Comparative Review of Three Approaches to Biofuel Production from Energy Crops as Feedstock in a Developing Country

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Abstract

This study is a comparative evaluation of three approaches to biofuel production from energy crops including biogas, bioethanol and biodiesel to ascertain which one is the most effective and more energy-efficient than the others. Moreover, the potential of biofuel production from the best option was studied. For this purpose, biogas generation from corn silage, bioethanol generation from corn, and biodiesel production from peanuts in Iran (as a case study) were studied. The results revealed that 10,683.36 m^3 of biogas, 2.53 m^3 of bioethanol and 0.70 m^3 of biodiesel could be produced per each hectare of energy crops. The total greenhouse gas emissions for each MJ energy generation of biogas, bioethanol and biodiesel were 0.01, 0.04 and 0.03 $kgCO_2eq$, respectively. Accordingly, the total annual biogas potential from corn silage (as the best option) in Iran is 3,953.74 million m^3, which is equivalent to 1515.94 million barrels of oil.

Keywords: Biodiesel, Bioethanol, Biogas, Energy crop, Renewable energy

Nomenclature

Acronyms			
BOE	Barrels of oil equivalent	L	Liter
CH_4	Methane	kg	kilogram
CO_2	Carbon dioxide	km	Kilometer
eq	Equivalent	MJ	Megajoule
GHG	Greenhouse gas	m^3	Cubic meter
GJ	Gigajoule	UK	United Kingdom
ha	Hectare		
t	tonne		

1. Introduction

On the one hand, fossil fuel-based sources are limited and they are being consumed faster than they can be reproduced (Ghadiryanfar et al., 2016; Moheimani and Parlevliet, 2013). On the other hand, the environmental consequences of consumption of fossil fuel resources are huge (Nikkhah et al., 2016a). Thus, replacement of a portion of fossil fuel with renewable-based resources is an urgent necessity (Fiala and Bacenetti, 2012; Pedraza, 2015).

In this regard, biomass is considered as one of the most promising renewable energy resources (Arumugam et al., 2016; Kim et al., 2016), which accounted for 59% of total renewable-based resources in 2015 in the European Union (Scarlat et al., 2015). The globally produced biomass energy equivalent was estimated 8 times higher than the world total energy requirement (Alavijeh and Yaghmaei, 2016).

Energy crops are one of the main resources of biomass (Testa et al., 2016). There are many ways to generate energy from this resource (Eryilmaz et al., 2016; Moreda, 2016; Karimi Alavijeh et al., 2016), but the main commercial types are biogas, biodiesel and bio-ethanol (Hijazi et al., 2016). Comparing various energy crops (feedstock) systems in terms of energy efficiency and greenhouse gas (GHG) emissions can help in deciding how to transform to sustainable biofuel production systems. In this study, biogas generation from corn silage, bioethanol generation from corn, and biodiesel fuel production from peanuts in Iran (as a case study) were studied.

2. Biogas generation

Biogas-a renewable fuel- is generated from anaerobic breakdown of various biological feedstocks through synergistic metabolic activities of hydrolytic, acidogenic, and methanogenic microorganisms (Kaur and Phutela, 2016; Sheets et al., 2017). Biogas consists of around 60% methane (CH_4), 40% carbon dioxide (CO_2), and around 2000 ppm hydrogen sulphide (H_2S) as the main impurity (Villadsen et al., 2019). Capturing methane in the biogas production process contributes positively to reduction of CH_4 emissions and also the captured methane could be used as a renewable energy source to all applications designed for natural gas (Atelge et al., 2018; Kapdi et al., 2005; Noorollahi et al., 2015).

Global biogas production in the world increased from 0.28 EJ in 2000 to 1.28 EJ in 2014, with the volume of 59 billion m^3 biogas (equaling 35 billion m^3 methane) (Scarlat et al., 2018). The biogas generation status in some leading countries is shown in Table 1.

Corn is cultivated largely for biogas production in some countries all over the world (Nkemka et al., 2015). Germany and Italy cultivate more than 2,282,000 and 1,172,000 hectares of corn a year, respectively in order to be co-digested in large farm biogas plants (Casati, 2013; Bacentti et al., 2014).

