Biofuels, 2015
Vol. 6, Nos. 5–6, 241–248, http://dx.doi.org/10.1080/17597269.2015.1090812

Oilseed halophytes: a potential source of biodiesel using saline degraded lands

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(*Received 7 July 2015; accepted 2 September 2015*)

The financial and technical aspects of using edible plants as a biodiesel source have been studied extensively, but research on the potential use of salt resistant, non-edible plants for this purpose remains relatively underexplored. Data available on salt tolerance range, seed oil content, composition of fatty acid methyl esters (FAME) and engine performance parameters – Iodine Value (IV), Cetane Number (CN) and Saponification Number (SN) – of 20 salt-resistant plants were examined to assess their suitability for use as diesel engine fuel. Most of the test species were perennial from family Amaranthaceae, exhibiting high salt tolerance. The quantity of their seed oil ranged from 10–30% while nine species contained >25% oil. The SN, IV and CN values varied from 130–206, 29–156 and 38–81, respectively. Based on the above mentioned parameters, seven halophytic plant species – *Salicornia fruticosa*, *Cressa cretica*, *Arthrocnemum macrostachyum*, *Alhagi maurorum*, *Halogeton glomeratus*, *Kosteletzkya virginica* and *Atriplex rosea* – appear to be promising biodiesel candidates. These non-food plants which can grow using saline resources and have an oil composition suitable for engine efficiency are more salt resistant than *Jatropha* or other glycophytic feedstock to serve in a bioenergy farming system. Cultivation of such plants for biodiesel production has the additional advantage of reclaiming degraded lands with the environmental benefit of carbon sequestration.

Keywords: biodiesel; halophyte; Iodine Value; biodiesel quality; salinity

Introduction

Industrial economies rely heavily on fossil fuels which are depleting and have dire environmental and ecological consequences due to greenhouse gas emissions. [1] Forces of increasing fuel demand and limited supply in global market cause price fluctuation generally with inflationary trends and eventually results in hardship for consumers. Biofuels can serve as a low cost, environment friendly and sustainable supplement to cope with this issue. However, use of edible crops as feedstock for this purpose may result in a shortage of food supply and high prices. This situation consequently creates immense pressure to search for suitable alternative crops for bioenergy feedstock. Since 1970s, efforts to increase biomass resources illustrate the need to replace or supplement fossil fuel with alternative bio-energy resources which are sustainable and environment friendly. [2] For instance, efforts have been made to convert plants seed oil into 'biodiesel' by several methods (transesterification, esterification and pyrolysis) which can be mixed in any proportion with diesel fuel to create a suitable biodiesel blend. [3,4]

One of the most important yardsticks in biodiesel production is the total oil yield from seeds. Additionally, engine parameters such as Saponification Number (SN), Cetane Number (CN) and Iodine Value (IV) influence the efficiency of running a vehicle and needs attention before recommending any biodiesel source. SN indicates a key factor of triglycerides in fatty acid methyl esters (FAME) depending upon their concentration and molecular weight. CN is related to the combustion quality of fuel and the duration it takes to ignite the combustion chamber. It also measures the time lapse between fuel injection and auto-ignition. [5] Another important consideration for biodiesel quality is the IV which is a direct measure of unsaturated fatty acid fraction needed to a certain extent to maintain fluidity of liquid fuel. [6]

Raw materials being used generally for biodiesel production include edible oil of conventional crops. The salinity tolerance of such crops including Rapeseed 120 mM, [7,8] *Jatropha curcus* 60 mM, [9] Soybean 50 mM, [10] Linseed 140 mM, [11] Palm 100 mM [12] and Castor 40 mM [13] is very low. Most of these are edible crops which need prime agricultural lands for optimal growth while *Jatropha curcus*, known as a promising biodiesel candidate, can tolerate a very low amount of NaCl [9] (see Table 4). Faced with rampant salinity, use of good quality lands for fuel may increase pressure on regular agriculture and hence should be avoided. Under these conditions, those plants need preference which produce sufficient amount of seed oil and can be grown on marginal/saline lands. For instance, non-traditional plants including halophytes, beside their other industrial applications, present immense utilization potential as sustainable source of energy feedstock which can be converted into biofuel. [14–19] The fact that over 8 million km^2 of the world is salt affected [20] where a variety of halophytes can grow makes it more relevant to use these resources which have been ignored and remained mostly unused. Cultivation of

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halophytes in such areas would not only provide an alternative fuel source, but also release arable lands and fresh water for conventional agriculture.

