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The Biodiesel of Microalgae as a Solution for Diesel Demand in Iran

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Abstract: Among the fossil fuels, diesel has the major share in petroleum product consumption. Diesel demand in Iran has increasingly grown due to the low price of diesel, a high subsidy, and an unsuitable consumption pattern. During 2006–2007, this growth imposed 2.2 billion liters of imports, which were equivalent to 7.5% of diesel production in 2007 and cost about $1.2 billion. Therefore, the government implemented fuel rationing in 2007 and a targeted subsidy law in 2010. These projects have not gained effective control of consumption due to the wide gap between the international diesel price and the domestic price. Diesel import after the implementation of fuel rationing and the targeted subsidy law in 2011 imposed 3.6 billion liters of import and cost about $2.2 billion. Therefore, the government will need fundamental strategies and policies to face and control the negative impact on the economy and the environment. Third generation fuels, biofuels, as another supplementary approach seems to have the capability to reduce the petroleum requirement. This paper investigates the potential of biodiesel as diesel alternative fuel from oil seeds and microalgae in Iran along with evaluating the policy for reducing diesel consumption. *Dunaliella salina* as an indigenous green microalga isolated from the Maharlu Salt Lake was cultivated in an integration of an airlift system and a raceway pond (IARWP) to prove microalgal potentials in Iran. Additionally, the natural culture medium from the Maharlu Salt Lake was utilized for *Dunaliella salina* in order to commercialize and reduce cultivation cost. Compared to oilseeds, microalgae because of their high lipid content have much potential to solve a fuel consumption problem. This paper found that only 21 percent of cultivable land is needed to replace the diesel currently consumed in Iran with microalgal biodiesel.

Keywords: Iran; biodiesel; Microlgae; oilseeds; diesel consumption

1. Introduction

Fossil fuels demand has grown faster due to economic development and the increase in the world's population [1–4]. Subsidized energy and the nonintegrated relationship between fuels consumption and vehicle production in Iran increases the consumption of fossil fuels [5–8]. A lack of a future sustainable resource of energy production and investment in the private sector in the production of petroleum products could change Iran from being one of the crude-oil-exporting countries to being a major fossil fuel importer.

As can be anticipated, there is a continuous increase in the diesel fuel demand worldwide as a consequence of the growth of energy demand in the commercial transport sector. Kalghatgi GT evaluated the demand for diesel fuel in the future and expected an 85% increase in diesel demand by 2040 [7]. Along with the growth of diesel demand worldwide, an artificially low price and government subsidies can aggravate diesel consumption in Iran. Iran consumed and imported 100 and 6.5 million liters of diesel per day in 2015, respectively (NIOPDC 2015). However, diesel consumption fell by an impressive 19 percent and reached 81.2 million liters per day. The constraints and contributing factors to Iran's gasoline supply were investigated by Aghaii Tabrizi. He concluded that the major solution to control fuel consumption is planning, organizing, and managing the consumption [9]. Other researchers, such as Rivlin and Stern, examined energy balance in Iran. Rivlin believes that Iran has artificially boosted demands while subsidizing energy products [10]. Iran's gasoline demand function over the period of 1968–2002 was evaluated by Ahmadian et al., and they concluded that the higher gasoline price decreased social welfare [11].

In 2016, about 98% of the total energy required by the country was provided by consuming petroleum products, including (liquid petroleum gas) LPG, gasoline, kerosene, diesel, fuel oil, jet fuels, and natural gas. The consumption of petroleum products in 2016 was the equivalent of 4385 thousand barrels of crude oil, which included 406 thousand barrels of gasoline (9.3%), 54 thousand barrels of kerosene (1.2%), 498 thousand barrels of diesel (11.4%), 156 thousand barrels of fuel oil (3.6%), 28 thousand barrels of jet fuels (0.6%), 46 thousand barrels of LPG (1%), and 3197 thousand barrels of natural gas (72.9%). Total consumption of petroleum products in 2016 was estimated to be more than 70 billion liters, which had an approximate value of 25 billion dollars with a share of 35.5% and 40.6% for gasoline and diesel, respectively.

Gasoline consumption in 2016 had an average of 71 million liters per day with 2% growth compared to the previous year. During this year, diesel consumption had an average of 81.2 million liters per day with a 19% decrease compared to the previous year. That decrease was due to the delivery of natural gas to power plants and sugar and cement factories, as well as more control over consumption and the prevention of smuggling of this petroleum product in the non-power sector. All of the above-mentioned data were officially published by the National Iranian Oil Refining and Distribution Company (NIOPDC).

In spite of some research on gasoline consumption in Iran, studies about diesel consumption in Iran are rare. With the current circumstances which have caused the low price of diesel in Iran, the necessity for a comprehensive evaluation seems more obvious. Some countries took policies to significantly reduce fuel consumption, such as policies in 1994 in the USA which failed [12]. In addition to a fuel tax, standards, and regulations in automobile manufacturing and public transit, another supplementary approach, such as alternative fuels, seems to be required to reduce fuel consumption. Growing demand for transportation fuels and efforts to decrease the dependency of this sector on fossil fuels create a strong interest in biofuel liquids for many researchers and policy-makers. Increasing transport demand is an inevitable consequence of economic development. Meanwhile, a cheap transport service also plays a significant role in the development of a country.

Recently, the share and utilization of a fuel supply of alternative fuels in the form of liquid or gaseous fuels, called biofuels, has grown rapidly. Utilization of biofuels corresponded to about 6% in European countries in 2010 and is planned to reach 10% in 2020 [13–15]. Biodiesel as a biofuel and an alternative fuel to diesel has been produced from edible oils, such as sunflower, palm oil, rapeseed, soybean, and other vegetable oils.

