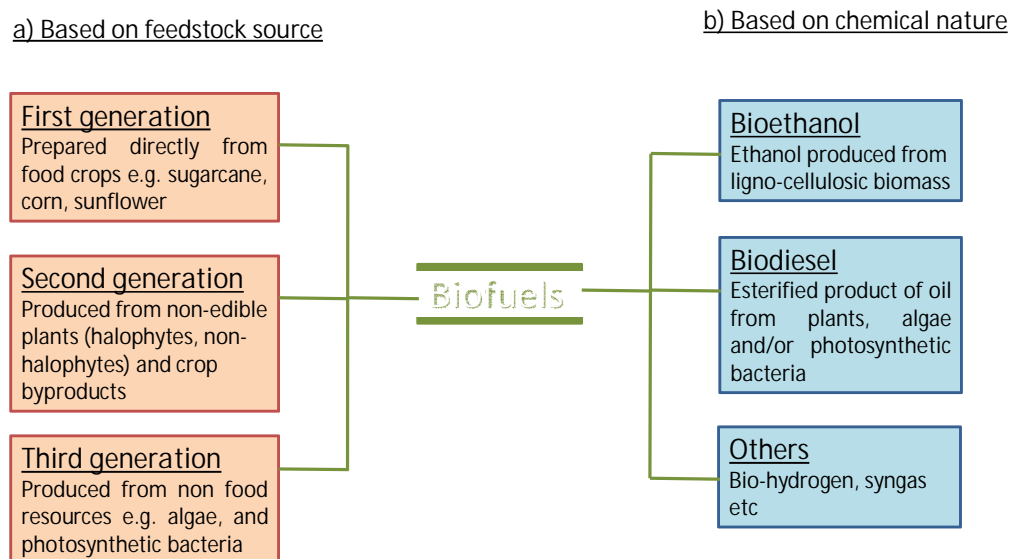


Figure 1. Classification of biofuels based on a) feedstock source and b) chemical nature.

Second and third generation resources as environment friendly, non-food feedstocks for biofuels

Second and third generation biofuels which utilize non-food commodities unlike first generation biofuels, pose minimum threat to food security and natural ecosystems (Abideen et al., 2012). They are produced from a generally less expensive biomass such as forest/agricultural/animal/municipal wastes and commodities which might be efficient in their water and nutrient requirements. Feedstocks which are grown using saline resources are highly productive on unit area basis compared to the productivity obtained by fresh water feedstocks (Gul et al., 2013) however, challenges like efficient conversion of biomass into biofuel still exist (Zhu and Ketola, 2012). In case of algae, geographical limitations exist in areas like Canada where temperatures for a large part of the year are below the optimal requirement for algal growth (Borowitzka and Moheimani, 2013; Lee and Lavoie, 2013). The future of biofuels hence necessitates combination of the three generations of feedstocks to cope with increased worldwide demand and depletion in the world's oil resources. Presented below is an overview of some promising non-food resources for biofuel production.

Halophytes

Halophytes are naturally salt resistant plants of both inland and coastal saline habitats worldwide (Flowers et al., 2010). Many of these salt resistant plants even grow better under saline conditions (Flowers and Colmer, 2008; Hameed and Khan, 2011), hence hold potential as bio-ethanol crop (Abideen et al., 2011). For instance, fresh biomass of a halophytic grass *Phragmites karka* increased substantially when sub-irrigated with 100 mM NaCl as compared to non-saline conditions (Figure 2a). Likewise, another halophytic grass *Panicum turgidum*, identified later as *Panicum antidotale* (Khan, unpublished) could produce significant biomass in 125 mM NaCl comparable to non-saline control (Figure 2b). These plants cultivated on saline barren lands using salty water irrigation could produce biomass which can be used to produce not only biofuel (Abideen et al., 2011), but also medicines (Qasim et al., 2014) and fodder (Khan et al., 2009; Koyro et al., 2014) as well as sequester CO₂ (Abideen et al., 2011). Therefore, halophytic grasses such as *Phragmites karka*, *Panicum turgidum*, *Halopurum mucronatum*,

Typha domingensis and *Desmostachya bipinnata* could be promising candidates for bioethanol production due to their fast growth rate under stressed conditions and higher cellulose/hemicellulose and lower lignin contents (Table 1). These species need minimum maintenance due to low pest infestations and are highly productive on saline soils irrigated with salty water. Recently, with the support of Boeing and Etihad Airways, a project has been launched in the UAE for assessing the suitability of utilizing halophytes for sustainable production of jet fuel (Anonymous, 2014).

