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Comprehensive Techno-Economic Analysis of a Multi-Feedstock Biorefinery Plant in Oil-Rich Country: A Case Study of Iran

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Abstract: The high energy consumption in Iran, particularly in the transportation sector, has contaminated large cities and jeopardized the society health. Therefore, in this study technical and economic features of the production of biodiesel plant in Iran from various wastes are investigated. Based on the Analytic Hierarchy Process (AHP) method's findings, the southern area of Iran is selected for establishing the biodiesel plant in Iran. The biorefinery, which includes three units of sewage sludge, edible waste oil and microalgae. The results of the economic evaluation show that the lowest costs of investment and production of biodiesel are related to microalgae units ($0.375/kg) and edible waste oil ($0.53/kg), respectively. Also, among all units, the lowest break even prices are related to biodiesel production ($1.17/kg) and the highest ATROR rate (29.16%) belongs to the microalgae unit. This indicates that this unit is more profitable than other units and the invested cost is returned to the investor in a shorter period of time (3.43 years). On the other hand, the results of sensitivity analysis show that the highest sensitivity of changes in the selling price of biodiesel and the cost of raw materials to ATROR to the microalgae and sludge unit. Therefore, the construction of a biorefinery in Iran has an economic justification.

Keywords: biodiesel; waste sources; AHP method; biorefinery; techno-economic analysis

1. Introduction

Over-utilization of natural sources raises concerns about environmental change and energy, food and water securities [1]. Nowadays, over 80% of the world's energy consumption generated from fossil energies, which have brought serious health and environmental damages [2]. This issue has led to a move towards an investigation of environmentally benign and renewable-based fuels. One of these fuels is biodiesel, which can be considered as one of the fossil fuels alternative options in the transportation part [3]. Biodiesel made of methyl ester fatty acids (C16–C18) produced from vegetable feed or fats of animals under the well-known transesterification process [4]. This renewable-based fuel is widely accepted in the energy market due to its specific features, consisting high cetane number compared to diesel, low sulfur, intrinsic lubrication, positive energy balance, maximum flash point and the ability to combine with diesel fuel and renewability [5]. In addition, biodiesel releases 20%, 30% and 50%, less than UHC, CO and smoke compared to diesel energy, respectively [6]. According to Table 1 [7], biofuels including biodiesel, are classified into five different generations in terms of production technologies and raw materials, which comprise 1-edible oils 2-non-edible oil products 3-edible and animal oil residues 4-algae and 5-genetically engineered oil products. The choice of raw materials for producing the biodiesel largely depends on geographic location characteristics, environmental situations, agricultural methods, and soil accessibility, which vary from region to region [1]. For example, in Malaysia because of favorable soil situation, palm oil is abundant. While in the United States, soybean oil is more abundant due to weather conditions [8]. Over 350 oil-bearing crops are used as feed for biodiesel production around the world. [9]. Currently, more than 95% of produced biodiesel made from first generation edible oils worldwide [10]. For instance, biodiesel production from first-generation, particularly soybean oil and sunflower oil, is more economically viable in countries with abundant water and soil resources [11]. Biodiesel production has not been widespread regarding economic and technical hardships, and supervision barriers [12]. The raw material is a critical factor in calculation of economic interest, and biodiesel production cost. This is due to the fact that the raw material accounts for 75% of the biodiesel production cost. [13]. Production of biodiesel from foods such as edible oils is 1.5 to 3 times costlier than diesel fuel, and hence, it includes 60–80% of the biodiesel production cost [14]. Furthermore, several parameters can have effect on biodiesel production costs such as labor, methanol and catalysts, seasonal variations, and geographical area [12].

Biodiesel from non-food could be made from resources such as sewage sludge, Waste Cooking Oil (WCO), microalgae, and fat of animal waste, as well as non-edible oils such as Jatropha, Pongamia, Neem, and Camelina [15]. In 2016, 30,701 million liters of diesel fuel were consumed in Iran (84.11 million liters per day), of which 17,030.06 million liters (46.65 million liters per day) were consumed in the transportation sector, in other words, 57.66% of the fuel (94, 17,372.01 thousand cubic meters equivalent to 94, 107.29 million barrels of crude oil equivalent per year) [16]. Energy usage in Iran depends on many elements such as population growth rate, economic growth and urbanization [17]. Luxury consuming life style among Iranian citizens, generous government subsidy panels, and poor source management has in turn led to the abrupt growth of energy usage, and high energy intensity in recent decades [18]. Besides that, the challenges mentioned above, air pollution caused by the excessive use of fossil energy has also become a major problem in Iranian metropolises. Iran's manufacturing and transportation sectors are heavily dependent on cheap energy sources, which have made the government unable to implement policies such as subsidizing the removal of fossil fuels. In the literature, to the best knowledge of authors of this article, there is no comprehensive techno economical study which is investigated the construction of a multi-feed biodiesel production plant in Iran. Besides, the best location to build this plant has been suggested. Therefore, in this study, first, based on official statistics, various types of waste sources in Iran are calculated and the amount of biodiesel produced from them is estimated. Then, based on Analytical Hierarchy Process (AHP), the best place for the construction of a biodiesel production plant in Iran is selected. Finally, this plant is analyzed from an economic point of view by COMFAR III software.

Table 1. The classification of biodisels based on their featurs [7].

Biodiesel Classification/Generation	Features/Aspect/Examples
Fossil fuel	Petroleum based: • Toxic pollutions • Deep GHG footprint • Finite unsustainable reserves • Creation of acidic rains
First generation	Editable oil-crops biodiesel: • Land use changes • GHG footprint • Food competition/Food price elevation • High cost of feedstock/Biodiesel • Water and fertilizer usage
Second generation	Non-edible crops biodiesel: • Land use changes • GHG footprint • Fertilizer and pesticides usage
Third generation	Waste based biodiesel: • No land or water usage • No GHG footprint • No food competition • Low cast • Good solution for waste disposal issue • Sustainable feedstock
Fourth generation	Algae biodiesel: • No land/water usage or food competition • No GHG footprint • Sustainable feedstock in long term
Fifth generation	Genetically engineered crops-based biodiesel: • No land/water usage or food competition • No GHG footprint • Sustainable feedstock in long term • High oil-yielding feedstock

2. Methodology

The performed steps of this research are as follows:

2.1. Data Gathering of Various Types of Waste in Iran

Data gathering in different types of waste in Iran is extracted from official sources such as the Program and Budget Organization and the Statistics Center of Iran. After collecting data, the potential of biodiesel production from these sources is measured through various technologies and processes.

2.2. Selecting the Best Place to Build a Multi-Feed Biodiesel Production Plant in Iran by AHP Method

Plant based biodiesel feedstock alternatives in Iran: sewage sludge, waste cooking oil, waste animal fats and algae oil are evaluated and ranked based on a set of qualitative and quantitative criteria by AHP method. It needs to be highlighted that the amount of residual oils produced from agricultural products has not been addressed because of managing the fertile soil resources as well as the risk of poultry and livestock feed. The Analytic Hierarchy Process (AHP) is a hierarchical-structured MCDM method for evaluation of alternatives with respect to quantitative and qualitative criteria using pairwise comparisons. AHP method covers both quantitative and qualitative criteria, which is a critical requirement for applying in techno economic assessments. Besides, it is utilized in real decision-making problems [19]. Each element in the hierarchy is assumed independent of the others which leads to dividing decision-making issues into several levels as well as hierarchical structure. Goals and criteria determination as a two main steps for utilizing AHP is crucial in this simulation since they will be affected on the formation of the hierarchical structure. The first hierarchical level in the structure is defining the main purpose of the problem. Then, criteria and sub criteria should be considered to reach a meaningful result.

2.3. Techno-Economic Assessment

The profitability analysis module includes the calculation of the Fixed Investment Costs (FIC), Total Manufacturing Costs (TMC), After Tax Rate of Return (ATROR) and biodiesel Break-Even Point (BEP) and the discounted payback period. Detailed information about the equipment module costing technique used to estimate the total bare module of the plant can be found in the literature [20]. The calculations of the financial assumptions used in this study are follows: an 18% rate of interest for the capital investment, plant life span of 20 years, 9% income tax rate, construction period 2 years, 330 working days per annum. Working capital is considered as 15% of fixed capital investment. In this study, COMFAR III was used to investigate the feasibility and conduct the economic analysis. The distinctive feature of this software is its capability for facilitating organization and generating financial and economic reports. Some of the strengths of this software include high flexibility, low error rate, and careful financial sensitivity analysis [21].

3. Result and Discussion

3.1. Potential Waste Sources for Biodiesel in Iran

3.1.1. The Potential of Biodiesel Production from Municipal and Industrial Sewage Sludge in Iran

According to Mesdaghinia et al. [22], the per capita sludge produced from Tehran wastewater is between 0.16 ± 0.02 and 0.11 ± 0.02 L per day. If this amount is considered for Iran, for a population of about 82.35 million people, 5410.7 million liters' sewage sludge will be obtained from Iranian municipal sewage annually. By using methanol, in the best case, the amount of lipid that can be extracted from primary and secondary sludge is 14.46 and 10.04 (% wt based on dry sludge), respectively. Since precise statistics are not available on the amount of primary and secondary municipal sewage sludge, for the primary sludge 5410.7 million liters is considered. On the other hand, the Fatty Acid Methyl Ester (FAME) yields from acid catalytic esterification-transesterification processes from extracted lipids of hexanes were 41.25% (based on lipids) for primary sludge, and 26.89% (for fat) on secondary sludge [23]. Thus, from primary sludge lipids 322.73 million liters' biodiesel is produced annually. Figure 1 presents the amount of biodiesel produced from the primary lipid sludge of municipal wastewater for provinces with a population of more than two million people. This, most of the production of biodiesel belongs to Tehran, Khorasan Razavi, and Isfahan provinces, respectively. The amount of wastewater produced from the industrial and mining sector in 2016 is estimated 2230.9 million cubic meters annually, that reaches the Iranian watersheds. Moreover, in the mining industry 4,223,851 people have worked, that the amount of industrial wastewater was 1447 lit/day per person. Regarding 14.46 wt. % lipid (based on dry sludge) from primary sludge sources, and FAME performance produced from acid catalytic esterification-transesterification processes from extracted lipids of hexanes 41.25 wt. % (based on lipids) for primary sludge, 364.56 million liters' biodiesel can be obtained from the primary sludge from industrial wastewater [23].

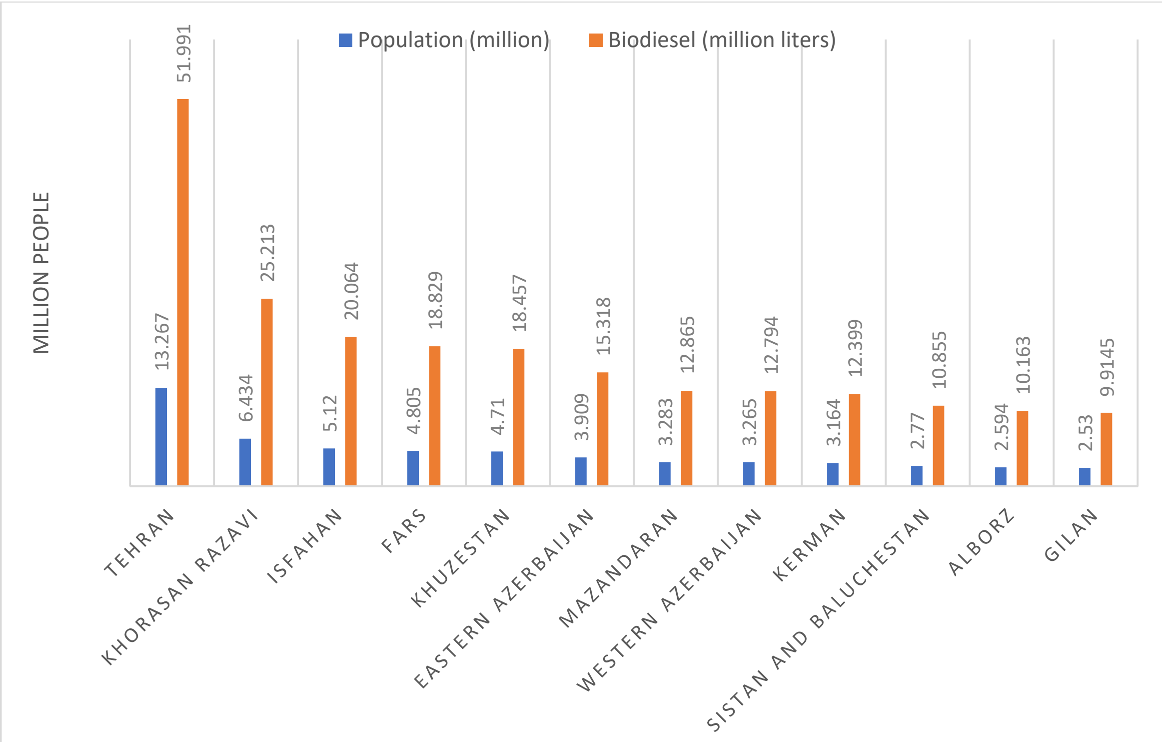


Figure 1. Amount of biodiesel produced from the primary lipid sludge of municipal wastewater for provinces with a population of more than two million people.

3.1.2. The Potential of Biodiesel Production from Waste Cooking Oils in Iran

Taking into account Iran's 82 million population and above-mentioned fact that the oil con sumption per capita in Iran is 20 kg annually, Iran would require an estimated amount of 1,640,000 tons of edible oil annually. Chen et al. presented a model to analyze waste production in China which is presented in Equation (1). The annual amount of Waste Oil Fats (WOF) that can be collected is expressed as follows: [24].

$$WOF_t = (P_t)\left(1 + \frac{U_t}{100}\right)(W_t) \quad (1)$$

where WOF_t, presents WOF produced in year t, P_t denote population in year t, U_t is urbanization rate in year t, W_t is waste oil production per capita (kg/person) in year t. According to the statistics of the edible oil residue amount collected in 2009, and the population of approximately 72 million people in 2009, the production of residual oil per capita is 6041 kg per person. Given the urbanization rate (the urbanization rate for Iran in 2010–2015 was 2.07%), and considering Iran's population (82.35 million) in 2019, using Equation (1), the amount of WOF produced in 2019 is estimated to be 507,800.93 tons. Given the conversion efficiency of edible waste oil to biodiesel through the process of transesterification is 98% [25], and regarding Equation (1), produced biodiesel from edible waste oil is calculated 497.6 Mt (565.51 million liters). Figure 2 presents the production rate of biodiesel from edible waste oils for provinces with a population of more than two million. Most of the produced biodiesel belongs to Tehran, Khorasan Razavi, and Isfahan provinces, respectively. In this regard, it should be mentioned that due to the lack of accurate databases, amounts of edible waste produced from restaurants, hotels, caterers and self-service centers of military, cultural and industrial centers are not considered.