These are the first-generation feedstocks for biodiesel production. Recently, due to the rapidly growing world population and a decrease in the dependency on edible oil, other crops as second feedstocks for biodiesel production, such as salmon oil, mahua, sea mango, tobacco seed, jojoba, jatropha, animal fats, and waste cooking oils, have been extensively investigated and utilized [16]. However, a low energy potential and lack of efficient technologies are the problems with these feedstocks for the commercial production of biodiesel [14].

Microalgae as the third generation of feedstocks have raised great interest due to their being a non-food source, having a fast growth rate that can withstand varying environmental conditions, and being able to cultivate them in salt water, wastewater, or seawater [17]. Microalgae are besides known as the third generation of feedstocks for biodiesel that can produce other biofuels, such as methane, hydrogen, and bio-ethanol. These micro-organisms even have the ability to mitigate CO_2 as a greenhouse gas from the exhaust gases of industrial points and in the atmosphere. In order to produce biodiesel from microalgae, a series of processes should be passed, including algal growth, harvesting, drying, extraction of lipid, and conversion to biodiesel. Microalgal cultivation involves three main types of growth conditions: photoautotrophic culture, which utilizes CO_2 and sunlight as the carbon and energy source, respectively; heterotrophic culture, which utilizes organic carbon materials as the carbon and energy source; and mixotrophic culture, which utilizes both cultures [18]. Microalgae are cultivated in open ponds, photobioreactors, and fermenters. Harvesting as the second process in biodiesel production from microalgae can be done by the main methods of centrifugation, filtration, flotation, and flocculation. Despite much research and the discovery of new methods, such as the magnetophoretic method, the harvesting process still needs further development to separate microalgae cells from culture while reaching the goal of a highly concentrated slurry that saves energy and does have any contamination.

After the recovery of microalgal cells from the culture, dewatering and drying is the main process for and major economic bottleneck of biodiesel production. The current methods of drying including freeze-drying, spray-drying, and sun drying, which need a great deal of energy or time [19,20]. However, state-of-the-art algae drying processes were proposed by Aziz et al., which can decrease the energy required by up to 90% of conventional heat recovery drying [18,21]. Microalgal lipid extraction can be done by chemical methods, including solvent and supercritical extraction methods, and mechanical methods, including grinding, pressing, bead-beating, crushing, microwave, and sonication [18].

Recently, researchers have reported new methods to extract the lipid, such as ionic liquid solvent, [BMIM][HSO_4] [22], or even the direct employing of wet algal biomass without dewatering to extraction of the lipids [23,24]. Among microalgal strains considered for research, *Dunaliella salina* (Chlorophyta, Chlorophyceae) is one of the most commonly studied species which can grow in saltwater and wastewater and can withstand high salt, temperature, and light conditions [25,26]. Despite over four decades of study and development on open ponds, only three strains of *Spirulina platensis*, *Dunaliella salina*, and *Chlorella* can be cultivated in a non-sterile and feasible way in outdoor culture ponds [27,28].

Therefore, the ability of *Dunaliella salina* to grow and produce lipids in various unsuitable environmental conditions is a significant economic consideration in terms of biodiesel production and can reduce operating costs and capital investment [29]. Since *Dunaliella salina* has been industrially cultured in outdoor ponds, the carbon fixation and lipid content of this strain have been considered by researchers [27,29–38]. Iran, with a total land area over 1.6 million km^2, is the second-largest and the 18th-largest country, respectively, in the Middle East and in the world and one-third of Iran's total land area would be arable if sufficient water is provided [39].

Iran will have the chance to develop algae-based fuels and mitigate fossil fuel consumption through proximity to the sea, the existence of multiple saline lakes with a wide and various range of microalgae species, variant climates (from arid or semiarid to subtropical along the Caspian shoreline), and considerable land expanse. Consequently, other factors, such as large amounts of CO_2 sources in Iran, besides the existence of various saline lakes and infinite access to saline water and sunshine have thrown a spotlight on the possibility of attaining economic cultivation of microalgae in various regions and attract government support in applying renewable energies.

Despite the rich history of microalgae cultivation and much research work on large-scale algae-to-biofuel methods, such as National Renewable Energy Laboratory (NREL)'s Algal Biofuels Techno-Economic Analysis group [38], microalgal biodiesel has not been produced on a large scale. It might be due to the high capital and operation costs [18]. To overcome these main bottlenecks, researchers have reported several major measures, such as the employment of genetic and metabolic engineering to enhance microalgal biological properties, the isolation of promising algal species for biodiesel production, improving the efficiency of microalgal bioreactors, the utilization of a wide range of culturing strategies, such as waste exhaust, CO_2 wastewater, etc., the enhancement of harvest methods, increasing the efficiency of lipid extraction and transesterification methods, and the development of valuable co-products, such as glycerol [18].

This paper has attempted to present Iran's current status of diesel demand and the government measures for tackling the existing situations of diesel consumption. Subsequently, a detailed survey was conducted to assess the compatibility of biodiesel feedstocks from oil seeds in Iran. Moreover, in order to overcome some of the mentioned bottlenecks for microalgal biodiesel production and reduce operating costs in Iran, the natural culture medium from the Maharlu Salt Lake was utilized for microalgal cultivation.

Dunaliella salina (Chlorophyta, Chlorophyceae) isolated from this lake was cultivated in an integration of an airlift system and a raceway pond (IARWP). This bioreactor besides simple mechanic and need less maintenance, can eliminate the energy consumption of paddle wheel in large microalgae cultivation by utilizing exhaust flue gases. The utilization of industrial CO_2 sources can lead to the achievement of commercialization and a reduction in cultivation cost besides the environmental benefits of carbon capture.