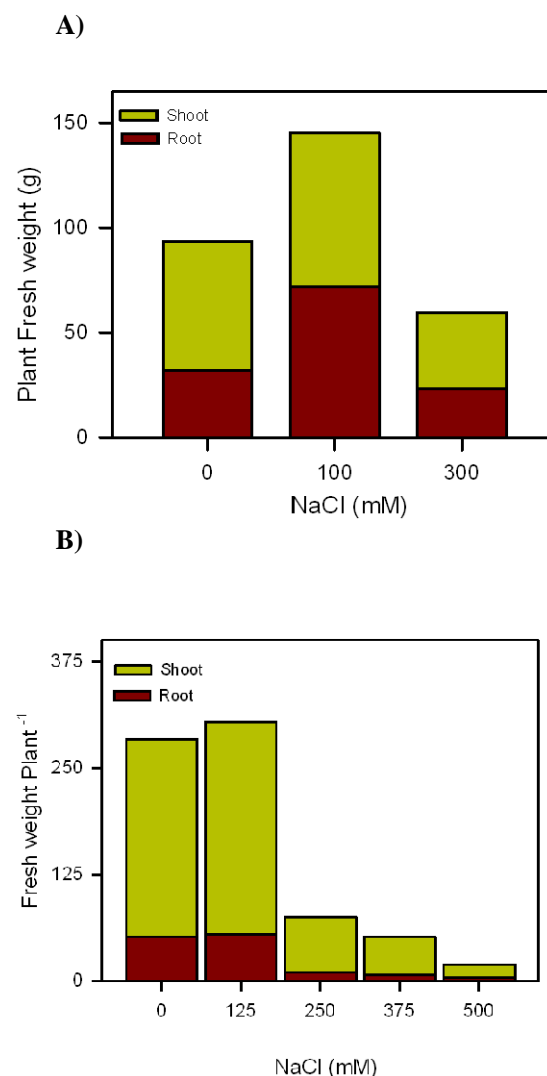


Figure 2. Growth responses of (A) *Phragmites karka* (Abideen et al., 2014) and (B) *Panicum turgidum* (Koyro et al., 2013) to increasing NaCl concentrations.

Table 1. Cell wall contents (percent of dry weight) of various biofuel commodities.

Generation	Example	Cellulose	Hemicellulose	Lignin	References
First	Sugar beet	20.0	25.0	20.0	Foster et al., 2001
	Sun flower	25.0	17.0	17.0	Gerçel, 2002
	Maize	33.8	25.4	8.6	Amon et al., 2007
	Corn stover	38.0	28.0	7.0	Ganjyal et al., 2004
	Alfalfa	34.4	6.7	7.2	Keys et al., 1969
	Brome	22.8	26.6	4.9	Keys et al., 1969
	Pine	44.0	21.9	27.8	Hamelinck et al., 2005
Second	<i>Non-halophytes</i>				
	<i>Panicum virgatum</i>	16.8	27.6	9.3	Gnansounou & Dauriat, 2010
	Coastal Bermuda grass	25.0	35.7	6.4	Reshamwala et al., 1995
	<i>Eucalyptus</i>	34.0	18.1	19.4	Gnansounou & Dauriat, 2010
	<i>Robinia pseudoacacia</i>	41.0	17.6	26.7	Hamelinck et al., 2005
	Poplar	21.3	28.7	13.0	Gnansounou & Dauriat, 2010
	Orchard grass	30.5	26.7	4.6	Keys et al., 1969
	<i>Halophytes</i>				
	<i>Halopyrum mucronatum</i>	37.0	28.7	5.0	Abideen et al., 2011
	<i>Panicum turgidum</i>	28.0	28.0	6.0	Abideen et al., 2011
	<i>Phragmites karka</i>	26.0	29.0	10.3	Abideen et al., 2011
	<i>Typha domingensis</i>	26.3	38.7	4.7	Abideen et al., 2011
	<i>Desmostachya bipinnata</i>	26.7	24.7	6.7	Abideen et al., 2011
Third	Barley straw	31.0	27.0	19.0	Rowell, 1997
	Sorghum stalks	27.0	25.0	11.0	Gressel & Zilberstein, 2003
	Husk of coconut	36.0	1.0	40.0	Banerjee et al., 2002
	Wheat straw	33.0	20.0	15.0	Sun & Cheng, 2002
	Rice husk	33.0	26.0	7.0	Jackson, 1977
	Nut shell	25.0	25.0	30.0	Sun & Cheng, 2002
	Rice Straw	40.0	18.0	5.5	Sun & Cheng, 2002
	Corn cobs	45.0	35.0	15.0	Sun & Cheng, 2002