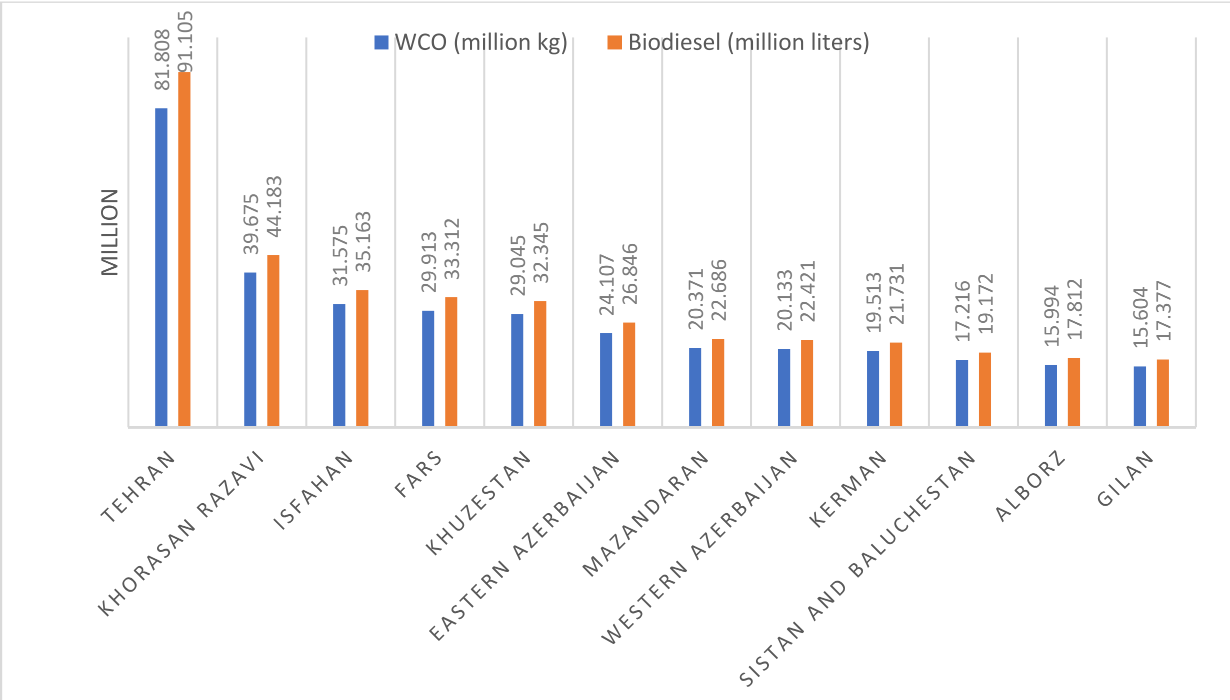


Figure 2. The production rate of biodiesel from edible waste oils for provinces with a population of more than two million.

3.1.3. The Potential of Biodiesel Production from Poultry Waste in Iran

The weight of live poultry for this number of active broilers is approximately 2,540,000 tons. For poultry, 41.4% of its total weight is not consumed and is slaughter waste (the weight of poultry is estimated to be 1.8 to 1.9 kg before slaughter), 12% of this slaughter waste is fat [26]. Taking into account that the conversion efficiency of fat to biodiesel through the process of transesterification that is 98%, and considering poultry weight (2540 thousand tons), and poultry waste of its total weight (41.4%), as well as residual fat content (12%), the biodiesel amount that can be produced from poultry waste is calculated to be 123 Mt (139.77 million liters). Table 2 presents the biodiesel production of poultry waste from provinces with an annual capacity of more than 90,000 tons. Most of the biodiesel produced from chicken waste belongs to Mazandaran, Golestan, and Khorasan Razavi provinces, respectively.

Table 2. The biodiesel production of poultry waste from provinces with an annual capacity of more than 90,000 tons.

Province	Broiler Chicken (Ton)	Biodiesel (Million Liters)
Mazandaran	317,234	17.55
Golestan	230,485	12.75
Khorasan Razavi	200,238	11.07
Gilan	190,818	10.55
Isfahan	176,246	9.75
Fars	167,201	9.25
Kurdistan	99,665	5.51
Eastern Azerbaijan	953,321	5.27
Khuzestan	92,654	5.12
Western Azerbaijan	91,980	5.09

3.1.4. The Potential of Biodiesel Production from Animal Waste in Iran

The number of slaughterhouses in Iran has been reported at 385 units in 2015, in which 476,000 tons of livestock being slaughtered. The fat content of cows, sheep, and goats is considered 32.67, 0.5 and 0.3 kg, respectively [27]. The carcass weight of slaughtered sheep, goats, cows, buffaloes and camels was 184, 37, 245, 5 and 5 thousand tons, respectively. And the average weight of each sheep, goat, cow, buffalo, and camel was 19.75, 14.6, 191.8, 170.27 and 206.6 kg, respectively. Therefore, given the amount of fat, carcass weight, and the weight of each cattle, the annual production of fat from livestock in Iran can be estimated at 0.42 million tons. It should be noted that due to the lack of accurate statistics, the amount of camel and cow fat is considered equivalent to fat content of a cow. Due to the high conversion efficiency of fat to biodiesel about 98% through the process of transesterification 416 Mt (472.72 million liters) of biodiesel is produced from animal fat. Figure 3 presents the five major Iranian provinces producing biodiesel from animal waste.

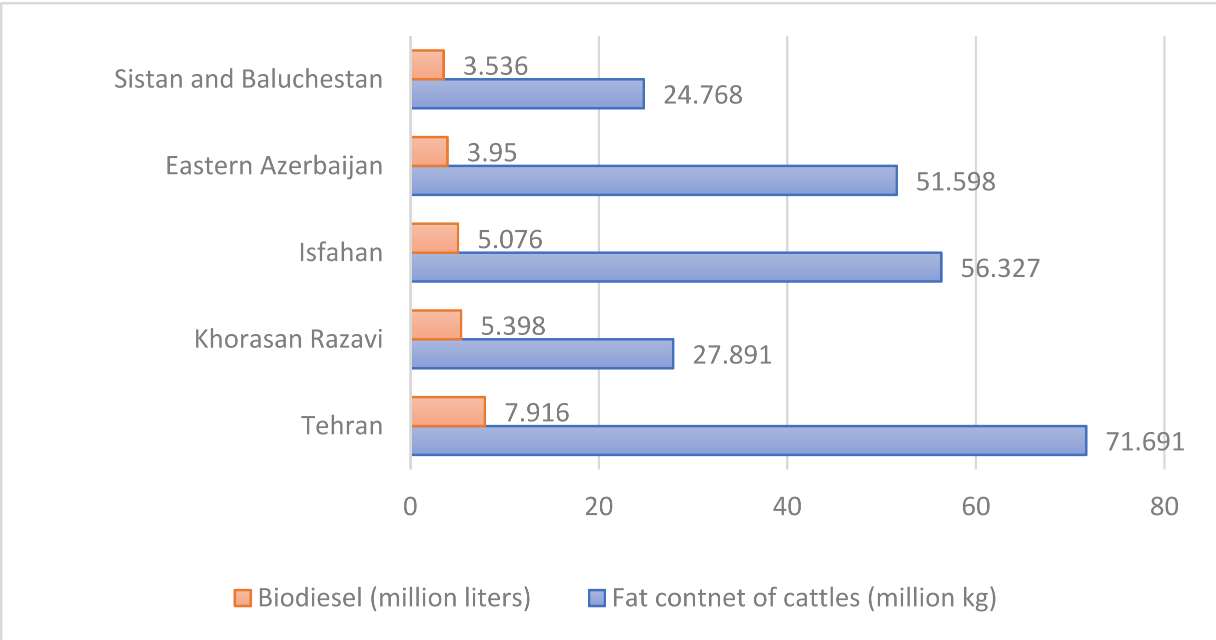


Figure 3. Animal waste is used to make biodiesel in five main Iranian provinces.

3.1.5. The Potential of Biodiesel Production from Fish Waste in Iran

The fishing and aquaculture rate in Iran is 1,093,719 tons annually that can be considered as a suitable source for biodiesel production. Generally, the fat content of fish waste is 50% [28]. If the conversion of animal fat to biodiesel is considered 98% [29], 213.6 Mt (242.72 million liters) of biodiesel from fish waste will be produced. Table 3 presents the amount of biodiesel produced from fish waste in Iran. According to Table 3, the highest biodiesel production from fishing is in Sistan and Baluchestan (55.69 million liters) and Hormozgan (53.89 million liters) provinces. Mazandaran, Khuzestan, and Gilan provinces have the highest share of biodiesel production in aquaculture. Generally, biodiesel production from fishing and aquaculture resources has the highest potential in Sistan and Baluchestan (58.52 million liters), Hormozgan (56.82 million liters) and Khuzestan (27.55 million liters), respectively.

Table 3. The amount of biodiesel produced from fish waste in Iran.

Province	Section	Fishery and Aquaculture Rates (Ton)	Biodiesel (Million Liters)
Sistan and Baluchestan	Fishery	250,044	55.69
	Aquaculture	12,702	2.829
	Total	262,746	58.52
Hormozgan	Fishery	241,972	53.89
	Aquaculture	13,148	2.92
	Total	255,120	56.82
Khuzestan	Fishery	47,788	10.64
	Aquaculture	75,919	16.90
	Total	123,707	27.55
Mazandaran	Fishery	19,357	4.31
	Aquaculture	76,703	17.08
	Total	96,060	21.39
Gilan	Fishery	13,288	2.95
	Aquaculture	51,939	11.56
	Total	65,227	14.52
Bushehr	Fishery	60,988	13.58
	Aquaculture	11,217	2.49
	Total	72,205	16.08
Lorestan	Fishery	0	0
	Aquaculture	27,178	6.05
	Total	27,178	6.05
Golestan	Fishery	751	0.16
	Aquaculture	20,946	4.66
	Total	21,697	4.83
Kermanshah	Fishery	0	0
	Aquaculture	16,148	3.59
	Total	16,148	3.59
Western Azerbaijan	Fishery	0	0
	Aquaculture	14,319	3.19
	Total	14,319	3.19

3.1.6. The Potential of Biodiesel Production from Microalgae

The southern coast of Iran extends for 2437 km along the Persian Gulf to the Oman Sea, providing suitable areas for microalgae cultivation [30]. Recently, more than 347 species of algae have been identified on the southern coast of Iran [31]. In Khuzestan and Hormozgan provinces, there are 5 and 23 suitable locations for algae cultivation, respectively. According to feasibility studies, the southern coast of Iran has a production potential for 540,000 tons of algae annually. Green algae contain more than 50 wt. % of fat [32]. Using the following equation, the yield of biocrude oil produced by the HTL process can be calculated [33]:

$$Y = B\,(0.5638\,L + 0.2106) \quad (2)$$

Here Y, B and L represent the yields of biocrude oil, algae biomass, and algae lipid fraction, respectively. Using this equation, 265,950 thousand tons of biomass was obtained from algae. The biodiesel yield of Botryococcus microalgae using two-step transesterification is more than 84%. The main fatty acid of biodiesel contains 27.3% of methyl palmitate, 18.7% of methyl oleate, 18.6% of methyl elaidate, and 7% of methyl stearate [34]. Botryococcus algae could be a viable option for the biofuel industry in the future [35]. Therefore, with the given conversion efficiency of Botryococcus microalgae into biodiesel 224 Mt (254.54 million liters) of biodiesel can be made from microalgae.

3.1.7. The Potential of Biodiesel Production from Macroalgae

More than 20,000 hectares of Anzali Wetland in Iran are full of Azolla. Steps of converting Azolla to biodiesel are such as lipid extraction, hydrothermal treatment, hydrothermal liquefaction, and the pyrolysis process. The annual production of Azolla bio-oil through pyrolysis and HTL-based processes are 13.2 and 20.2 tons per hectare, respectively. Moreover, it is also anticipated that the annual lipid production of Azolla is 1.68 tons per hectare which will be increased to 82 tons per hectare if the plant grows under normal situations. The efficiency of this oil was dramatically higher than soybean (0.44 tons per hectare), sunflower (0.78 tons per hectare), rapeseed (1.17 tons per hectare), and palm oil (6.0 tons per hectare). However, it is lower than the productivity of microalgae (up to 73 tons per hectare for Nannochloropsis sp.) [36]. Therefore, considering the biodiesel yield of algae which is 84% [34], and taking into account the amount of Azolla lipid (8 tons per hectare) [36] and the area covered by the Anzali Wetland (20,000 hectares), biodiesel production from Azolla would be 134.4 Mt (152.72 million liters).

3.2. Selecting the Best Location for Establishing the Biodiesel Factory

Many studies were analyzed to find out the right determining factors in choosing the best location for the biodiesel production plant. In the end, a combination of factors has been extracted from the text and tables of the papers, which are summarized in Table 4.

Table 4. A comprehensive framework of criteria to evaluate technologies converting biomass into biofuels.

Category	Criteria	Definition	Reference
Technical	Biomass resource availability	The number of required biomass sources for each technology	[37–39]
Economic	Investment cost	The cost of the initial investment such as buying equipment	[38–44]
Environmental	Land use	Land used for biomass production	[45–47]
Social	Job creation	The manpower required for the use of technology	[37,42,48]

Moreover, the southern area (Hormozgan province), southwest area (Khuzestan and Bushehr provinces), and northern area (Tehran, Gilan, and Alborz provinces) as three under evaluation areas were selected because of their high potential for accessing to the raw materials and the short distances petrochemical plants (Figure 4).