Although many studies have been done on *Dunaliella Salina* isolated from the Maharlu Salt Lake [39–43], its natural culture medium has not been yet used for cultivation of *Dunaliella Salina*. Based on the thorough investigation carried out herein, only less than 23 percent of cultivable land is required to produce biodiesel from microalgae to replace all diesel currently consumed in Iran. Therefore, this work recommends that Iran can mitigate the import of fossil fuel using renewable energies. However, more research is needed to survey the economic issues related to biofuels in Iran.

2. Overview of Diesel Status

In this section, by using the last data formally published by the National Iranian Oil Refining and Distribution Company (NIOPDC), diesel consumption, production, import, and price in Iran for the recent years are reviewed (NIOPDC 2016).

Diesel Consumption, Production, and Import

Table 1 shows petroleum products consumption during 2006–2016. According to this table, petroleum products consumption decreased by 13.8% compared to the previous year, while gasoline consumption increased. As can be observed from Table 1, the largest share of petroleum products consumption was related to diesel with 42.4% in 2016.

Table 1. Main petroleum products consumption during 2006–2016 (million liters per day).

Year	LPG	Gasoline	Kerosene	Diesel	Fuel Oil	Total
2006	6.1	67	20.5	79.4	40.7	213.7
2007	6.1	73.6	19.7	86.2	42.8	228.4
2008	6.1	64.5	20.2	89.7	45.3	225.8
2009	6.1	67	18.4	92.5	47.2	231.2
2010	6.8	64.8	17.8	92.8	45.0	227.2
2011	6.7	61.3	13.8	95.2	40.3	217.3
2012	6.1	59.9	13.5	96.8	42.9	219.2
2013	6.0	63.5	12.3	97.2	51.7	230.7
2014	5.6	68.4	11.9	105.4	50.7	242
2015	5.6	69.6	10.1	100.1	36.7	222.1
2016	5.6	71.0	9.1	81.2	24.5	191.4

Diesel is used in various sectors, such as the transportation sector as a diesel engine fuel, the agricultural sector as fuel for agricultural machinery and irrigation pumps, the industry sector as fuel for industrial machinery and equipment, the power plant sector as fuel to generate electricity, and the commercial and domestic sectors for heating and the production of hot water. The consumption of diesel in each sector is shown in Table 2.

Table 2. Diesel consumption by various sectors (2015–2016).

Transport	Power Plant	Agriculture	Industry	Domestic	Others
53	26	9	7	0	5
56	19	11	8	0	6

As can be seen from this table, the transport sector was the major consumer of diesel fuel. The diesel consumption rate increased from 2006 to 2014, but it has reached about 81.2 million liters per day in 2016 with the growth of −19% compared to the previous year. This decrease was mainly related to the switching fuel consumption of power plants. Diesel consumption in power plants decreased 31% compared to the previous year and reached 15.9 million liters per day. However, a restriction has been imposed on the Iranian National Gas Company on the delivery of gas to power plants in winter due to the temperature decrease and increasing gas consumption in the domestic sector. Therefore, diesel consumption increased mostly in the power plants sector in winter. In 2016, feed for Iranian refineries was about 1.75 million barrels per day, which produced 57.4 and 89.4 million liters of gasoline and diesel per day, respectively. Diesel consumption and production trends during 2010–2016 are shown in Figure 1.

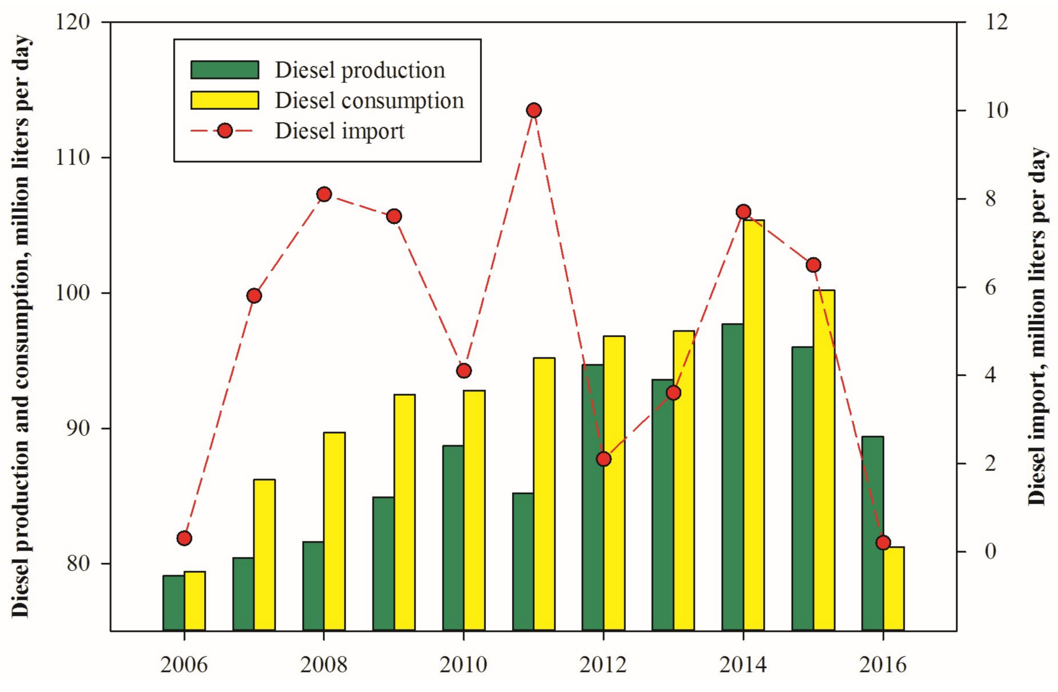

Figure 1. Diesel production, consumption, and import (2006–2016).