Many of the halophytic species adapted to semiarid/drought conditions bear oilseeds suitable for biodiesel production. We report here the suitability of halophytic oil for diesel engines based on criteria like CN, IV and SN. These values have been calculated empirically and assessed according to the specifications of European, [21] German [22] and US [23] biodiesel standards.

Materials and methods

Seed oil content and fatty acid composition of halophytic seeds from the available data [24–32] were used to calculate SN, IV and CN values with the help of equations 1–3. [33] The accuracy of results improves and the relative error decreases by using multiple equations in these calculations. [34] The calculated SN, CN and IV are generally in line with the values reported earlier. [34,35]

$$SN = \sum (560 \times Ai)/MWi \tag{1}$$

$$IV = \sum (254 \times D \times Ai)/MWi \tag{2}$$

Where Ai = fatty acid percentage, D = total number of double bonds and MWi = molecular mass of each component.

CN was calculated from Equation (3) [35]

$$CN = 46.3 + 5488/SN - (0.225 \times IV) \tag{3}$$

General information about test species

Table 1 shows the distribution, life strategy, habit and salt tolerance (at germination stage) of the studied halophytes. Most of the species (16) belong to the family Amaranthaceae and one each to Malvaceae, Convolvulaceae, Papilionaceae and Poaceae. The majority of the plants (12) were perennial with coastal distribution, some were found in moist mountains and deserts. A wide variation of salinity tolerance (at germination level) was recorded: 17 species exhibited high tolerance (500–1000 mM NaCl) while three were less tolerant (< 500 mM NaCl, Table 1). The salt resistance capacity of these halophytes is much higher than available biodiesel crops. The dry biomass of a well-known biodiesel candidate (*Jatropha curcus*) is significantly reduced at 100 mM NaCl within a week and it may survive for more time at or below 60 mM NaCl only, [9] while other biodiesel crops are also salt sensitive as already discussed. Halophytic species on the other hand, are well-adapted to saline conditions along with suitable oil contents for biodiesel production which opens the opportunity of utilizing vast areas of barren saline lands and brackish water. [36] Research focused on non-edible salt-resistant biofuel crops would have greater environmental performance and better resource management while saving fresh water and arable lands for conventional agriculture. Apart from providing energy security, biodiesel development from the salt-resistant plants could become a part of major poverty alleviation programs for the rural poor by upgrading non-farming saline areas to productive energy sector.

Seed oil contents

The seed oil content of plants in this study ranged from 10 to 30% with nine species having >25% oil. The highest amount of oil (30%) was found in three species – *Salicornia europaea*, *Salicornia bigelovii* and *Suaeda aralocaspica* – whereas low oil yield was recorded in *Atriplex rosea* (13%) and *Kochia scoparia* (10%). The oil content of *Salicornia europaea, S. bigelovii* and *Suaeda aralocaspica* is comparable with other high oil yielding species such as *Glycine max* (20%), *Ricinus communis* (30%), *Pongamia pinnata* (18–27%) and *Jatropha curcas* (29–38%) which are considered potential biodiesel crops. [37] It is noteworthy that *Pongamia pinnata* produces fruits after 5–7 years of initial period with slow growth and low yield in the beginning, [37] *Glycine*, *Ricinus* and *Jatropha* species are salt sensitive, whereas halophytes identified in this study are fast growing, salt tolerant plants with a capacity to produce seeds twice or more in a year.

Research on domestication of halophytes is almost non-existent. However, efforts have been made to improve seed oil yield in *Hardwickia bipinnata,* [38] *Cholosphospermum mopane* [39] and *Jatropha curcas* [40] by using good quality seeds and increasing seed rate for better plant populations which may lead to higher seed yields. *Pongamia pinnata* seed oil yield was also enhanced by using different solvent systems [41] which points to optimization of extraction techniques for better oil yields in halophytes. Similarly, agronomic trials for improving growth and seed yield of halophytes on saline and water logged soils are largely missing which needs attention.