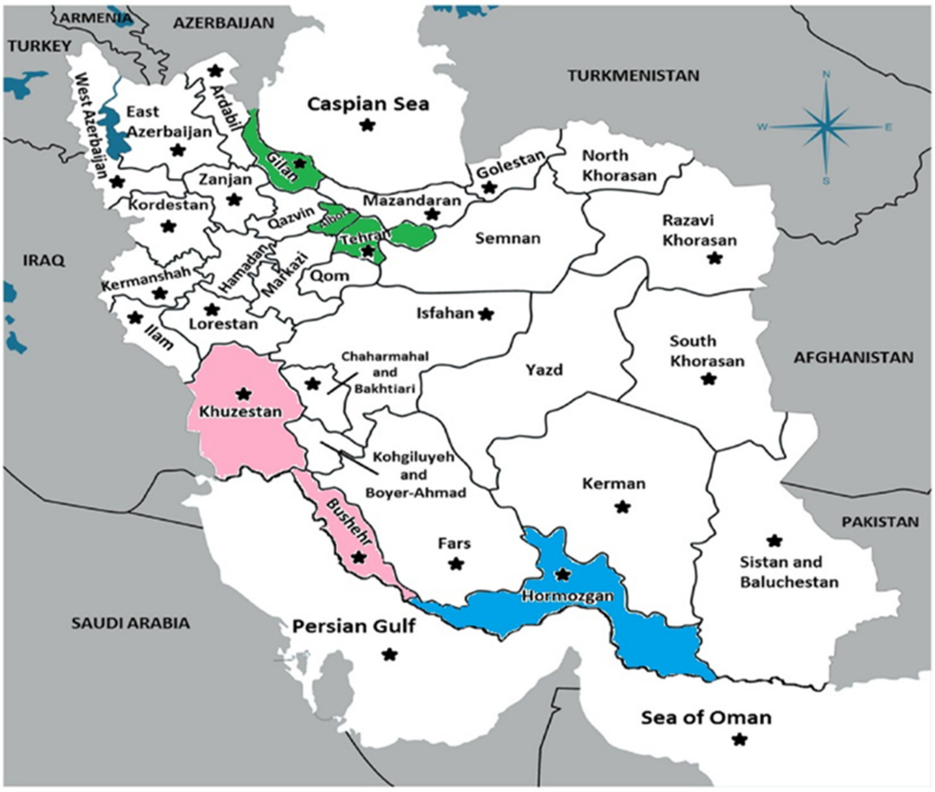


Figure 4. High potential areas nominated for establishing the biodiesel plant in Iran.

After introducing the target, indicators, and options, it is needed to utilize the analytic hierarchy tree (AHT). The extracted AHT for this study has been illustrated in Figure 5.

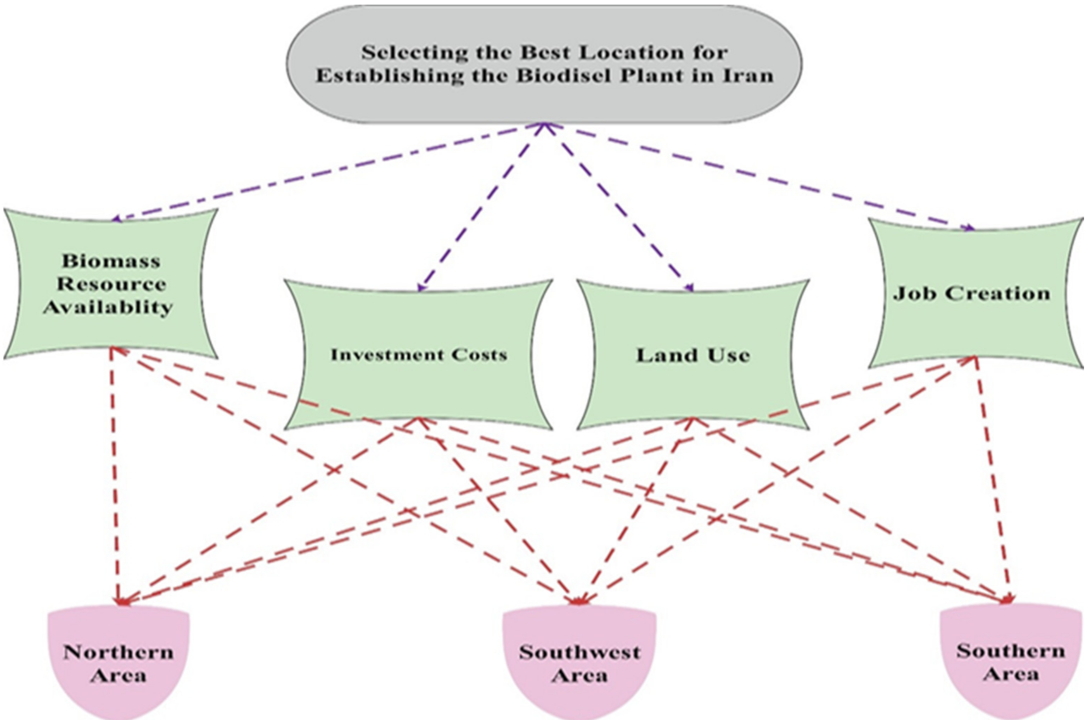


Figure 5. The analytic hierarchy tree (AHT) for selecting the best area for establishing the biodiesel plant in Iran.

3.2.1. Pair Comparison between Parameters and Targets

The steps of AHP are explained below. To pair comparison between parameters and targets, it is needed to perform the parameters pair comparison matrix (A) [49]. In order to assess the weight of the criteria, the following paired comparison matrix was created (Equation (3),

$$A = (P_{ij})_{n \times n} = \begin{pmatrix} P_{11} & P_{12} \cdots & P_{1n} \\ \vdots & \vdots & \vdots \\ P_{n1} & P_{n2} \cdots & P_{nn} \end{pmatrix} \tag{3}$$

where P_{ij} represents the relative significance of Factor i in comparison with Factor j, which is determined using a pairwise comparison method. For pairwise comparison, we used the measured values of the 9 quantities shown in Table 5.

Table 5. Comparative comparison of indicators [49].

Absolute Importance	Very High Importance	High Importance	Weak Importance	Same Importance
9	7	5	3	1
2, 4, 6 and 8 are the fundamental values				

The pair comparison matrix has been reported in Table 6. After providing the pair comparison matrix (A), it is needed to compare the weights of indicators.

Table 6. The pair comparison matrix (A).

	Biomass Resource Availability	Land Use	Investment Cost	Job Creation
Biomass resource availability	1	5	3	7
Land use	0.2	1	1	3
Investment cost	0.333	1	1	3
Job creation	0.143	0.333	0.333	1

The mentioned comparison is carried out by arithmetic average and geometric mean, total row, and column method, ordinary least squares technique and minimum logarithmic squares methods. In current investigation, the arithmetic average method is utilized to compare between weights of indicators. The normalization of columns is applied to find the weight of each indicator. The elements of matrix A were normalized using Equation (4) [50]. The normalized values of each indicator have been listed in Table 7.

$$P_{ij}^{*} = \frac{Pij}{\sum_{j=1}^{n} Pkj} \; \forall \; i\&j = 1, 2, \ldots n \tag{4}$$

Table 7. The normalized values of indicators.

	Biomass Resource Availability	Land Use	Investment Cost	Job Creation
Biomass resource availability	0.5966587	0.6818492	0.5625352	0.5
Land use	0.1193317	0.1363698	0.1875117	0.2142857
Investment cost	0.1986874	0.1363698	0.1875117	0.2142857
Job creation	0.0853222	0.0454112	0.0624414	0.0714286

To obtain the relative importance of each criterion (W_i^*), Equation (5) was applied.

$$W_i^* = \sum_{j=1}^{n} P_{ij}^* \;\; \forall \; i = 1, 2, \ldots n \tag{5}$$

These values are presented in Table 8. To determine the incompatibility rate (IR) of each indicator it is needed to calculate the weight summation vector (W_i) and the compatibility vector (CV). The criteria weight summation vector, was calculated using Equation (6):

$$w_i = \frac{W_i^*}{\sum_{k=1}^{n} W_k^*} = \forall \; i = 1, 2, \ldots n \tag{6}$$

Table 8. Values of W_i^* for each indicator.

Indicator	W_i^*
Biomass resource availability	0.5852608
Land use	0.1643748
Investment cost	0.1842137
Job creation	0.0661508

Compatibility vector is determined by the result of dividing by W_i to W_i^*. Table 9 show the values of CV [36]. Another parameter that needs to be calculated is the Inconsistency Index ($I.I$). This parameter is determined by Equation (7) in which λ_{max} is the arithmetic average of each element in the CV and n shows the number of indicators [49]. The Inconsistency Ratio (IR) of each indicator is determined by Equation (8). In this equation, the IIR means the Inconsistency Index of Random that has been indicated for each indicator based on Table 10 [49]. According to the above equation, The Inconsistency Ratio (IR) is equal to 0.01899, which is less than 0.1, so there is consistency in pairwise comparisons (no need to revise pairwise comparisons).

$$I.I = \frac{\lambda_{max} - n}{n - 1} \tag{7}$$

$$IR = \frac{I.I}{IIR} \tag{8}$$

Table 9. Values W_i of and CV for each indicator.

Indicator	W_i	CV
Biomass resource availability	2.42	4.13
Land use	0.663	4.04
Investment cost	0.741	4.02
Job creation	0.265	4.01

Table 10. The Inconsistency Index of Random.

n	1	2	3	4	5	6	7	8	9	10
IIR	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

3.2.2. Pair Comparison between Options and Indicators

The problem of the current study consists of three options and four indicators that need to provide a 3 × 4 pair comparison matrix [49]. Table 11 provides a pair comparison and IIR index for each indicator. To find the best area based on the AHP method, it is needed to calculate the final weight of any option (V). To determine the mentioned factor, Equation (9) is applied to each indicator. Regarding Equation (9), the final weight (V) of each area is calculated by multiplying the comparative weight matrix of options (W_k) by weight matrix of indicators (W_i^*) [49]. This calculation has been showed in Equation (9) as following:

$$V = \frac{W_i^*}{\sum_{k=1}^{n} W_k} = \forall\, i = 1, 2, \ldots n \tag{9}$$

Table 11. The pair comparison and IR for each indicator.

Pair Comparison for Biomass Resource Availability Indicator				
	Southern area	South west area	Northern area	Weight (W_k)
Southern area	1	3	2	0.549
South west area	.033	1	1	0.210
Northern area	0.50	1	1	0.241
IR		0.017		
Pair Comparison forLand UseIndicator				
	Southern area	South west area	Northern area	Weight (W_k)
Southern area	1	5	9	0.748
South west area	0.2	1	3	0.180
Northern area	0.11	0.33	1	0.071
IR		0.027		
Pair Comparison forInvestment CostIndicator				
	Southern area	South west area	Northern area	Weight (W_k)
Southern area	1	7	7	0.767
South west area	0.143	1	2	0.143
Northern area	0.143	0.5	1	0.090
IR		0.051		
Pair Comparison forJob CreationIndicator				
	Southern area	South west area	Northern area	Weight (W_k)
Southern area	1	0.33	4	0.274
South west area	3	1	6	0.639
Northern area	0.25	0.17	1	0.087
IR		0.051		

Based on this equation the final weights of nominated areas are measured and according to the final result, the highest value of this parameter demonstrates the best location for establishing the plant. Based on the calculations, and the final weights of nominated areas, the southern area of Iran has the highest weight (0.604). As a result, based on the AHP method, the southern area of Iran is the best location for establishing the multi-feed biodiesel plant in comparison to other nominated areas.

3.3. Processes Description

3.3.1. Biodiesel Production Process from Sewage Sludge

In this section, a biodiesel plant with an annual production capacity of 5683 tons of biodiesel from sewage sludge is investigated. To this end, an urban wastewater treatment plant (WWTP) is considered for feeding raw sewage sludge into the biodiesel plant. This eliminates the costs of transportation of raw sludge to the biodiesel plant. The goal of the proposed process is to improve biodiesel production from sewage sludge by eliminating the sludge water removal (highly energy-consuming), drying, and heating processes in the lipid extraction process. A mix of M-palmitate and M-oleate was chosen to show the biodiesel product. Also, palmitic acid representing the content of FFA, triolein representing the glycerides, and saturated fatty acid ester representing the non-saponifiable lipids (palmitate ester) were chosen. The reason for choosing palmitic acid is the presence of this acid in sludge lipids and consequently in the produced biodiesel.

In order to anticipate the physical and chemical properties of the chemical components (for instance, high-density solutions containing 95% of sulfuric acid) [51,52]., the PRSV equation of state was used as the thermodynamic fluid package. The Peng-Robinson versions are the best options for assessing the vapor-liquid equilibrium of common and uncommon liquid solutions [53]. Using the PRSV allows for a precise prediction of the properties of relatively non-ideal systems. In addition, it is used to finely separate the aqueous systems containing methanol and glycols, as well as hydrocarbons in the second liquid phases. The process simulation is run in two stages using the existing technologies. In the first stage, lipids are extracted from the liquid raw sludge (containing 96% of water) and the second stage involves the acid-catalyzed esterification/transesterification process. In the following section, both stages will be explained in detail.

Lipid Extraction from Liquid Primary Sludge

The primary sludge is mixed with acid before extraction and then lipid is extracted using continuous stirred-tank reactors (CSTR-reactor I, II). Hexane was used as a solvent in the countercurrent system (Figure 6). The operational data was borrowed from the test results of [51]. In order to determine the optimized number of stages (number of trays) to achieve the most economically efficient results, different items such as the sludge PH, residence time in the extraction stage, and the sludge to hexane ratio (depending on the amount of hexane consumed) are modeled.

In this study, the feedstock solvent and extraction solvent flow rates are assumed unchanged and the concentration of solutes are given as the weight ratios of the solute to the feed solvent, extraction solvent in the raffinate and the extract phases, respectively. The raffinate phase is comprised of the remaining biomass and over 96% of water which can be recycled in the WWTP to eventually be used as a substrate for biogas production by anaerobic digestion. This process is widely used in urban WWTPs to prevent new waste sludge. As shown earlier, extracted sludge is easily digested anaerobically with the remaining lipids, producing biogas that preserves a similar composition, meaning methane content (from the excess raw sludge) [51]. Moreover, the extract is sent to an equilibrium-flash separator (Separation Tower II) in which over 99% of the hexane is recovered and will be recycled in the extraction unit.