Table 1

The status of biogas generation in some countries (Kummamuru, 2015; Statista, 2017; Scarlat et al., 2018; Nikkhah et al., 2019)

Country	Year	Biogas generation (billion m^3)
Brazil	2013	0.29
Canada	2014	0.79
China	2014	15
Germany	2013/14	13.5
India	2014	0.81
Korea	2013	0.43
Thailand	2014	1.3
The Netherlands	2012	0.52
UK	2013	3.16
United states	2014	8.48

3. Bioethanol production

Bioethanol is considered as a renewable, and green combustible liquid fuel as alternative to gasoline (Thangavelu et al., 2016). It is easily used as oxygenated portion in gasoline for cleaner combustion (Thangavelu et al., 2016). Bioethanol production process includes treatment, enzyme hydrolysis, fermentation, recovery and the refining process (Wei et al., 2014; Gupta and Verma, 2015). Bioethanol as a fuel was initiated during the global fuel crisis in the 1970s and the capacity of its production rose from less than one billion L in 1975, to 39 billion L in 2006 due to its wide application in many sectors (Sirajunnisa and Surendhiran, 2016). Table 2 shows the world's largest ethanol producers in 2014.

Bioethanol is primarily generated from agricultural products with high content of sugar or starch, i.e. corn (Ho et al., 2014). Corn is widely grown around the globe, and globally, 817 million tons of it was produced in 2009, more than rice (678 million tons) and wheat (682 million tons) (Koçar and Civaş, 2013).

Table 2

World's largest ethanol producers in 2014 (Renewables global status report, 2015)

Country	Ethanol production (billion L)	Change relative to 2013 (%)
United States	54.3	+3.9
Brazil	26.5	+1.6
Germany	0.9	+0.6
China	2.8	+0.3
Argentina	0.7	+0.8
Indonesia	0.1	+0.9
France	1	+0.1
Netherlands	0.4	+0.2
Thailand	1.1	+0.4
Canada	1.8	+0.1
Belgium	0.6	+0.2
Spain	0.4	+0.1
Poland	0.2	+0.1
Colombia	0.4	No change
Australia	0.2	-0.1

4. Biodiesel production

Biodiesel -an alternative fuel for diesel- may be applied in conventional diesel engines without any major hardware alteration (Murugesanet al., 2009; Zhang et al., 2016). “Bio” implies its bio and renewable source, and “diesel” displays its application as fuel for diesel-based engines (Canakci and Özsezen, 2005). Biodiesel can be produced from oil seeds like peanut, canola, soybeans and sunflower through the process of transesterification (Ardebili et al., 2011).

It could be an optimum alternative fuel in some countries such as Germany, Italy, France and Turkey (Eryilmaz et al., 2016). Fig. 1 demonstrates the largest biodiesel producers in the world in 2014.

Oil seeds are one of the remarkable resources for biodiesel generation (Gui et al., 2008). In this regard, peanut is known as one of the main resources of oilseeds for biodiesel production and peanut-based biodiesel was the first biofuel to power a diesel engine (Hogan et al., 2017). The advantages of biodiesel are biodegradability, renewability, higher flash point, and absence of sulfur and aromatic compounds (Kralova et al., 2010). However, when the source of its production is oil seeds, production of feedstock necessitates consumption of some inputs such as diesel fuel and chemical fertilizers that can contribute to the GHG emissions (Nikkhah et al., 2016b).