As can be seen, due to the rapid growth rate of diesel consumption, a considerable gap has appeared between consumption and production. This gap has led to the import of diesel in recent years. The difference between this gap and importation was due to the supply of diesel from the domestic production of petrochemical complexes. This amount of import has imposed additional costs on the government. The total amount of diesel imports has reached 30.4 million liters per day during these years, which equals 33.8% of diesel production in 2016. Recently, Iran increased its production of petroleum products, especially diesel and gasoline, by 15.5 and 5 million liters per day, respectively, by an increase of refining capacity and the construction of new refineries. Nevertheless, this increase cannot be the response to petroleum consumption in Iran.

3. Policy Solutions of Diesel Demand

The continuous growth of diesel demand obligated the government to construct new refineries and increase the capacity of refineries. Nevertheless, the government should apply other policies besides the increase of refinery capacity to the response to the high and rapid growth rate of petroleum products, especially for diesel and gasoline consumption in the future.

3.1. Rationing

One of the strategies to control petroleum products consumption was rationing, which occurred by giving 'Intelligent Fuel Cards' and was performed on June 2007 with the aim of selling domestic gasoline to consumers with a supportive price and selling imported gasoline with its cost price [44]. The rationing system allows private drivers only a specific amount of fuel per month at the subsidized price.

In accordance with the annual average growth rate of diesel consumption in 2006, it was expected that diesel consumption would reach 93.5 million liters due to the rationing plan, while it reduced to 89.7. This decrease in diesel consumption had the benefit of saving $797 million in 2007. During 2008 and 2009, the total benefit gained from this plan was a 4.7 billion liter reduction in diesel consumption, which has saved 2.3 billion U.S.$. Figure 2 shows scenarios of diesel consumption without the rationing plan with the constant annual average growth rate between 2006 and 2007 and the saving from the implementation of this plan.

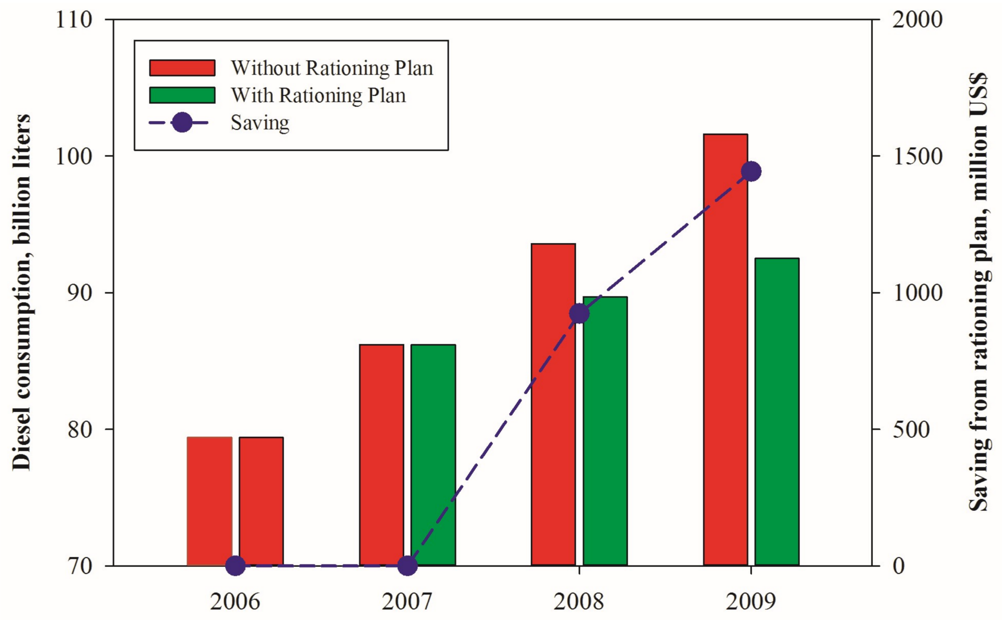

Figure 2. Effect of rationing plan on diesel consumption and benefits.

3.2. Targeted Subsidy Plan

In 2009, the number of subsidies allocated to diesel was equivalent to 1.16 billion U.S.$, which decreased 38.2% relative to the previous year. This price was 44.2% of total subsidies, which was allocated to five main petroleum products. Approximately, the subsidies on energy price and many consumer goods were $100 billion per year [45]. Diesel supply in the country with low prices, a lack of proper control of consumption in the transport sector and for old industrial machinery caused an unsuitable consumption pattern in the transport sector and heavy spending on subsidies for diesel. Being reasonable on the diesel price is one of the important possible solutions for controlling the consumption of this product in the country. Therefore, the Iranian Parliament on 5 January 2010 passed the Iranian targeted subsidy plan [46].

In accordance with the Five Year Economic Development Plan, the government implemented this plan to replace subsidies on food and energy (80% of total) with targeted social assistance [47]. Implementation of this law decreased diesel consumption by 944 million liters in 2010, which saved $559 million. Trends of domestic diesel price in Iran and the international free on board (FOB) Persian Gulf prices of diesel during 2007–2011 are listed in Table 3. The government implemented targeted subsidy laws and after that diesel has been sold at two prices.

Table 3. Domestic and import prices of diesel in Iran, 2007–2011.

Year		Domestic Price (USD/Liter)	Import Price, FOB Persian Gulf (USD/Liter)
2007		0.018	0.575
2008		0.017	0.652
2009		0.017	0.435
2010	Before TSL	0.015	0.592
	After TSL	0.136, 0.318	
2011		0.076, 0.177	0.787

TSL: targeted subsidy law.