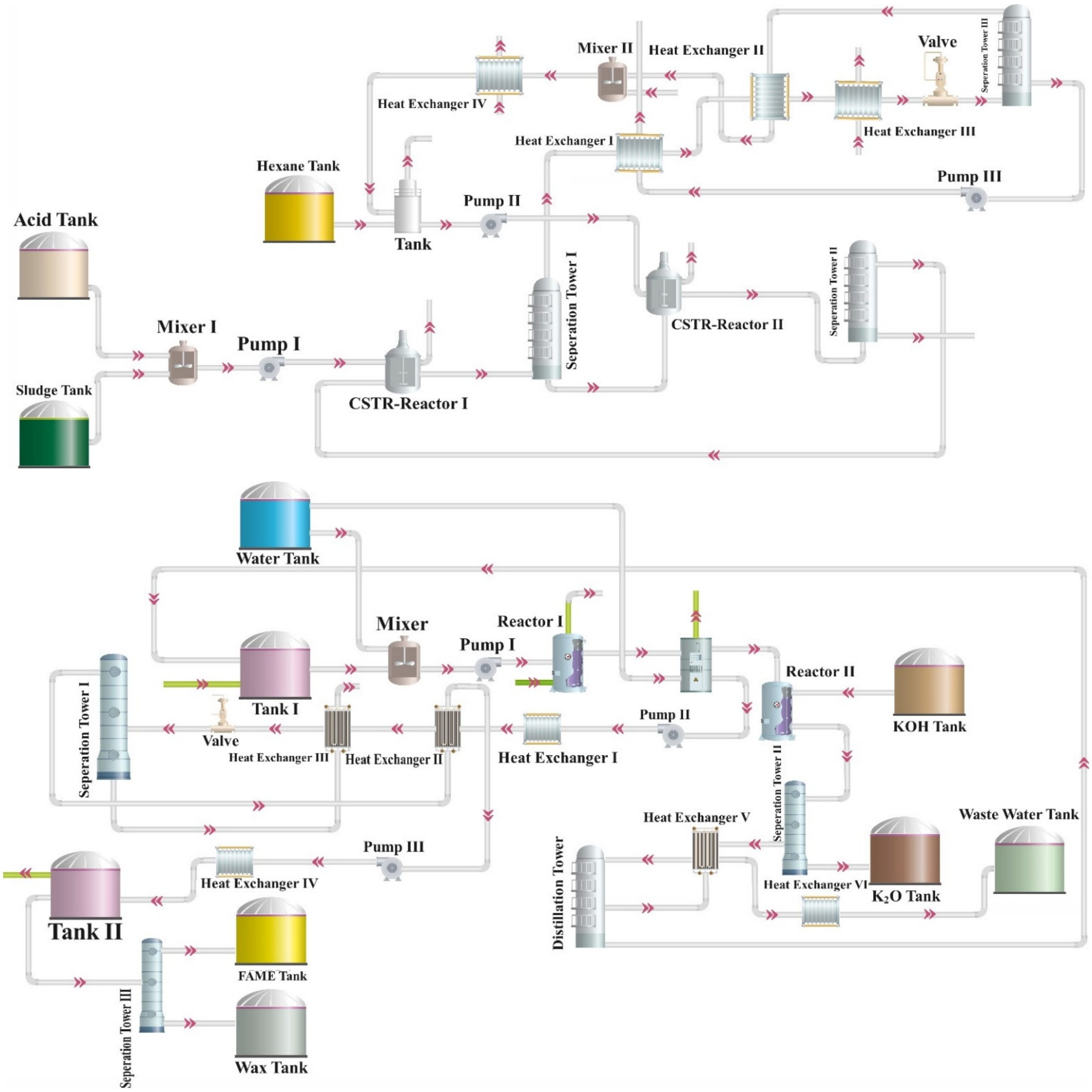


Figure 6. Biodiesel production unit simulation feed by municipal wastewater sludge [54].

Biodiesel Production

An acid-catalyzed reaction system was proposed for the production of FAME using methanol as a reactant. In Reactor I, two reactions occur. In the first section, which is the acid esterification of the FFA, FAME, and water are produced. In the second reaction, which is the acid transesterification reaction of triglycerides, FAME and glycerol are produced. The product flow is sent to the Decanter where they are separated by a two-phase water wash. The light phase was used to remove hexane and methanol from the biodiesel produced. The heavy phase involves water, methanol, a small amount of glycerol (as a byproduct of the transesterification process), and the acid used as a catalyst. In order to recover the methanol, the heavy phase is neutralized in Reactor II by adding potassium hydroxide. The valuable byproduct of this reaction is potassium sulfate.

Then, the neutralized stream is sent to Distillation Tower II where 79% of methanol is recovered there. Since the produced biodiesel contains non-saponifiable lipids, we use a slight crystallization process to break the biodiesel into a fluid with a low melting point and a solid part with a high melting point (e.g., sterols and/or waxes) to obtain FAME with over 98% of density. In particular, traditional crystallization has two stages. The first stage involves crystallization under a totally controlled cooling rate with slight agitation and the second stage includes separation with filtration.

3.3.1.3. Biodiesel Production Process from Edible Oil Waste and Animal Fat

In this part of the supercritical two-stage technique, methanol was used without a catalyst to produce biodiesel from WCO. The scheme of the mentioned plant has been depicted in Figure 7 [25]. Salehi et al. [25] used RK-ASPEN thermodynamic model to determine the coefficients of the material activity in the liquid phase. Among the advantages of this method are the elimination of catalysts, elimination of separation and neutralization units, and the significant time decrease in the reaction time. These benefits led to a reduction in the production cost, but it also has drawbacks such as toxicity and high energy consumption. The simulation of the above-mentioned process is as follows.

First, triolein (feedstock: waste cooking oil) and water are mixed with a water-to-oil molar ratio of 20:1, and then the mixture is compacted to 17 atm. It is then sent to the Heat Exchanger II to reach a temperature of 270 °C. The output stream is then relocated from the Heat Exchanger II to the hydrolysis reactor (Reactor I) where triolein is converted to oleic acid through a hydrolysis reaction. Methanol (methanol-to-oil molar ratio of 20:1) is heated in Heat Exchanger II to 270 °C and then is compacted to 27 atm. In the next stage, this stream is mixed with Reactor I output stream and is sent to the esterification reactor (Reactor II). Due to the esterification reaction, 98% of oleic acid is converted to FAME. The esterification reactor output is sent to Distillation Tower I with six theoretical stages and a reflux ratio of 2. Biodiesel with 98.47 wt. % is obtained from the upper part of the tower. In order to obtain glycerol with high purity, the lower stream of Distillation Tower I is sent to Distillation Tower II. The number of theoretical stages and the reflux ratio of this tower is similar to Distillation Tower I. Glycerol with 99.40 wt. % is obtained for the lower part of this tower. Furthermore, the upper stream of this tower is sent to the separation tower to recycle the methanol and water.

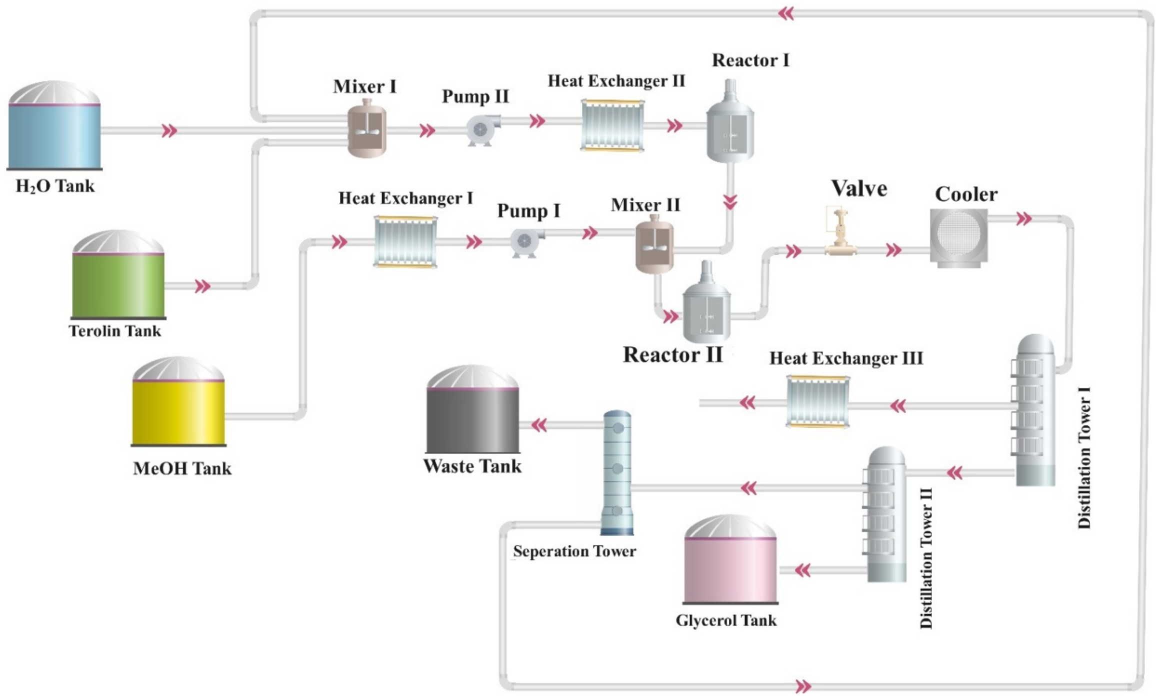


Figure 7. Biodiesel Production Process from Edible Oil Waste and Animal Fat [25].

3.3.1.4. Biodiesel Production Process from Microalgae

An industrial source that emits flue gas (such as a power plant) can be employed to separate CO_2 from the flue gas and to improve algae growth for biodiesel production.

An alternative process for diesel production using algae cultivation is investigated in this section and its technical and economic feasibility is examined. This system constitutes two main sections. The first section (upstream process) is aimed at separating the CO_2, cultivating algae, and producing lipids. The second section (downstream process) includes several steps including lipid pretreatment, transesterification, separation, and biodiesel synthesis.

Feedstock Composition

The algae species selected for cultivation should have certain properties so that the flue gas can be used as a CO_2 source. A number of species were found to meet the criteria for using flue gas to grow them. One is Chlorella, a single-cell green alga. The dry weight of the Chlorella oil is usually between 28% and 32% [55] but may reach to as high as 55% if grown heterotrophically [56]. Due to reasons such as potential ease of use and available data for its growth, harvesting, and extraction, Chlorella is selected for this simulation. The assumed wt. % of FFA content is 0.05 so there is no need for the pretreatment stage. In this study, the temperature is set at 60° Celsius, methanol is used as alcohol, NaOH acts as a catalyst, and the methanol-to-oil molar ratio is set at 6:1. Also, NRTL and RK-Soave thermodynamic models are utilized in the simulation

FAME and Glycerol Separation

Sodium hydroxide with 1 wt. %, methanol, and algae oil (99.95 wt. %) are fed into Reactor I. In order to maximize the efficiency, two transesterification reactions are employed. The transesterification products, which include fatty acid methyl esters (FAME) and glycerol, are cooled from 60 °C to 33.3 °C in Reactor I and then are pumped into Decanter I where FAME and byproducts are separated (Figure 8). The biodiesel and glycerol produced in Reactor II undergo a more intensive separation process in Decanter II. Because of the unmixability of the biodiesel and glycerol and the gravity difference, they are separated at a temperature lower than the reaction temperature and atmospheric pressure. Since the glycerol phase is much heavier than the biodiesel phase, they can be separated with the help of gravity (glycerol is deposited in the bottom of the pot).

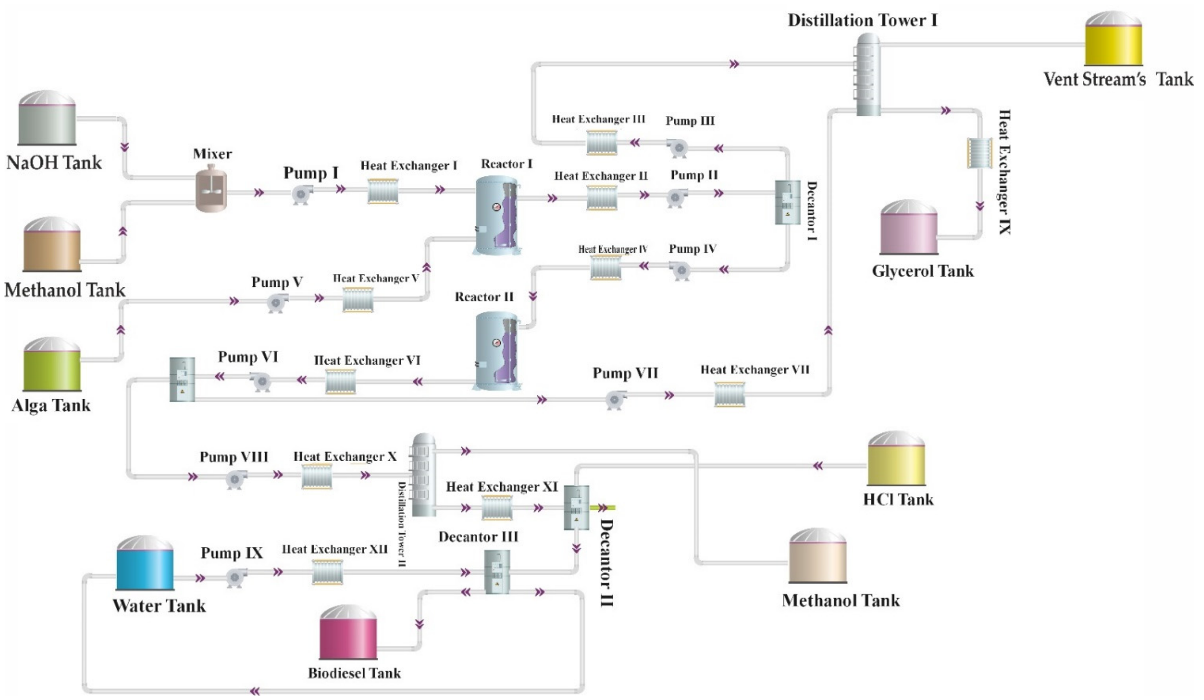


Figure 8. Simulation of a biodiesel production unit from microalgae [57].

Methanol Recovery

Biodiesel constitutes the major part of light products, which is separated in Decanter II, heated up to 60 °C and then sent to Distillation Tower II with theoretical stages of 6, a total condenser, and a kettle reboiler so that methanol can be separated from biodiesel phase through the overhead as vapor and recycled. The reflux ratio is considered 1.5 in order to achieve a satisfactory separation of methanol and other components.

Alkali Removal

The end effluents from Distillation Tower II are cooled down to 25 °C and then are sent to Decanter III to neutralize the excess sodium hydroxide with hydrogen chloride. Hydrogen chloride is added to remove the residual sodium hydroxide catalyst and destroy any soap that might have been formed through the reverse saponification reaction. By neutralizing the stream before the water wash stage we can lower the water consumption for biodiesel purification and minimize the possibility of emulsion formation when adding washing water to the biodiesel.

Water Washing (FAME Purification)

After being separated from other components (such as sodium hydroxide and triglyceride), biodiesel is sent to Decanter IV where it undergoes purification by slow washing with warm water and becomes free from any residual catalyst, salt, methanol, free glycerol, and soap. To meet the ASTM D 6751 specifications, the produced biodiesel should have a wt. % of 99.65. The discharging effluents from the water wash process can be recycled.

Glycerol Purification

The glycerol stream is heated to 60 °C after separation in Decanter I and then is sent to Distillation Tower I with five theoretical stages, a total condenser, and a kettle reboiler. The residual biodiesel comes out of the overhead column as vapor and the glycerol comes out through the bottom of the walls and cools down eventually. The produced glycerol can be commercially used as a byproduct.