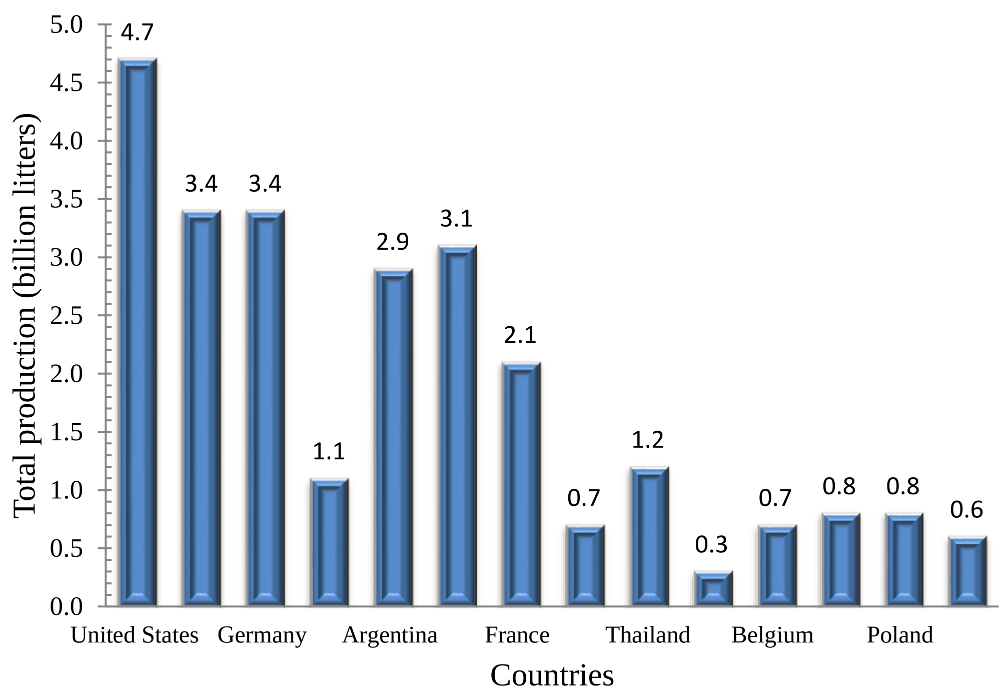

Fig. 1. World's largest biodiesel producers in 2014 (Hajjari et al., 2017)

5. Comparing the green technologies to generate energy

The yields of corn silage, corn and peanuts production were adapted from literature review which are cited in Table 3. After that, the conversion coefficients were used to calculate the amount of biofuel and energy generation per hectare of farm. Table 3 displays the possible amounts of biofuel production from various technologies based upon cultivation of one hectare of different energy crops. The produced volumes were 10,683.36 m^3 of biogas, 2.53 m^3 of bioethanol and 0.70 m^3 of biodiesel. The energy content of biogas generation from corn silage, bioethanol from corn and biodiesel from peanut were determined to be 267084.00, 26786.58 and 59,204.61 $MJha^{-1}$, respectively. The results clearly illustrated that the net energy from biogas generation using corn silage was higher than that of the two other systems of biofuel production.

Table 3

The potential of different technologies to energy generation from energy crops

Biofuel production system	Energy crop	Yields		Energy conversion coefficient		Product consumption	Energy content		Energy consumption
		Yield ($kgha^{-1}$)	Reference	Coefficient	Reference	Total biofuel production (m^3ha^{-1})	unit	Reference	Total energy production ($MJha^{-1}$)
Biogas	Corn silage	18547	Pishgar Komleh et al., (2011)	576 m^3t^{-1}dry matter	Pöschl et al., (2010)	10,683.36	25 MJm^3	Hellgren et al., (2015)	267,084.00
Biodiesel	Peanut	3209	Nikkhah et al., (2016b)	0.22 $L.kg^{-1}$	Jaruwongwittaya and Chen, (2010)	0.70	38 $MJkg^{-1}$	Kalnes et al., (2009)	26, 786.58
Bio-ethanol	Corn	6806	Banaeian and Zangeneh, (2011)	0.37 $L.kg^{-1}$	Shapouri et al., (2003)	2.53	23.4 MJL^{-1}	Wilcock et al., (2012)	59,204.61

Figure 2 illustrates the barrels of oil equivalent (BOE) for each biofuel. The energy yield per hectare of corn silage to generate biogas was 43.1 BOE; then were 9.5 and 4.3 for bioethanol and biodiesel, respectively.