Engine performance parameters

CN, SN, IV and composition of FAMEs of halophytic seed oils are shown in Tables 2 and 3. The SN and IV depend upon the amount and molecular weights of fatty acids present in FAMEs, however, number of double bond(s) is also required to calculate IV. Among plants used in this study, the CN and IV ranged from 38–81 and 130–206, respectively, whereas SN value varied from 29–156. CN represents the ignition capacity of liquid fuel and its higher value accounts for better ignition. It is considered as one of the important selection parameters of biodiesel as it helps to ensure good and cold engine start and reduce white smoke formation. CN values specified for optimal biodiesel performance are 51 by European, [21] 49 by German [22] and 47 by American [23] standards. Among the FAMEs of 20 species studied (Table 2), *Atriplex bunge* (57) *Alhagi maurorum* (51)*, Salicornia fruticosa* (51)*, Sarcocornia ambigua* (51)*, Suaeda fruticosa* (51)*, Halogeton glomeratus* (*50), Suaeda salsa* (*48*), *Atriplex rosea* (49)*, A. occidentialis* (47), *Cressa cretica*

Table 1. List of halophytes species as potential sources of biodiesel.

Species	Family	Distribution	Habit	Life strategy	Salinity tolerance (mM NaCl)
Alhagi maurorum Medic.	Papilionaceae	Cosmopolitan	Shrub	Annual or Biennial	500
Allenrolfea occidentalis (S. Watson) Kuntze, Revis.	Amaranthaceae	Salt playas	Shrub	Perennial	700
Arthrocnemum indicum (Willd.) Moq.	Amaranthaceae	Coast, Marshes	Shrub	Perennial	1000
Atriplex heterosperma Bunge, Beitr.	Amaranthaceae	Wetlands	Herb	Annual	400
Atriplex rosea L.	Amaranthaceae	Wetlands	Forb/Herb	Annual	1000
Cressa cretica L.	Convolvulaceae	Cosmopolitan	Under shrub	Perennial	400
Halogeton glomeratus (M. Bieb.) C. A. Mey.	Amaranthaceae	Moist mountains	Forb/Herb	Annual	1000
Halopyrum mucronatum (L.) Stapf	Poaceae	Coast	Herb	Perennial	200
Haloxylon stocksii (Boiss.) Benth. & Hook.	Amaranthaceae	Cosmopolitan	Under shrub	Perennial	500
Kochia scoparia (L.) Schrad.	Amaranthaceae	Cosmopolitan	Forb/Herb	Annual or Biennial	900
Kosteletzkya virginica (L.) Presl.	Malvaceae	Salt marsh	Herb	Perennial	400
Salicornia bigelovii Torrey	Amaranthaceae	Cosmopolitan	Herb	Annual	800
Salicornia brachiata Roxb.	Amaranthaceae	Cosmopolitan	Herb	Annual	500
Salicornia europaea L.	Amaranthaceae	Salt marsh	Herb	Annual	800
Salicornia fruticosa L.	Amaranthaceae	Salt marsh	Herb	Perennial	800
Sarcobatus vermiculatus (Hooker) Torrey	Amaranthaceae	Salt playas	Shrub	Perennial	1000
Sarcocornia ambigua (Michx.) M.A. Alonso	Amaranthaceae	Salt Marsh, Salt desert	Shrub	Perennial	800
Suaeda aralocaspica (Bunge) Freitag & Schütze	Amaranthaceae	Desert	Herb	Perennial	500
Suaeda fruticosa Forssk. ex J. F. Gmelin	Amaranthaceae	Cosmopolitan	Under shrub	Perennial	1000
Suaeda salsa (L.) Pall.	Amaranthaceae	Salt marsh	Herb	Annual	800
Suaeda torreyana S. Wats.	Amaranthaceae	Pine-oak forest, Grass land	Shrub or Forb	Perennial	1000

Table 2. Saponification Number (SN), Iodine Value (IV) and Cetane Number (CN) of fatty acid methyl esters of some halophytes seeds oils.