3.4. Economic Evaluation of the Construction of a Biodiesel Production Plant from Various Types of Waste

In this section, different factors are discussed to evaluate the economic aspect of each process, including fixed investment cost (FIC), total manufacturing cost (TMC), after-tax rate of return (ATROR), and biodiesel break-even point (BEP).

3.4.1. Economic Evaluation of Biodiesel Production from Sludge

Fixed Investment Costs

Biodiesel production from sewage sludge constitutes four stages: 1-extraction (extracting lipid from liquid sludge), 2-recovery (recovering lipids from solvent), 3-reaction (biodiesel synthesis), and 4-purification (biodiesel separation, purification, and catalyst neutralization).

We have updated the results of Magdalena Olkiewicz's study [54] according to the Chemical Engineering Index to estimate the investment and plant construction cost. These results are provided in Tables 12 and 13. Extrapolation of the purchase costs to other capacities and scales is based on the scaling factor rule:

$$\frac{cost\ B}{cost\ A} = \left(\frac{size\ B}{size\ A}\right)^n \quad (10)$$

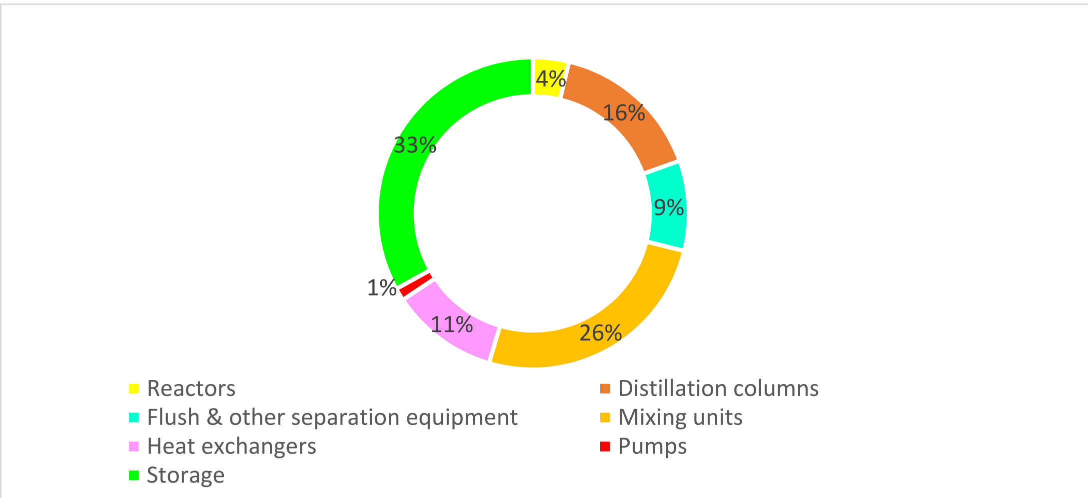
where *cost A* and *cost B* represent the purchase costs of a unit operation with size or capacity *size A* and *size B*. n is the corresponding scaling factor for the equipment. According to Table 12, the total investment cost for the construction of a biodiesel production unit from sewage sludge is $9.86 million. Regarding the total investment cost, the extraction step is responsible for 54 % of the total investment followed by purification, recovery and reaction (Table 12). On the other hand, according to Figure 9a, the largest share of the total investment cost belongs to the cost of tanks (33%), mixer units (26%), respectively. The lowest cost of equipment is for pumps (1%).

Table 12. Total investment costs for the construction of a biodiesel production unit from sewage sludge.

Item	Extraction	Recovery	Reaction	Purification	Total
Land purchase	60,480	8960	8960	33,600	112,000
Site preparation and development	12,096	1792	1792	6720	22,400
Civil works, structures and building	84,672	12,544	12,544	47,040	156,800
total land purchase and civil works	156,816	23,232	23,232	87,120	290,400
Total equipment cost (TEC)	**2,113,998**	**182,918**	**287,587**	**1,110,686**	**3,895,407**
Reactors	0	0	115,569	30,269	145,838
Distillation columns	0	0	0	614,734	614,734
Flush & other separation equipment	234,521	59,690	0	69,752	363,962
Mixing units	887,070	90,752	8996	12,860	999,679
Heat exchangers	0	222,612	0	210,984	433,596
Pumps	24,209	9864	3735	12,800	50,608
Storage	968,198	0	159,287	159,287	1,286,992
Fix. cap. costs (bare, cont. aux.)	3,295,301	595,407	458,672	1,784,313	6,133,693
Auxiliary and service plant, 30% TEC	634,200	54,876	86,277	333,207	1,168,622
Project implementation, 10% TEC	211,400	18,292	28,759	111,069	389,541
Contingencies,18% Civil works, TEC and Auxiliary	522,902	46,985	71,477	275,582	963,797
Working capital	491,505	88,807	68,414	266,136	914,862
Total investment costs	**5,312,124**	**827,599**	**736,831**	**2,857,427**	**9,860,995**

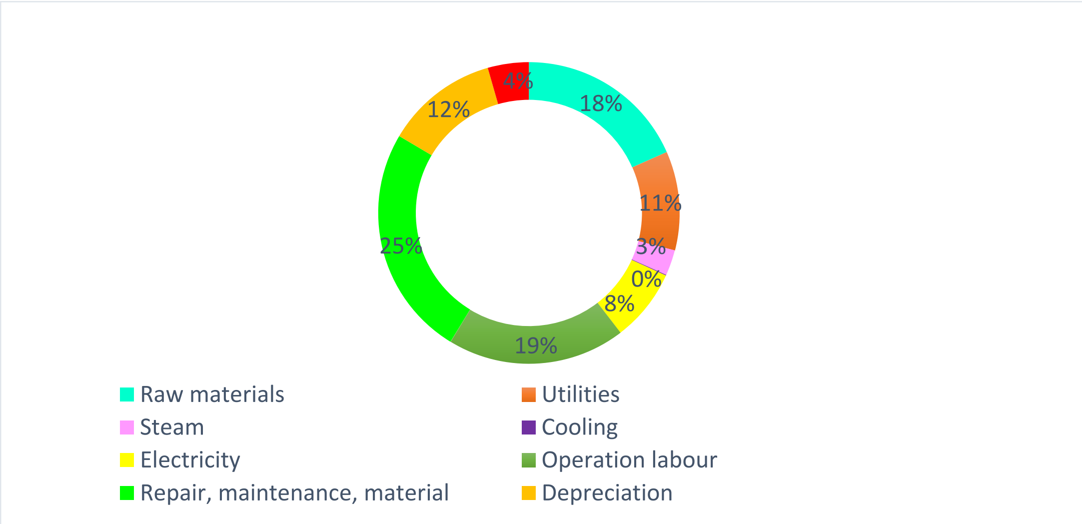
Table 13. Total cost of biodiesel production unit from sewage sludge.

	Extraction	Recovery	Reaction	Purification	Total
Raw materials	251,932	0	290,519	49,557	592,008
Utilities	250,835	41,245	0	49,810	341,890
Steam	0	41,196	0	47,424	88,620
Cooling	0	0	0	2266	2266
Electricity	250,841	0	0	0	250,841
Operation labour	251,101	37,665	144,382	182,047	615,195
Repair, maintenance, material	402,737	56,735	152,625	186,985	799,082
Depreciation	196,329	27,657	74,402	91,153	389,541
Direct manufacturing cost	1,603,775	204,500	661,928	609,242	3,079,443
Overhead	57,753	8663	33,208	41,871	141,495
Total manufacturing costs	**1,661,528**	**213,163**	**695,136**	**651,113**	**3,220,938**
Unit cost of production biodiesel ($/kg)					0.567



(**a**)

Figure 9. *Cont.*



(**b**)

Figure 9. (**a**) The share of each device in the total cost of equipment. (**b**) The share of each item in the total cost of production (unit of sewage sludge).

Total Manufacturing Cost

The total cost of biodiesel production from sewage sludge is presented in Table 13. According to this table the unit cost of biodiesel production is 0.567$ per kg.

With respect to manufacturing cost, the extraction step is also the most expensive, representing 51% of the total, while purification, reaction and recovery account for 23%, 19% and 7%, respectively (Table 13). On the other hand, maintenance costs (25%) and cooling have the highest and lowest share of production costs, respectively (Figure 9b). After maintenance costs (19%), the largest share of production costs belongs to operating costs (18%).

The results of this economic evaluation of biodiesel production from sewage sludge show that the proposed direct lipid extraction from liquid sludge is the costlier stage for investment as well as in terms of process manufacturing. Accordingly, any improvement in the lipid extraction stage will have a dramatic positive effect on the final profitability and consequently on the final price of the produced biodiesel.

3.4.2. Economic Evaluation of Biodiesel Production from Edible Waste Oil

Fixed Investment Costs

The cost of fixed equipment for biodiesel production unit based on the non-catalytic supercritical process was updated by Malkovich et al. [58] and Yan Cao et al. [59] The details are presented in Table 14.

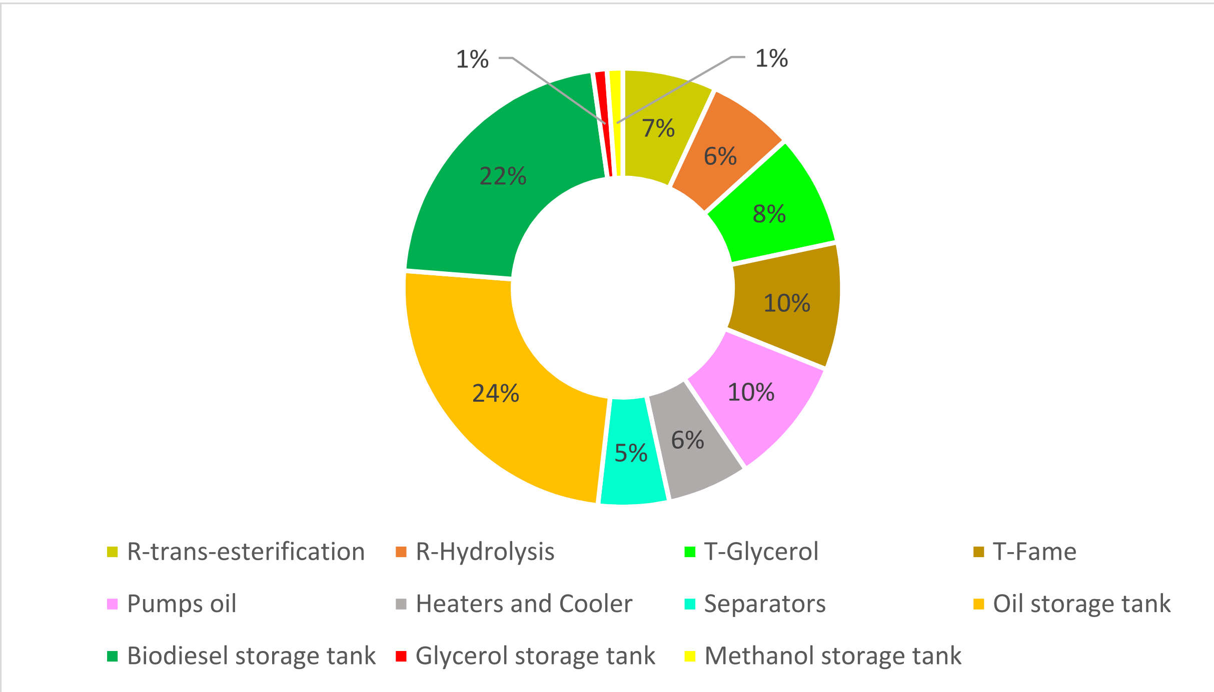
Table 14. Total fixed investment costs ($).

Item	Cost
Land purchase	112,000
Site preparation and development	22,400
Civil works, structures and building	156,800
Total Land purchase, Site preparation and Civil works	290,400
Plant machinery and equipment	
Reactors	319,331
R-trans-esterification	166,036
R-Hydrolysis	153,264
Distillation towers	472,164
T-Glycerol	201,986

Table 14. *Cont.*

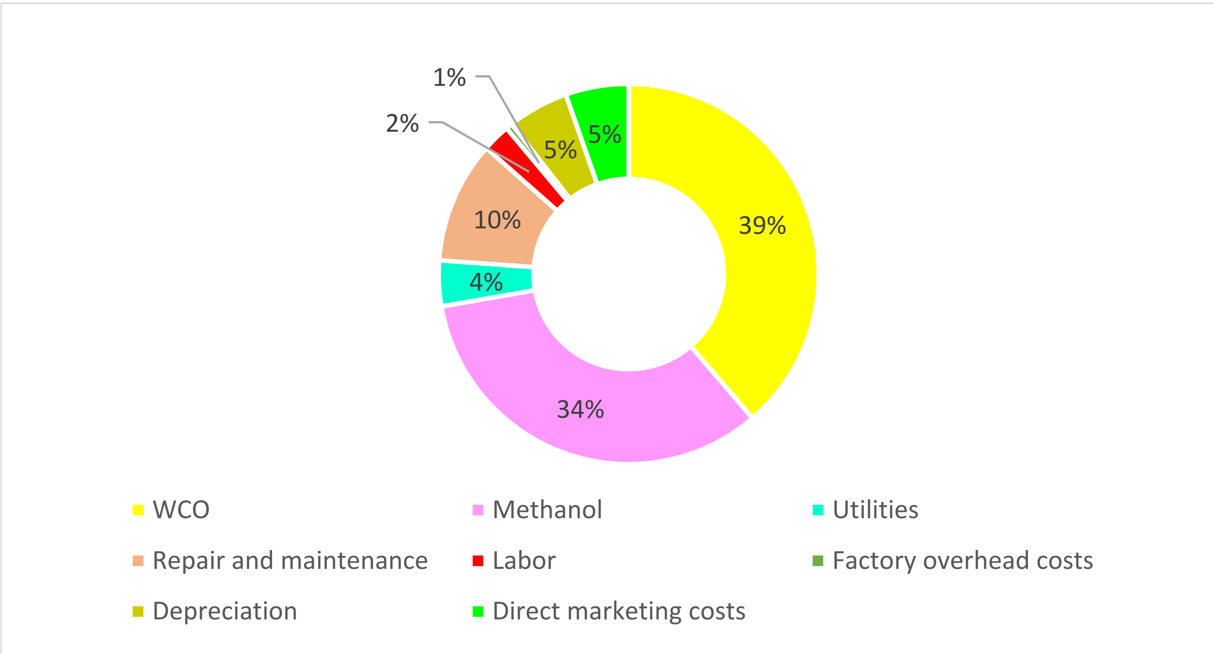
Item	Cost
T-Fame	226,638
Pumps oil	227,095
Heaters and Cooler	145,433
Separators	126,112
Tanks	1,158,787
Oil storage tank	587,265
Biodiesel storage tank	518,195
Glycerol storage tank	25,504
Methanol storage tank	27,823
Total equipment cost (TEC)	**2,739,291**
Auxiliary and service plant, 30% TEC	821,787
Project implementation, 10% TEC	273,929
Contingencies,18% Site preparation, Civil works, TEC and Auxiliary	693,266
Working capital, 15% TEC	410,894
Total fixed investment costs (FIC)	**5,299,567**

Figure 10a shows the share of each equipment in the total cost of purchasing equipment as a percentage. According to this figure, the highest and lowest share of equipment costs are oil storage tanks (24%) and glycerin (1%), respectively. After oil storage tank, the largest share of equipment costs is related to biodiesel storage tank (22%).