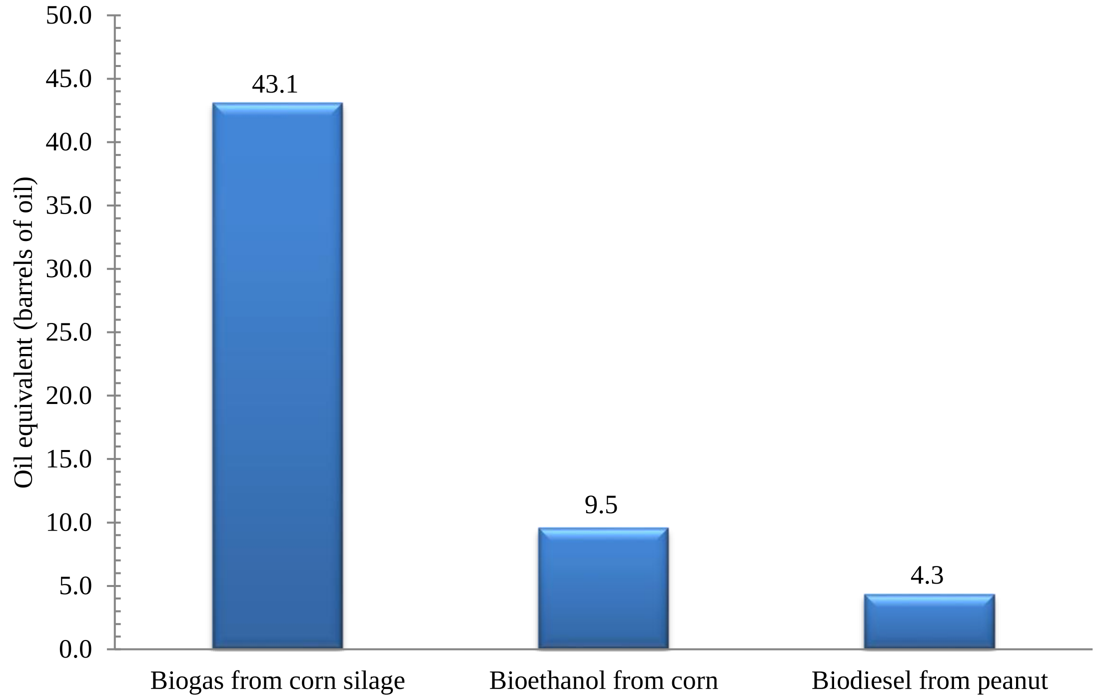

Fig. 2. Potential barrels of oil equivalent per hectare for each biofuel

Fig 3 illustrates the distance that a typical car can travel feeding with various biofuels (the biofuels are obtained from one hectare of energy crop) assuming the consumption rate of ten L of gasoline per 100 km. The distances that a car can travel using biogas, bioethanol and biodiesel fuels were rouhgly estimated to be 62,000, 14,000 and 6,000 km, respectively. It means that generated biogas from one hectare of corn silage has the greatest potential to be used as transportation fuel compared to bioethanol and biodiesel. Biogas is applied as an environmentally-efficient transportation fuel in some countries (Hamad et al., 2014; Raboni and Urbini, 2014). The European Union also has set a goal to increase the biofuel consumption; more specificly, 10% of fuels consumed in the transportation sector should be biofuels-based in 2020, and after 2020, the percentage should further increase (Uusitalo et al., 2013). Moreover, based on the the Paris agreement, Iran has agreed for mitigating its GHG emissions (Ahmad et al., 2017).

Thus, application of upgraded biogas instead of fossil fuels in the transportation sector could contribute to GHG emissons mitigation. In Sweden, biogas consumption since 2002 in urban transport alone has mitigated CO_2 emissions by 9000 t per year (Makareviciene et al., 2013).

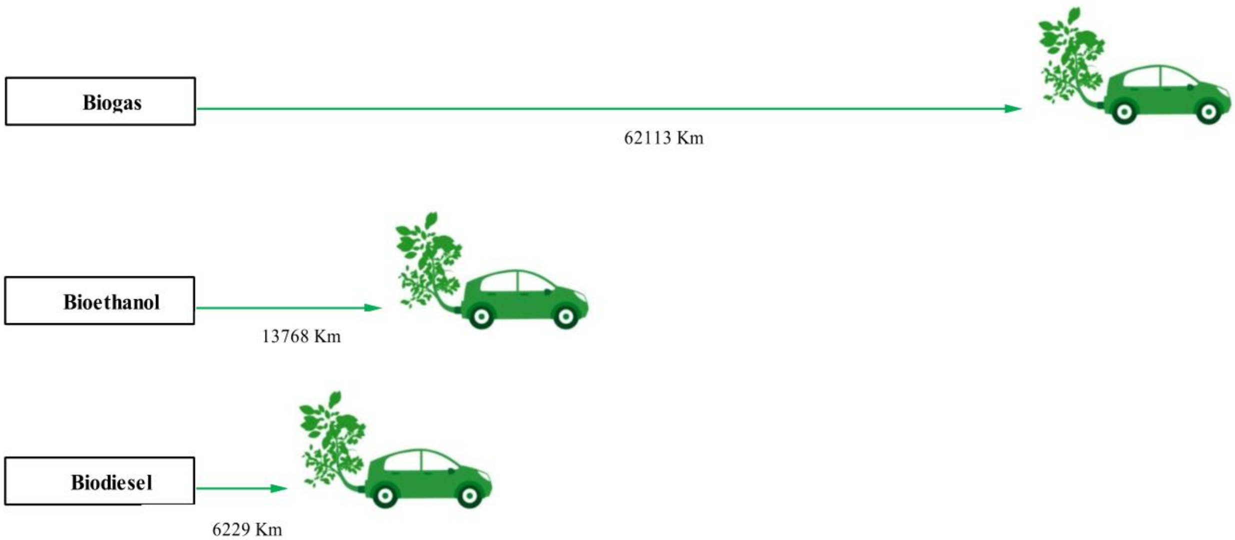

Fig. 3. The distance a car can travel using various biofuels (average fuel consumption was assumed to be 10 L/100km)