Name of species	Oil content %	SN	IV	CN
Alhagi maurorum	22	202.31	97.31	51.38
Allenrolfea occidentialis	14	193.44	121.36	47.21
Arthrocnemum macrostachyum	25	205.66	115.5	46.86
Atriplex bunge	16	194.89	75.29	57.35
Atriplex rosea	13	194.05	115.5	49.33
Cressa cretica	23	203.5	114.27	47.41
Halogeton glomeratus	25	199.82	103.47	50.31
Halopyrum mucronatum	23	202.95	124.63	45.15
Haloxylon stocksii	23	203.27	121.71	45.77
Kochia scoparia	10	200.56	138.69	42.31
Kosteletzkya virginica	22	205.99	113.14	47.37
Sacrobatus vermiculatus	18	199.22	139.84	42.23
Salicornia bigelovii	30	200.86	154.32	38.78
Salicornia brachiata	22	129.89	29.7	81.67
Salicornia europaea	30	202.55	155.96	38.19
Salicornia fruticosa	26	204.38	93.68	51.96
Sarcocornia ambigua	13	187.19	106.66	51.49
Suaeda fruticosa	26	204.38	93.68	51.96
Suaeda aralocaspica	30	198.7	146.59	40.82
Suaeda salsa	26	171.1	133.9	48.1
Suaeda torreyana	25	202.02	154.77	38.49

(47) and *Allenrolfea occidentialis* (47) meet these requirements and are also comparable to the other conventional biodiesel plants such as *Glycine max* (51), *Jatropha curcus* (52) and *Pongamia pinnata* (56). [42]

IV is another critical measure for the selection of biodiesel feedstock which determines the degree of unsaturation in FAMEs. The unsaturated fatty acids are required in a certain amount to protect FAMEs from solidification. The international biodiesel standards [21–23] recommend fuel IV not exceeding 115 for proper functioning of engine. In the present study, the IV of *Atriplex bunge* (75), *Suaeda fruticosa* (93), *Salicornia fruticosa* (93), *Alhagi maurorum* (97), *Arthrocnemum macrostachyum* (115)*, Atriplex rosea* (115)*, Cressa cretica* (114) and *Halogeton glomeratus* (103) are not only meeting the standard criterion, but are also comparable with other glycophytic biodiesel crops such as *Ricinus communis* (91), *Jatropha curcas* (93), *Pongamia pinnata* (80) and *Brassica napus* (110). [42,43]

Fatty acid composition

In addition to the above criteria, quality of oil is also a function of its fatty acids composition. Oils containing fatty acids with four double bonds and high level of linolenic acid (> 12%) are unsuitable for biodiesel production. [22] In this study, no single species among 20 halophytes contained fatty acid with four double bonds in one chain or linolenic acid over 12% except *Atriplex rosea* which has 21% linolenic acid, rendering it unsuitable for use. High amounts of cerotic acid (26:0) and ximenic acid (26:1) are also not suitable for biodiesel production as they increase the boiling point of fuel over the acceptable temperature (360°C). [22] As per the specification of international biodiesel standards, the FAMEs should contain high amount of fatty acids having chain length between C_{12}–C_{22} because this chain length has boiling points in the range of 330–357 °C. Halophytes studied did not contain any cerotic acid (26:0) and ximenic acid (26:1) except for a few species which have very low amounts of those fatty acids.

Promising halophytic plant species

Generally, FAMEs with higher CN values are favored for biodiesel purpose. However, higher CN value decreases IV which ultimately reduces unsaturated FAMEs moiety and results in solidification of liquid fuel. To avoid this situation an upper limit of (65) has been fixed by American biodiesel standard for CN. [23] FAMEs from all 20 species reported here have low IV while CN values are within the permissible limit except for *Salicornia brachiata* (82). Hence, seven halophytes of this study including *Salicornia fruticosa*, *Arthrocnemum macrostachyum*, *Alhagi maurorum, Cressa cretica, Halogeton glomeratus, Kosteletzkya virginica* and *Atriplex rosea* which meet major specifications of biodiesel standards of America, [23] Germany [22] and the European [21] standard organization are recommended as potential feedstocks for biodiesel production. Some details about the economic importance and ecophysiological responses of these species under saline conditions are presented below for future energy farming system.