(a)

Figure 10. *Cont.*



(**b**)

Figure 10. (**a**) The share of each device in the total cost of equipment. (**b**) The share of each item in the total cost of production (edible waste oil unit).

Total Manufacturing Cost

The flow rate of the raw material and the amount of catalyst, water, and electricity were taken from the results of Salehi's study [25]. These results are shown in Table 15. According to this table, the waste cooking oil cost amounts to $2.044 million which is the highest among the production costs. Therefore, feedstock cost plays the biggest part in the total manufacturing cost. According to Figure 10b and Table 15, methanol cost stands at $1.773 million, which is a big share of the total manufacturing cost compared to other processes. The reason for this is the high molar ratio of methanol to oil.

Table 15. Total manufacturing costs ($).

Item	Cost
WCO [a]	2,043,956
Methanol [b]	1,772,837
H_2O [c]	555 (347.7 kg/h [43])
Utilities [d]	204,692 (1,860,838.6 KW)
Repair and maintenance	547,858
Labor [e]	125,738 (9 Person/d (in 3 shift))
Factory overhead costs (insurance)	28,920
OPERATING COSTS	4,724,001
Depreciation	273,929
TOTAL PRODUCTION COSTS	4,997,930
Direct marketing costs	283,180
Total Manufacturing Costs (TMC)	**5,281,110**
Unit cost of production biodiesel ($/kg)	0.53

[a] 50% of fresh vegetable oil price 0.25 $/kg; [b] 300 $/ton; [c] Assuming 30% waste-water recycle 0.18 $/m^3; [d] 0.018 $/kW; [e] 9240 $/y.

One of the advantages of this process is the non-use of catalysts, which reduces the costs of purchasing catalysts and separation. In Iran, energy and labor prices are comparatively inexpensive. As a consequence, these costs have no significant effect on TMC as shown in Table 15. According to Table 15, the cost of biodiesel production by the non-catalytic two-stage methanol supercritical process method is $0.530/kg.

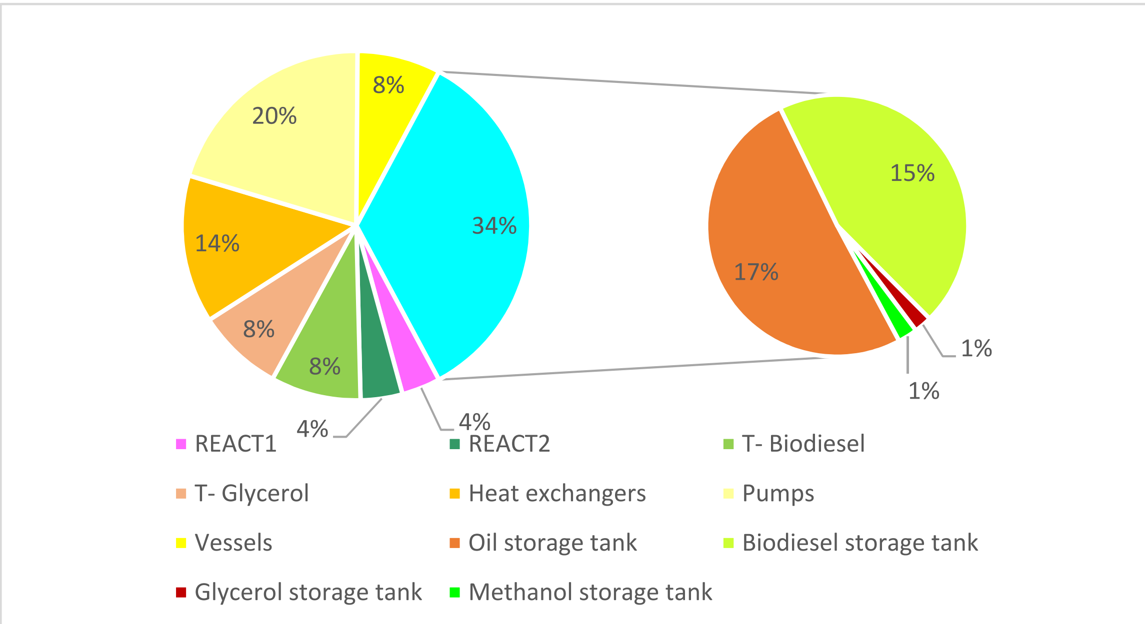
3.4.2.3. Economic Evaluation of Biodiesel Production from Microalgae

Fixed Investment Costs

The scale-up information and capital costs for each unit operation for harvesting and dewatering has been presented in Table 16. According to Table 16, the total investment cost to build a biodiesel production unit from microalgae is $927.68 million. Also, based on Figure 11a, the highest and lowest share of equipment costs are related to pumps (20%) and glycerin storage tank (1%), respectively. After pumps, the largest share of equipment costs belongs to heat exchangers (14%), but it should be noted that the total cost of biodiesel and glycerin towers (16%) is more than the cost of heat exchangers.

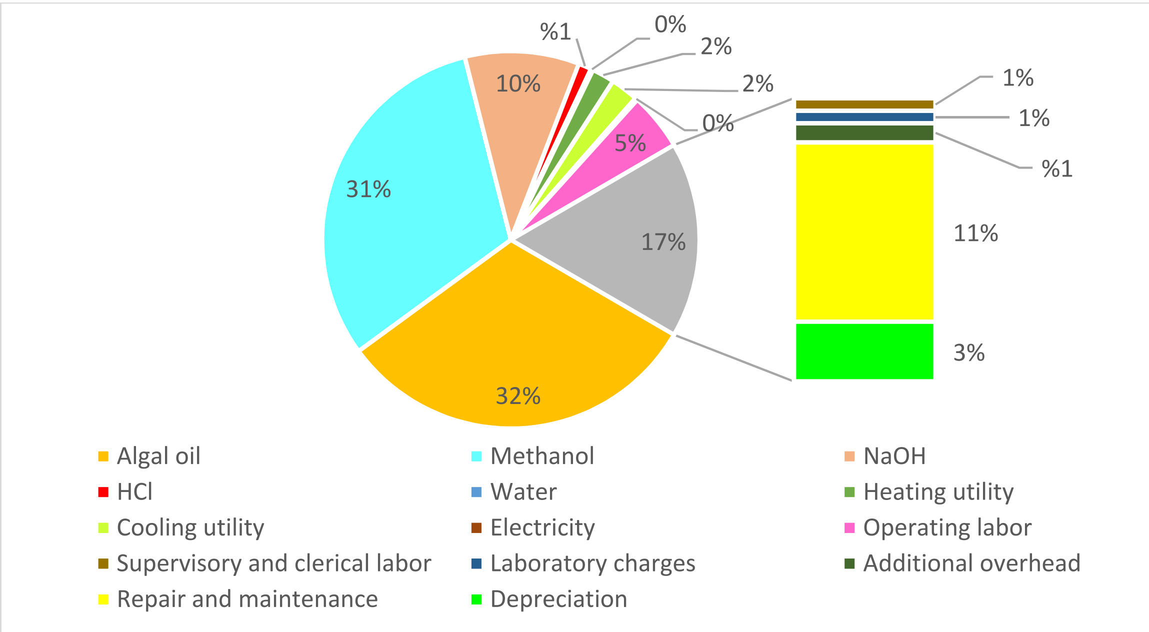
Table 16. Scale-up information and capital costs for each unit operation for harvesting and dewatering.

Item	Cost
Land purchase	2,240,000
Site preparation and development	440,800
Civil works, structures and building	3,211,600
Total land purchase and civil works	5,800,800
Equipment	
REACT1	1,248,051
REACT2	1,341,318
T-Biodiesel	2,901,212
T-Glycerol	2,769,119
Heat exchangers	4,768,350
Pumps	7,112,922
Vessels	2,689,245
Oil storage tank	6,044,349
Biodiesel storage tank	5,339,745
Glycerol storage tank	262,805
Methanol storage tank	286,699
Total equipment cost (TEC)	**34,799,815**
Auxiliary and service plant, 30% TEC	10,439,944
Project implementation, 10% TEC	3,479,981
Contingencies,18% Civil works, TEC and Auxiliary	9,187,301
Working capital, 15% TEC	5,219,972
Total investment costs	**68,927,812**



(**a**)

Figure 11. *Cont.*



(**b**)

Figure 11. (**a**) The share of each device in the total cost of equipment. (**b**) The share of each item in the total cost of production (microalgae unit).

According to Table 16, the total investment cost to build a biodiesel production unit from microalgae is $927.68 million. Also, the highest and lowest share of equipment costs are related to pumps (20%) and glycerin storage tank (1%), respectively (Figure 11a). After pumps, the largest share of equipment costs belongs to heat exchangers (14%), although it should be noted that the total cost of biodiesel and glycerin towers (16%) is more than the cost of heat exchangers.

Total Manufacturing Cost

The feasible outputs and specific energy requirement of unit operations has been reported in Table 17. Based on Table 17, prices for electricity, natural gas, and steam are presumed to be $0.11, $0.044, and $0.055, per KW/h [60], respectively. Labor costs are calculated based on Iran's minimum wage in 2020.

Table 17. Feasible outputs and specific energy requirement of unit operations.

Item	Amount	Cost per Unit ($/unit)	Cost ($)
Algal oil	184,144,433 kg	0.168	31,061,115
Methanol	102,027,219 kg	0.3	30,608,166
NaOH	2,222,659 kg	4.34	9,646,340
HCl	717,987 kg	1.519	1,090,622
Water	64,577m^3	2.891	186,692
Total raw material costs			**72,592,935**
Heating utility	17,376,480 kwh		1,911,413
Cooling utility	21,170,160 kwh		2,328,718
Electricity			201,454
Total Energy costs			**4,441,585**
Operating labor			4,856,008
Supervisory and clerical labor			728,401
Laboratory charges			728,401
Additional overhead			1,116,882
Repair and maintenance			10,439,944
Depreciation			3,479,981
Distribution and selling costs			1,258,144
Total Manufacturing Costs			**99,669,281**
Unit cost of biodiesel ($/kg)			0.543

According to Table 17, the total cost of biodiesel production from microalgae is estimated at \$99.669 million, and the unit cost of biodiesel production is \$0.543 per kilogram. According to Figure 11b, the highest and lowest share of production costs are related to algal costs (32%) and water consumption, respectively. After algae, the largest share of production costs belongs to the purchase costs of methanol (31%) and sodium hydroxide catalyst (10%), respectively.

3.4.3. Break-Even Prices

The break-even price of biodiesel production is calculated based on Equation (11). These values are presented for all units in Table 18. The break-even price of biodiesel production of microalgae unit is lower than other units, which indicates that this unit is more profitable than other units.

$$BEP = \frac{(FIC)(S)}{(S - VC)(PC)} \tag{11}$$

where:

Table 18. Break-even sales analysis for each process.

	Microalgae	Sludge	WCO
Total fixed investment costs	68,927,812	9,860,995	5,299,567
Gross unit price (\$/kg)	0.8	0.8	0.8
unit cost of production biodiesel (\$/kg)	0.543	0.567	0.53
Plant capacity (kg)	183,592,000	5,683,296	9,959,375
Break-even sales (\$/kg)	1.168	5.957	1.576

FIC: Fixed Investment Cost; *S*: Selling price per unit of biodiesel; *VC*: variable cost per unit; *PC*: Capacity Factory.

3.4.4. ATROR

A summary of the economic results of all units is presented in Table 19. According to this table, ATROR biodiesel production units from edible waste oil and microalgae is more than the discount rate in Iran (18%), which indicates the economic justification of these units. In other words, the mentioned units have a good profitability. It should be noted that the biodiesel production unit from sewage sludge has no economic justification for investment due to its lower ATROR in comparison with the discount rate. Among all units, the highest percentage of ATROR belongs to the microalgae unit. In general, biorefinery has a good profit margin, so the construction of biorefinery in Iran has economic justification.

Table 19. A summary of income and costs as well as economic indicators.

	Microalgae	Sludge	WCO	Biorefinery
Total fixed investment costs	68,927,812	9,860,995	5,299,567	80,770,739
Biodiesel	146,873,600	4,546,637	7,967,500	159,387,737
Glycerin	5,801,507	6508	436,611	443,119
K_2SO_4	0	79,566	0	79,566
Total sales revenue	152,675,107	4,632,711	8,404,111	159,910,422
Total manufacturing costs	99,669,281	3,220,938	5,281,110	108,171,329
Tax (9%)	4,770,524	127,059	281,071	4,656,518
Net profit	48,235,302	1,284,714	2,841,930	51,082,575
Ratios				
ATROR (%)	29.16	10.33	25.87	27.92
Normal payback (years)	3.43	9.67	3.86	3.58

3.4.5. Sensitivity Analysis

3.4.5.1. Sensitivity Analysis of the Effect of Sales Revenue on ATROR

Since the price of glycerin includes only about 5% of sales revenue of all units, so the effect of this item on sales revenue is ignored and only the sensitivity of the effect of biodiesel price on ATROR is analyzed. The results of the sensitivity analysis of the effect of biodiesel price on ATROR for all units are shown in Figure 12. Accordingly, the highest and lowest impact of biodiesel price on ATROR belongs to microalgae and sludge units, respectively.