6. Net energy comparison

Table 4 summarizes the energy inputs for energy crops production. Agricultural machineries were the greatest energy consumers during corn production. Bacentti et al., (2013) reported that diesel fuel consumption is the main contributor to global warming in corn production systems in Italy. The greatest energy consumption of peanut production in Iran was attributed to diesel fuel, followed by chemical fertilizers.

The energy productivity to generate biogas, bioethanol and biodiesel were 0.15 m^3MJ^{-1}, 0.05 LMJ^{-1} and 0.04 LMJ^{-1}, respectively. The net energy for producing biogas, bioethanol and biodiesel were determined to be 198,156, 6,629 and 7,379 $MJha^{-1}$, respectively. The results revealed that the biogas production from some crops, such as corn silage is the most energy efficient. For its generation, various processes are employed that may be divided in dry and wet fermentation approaches (Weiland, 2010). Berglund and Bőrjesson, (2006) investigated the energy performance of biogas generation. They concluded that the energy input for producing biogas corresponds to 20–40% of the total energy content of produced biogas. Jankowskia et al. (2016) evaluated the efficiency of energy consumption in biogas generation using corn, sweet sorghum, giant miscanthus, Virginia fanpetals, Amur silver grass, and alfalfa with timothy grass grown in Poland. They concluded that giant miscanthus was the most energy-efficient crop (25.0%), followed by corn (15.8%). Cvetković et al. (2014) claimed that corn silage is widely used as a co-substrate in biogas plants built on the farms in Serbia.

Table 4

Energy consumption and energy indices of energy crop production

	Corn silage (Pishgar Komleh et al., 2011)		Corn (Banaeian and Zangeneh, 2011)		Peanut (Emadi et al., 2015)	
Inputs	Average (MJ ha^{-1})	Percentage (%)	Average (MJ ha^{-1})	Percentage (%)	Average (MJ ha^{-1})	Percentage (%)
Diesel fuel	10800	16	12867	24	9714	50
Agricultural machineries	28944	42	15575	29	2184	11
Chemical fertilizers	19550	28	5646	33	3715	19
Electricity	-	-	-	-	2065	11
Water	6372	9	2927	6		
Biocide			683	1	219	1
Seeds	3178	5	2773	5	331	2
Farmyard manure			183	1		
Human labor	86	0.12	591		1179	6
Total energy inputs	68928	-	52575	-	19407	-
Energy productivity	0.15	-	0.05 L.MJ^{-1}	-	0.04 L.MJ^{-1}	-

	m^3MJ^{-1}					
Net energy	198156.00	-	6629.61	-	7379.22	-

Figure 4 displays the net energy for different technologies per hectare of energy crops. The net energy per hectare of corn silage to generate biogas is equal to 32.0 barrels of oil. The net energy per hectare of bioethanol and biodiesel production were determined to be 1.1 and 1.2 barrels of oil, respectively.