Seeds of many halophytes may contain >20% (per g dry weight basis) oil (Weber et al., 2007). For instance, *Salicornia bigelovii* seeds contain 30% oil (Glenn et al., 1998), *Suaeda fruticosa* and *Arthrocnemum macrostachyum* seeds contain about 25% oil, while those of *Halopyrum mucronatum*, *Cressa cretica*, *Haloxylon stocksii* and *Alhaji maurorum* contain 22.7%, 23.3%, 23.2% and 21.9% oil respectively (Table 2; Weber et al., 2007). Oil from these halophytes could be utilized as source for biodiesel. Fatty acid methyl esters (FAME) of many halophyte oils found comparable to those of oils conventionally being used for biodiesel production are presented in Table 2 (Abideen and Khan, unpublished).

The ash content is generally higher in above ground biomass of halophytes than that of glycophytes because the former absorb salts from their saline habitats whereas low salt load is better and excessive amount of salt in the foliage might pose problems in processing for efficient biofuel production (Abideen et al., 2012). Halophytes which restrict ion uptake and avoid excessive salt buildup in foliage are hence preferable feedstock. Ash may also cause a number of problems to power

plants through slagging, corrosion and fouling (Misra et al., 1993). It has further been demonstrated that heating values are negatively related with ash content; every 1% increase in ash concentration decreases the heating value by 0.2 MJ kg⁻¹ (Cassida et al., 2005). Knowledge of salt uptake and deposition in above ground tissues is hence an important prerequisite for biofuels production using saline resources (Abideen et al., 2014).

Algae

Algae are photo-autotrophic organisms, belonging to either kingdom Protista or Plantae and occupy diverse habitats ranging from moist river banks to oceanic waters (Cellamare et al., 2010; Mutanda et al., 2011; Pereira et al., 2011; Guiry and Guiry, 2012). They are emerging as a promising biofuel source because of their growth rates faster than land plants, their higher triacylglyceride contents (>50% on dry weight basis in some cases) and their independence on arable land (Scott et al., 2010). They can produce 58700 L/ha biodiesel compared to 1190 L/ha biodiesel from rapeseed and canola (Schenk et al., 2008). Although growth rate

and triacylglyceride contents vary among species of algae (Leite and Hallenbeck, 2012), still a number of suitable candidates have been identified. For instance, *Chlamydomonas reinhardtii*, *Dunaliella salina*, *Chlorella* spp., *Botryococcus braunii*, *Phaeodactylum tricorutum* and *Thalassiosira pseudonana* have been reported as promising biofuel candidates (Scott et al., 2010). Some species of *Laminaria* (Chynoweth, 2005) and *Ulva* (Harun et al., 2014) are promising sources for bio-methane.

Algae can be mass produced using low quality water but with several fold higher N and P

supplement than needed for land plants (Grobbelaar, 2004), which make their products expensive and requires measures to decrease the cost. Other limitations may include need for controlled temperature and optimum light requirement for photosynthesis. Photo-bioreactors may be too costly to run while open ponds in areas where adequate sunlight is available, requires appropriate infrastructure adding to the cost of production. Growing salt resistant/ marine algae in saline water may be feasible but only after careful preliminary trials (Gul et al., 2013).

Table 2.Oil content (percent of dry weight) of various biodiesel candidates.