Arthrocnemum macrostachyum is a stem succulent, perennial shrub found near the coastal salt marshes of the Arabian Sea. [44] Plants can tolerate saline flooding with up to 1000 mM NaCl salinity. It blooms between October to December and produces a heavy lot of non-dormant seeds during April–May. Medicinally important phytochemicals such as phenols, alkaloids, flavonoids and tannins are also reported from this species with strong antiradical and antioxidant activities. [45–46] Seeds of *A. macrostachyum* contain 25% oil with suitable engine value parameters (SN 205.66, IV 115.5 and CN 49.33).

Alhagi maurorum is a perennial halophytic shrub commonly known as Camel thorn. It is a significant component of halophytic vegetation of inland as well as coastal plant communities of Pakistan. The plant grows 0.5–1.5 meters high [47] and can tolerate extreme conditions such as drought, high temperatures, frost and NaCl salinity. [48] It is used against gastrointestinal discomforts, urine and liver problems, and is also reported to have anti-allergen and nerve soothing properties. [49–50] *Alhagi maurorum* displayed good potential as a source of biodiesel feedstock because of its oil contents (22%) and optimal engine value performance (SN 202.31, IV 97.31 and CN 51.38).

Cressa cretica is a perennial under-shrub of family Convolvulaceae, widely distributed along the coastal and

Table 3. Fatty acid composition of halophytic seed oil reported in literature.

Species	Fatty acid composition (%)
Alhaji maurorum	C12:0(0.38), C15:0(0.21), C16:0(21.79), C16:1(0.46), C18:0(3.94), C18:2(66.24), C19:0(0.93), C20:0(1.56), C20:1(1.53), C21:0(0.17), C22:0(0.87), C23:0(0.16), C24:0(0.77), C26:0(0.11)
Allenrolfea occidentialis	C15:0(0.07), C16:0(5.34), C16:1(0.51), C:17:0(0.24), C18:0(2.32), C18:1(21.80), C18:2(35.62), C:18:3(6.49), C20:0(1.27), C20:1(0.49), C22:0(1.164), C22:1(13.35), C24:0(1.11)
Arthrocnemum macrostachyum	C12:0(0.23), C14:0(0.71), C150(0.52), C16:0(26.93), C16:1(0.87), C18:0(3.17), C18:2(63.02), C19:0(0.62), C20:0(0.93), C20:1(0.56), C21:0(0.15), C22:0(1.00), C23:0(0.22), C24:0(0.63), C26:0(0.42)
Atriplex heterosperma	C11:0(0.43), C16:0(10.68), C16:1(0.51), C18:0(2.23), C18:1(63.82), C18:3(0.75), C20:0(1.72), C20:1(5.93), C22:1(12.81), C24:1(0.86)
Atriplex rosea	C11:0(0.36), C15:0(0.10), C16:0(9.07), C16:1(0.25), C18:0(1.98), C18:1(38.13), C18:2(1.40), C18:3(20.82), C20:0(1.75), C20:1(10.23), C21:0(0.19), C22:1(11.49), C22:0(0.66), C23:0 (0.142), C24:1(0.28)
Cressa cretica	C12:0(0.15), C15:0(0.16), C16:0(17.04), C16:1(0.56), C18:0(4.61), C18:2(72.08), C19:0(1.08), C20:0(1.09), C20:1(0.65), C22:0(0.83), C23:0(0.24), C24:0(0.85), C26:0(0 .25)
Halogeton glomeratus	C16:0(12.17), C16:1(0.40), C18:0(1.80), C18:1(56.14), C18:2(17.89), C18:3(6.25), C20:0(0.71), C20:1(2.05), C22:0(0.47), C22:1(1.07), C23:0(0.04), C24:1(0.27), C26:0(0.15)
Halopyrum mucronatum	C12:0(0.11), C15:0(0.23), C16:0(29.38), C16:1(0.23), C18:0(11.01), C18:2(53.28), C19:0(0.16), C20:0(1.57), C20:1(0.68), C21:0(0.21), C22:0(1.24), C23:0(0.25), C24:0(0.64)
Haloxylon stocksii	C16:0(25.75), C16:1(0.12), C18:0(8.26), C18:2(67.20), C20:0(1.19), C20:1(0.63), C22:0(0.28), C24:0(0.28)
Kochia scoparia	C16:0(13.06), C16:1(3.57), C18:0(3.20), C18:2(72.32), C20:0(0.88), C20:1(1.85), C22:0(0.69), C22:1(2.09), C24:1(0.67), C26:0(0.16)
Kosteletzkya virginica	C14:0(0.144), C16:0(26.819), C16:1(0.353), C18:0(1.625), C18:1(18.001), C18:2(46.412), C18:3 (4.205), C20:0(1.450), C20:1(1.190)
Salicornia bigelovii	C16:0(7.52), C18:0(1.45), C18:1(13.42), C18:2(75.50), C18:3(1.98)
Salicornia brachiata	C14:0 (12.88), C16:0 (16.48), C18:1 (32.79)
Salicornia europaea	C16:0(7.02), C18:0(2.37), C18:1(13.04), C18:2(75.62)
Salicornia fruticosa	C12:0(0.91), C14:0(1.78), C16:0(16.4 0), C16:1(0.09), C18:0(2.50), C18:1(56.58), C18:2(17.4 0), C18:3(3.98), C20:0(0.36)
Sarcobatus vermiculatus	C14:0(2.77), C16:0(13.59), C16:1(0.35), C18:0(1.23), C18:2(76.09), C20:0(1.04), C20:1(0.96), C21:0(0.43), C22:0(0.75), C22:1(0.99), C23:0(0.31), C24:0(0.26), C24:1(0.22), C26:0(0.32)
Sarcocornia ambigua	C16:0(20.4), C16:1(1.4), C18:0(4.5), C18:1(18.5), C18:2(42.0), C18:3(4.0), C18:4(1.5)
Suaeda aralocaspica	C14:0(0.052), C16:0(3.880), C16:1(0.093), C18:0(1.487), C18:1(22.427), C18:2(68.431), C18:3 (0.615), C20:0(0.992), C20:1(0.525), C20:2(0.064), C22:0(0.275), C24:0(0.020)
Suaeda fruticosa	C15:0(0.22), C16:0(24.20), C16:1(0.35), C18:0(3.27), C18:2(68.43), C20:0(0.93), C20:1(0.37), C22:0(1.11), C23:0(0.24), C24:0(0.43)
Suaeda salsa	C12:0(0.35), C14:0(0.49), C16:0(8.83), C16:1(1.59), C18:0(1.59), C18:1 (0.62), C18:2(65.03), C18:3(5.13), C20:0(0.61)
Suaeda torreyana	C11:0(0.45), C14:0(0.15), C16:0(6.07), C16:1(6.55), C18:0(2.05), C18:2(77.31), C18:3(0.93), C20:0(0.63), C21:0(0.07), C20:1(1.00), C22:0(0.65), C22:1(2.14), C24:0(0.63), C24:1(0.15), C26:0(0.07)