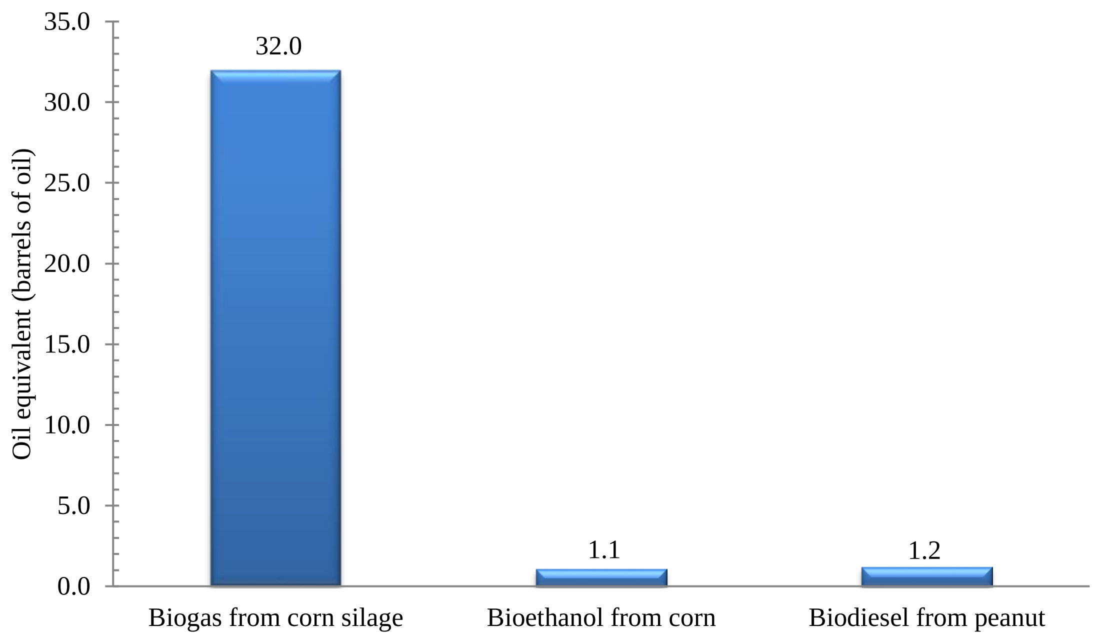

Fig. 4. The net energy produced by different technologies (per each hectare)

7. **Comparison of greenhouse gas emissions**

The raw data related to inputs-output production of corn silage was adapted from Pishgar Komleh et al. (2011), corn from Banaeian and Zangeneh, (2011), and peanut from Nikkhah et al., (2016b). Then, the GHG emissions coefficients were used to compute the corresponding GHG emission of each input. The GHG emissions for each hectare of energy crops production were calculated by equation 1 (based on Eren et al., 2019).

$$GHG\ emissions = \sum_{i=1}^{n} R(i) \times EF(i) \qquad (1)$$

where R(i) is the amount of input i consumption per hectare, and EF(i) is the GHG emission coefficient of input i (kgCO_2eq).

Table 5 shows the GHG emissions calculated in this study from the investigated energy crop production systems. The results highlighted that the total GHG emissions footprint from potential feedstock production of biogas, bioethanol and biodiesel production were 2989, 2159 and 822 kgCO_2eq ha^{-1}, respectively. The GHG emissions for each MJ energy generation of biogas, bioethanol and biodiesel were determined to be 0.01, 0.04 and 0.03 kgCO_2eq ha^{-1}, respectively. It implies that the total GHG emissions to generate one MJ of biogas were lower than those of bioethanol and biodiesel technologies. Moreover, the GHG emissions per net energy ratio of biogas, bioethanol and biodiesel production were determined to be 0.02, 0.33 and 0.11 kgCO_2eq MJ^{-1}, respectively. González-García et al. (2013) evaluated three different energy crops such as corn, wheat, and triticale to generate biogas in Italy. The best results were reported for corn in most impact categories (González-García et al., 2013). Börjesson et al. (2015) studied the crop-based biogas production from six agricultural crops to be used as vehicle fuel. The results showed that ley crop-based biogas systems contributed to the largest GHG mitigation followed by corn, wheat, hemp, triticale and sugar beet. Overall, in all the studied cases, biogas consumption in the transportation sector has led to mitigation of GHG emissions compared to fossil transportation fuels (Uusitalo et al., 2014).

Table 5
GHG emissions from the production of energy crops to generate energy

	Corn silage		Corn		Peanut	
Inputs	Average (kg CO_2eq ha^{-1})	Percentage (%)	Average (kg CO_2eq ha^{-1})	Percentage (%)	Average (MJ ha^{-1})	Percentage (%)
Diesel fuel	624	21	632	29	476.12	57.90
Agricultural machineries	2055	69	1106	51	155.04	18.86
Chemical fertilizers	310	10	326	15	71.61	8.71
Electricity	-	-	-		105.27	12.80
Biocide	-	-	18	1	14.26	1.73
Farmyard manure	-	-	77	4	-	-
Total GHG emissions	2989	-	2159		822	-
Energy productivity	0.01	-	0.04	-	0.03	-
$\frac{\text{GHG emission}}{\text{Net energy}}$	0.02	-	0.33	-	0.11	-

8. Potential of biogas production from corn silage

Table 6 shows the amounts of corn silage production in various provinces of Iran and their biogas yields. The greatest potential for biogas production were attributed to Fars (14%), followed by Khuzestan province (12%). Tehran province with a share of 11% was the third largest potential producer of biogas from corn silage. Figure 5 displays an atlas of annual potential biogas generation from corn silage in Iran.