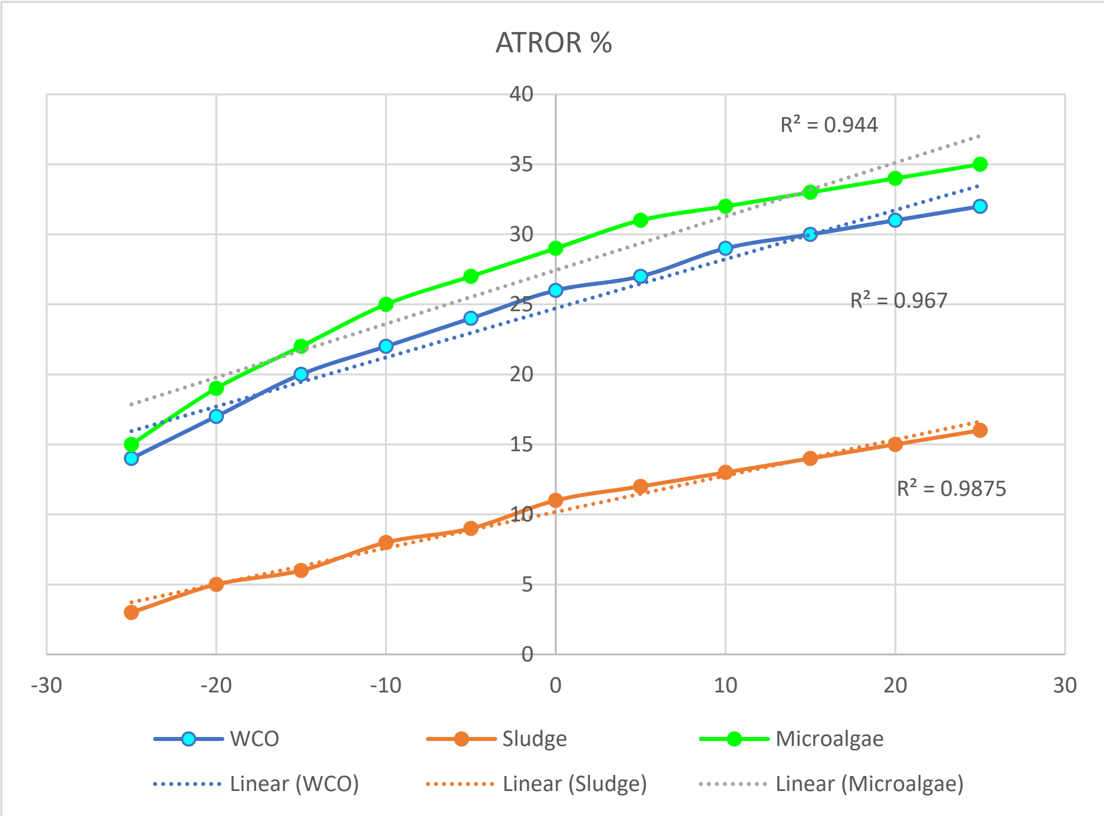


Figure 12. Sensitivity analysis of the impact of biodiesel prices on ATROR.

3.4.5.2. Sensitivity Analysis of the Effect of Biodiesel Production Cost on ATROR

The highest share of the production cost of sludge unit is related to maintenance items (25%), operating force (19%) and total raw materials (18%), respectively. Also, the largest share of production cost of edible waste oil unit, belongs to edible waste oil (39%), methanol (34%) and maintenance (10%), respectively. On the other hand, the largest shares of the cost of microalgae production are algae items (32%), methanol (31%) and NaOH (10%). As mentioned before, the cost of biodiesel production of all units consists of different items, so to facilitate sensitivity analysis, only the effect of the most important item, the cost of raw materials (sludge, edible waste oil and algae), methanol and catalysts (NaOH and HCl) are applied to the ATROR. The results of raw material's cost sensitivity analysis on ATROR for all units are shown in Figure 13. As shown in Figure 13, the maximum and lowest cost impact of raw materials on ATROR belong to microalgae and sludge units, respectively.

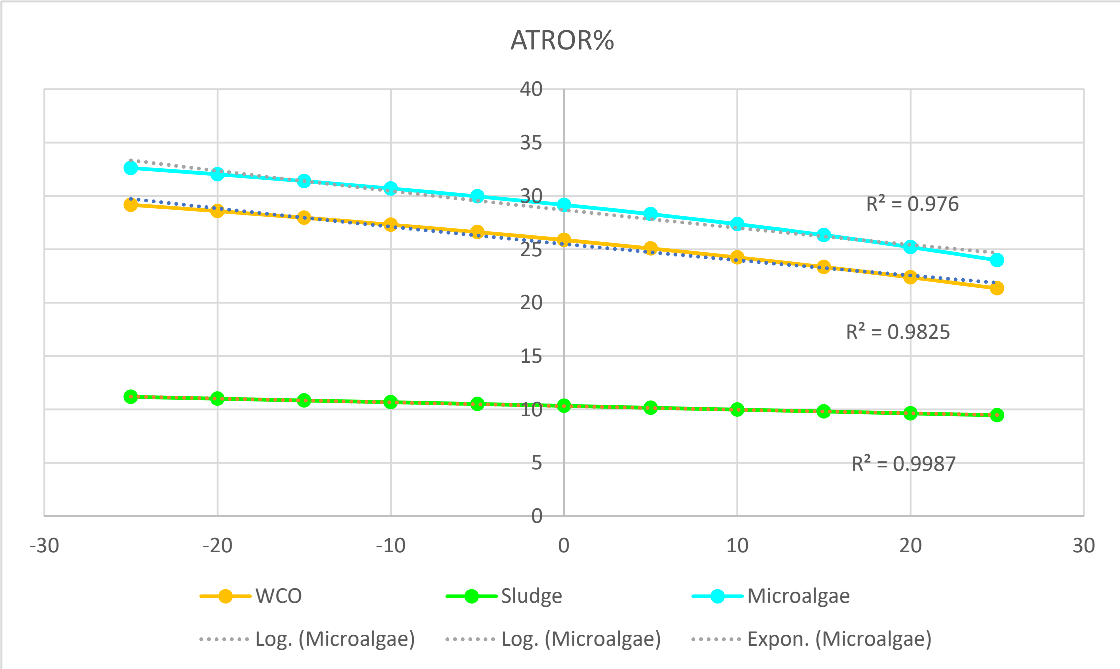


Figure 13. Sensitivity analysis of the impact of raw material costs on ATROR.

3.4.5.3. Sensitivity Analysis of the Effect of Fixed Investment Cost on ATROR

The cost of purchasing equipment for sludge units, edible waste oil and microalgae units is 39.5%, 51.7% and 50.5% of the total fixed investment cost, respectively. As a result, a major share of the total cost of fixed investment is allocated to the cost of purchasing equipment, so only the impact of this item on ATROR is examined and the impact of other items on ATROR is ignored. As shown in Figure 14, the maximum and minimum impact of equipment purchase cost on ATROR belongs to the units of sludge and edible waste oil, respectively.

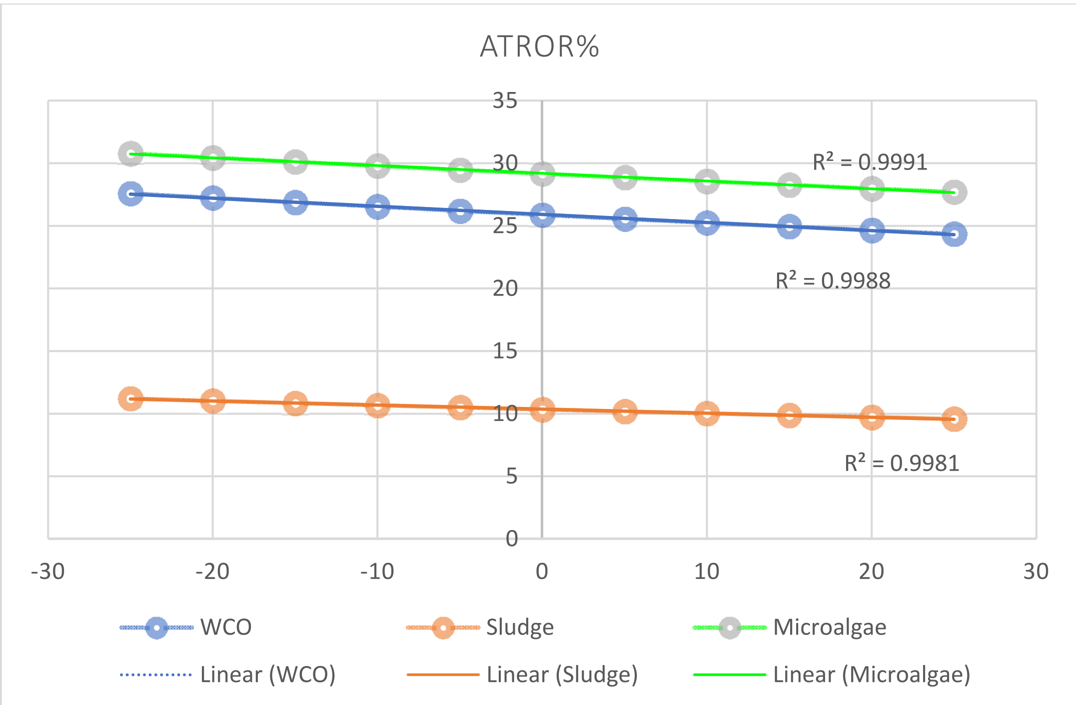


Figure 14. Sensitivity analysis of the impact of equipment purchase cost on ATROR.

3.4.5.4. Sensitivity Analysis of the Effects of Sales Revenue and Fixed Production and Investment Costs on ATROR

This section analyzes the sensitivity of the effects of total sales revenue and total production costs and fixed investment on the ATROR bio-refinery. To analyze the sensitivity of the total revenue from sales and production costs and fixed investment is considered. The results of this sensitivity analysis are shown in Figure 15. As shown in Figure 15, the highest and lowest impacts on ATROR belong to sales revenue items and fixed investment costs, respectively.

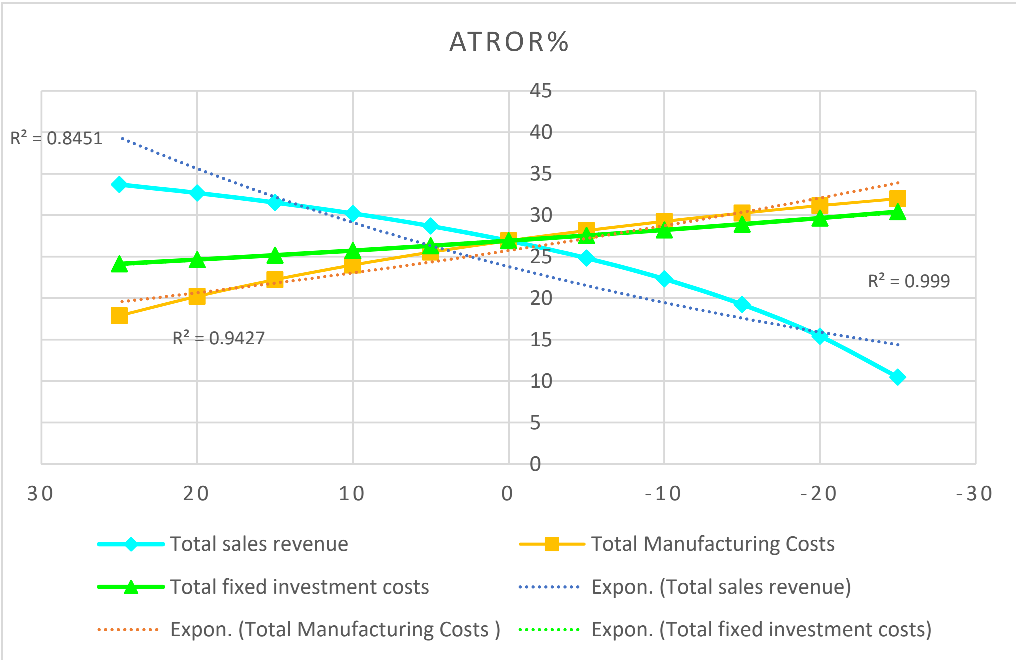


Figure 15. Sensitivity analysis of the impact of sales revenue items and fixed production and investment costs on ATROR.

4. Conclusions

- Among all types of waste, municipal and industrial wastewater sludge (687.29 million liters) has the highest potential of biodiesel production in terms of quantity, ease of gathering and collection, and cost. waste cooking oil (565.51 million liters) and animal fat (472.72 million liters) are in the next rankings. Generally, Iran can produce 2515.27 million liters of biodiesel annually from different types of fats derived from wastes.
- The analytic hierarchy process (AHP) method was utilized to determine the best location for establishing the biodiesel production plant. From various criteria, four which are biomass resource availability, investment cost, land use and job creation were chosen. Moreover, three areas of Iran (southern, southwest and northern areas,) were nominated. After considering all options and indicators and based on the AHP method’s findings, the southern area of Iran is selected for establishing the biodiesel plant in Iran.

A biorefinery, which includes three units of sewage sludge, edible waste oil and microalgae, economic evaluation and sensitivity analysis for all units and the whole biorefinery are performed in COMFAR software. The results are as follow:

- Fixed investment value: The highest and lowest investment costs per unit of production belong to the units of sewage sludge ($1.735/kg) and microalgae ($0.375/kg), respectively.
- Production costs: The highest and lowest production costs are related to wastewater sludge units ($0.567/kg) and edible waste oil ($0.530/kg), respectively.

- The highest and lowest break even prices of biodiesel production belong to sewage sludge units ($5.957/kg) and microalgae ($1.168/kg), respectively, indicating that the microalgae unit is more profitable than other units.
- The highest and lowest ATROR belong to microalgae units (29.16%) and sewage sludge (10.33%), respectively. In other words, the microalgae unit is more profitable than other units and the invested cost is returned to the investor in a shorter period of time (3.43 years). On the other hand, due to having ATROR lower than the discount rate (18% in Iran), the sewage sludge unit has no economic justification for investment.
- The results of sensitivity analysis show that the highest and lowest impact of biodiesel price on ATROR belongs to microalgae and sludge units, respectively. Also, the highest and lowest impact of raw material cost on ATROR belongs to microalgae and sludge units, respectively. On the other hand, the highest and lowest impact of equipment purchase cost on ATROR is related to sludge and edible waste oil units, respectively.
- The results of the sensitivity analysis of total sales revenue, total production costs and fixed investment on ATROR Biorefinery indicate that the highest and lowest impact on ATROR belong to sales revenue items and fixed investment costs, respectively.

In general, biorefinery provides a good profit margin of 27.92% due to its ATROR, so that the invested cost is returned to the investor in a period of 3.58 years. Therefore, the construction of biorefinery in Iran should have economic justification.