inland salt marshes. It flowers throughout the year and is a good indicator of dry, salty and sandy habitats by tolerating up to 800 mM NaCl. [51] The plant is commonly used as camel fodder and also known as a traditional medicine of skin, stomach, leprosy, asthma and urine related problems. [52] The high seed oil content (23%) and good engine parameters (SN 203.5, IV 114.27 and CN 47.41) make it a suitable biodiesel candidate.

Halogeton glomeratus belongs to family Amaranthaceae and is among the most dominant plants of temperate northern moist mountainous region of Pakistan. [53] The plant blooms during June–July, grows up to 4 meters high and can tolerate up to 1000 mM NaCl equivalent salinity in the medium. [54] It may contain high concentration of oxalates, which can be poisonous to grazing animals. [55] This non-edible salt-resistant plant contains about 25% seed oil and engine value parameters (SN 199.82, IV 103.47 and CN 50.31) make it suitable for consideration as a biodiesel candidate.

Kosteletzkya virginica is an herbaceous perennial plant commonly known as salt marsh mallow. It is an obligate wetland species native to southeastern US. It can grow over 1 meter in height and blooms from July to October. It can tolerate heavy wind and soil salinity more than 400 mM NaCl and produces enormous seeds (1500 kg/ha) with high protein (32%) and oil (22%) content. [56] Plants provide multiple products including biodegradable absorbent, fiber products such as animal bedding, hydromulch and cat litter. [57] It is also used to make thread and is a good source of

Table 4. Salinity tolerance, oil content (%), Saponification Number (SN), Iodine Value (IV) and Cetane Number (CN) of fatty acid methyl esters of some biodiesel candidates.