The results showed that total potential yield of biogas was 3954 million m^3 and its energy content was 98,843,613 GJ. The amount of biogas production from corn in Poland was reported to be 551 million m^3 per annum (Igliński et al., 2015). Mohammadi Maghanaki et al. (2013) claimed that the amount of biogas production from animal wastes, agricultural wastes, municipal wastes and industrial and municipal wastewater in Iran can generate 16146 million m^3. Annually

81.5–279.4 million m^3 of biogas could be produced from food industries in Iran (Iran Renewable Energy Organization, 2013). 74,946 tons of animal-based wastes are available each year in Iran and It could generate 8,668 million m^3 of biogas (Mohammadi Maghanaki et al., 2013). There are different views about energy generation from different resources in Iran. On the one hand, Iran is considered as the world's fourth highest producer of crude oil and natural gas (Nikkhah et al., 2015). It has large amount of non-renewable energy resources and 99 percent of energy generation of Iran comes from non-renewable resources (Nikkhah, 2018). On the other hand, Iran was reported as the biggest CO_2 emitter among the Middle East countries (Alshehry and Belloumi, 2014; Alizadeh et al., 2015), and environmental impacts are a major concern in Iran. Renewable energy generation fromenergy cropscan increase the share of renewable-based energy in Iran's energy production and contributing to the environmental impacts mitigation.

Table 6

Amounts of corn silage production in various provinces of Iran, and their potential biogas yield

Province	Cultivated area (ha) (Ministry of Jihad-e-Agriculture of Iran, 2019)	Production (t) (Ministry of Jihad-e-Agriculture of Iran, 2019)	Biogas yield (m^3)	Energy content (GJ)	Percentage
Alborz	8,433	418059	168561389	4214035	4.26
Ardabil	10,892	434204	175071053	4376776	4.43
Bushehr	388	25385	10235232	255880.8	0.26
Chaharmahal and Bakhtiari	3,060	167986	67731955	1693299	1.71
East Azerbaijan	3,565	159439	64285805	1607145	1.63
Fars	23,435	1334748	538170394	13454260	13.61
Golestan	8,650	334574	134900237	3372506	3.41
Guilan	36	567	228614	5715.36	0.01
Hamedan	2,850	156750	63201600	1580040	1.60
Hormozgan	148	8310	3350592	83764.8	0.08
Illam	2,491	70577	28456646	711416.2	0.72
Isfahan	17,595	912638	367975642	9199391	9.31

Kerman	4,759	239896	96726067	2418152	2.45
Kermanshah	3,500	146582	59101862	1477547	1.49
Khuzestan	21,846	1207915	487031328	12175783	12.32
Kohgiluyeh and Boyer-Ahmad	239	6631	2673619	66840.48	0.07
Kurdistan	192	8430	3398976	84974.4	0.09
Lorestan	2,198	90230	36380736	909518.4	0.92
Markazi	7,386	331343	133597498	3339937	3.38
Mazandaran	3,290	79807	32178182	804454.6	0.81
North Khorasan	598	29696	11973427	299335.7	0.30
Qazvin	21,980	1105922	445907750	11147694	11.28
Qom	1,367	50570	20389824	509745.6	0.52
Razavi Khorasan	16,526	762756	307543219	7688580	7.78
Semnan	2,244	86375	34826400	870660	0.88
Sistan and Baluchestan	4,110	167419	67503341	1687584	1.71
South Khorasan	840	31045	12517344	312933.6	0.32
Southpart of Kerman	929	33539	13522925	338073.1	0.34
Tehran	22,345	1082155	436324896	10908122	11.04
West Azerbaijan	5,738	273948	110455834	2761396	2.79
Yazd	317	16644	6710861	167771.5	0.17
Zanjan	930	31776	12812083	320302.1	0.32
Iran	**202,985**	**9805914**	**3953744525**	**98843613**	**100**