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Nomenclature

AHP	Analytic Hierarchy Process
UHC	Unburned hydrocarbons
WCO	Waste Cooking Oil
MCDM	Multiple-Criteria Decision Making
FIC	Fixed Investment Costs
TMC	Total Manufacturing Costs
CEPCI	Chemical Engineering Plant Cost Index
ATROR	After Tax Rate of Return
BEP	Break-Even Point
UNIDO	United Nation Industrial Development Organization
FAME	Fatty Acid Methyl Esters
WOF	Waste Oil Fats
HTL	Hydro Thermal Liquefaction
AHT	Analytic Hierarchy Tree
I.I	Inconsistency Index
IR	Inconsistency Ratio
IIR	Inconsistency Index of Random
WWTP	Waste Water Treatment Plant
FFA	Free Fatty acid
PRSV	Peng–Robinson Soave

References

1. Ghasemi, A.; Moghaddam, M. Thermodynamic and Environmental Comparative Investigation and Optimization of Landfill vs. Incineration for Municipal Solid Waste: A Case Study in Varamin, Iran. *J. Therm. Eng.* **2020**, *6*, 226–246. [CrossRef]
2. Kumar, M.; Sharma, M.P. Selection of potential oils for biodiesel production. *Renew. Sustain. Energy Rev.* **2016**, *56*, 1129–1138. [CrossRef]
3. Demirbas, A.; Rehan, M.; Al-Sasi, B.O.; Nizami, A.S. Evaluation of natural gas hydrates as a future methane source. *Pet. Sci. Technol.* **2016**, *34*, 1204–1210. [CrossRef]
4. Ouda, O.K.M.; Raza, S.A.; Nizami, A.S.; Rehan, M.; Al-Waked, R.; Korres, N.E. Waste to energy potential: A case study of Saudi Arabia. *Renew. Sustain. Energy Rev.* **2016**, *61*, 328–340. [CrossRef]
5. Aghbashlo, M.; Shamshirband, S.; Tabatabaei, M.; Yee, P.L.; Larimi, Y.N. The use of ELM-WT (extreme learning machine with wavelet transform algorithm) to predict exergetic performance of a DI diesel engine running on diesel/biodiesel blends containing polymer waste. *Energy* **2016**, *94*, 443–456. [CrossRef]
6. Shamshirband, S.; Tabatabaei, M.; Aghbashlo, M.; Yee, P.L.; Petković, D. Support vector machine-based exergetic modelling of a di diesel engine running on biodiesel-diesel blends containing expanded polystyrene. *Appl. Eng.* **2016**, *94*, 727–747. [CrossRef]
7. Hajjari, M.; Tabatabaei, M.; Aghbashlo, M.; Ghanavati, H. A review on the prospects of sustainable biodiesel production: A global scenario with an emphasis on waste-oil biodiesel utilization. *Renew. Sustain. Energy Rev.* **2017**, *72*, 445–464. [CrossRef]
8. Huang, G.H.; Chen, F.; Wei, D.; Zhang, X.W.; Chen, G. Biodiesel production by microalgal biotechnology. *Appl. Energy* **2010**, *87*, 38–46. [CrossRef]
9. Demirbas, A. Biofuels securing the planet's future energy needs. *Energy Convers. Manag.* **2009**, *50*, 2239–2249. [CrossRef]
10. Sajjadi, B.; Raman, A.A.A.; Arandiyan, H. A comprehensive review on properties of edible and non-edible vegetable oil-based biodiesel: Composition, specifications and prediction models. *Renew. Sustain. Energy* **2016**, *63*, 62–92. [CrossRef]
11. Panichelli, L.; Dauriat, A.; Gnansounou, E. Life cycle assessment of soybean-based biodiesel in Argentina for export. *Int. J. Life Cycle Assess.* **2009**, *14*, 144–159. [CrossRef]
12. Martín, M.; Grossmann, I.E. Design of an optimal process for enhanced production of bioethanol and biodiesel from algae oil via glycerol fermentation. *Appl. Energy* **2014**, *209*, 409–425. [CrossRef]
13. Borges, M.E.; Díaz, L. Recent developments on heterogeneous catalysts for biodiesel production by oil esterification and transesterification reactions: A review. *Renew. Sustain. Energy Rev.* **2012**, *16*, 2839–2849. [CrossRef]
14. Atabani, A.E.; Silitonga, A.S.; Ong, H.C.; Mahlia, T.M.I.; Masjuki, H.H.; Badruddin, I.A.; Fayaz, H. Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production. *Renew. Sustain. Energy Rev.* **2013**, *18*, 211–245. [CrossRef]
15. Rathore, D.; Nizami, A.S.; Singh, A.; Pant, D. Key issues in estimating energy and greenhouse gas savings of biofuels: Challenges and perspectives. *Biofuel Res. J.* **2016**, *3*, 380–393. [CrossRef]
16. Ministry I Energy. Energy Balance Sheet, Deputy of Electricity and Energy Planning. Available online: http://news.moe.gov.ir/Home (accessed on 10 September 2021).
17. Hosseini, S.E.; Andwari, A.M.; Wahid, M.A.; Bagheri, G. A review on green energy potentials in Iran. *Renew. Sustain. Energy Rev.* **2013**, *27*, 533–545. [CrossRef]
18. Moshiri, S.; Atabi, F.; Panjehshahi, M.H.; Lechtenböehmer, S. Long run energy demand in Iran: A scenario analysis. *Int. J. Energy Sect. Manag.* **2012**, *6*, 120–144. [CrossRef]
19. Ho, W. Integrated analytic hierarchy process and its applications–A literature review. *Eur. J. Oper. Res.* **2008**, *186*, 211–228. [CrossRef]
20. Turton, R.; Bailie, R.C.; Whiting, W.B.; Shaeiwitz, J.A. *Analysis, Synthesis and Design of Chemical Processes*, 2nd ed.; Prentice Hall: Hoboken, NJ, USA, 2003.
21. United Nations. COMFAR Software. Available online: https://www.unido.org/resources-publications-publications-type/comfar-software (accessed on 10 September 2021).
22. Mesdaghinia, A.; Nasseri, S.; Mahvi, A.H.; Tashauoei, H.R.; Hadi, M. The estimation of per capita loadings of domestic wastewater in Tehran. *J. Environ. Health Sci. Eng.* **2015**, *13*, 25. [CrossRef] [PubMed]
23. Siddiquee, M.N.; Rohani, S. Experimental analysis of lipid extraction and biodiesel production from wastewater sludge. *Fuel Process Technol.* **2011**, *92*, 2241–2251. [CrossRef]
24. Chen, W.; Wu, F.; Zhang, J. Potential production of non-food biofuels in China. *Renew. Energy* **2016**, *85*, 939–944. [CrossRef]
25. Salehi, A.; Karbassi, A.; Ghobadian, B.; Ghasemi, A.; Doustgani, A. Simulation process of biodiesel production plant. *Environ. Prog. Sustain. Energy* **2019**, *38*, 1–12. [CrossRef]
26. Alptekin, E.; Canakci, M.; Sanli, H. Biodiesel production from vegetable oil and waste animal fats in a pilot plant. *Waste Manag.* **2014**, *34*, 2146–2154. [CrossRef] [PubMed]
27. Martinez, E.; Marcos, A.; Al-Kassir, A.; Jaramillo, M.A.; Mohamad, A.A. Mathematical model of a laboratory-scale plant for slaughterhouse effluents biodigestion for biogas production. *Appl. Energy* **2012**, *95*, 210–219. [CrossRef]
28. Yahyaee, R.; Ghobadian, B.; Najafi, G. Waste fish oil biodiesel as a source of renewable fuel in Iran. *Renew. Sustain. Energy Rev.* **2013**, *17*, 312–319. [CrossRef]

29. Shahzad, K.; Nizami, A.S.; Sagir, M.; Rehan, M.; Maier, S.; Khan, M.Z.; Ouda, O.K.M.; Ismail, I.M.I.; BaFail, A.O. Biodiesel production potential from fat fraction of municipal waste in Makkah. *PLoS ONE* **2017**, *12*, e0171297. [CrossRef] [PubMed]
30. Najafi, G.; Ghobadian, B.; Yusaf, T.F. Algae as a sustainable energy source for biofuel production in Iran: A case study. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3870–3876. [CrossRef]
31. Sohrabipour, J.; Rabiei, R. Algal vegetation in southern coastline of Iran. *Iran Nat.* **2017**, *2*, 62–68. [CrossRef]
32. Chhetri, A.; Watts, K.; Islam, M. Waste Cooking Oil as an Alternate Feedstock for Biodiesel Production. *Energies* **2008**, *1*, 3–18. [CrossRef]
33. Frank, E.D.; Elgowainy, A.; Han, J.; Wang, Z. Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae. *Mitig. Adapt. Strateg. Glob. Chang.* **2013**, *18*, 137–158. [CrossRef]
34. Kalacheva, G.S.; Zhila, N.O.; Volova, T.G.; Gladyshev, M.I. The effect of temperature on the lipid composition of the green alga Botryococcus. *Microbiology* **2002**, *71*, 286–293. [CrossRef]
35. Xu, H.; Miao, X.; Wu, Q. High quality biodiesel production from a microalga Chlorella protothecoides by heterotrophic growth in fermenters. *J. Biotechnol.* **2006**, *126*, 499–507. [CrossRef]
36. Brouwer, P.; van der Werf, A.; Schluepmann, H.; Reichart, G.J.; Nierop, K.G.J. Lipid Yield and Composition of Azolla filiculoides and the Implications for Biodiesel Production. *Bioenergy Res.* **2016**, *9*, 369–377. [CrossRef]
37. Amer, M.; Daim, T.U. Selection of renewable energy technologies for a developing county: A case of Pakistan. *Energy Sustain. Dev.* **2011**, *15*, 420–435. [CrossRef]
38. Cutz, L.; Haro, P.; Santana, D.; Johnsson, F. Assessment of biomass energy sources and technologies: The case of Central America. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1411–1431. [CrossRef]
39. Onar, S.C.; Oztaysi, B.; Otay, I.; Kahraman, C. Multi-expert wind energy technology selection using interval-valued intuitionistic fuzzy sets. *Energy* **2015**, *90*, 274–285. [CrossRef]
40. Bayazit, O. Use of AHP in decision-making for flexible manufacturing systems. *J. Manuf. Technol. Manag.* **2005**, *16*, 808–819. [CrossRef]
41. Braglia, M.; Carmignani, G.; Frosolini, M.; Grassi, A. AHP-based evaluation of CMMS software. *J. Manuf. Technol. Manag.* **2006**, *17*, 585–602. [CrossRef]
42. Liang, X.; Wang, X.; Shu, G.; Wei, H.; Tian, H.; Wang, X. A review and selection of engine waste heat recovery technologies using analytic hierarchy process and grey relational analysis. *Int. J. Energy Res.* **2015**, *39*, 453–471. [CrossRef]
43. Ren, J.; Fedele, A.; Mason, M.; Manzardo, A.; Scipioni, A. Fuzzy Multi-Actor Multi-Criteria Decision Making for sustainability assessment of biomass-based technologies for hydrogen production. *Int. J. Hydrog. Energy* **2013**, *38*, 9111–9120. [CrossRef]
44. Tan, K.H.; Noble, J.; Sato, Y.; Tse, Y.K. A marginal analysis guided technology evaluation and selection. *Int. J. Prod. Econ.* **2011**, *131*, 15–21. [CrossRef]
45. Khishtandar, S.; Zandieh, M.; Dorri, B. A multi criteria decision making framework for sustainability assessment of bioenergy production technologies with hesitant fuzzy linguistic term sets: The case of Iran. *Renew. Sustain. Energy Rev.* **2017**, *77*, 1130–1145. [CrossRef]
46. La Rovere, E.L.; Soares, J.B.; Oliveira, L.B.; Lauria, T. Sustainable expansion of electricity sector: Sustainability indicators as an instrument to support decision making. *Renew. Sustain. Energy Rev.* **2010**, *14*, 422–429. [CrossRef]
47. Troldborg, M.; Heslop, S.; Hough, R.L. Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renew. Sustain. Energy Rev.* **2014**, *39*, 1173–1184. [CrossRef]
48. Farooq, S.; O'Brien, C. An action research methodology for manufacturing technology selection: A supply chain perspective. *Prod. Plan. Control* **2015**, *26*, 467–488. [CrossRef]
49. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*; McGraw-Hill International Book Co.: New York, NY, USA, 1980.
50. Saaty, T.L. *Fundamentals of Decision Making and Priority Theory*, 2nd ed.; McGraw Hill Publishers: New York, NY, USA, 2000.
51. Olkiewicz, M.; Caporgno, M.P.; Fortuny, A.; Stüber, F.; Fabregat, A.; Font, J.; Bengoa, C. Direct liquid-liquid extraction of lipid from municipal sewage sludge for biodiesel production. *Fuel Process Technol.* **2014**, *128*, 331–338. [CrossRef]
52. Olkiewicz, M.; Fortuny, A.; Stüber, F.; Fabregat, A.; Font, J.; Bengoa, C. Effects of pre-treatments on the lipid extraction and biodiesel production from municipal WWTP sludge. *Fuel* **2015**, *141*, 250–257. [CrossRef]
53. Ghosh, P. Prediction of vapor-liquid equilibria using Peng-Robinson and Soave-Redlich-Kwong equations of state. *Chem. Ing. Technol.* **1999**, *22*, 379–399. [CrossRef]
54. Olkiewicz, M.; Torres, C.M.; Jiménez, L.; Font, J.; Bengoa, C. Scale-up and economic analysis of biodiesel production from municipal primary sewage sludge. *Bioresour. Technol.* **2016**, *214*, 122–131. [CrossRef]
55. Chisti, Y. Biodiesel from microalgae beats bioethanol. *Trends Biotechnol.* **2008**, *26*, 126–131. [CrossRef] [PubMed]
56. Miao, X.; Wu, Q. Biodiesel production from heterotrophic microalgal oil. *Bioresour. Technol.* **2006**, *97*, 841–846. [CrossRef] [PubMed]
57. Pokoo-Aikins, G.; Nadim, A.; El-Halwagi, M.M.; Mahalec, V. Design and analysis of biodiesel production from algae grown through carbon sequestration. *Clean Technol. Environ. Policy* **2010**, *12*, 239–254. [CrossRef]

58. Martinovic, F.L.; Kiss, F.E.; Micic, R.D.; Simikic, M.; Tomic, M.D. Comparative technoeconomic analysis of single-step and two-step biodiesel production with supercritical methanol based on process simulation. *Chem. Eng. Res. Des.* **2018**, *132*, 751–765. [CrossRef]
59. Cao, Y.; Doustgani, A.; Salehi, A.; Nemati, M.; Ghasemi, A.; Koohshekan, O. The economic evaluation of establishing a plant for producing biodiesel from edible oil wastes in oil-rich countries: Case study Iran. *Energy* **2020**, *213*, 118760. [CrossRef]
60. Eurostat Statistics Explained. Available online: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics (accessed on 10 September 2021).