In spite of the implementation of targeted subsidy laws, diesel consumption increased in 2011 compared to 2010 because of the Iranian currency value reduction relative to the dollar. The stricter international economic conditions caused the value of Iranian currency to plunge from autumn 2011 so that it had been devalued up to 200%. With the price of the dollar in July 2013 in Iran, the diesel price reached between 0.0454 and 0.106, which was a decrease of 66.7% relative to the price before these conditions. This change in diesel price and increasing subsidies on diesel lead to the smuggling of more fuels out of the country every day (17% of fuel production daily in 2009, equivalent to some 40 million liters) and the government importing more fuel. The wide gap between domestic and FOB prices can be traced to the intensity in dependence of the goods prices on fuel prices in Iran.

Nevertheless, since the change in prices of petroleum products in 2010, domestic prices still have not had any effect because of fluctuations of the international prices. In order to control inflation, the government was obligated to maintain fuel prices at low levels. Therefore, the government needs fundamental strategies and policies to solve the diesel consumption problem.

4. Biodiesel as Alternative Fuel

Biodiesel as an alternative diesel fuel is produced by the transesterification of oils with alcohol, especially methanol, in the presence of a catalyst. In addition to good properties compared to diesel, such as being biodegradable, non-toxic, and environmentally friendly, it can run diesel engines [48].

4.1. Oil Seeds Production in Iran

As mentioned before, if adequate water distribution exists, roughly one-third of Iran's total surface area is suitable for cultivation. However, only 12% of this large area is under cultivation. In spite of this potential for agriculture, 63% of the lands suitable for cultivation have not been used and only half of the capacity of some of the present farms is being used. In recent years, oil seeds were a concern of the Iranian government's policy in the agriculture sector so that dry-farming lands were considered as one of the development areas for these products. In dry conditions, the possibility of growing the three crops of rapeseed oil, safflower, and sunflower exist. According to the country's plans for increasing oil production, dry tropical regions for rapeseed, mild cold regions for safflower, and all three regions for sunflower were considered. The crops, including walnut, corn, cotton, almond, canola, soybean, olive, hazelnut, and coconut, and the other oilseeds, such as sesame, sunflower, and safflower, are growing in most of the provinces in Iran. All of the data in this section was retrieved from the Agricultural Statistics of 2016, which is published by the Ministry of Agriculture-Jahad (Ministry of Agriculture-Jahad 2016).

4.1.1. Corn and Walnut Seeds

The arable land for corn and walnut seeds was estimated to be about 282 thousand hectares in 2016. Corn seed production was estimated to be about 1.17 million tons in 2016, and the Khuzestan, Kermanshah, and Fars provinces had the highest corn production share at 30.0, 13.0, and 10.5%, respectively. Corn yield production in 2016 was 7384 kg per hectare in irrigated land. Walnut seed production was assessed to be about 252.2 thousand tons with a yield production of 3513 kg per hectare in 2016. Although the production of walnut seeds was lower than that of corn seeds, walnut seeds produced oil more than corn seeds because of their higher oil content.

4.1.2. Cotton and Sesame Seed

Cotton and sesame seed arable land in 2016 was estimated to be about 70.6 and 42.5 thousand hectares, respectively, of which around 89% came from irrigated land. Only in the Golestan and Mazandaran provinces were cotton seeds harvested on dry farming land. The Khorasan Razavi and Fars provinces, with 29.3 and 27.2%, respectively, have the highest share of the cotton seed arable land. Cotton and sesame seed production was estimated to be around 161.2 and 36.9 thousand tons in 2016, respectively. Yield production of cotton and sesame seed in irrigated lands was 2302 and 1074 kg per hectare, respectively.

4.1.3. Soybean and Canola Seed

Soybean and Canola arable land in 2016 were estimated to be about 52.4 and 52.3 thousand hectares, respectively. From irrigated lands came 80.8% of canola and 88.7% of soybean. Soybean was harvested only in six provinces.

The Golestan, Mazandaran, and Ardabil provinces totally own 99.8% of soybean production. Soybean and canola production in 2016 were about 139.3 and 68.2 thousand hectares, respectively. Yield production of soybean in irrigated and dry farming land was 2317 and 1815.5 kg/ha, respectively. Yield production of canola was 1463 kg/ha in irrigated land and 901 kg/ha in dry farming land. The Kordestan province, with the yield of 3833 kg/ha canola, has the highest yield in irrigated land and the Golestan province, with the yield of 1329 kg/ha canola ranks first in yield in dry farming land.

4.1.4. Other Oil Seeds

Other important oil seeds, such as sunflower and safflower, were cultivated on 18.7 thousand hectares in various points of Iran and 18.8 thousand tons of oil were produced from them in 2016. Golestan and Fars have the highest share in the plantation of these oil seeds. More than 600 thousand hectares of land from 31 provinces are estimated to be the potential land for growing oil seeds as shown in Figure 3.

Figure 3. Important regions in Iran for the plantation of oil seeds.

4.2. Microalgae Production Potential in Iran

Microalgae species utilize very efficiently water, CO_2, sunlight, and nutrients through the mechanism of photosynthesis so that they have an ability to produce 30 times the amount of oil per unit area of land compared to oil seeds. This potential, besides being a non-food source, has in recent years made researchers consider utilizing algae as a sustainable source of energy [49].

4.2.1. Algae in Iran

Due to enough sunlight, the warm and moderate climate, and having approximately 740 km of coastline of the Caspian Sea and 2440 km along the Persian Gulf and the Gulf of Oman, algae has suitable growth conditions in Iran. Recent research indicates that the Persian Gulf and the Caspian Sea are the habitats of greenish blooms of algae [39].