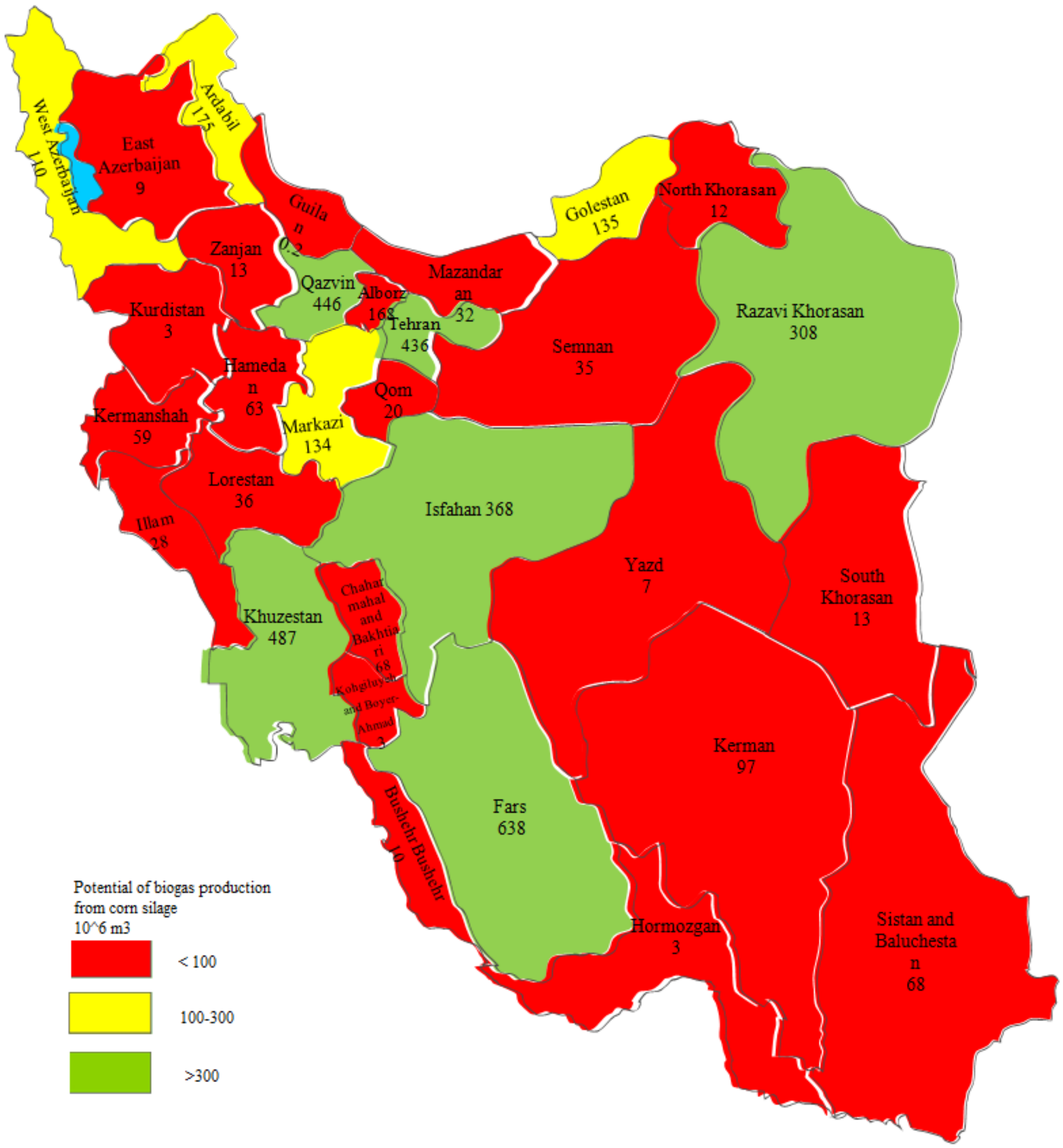

Fig. 5. Atlas of annual potential biogasproduction from corn silage in Iran.
* the figure was generated using the data calculated in this study

The biogas generation potential from corn silage in Iran is equal to 15,941,241 barrels of oil per year. Iran's biomass potential is approximately 140 million barrels of crude oil equivalent (Noorollahi et al., 2015). It is concluded that consideration of energy crops like corn silage for biogas generation in Iran could have a remarkable impact on the energy matrix. Overall, according to the results, it can be well argued that corn silage biogas plans are energy-efficient as well as environmentally feasible as a long-term perspective.

9. Conclusions and future work

This study evaluated the potential of energy production from some energy crops feedstocks and their GHG emissions. It can be concluded that biogas production from corn silage is the most energy efficient way for energy generation compared to the other investigated approaches. This study also provided an atlas of annual potential biogas production from corn silage in Iran. Accordingly, total potential yield of biogas from corn silage in Iran was 3954 million m^3, equal to 15.94 million barrels of oil. Further studies should be carried out on the economic analysis of biofuel production from corn silage in this region.

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