Biodiesel plants	Salinity tolerance (mM NaCl)	Oil	IV	CN	SN
Conventional crops					
Jatropha curcus (Physic nut)	60	29	93	52	202
Brassica napus (Canola)	120	36	110	60	188
Glycine max (Soybean)	50	20	86	51	190
Elaeis guineensis (Palm)	100	45	55	62	190
Pongamia pinnata (Karanja)	160	27	81	56	196
Ricinus communis (Castor)	40	30	91	80	180
Studied halophytes					
Salicornia fruticosa	100	26	94	51.96	204
Arthrocnemum macrostachyum	100	25	115	46.86	206
Halogeton glomeratus	100	25	103	50.31	200
Cressa cretica	420	23	114	47.41	203
Alhagi maurorum	500	22	97	51.38	202
Kosteletzkya virginica	420	22	113	47.37	206
Atriplex rosea	100	13	115	49.33	194

animal feed. [56] Seeds contain oil (22%) having suitable engine parameters (SN 206, IV 113.14 and CN 47.37) for biodiesel production.

Suaeda fruticosa is a perennial shrub of family Amaranthaceae distributed on both water logged and drier sandy soils of coastal and inland areas of Pakistan. It is considered a facultative halophyte which can grow up to 1.6 meters in height and tolerate 1000 mM NaCl substrate salinity. The plant is ecologically the most adaptive and common species of this genus in Pakistan but is also found in the north, the centre and the south of Tunisia. [58] This leaf succulent species is considered an excellent salt scavenger to reclaim saline lands and was grown as a companion crop with *Panicum turgidum* to remove salt from the soil. [14] Its flowering period is from April to September. It is locally used as camel fodder and its ash is commercially used for extracting soda. Traditionally it is used as a cardiac tonic and anti-infective remedy and also reported for hypoglycemic and hypolipidemic activities. [58] This economically important halophyte is a potential diesel candidate due to its oil content (26%) and engine performance parameters (SN 204.38, IV 93.68 and CN 51.96).

Salicornia fruticosa also known as *Sarcocorina fruticosa* belonging to the family Amaranthaceae, is a perennial herb with horizontal or erect blue-green stem, widely distributed in south and west Europe coastal areas and salt marshes of Spain. [59] It grows in tidal zones where it occasionally faces tidal inundation and resists salinity up to 940 mM NaCl. [60] Juice and methanolic extract of ariel parts showed high antioxidant and antibacterial activity to cure many diseases. [61] *Salicornia fruticosa* contains 26% seed oil with suitable engine performance (SN 204.38, IV 93.6 and CN 51.96) comparable to many glycophytic non-salt-resistant plants.

Conclusions

Biofuel production from edible crops and diversion of land from food production to energy biomass may lead to food land crisis. This study provides an option of selecting perennial halophytes that contain seed oil with suitable engine value parameters for biodiesel production and can compete with other conventional sources. Because of their better adaptability to saline conditions, these plants could be grown in saline wastelands with low maintenance costs and provide raw materials for biodiesel production which can replace or supplement fossil fuel. Genetic manipulations for desirable characters, yield maximization through agronomic trials and interrelated aspects needs investigation but the information on engine value parameters of biodiesel produced using halophytes as feedstock opens new avenues to develop a feasible and sustainable biofuel production system.

Future perspective

The economic viability of the biodiesel industry relies on a consistent supply of feedstock in terms of both quantity and quality of seed oil. This study investigated the potential of new plant sources with the ability to grow in saline and marshy habitats. Although these plants do not have a very high content of seed oil, they are still comparable with some of the main biodiesel feedstock crops like rapeseed and soybean. Large-scale development and industrial production of halophytes could be adopted as a new agriculture option by utilizing suitable locations along coastal areas. Most halophytes are however still wild and their yields are low which requires extensive studies dealing with ecophysiological analysis, agronomy and other aspects of saline agriculture. Systematic analysis of halophytes to screen out high energy species and their breeding for desirable attributes needs to be pursued.

Disclosure statement

No potential conflict of interest was reported by the authors.

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