Moreover, various species of microalgae have existed in Iran in the Urmia Salt Lake, the third largest saltwater lake in the world, and the Maharlu, Qom, and connected salt lakes along the Iran-Afghanistan border. Some of these salt lakes are shown in Figure 4.

Besides sea and salt lakes in Iran, rivers, water bodies, and swamps have numerous microalgae species. DB Zarei found 182 species of blue-green algae among 125 water bodies in Iran. Furthermore, he reported algal flora in rivers in Iran from 8 divisions of algae, including 111 species [50].

Additionally, Naser Jafari reported blue green-algae and diatoms in the Babolrood River at Mazandaran province. He also revealed the famous green algae Scenedesmus and Chlamydomonas [51]. T. V. Dogadina et al. reported 534 microalgae species in Enzeli Swamp in Gilan province [52]. In addition, 225 algae species in the Boujagh National Park were identified by Mostafa Noroozi [53]. Species such as *Chlorella vulgaris*, *Chlamydomonas* sp., and *Chlorella* sp. were reported in rice paddy-field soil samples of Fars province [39]. Mohammad Hossein Morowvat isolated *Chlamydomonas* sp. with the total fatty acid content of 25% and concluded that *Chlamydomonas* sp. was suitable for biodiesel production due to the simple and inexpensive culture medium [54]. Fars province also has shallow-marine lime stones in the Zagros Mountains, which have a diverse range of microalgal species [39]. Cyanobacteria, such as *Chrococcus* sp. and *Synechocuus* sp., green algae species, such as

Dunaliella sp., and diatom, such as *Gyrosigma* sp., have been reported in Lake Urmia [55–60]. However, *Dunaliella salina* is the dominant species of the Urmia and Maharlu Salt Lakes.

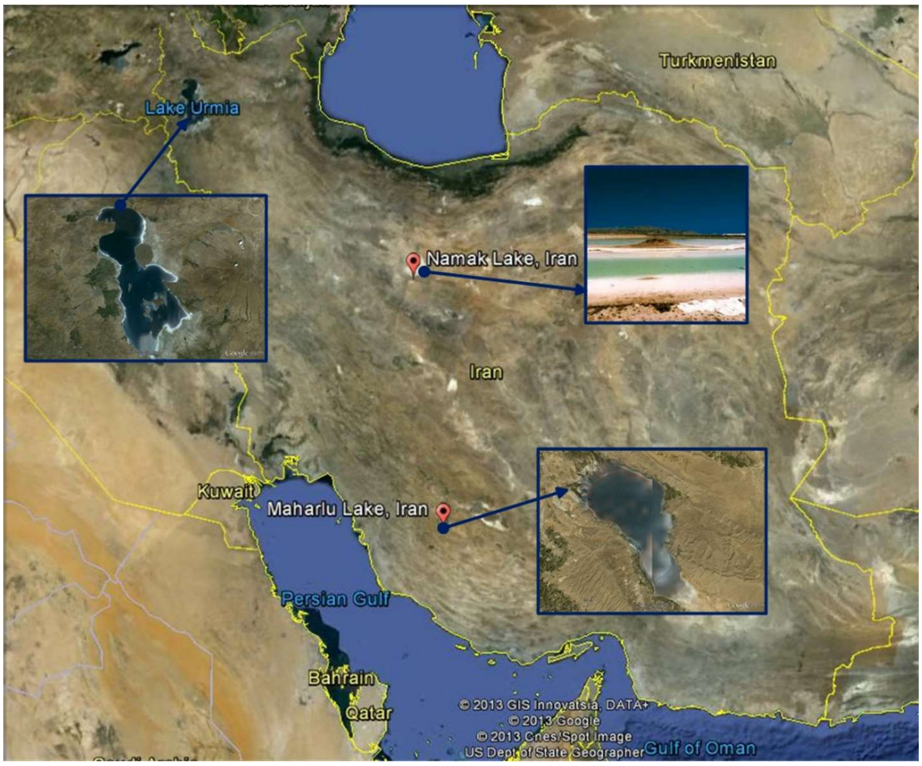

Figure 4. The location of the Urmia, Maharlu, and Namak Lakes in Iran.

4.2.2. Cultivation of Indigenous Microalgae, *Dunaliella salina*

As mentioned in the previous section, Iran has much potential to culture microalgae. Therefore, the authors of this paper decided to investigate the cultivation of indigenous microalgae as a potential biodiesel feedstock. The microalga *Dunaliella salina* MCCS AB105 M.H. Morowvat and Y. Ghasemi was isolated from the Maharlu Salt Lake [42,61]. Maharlu Salt Lake medium for the first time was utilized for microalgae growth.

The authors proposed an integration of a raceway pond and an airlift pump (RWPAP) so that the energy consumption of the paddle wheel could be eliminated by utilizing flue gases from industrial processes. The RWPAP reactor was a glass reactor with a depth of 45 cm, a width of 15 cm, and a length of 30 cm, which comprised a middle wall with one open side. A plexiglass airlift tube with a 0.75-inch inner diameter size and a total length of 43 cm was located at the closed side of the middle wall, whose foot ended 2 cm above the bottom.

The medium had a 40-cm depth and an air flow rate of 0.83 $L{\cdot}min^{-1}$ from an air pump mixed with CO_2 at a flow rate of 0.4 $L{\cdot}min^{-1}$ at the pressure of 1.045 bar and was injected at the bottom of the tube to lift the medium in the tube. The medium was lifted due to the decrease of density in the tube compared to the medium outside of the tube. The lifted medium was directed to the other side of middle wall and circulated in the reactor as illustrated in Figure 5.