Generations	Examples	Oil content (% DW)	References
First	Soybean	20	Atabani et al., 2012
	Palm oil	30	Atabani et al., 2012
	Coconut	63	Atabani et al., 2012
	Rapeseed	38	Atabani et al., 2012
	Sunflower	25	Atabani et al., 2012
	Peanut oil	45	Atabani et al., 2012
	Olive oil	45	Atabani et al., 2012
	Cottonseed	18	Atabani et al., 2012
Second	Non-halophytes		
	<i>Moringa oleifera</i>	40	Kibazohi and Sangwan, 2011
	<i>Aleurites moluccana</i>	20	Kibazohi and Sangwan, 2011
	<i>Madhuca indica</i>	35	Balat and Balat (2010)
	<i>Aleurites fordii</i>	30	Sharma et al., 2011
	<i>Jatropha curcus</i>	30	Chhetri, 2008
	Halophytes		
	<i>Suaeda glauca</i>	25	Du et al., 2009
	<i>Kosteletzkya virginica</i>	17	Guo et al. 2011
	<i>Suaeda salsa</i>	22	Mo and Li, 2010
	<i>Ricinus communis</i>	47	Zhou et al. 2010
	<i>Helianthus annuus</i>	35	Chen and He, 2011
	<i>Suaeda fruticosa</i>	25	Weber et al., 2007
	<i>Cressa cretica</i>	23	Weber et al., 2007
	<i>Arthrocnemum macrostachyum</i>	22	Weber et al., 2007
	<i>Haloxylon stocksii</i>	23	Weber et al., 2007
<i>Salicornia bigelovii</i>	30	Weber et al., 2007	
<i>Halopyrum mucronatum</i>	23	Weber et al., 2007	
Third	Microalgae		
	<i>Botryococcus braunii</i>	25	Chisti, 2007
	<i>Chlorella</i> sp.	28	Chisti, 2007
	<i>Cryptocodinium cohnii</i>	20	Chisti, 2007
	<i>Monallanthus salina</i>	20	Chisti, 2007
	<i>Nannochloropsis</i> sp.	31	Chisti, 2007
	<i>Neochlorisoleoabundans</i>	35	Chisti, 2007
	<i>Nitzschia</i> sp.	45	Chisti, 2007
	<i>Schizochytrium</i> sp.	50	Chisti, 2007
	Cyanobacteria		
	<i>Rhodospseudomonas palustris</i>	22	Kim et al., 2013
	<i>Acinetobacter calcoaceticus</i>	27	Meng et al., 2009
	<i>Rhodococcus opacus</i>	24	Meng et al., 2009
	<i>Bacillus alcalophilus</i>	18	Meng et al., 2009

Photosynthetic bacteria

Photosynthetic bacteria such as cyanobacteria can also be utilized as biofuel source (Antoni et al., 2007; Nakashimada et al., 2014). Similar to algae, cyanobacteria have fast growth, high triacylglyceride yield and don't need land for growth (Parmar et al., 2011; Moazami et al., 2011). They contain slightly lower (about 20 to 40% on dry weight basis) triacylglycerides than algae but many cyanobacteria can fix atmospheric N, thereby require lower N input (Lundquist et al., 2010). Recently, Kim et al. (2013) demonstrated continuous cultivation of photosynthetic bacteria *Rhodobacter sphaeroides* for fatty acids production (Lee et al., 2013). Cyanobacteria can also generate biohydrogen which can be used as fuel (Sakurai and Masukawa, 2007; Tamagnini et al., 2007). A cyanobacterium *Arthrospira platensis* is reported to generate significant quantities of biomethane, another fuel (Converti et al., 2009). Another advantage of using bacteria for biofuel production is their small genome size, which can easily be manipulated to bring desirable changes. Hence, cyanobacteria hold great potential to become a biofuel source, however intense research regarding their cultivation and processing is required.

Conclusions

Fast growing human population is intensifying pressure on current food and fuel supplies thereby compelling us to look for innovative alternatives, which are both ecologically sustainable and commercially feasible. Increasing fossil fuel consumption has many downsides including its non-renewable nature and environmental pollution. Use of non-food commodities such as crop residues, organic waste, salt/drought resistant wild plants, algae and photosynthetic bacteria for producing biofuel can ensure a sustainable supply of fuel for the future, besides mitigating rising CO₂ concentrations, which is the key cause for global climate change. It is however highly unlikely that biofuel or any other innovation will solve the problem as a sole source of energy in the near future. This may require an intelligent mix of all kind of energy sources derived from sunlight, water, air, nuclear and of course fuel from fossil sources and plant biomass etc., coupled with more fuel efficient motors/gadgets to keep the wheels of our economies running.

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