CO_2 injection occurred for five minutes, every two hours in order to have a constant pH for the cultivation of microalgae. During the growth, the illumination and temperature of the reactor was kept at 72 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$ and 30 °C, respectively. The biomass productivity was determined from the biomass dry weight according to the instructions of centrifuging, rinsing with de-ionized water, and drying [62]. The lipid was extracted and the methyl ester of fatty acids was analyzed by Hewlett–Packard 6890 GC/MS with the technique described in the papers of Mooney et al. and Rasoul-Amini et al. [63,64]. The reactor gave a comparable batch biomass productivity of 0.096 g·L^{-1}·day^{-1} after two weeks, which was higher than the biomass productivity of 0.085 dry g·L^{-1}·day^{-1} reported by Morais and Costa in a 2-L conical flask with *Scenedesmus* sp. in a 20-day batch run [65]. The systematic name, common name, chemical formula, and number of double bonds of the major fatty acid of *Dunaliella salina* isolated from the Maharlu Salt Lake are presented in the following table.

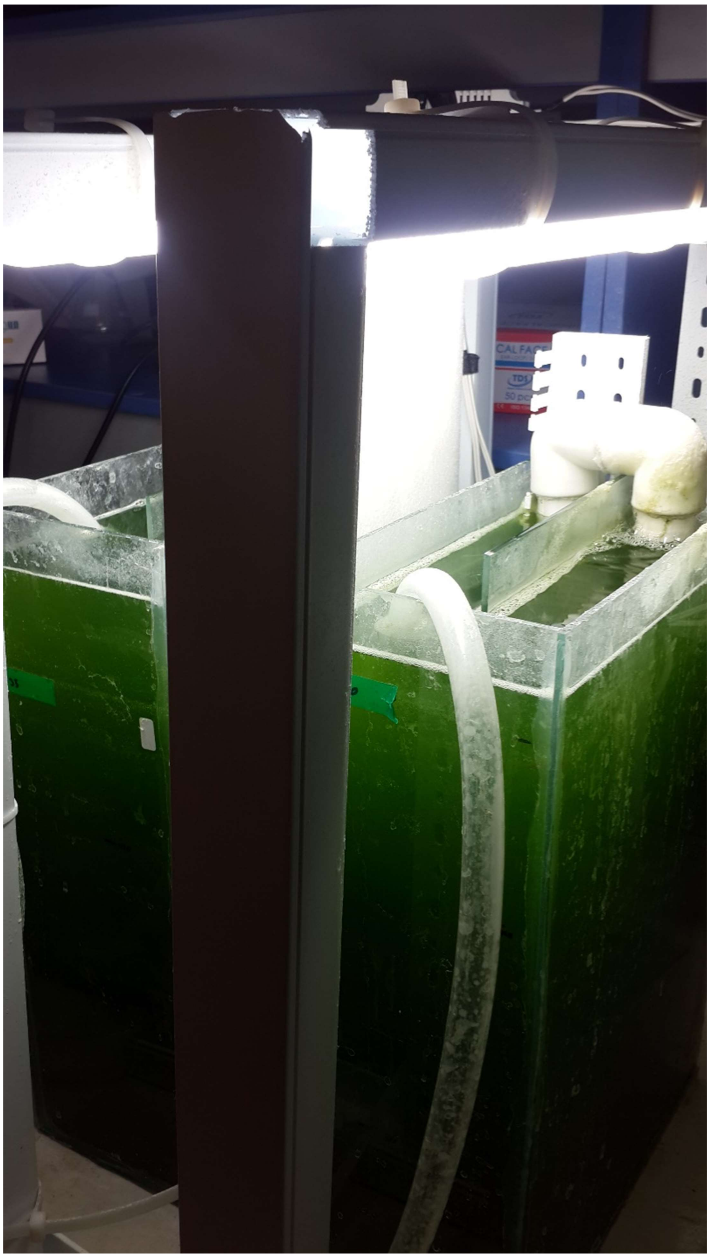

Figure 5. Raceway pond and airlift pump (RWPAP) reactor.

Many types of research demonstrate that the carbon chain sizes, amount of double bonds, and the ratio of saturated to unsaturated fatty acids (FAs) determine biodiesel quality, such as the Cetane umber, Iodine Value, Cold Filter Plugging Point, and resistance to degradation and oxidation [66–69].

Mandal et al. studied Lipid accumulation in *Scenedesmus obliquus* and reported that this strain was a suitable feedstock for biodiesel production due to the presence of saturated and mono-unsaturated fatty acids in the total fatty acid profile, which was 75% [70]. Yusuf Chisti mentioned that polyunsaturated fatty acids (PUFA), especially PUFAs with four or more double bonds, decrease the acceptance of microalgal oil due to the oxidation quality of the biodiesel [70,71]. Moreover, Doan et al. reported that long-chain polyunsaturated FAs in Nannochloropsis as promising sources of oil feedstock for biodiesel production could unfavorably influence the ignition quality and oxidative stability of the biodiesel [66,72]. Furthermore, a PUFA with or more than four double bonds for producing biodiesel was restricted to under 1% by the European standard EN 14214 [73,74]. As shown in Table 4, fatty acid analysis of *Dunaliella salina* isolated from the Maharlu Salt Lake indicated that this strain has a significant ratio of saturated to unsaturated FAs, which is considered suitable for biodiesel production. Furthermore, having a variety of FAs harboring 16–18 carbon atoms and no polyunsaturated fatty acids are other advantages of this strain.

Table 4. Fatty acid (FA) composition of *Dunaliella salina* MCCS AB105

Systematic Name	Common Name	Formula	No. of Double Bond(s)	Fatty Acid Content (% Total)	Family
N-Hexadecanoic acid	Palmitic acid	$C_{16}H_{32}O_2$	0	43.00	Saturated FA
Octadeca-10,13-dienoate acid	-	$C_{18}H_{34}O_2$	2	9.60	Monounsaturated FA
Octadeca-9,12,15-trienoic acid	α-Linoleic acid	$C_{18}H_{32}O_2$	3	10.98	Monounsaturated FA
N-Octadecanoic acid	Stearophanic acid	$C_{18}H_{36}O_2$	0	23.72	Saturated FA
N-Heneicosanoic acid	Heneicosylic acid	$C_{21}H_{42}O_2$	0	3.80	Saturated FA
N-Docosanoic acid methyl ester	Methyl behenate	$C_{23}H_{46}O_2$	0	8.90	Saturated FA

4.3. Biodiesel Production Potential in Iran

The lipid content of important oil seeds and microalgae species in Iran are tabulated in Table 5. Moreover, in this table, the amount of cropping area needed to displace diesel import or even consumption in 2016 was calculated. As mentioned before, Iran consumed 81.2 million liters of diesel per day, which imposed a 4.4 million liter per day import requirement of diesel in 2015–2016.

Table 5. Comparison of the biodiesel production potential of oil seeds and microalgae to displace diesel in Iran.

Oil Seeds	Oil Content (%)	Oil Yield (L ha^{-1} year^{-1})	Percent of Iran Cropping area to Displace Diesel Import in 2015–2016	Percent of Iran Cropping Area to Displace Diesel Consumption in 2016
Walnut	60	2108.1	6.5	119.4
Corn	10	738.4	18.6	341.0
Cotton	40	1469.2	9.29	171.4
Almond	54	905.6	15.1	278.1
Canola	30	709.2	19.2	355.1
Soybean	18	900.4	15.2	279.7
Olive	20	542.8	25.1	463.9
Hazelnut	62	1265.3	10.8	199.0
Sesame	50	618.5	22.1	407.1
Microalgae (10 g·m^{-2}·day^{-1})	30	12,000	1.1	21.0
Microalgae (50 g·m^{-2}·day^{-1})	50	98,500	0.1	2.5

Ref. [75] (Ministry of Agriculture-Jahad 2016).

As shown in the table, microalgae with the productivity of 10 g·m^{-2}·day^{-1} with 30% oil content in raceway pond cultivation, which is considered common productivity, would require only 21% of cultivable lands in Iran to potentially replace diesel consumption of Iran in 2016. Moreover, only around 1.1% of Iran's cropping area will be needed to ensure a reduction in the diesel import demand. As can be seen from the table, the best choice of oil seeds compared to microalgae will be Walnut. However, microalgal species contain many advantages over oil seeds, but significant water and nutrient requirements increase the economic cost of microalgal biodiesel production.

The Microalgal biodiesel production cost could be influenced by many variables, such as geographic distributions and algal species [76]. Jia Yang et al. analyzed these variables and concluded that 3726 kg of freshwater and around 1 kg of nutrients will be needed to produce 1 kg microalgal biodiesel. Moreover, they found that if the recycling harvest and sea or wastewater were utilized, the water requirement could be reduced by around 90% [77]. In this paper, a natural medium with the least cost was used to prove the ability of microalgal cultivation in Iran. Therefore, biofuels in Iran could be a viable energy source and have an important share in the supply of fuels. At present, the Renewable Energy Initiative Council in the Southern regions of Iran focuses on the cultivation of cellulose and oil sources for biofuels production [39]. This council was established in 2008 and consists of seven different departments, such as biomass.

5. Conclusions

Concerning the cited circumstances about the current conditions and rapid growth rate of diesel consumption, it is obvious that Iran should seek a fundamental solution and strategies besides those of increasing production and imports of diesel. Therefore, the government implemented fuel rationing and a targeted subsidy law during 2007–2010 to reduce diesel consumption and import. While these plans have not reduced diesel consumption efficiently because of the too-low price of diesel due to a decrease in Iran's currency despite the implementation of the subsidy plan, the high subsidy of fuels due to not implementing the subsequent phases of the subsidy plan have caused a catastrophic decreasing of social welfare, an economy intensively dependent on fuel price, an incompatible relationship between fuel consumption and vehicle production, old technologies of manufactured vehicles, and undeveloped and weak public transportation.

During 2006–2007, before these plans, diesel consumption imposed a 2.2 billion liter import requirement. After these plans in 2011, diesel consumption imposed a 3.6 billion liter import requirement and cost about $2.2 billion Consequently, the government will need fundamental strategies and policies to solve the problem of catastrophic diesel consumption in the future, and increasing fossil fuels production without implementing strategies to control and optimize the consumption pattern results in the misuse of national assets. This paper, besides evaluating government policy for reducing diesel consumption, attempts to propose a fundamental solution to confront a future diesel crisis. Therefore, oil seeds and microalgae production potential in Iran to produce biodiesel as an alternative fuel was assessed. This paper investigates the potential for producing microalgal biodiesel by the cultivation of *Dunaliella salina* as an indigenous microalgae in its natural culture medium in an integration of an airlift system and a raceway pond (IARWP). This research concluded that microalgae has potential to ensure a reduction of diesel demand in Iran by only 21% of Iran's cropping area. This paper suggests that due to the existence of wide and various ranges of microalgae species and a favorable climate, there is considerable potential for the utilization of algae oil to produce alternative fossil fuels and fundamentally solve the problem of catastrophic diesel demand in Iran in the future.

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