

Methyl ester production from chicken fat with high FFA

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Abstract: In biodiesel production, to use low cost feedstock such as rendered animal fats may reduce the biodiesel cost. One of the low cost feedstock is the chicken fat for biodiesel production. However, chicken fats often contain significant amounts of free fatty acid (FFA) which cannot be converted to biodiesel using an alkaline catalyst due to the formation of soap. Therefore, the FFA level should be reduced to desired level (below 1%) by using an acid catalyst before transesterification. For this aim, sulfuric, hydrochloric and sulfamic (amidosulphonic) acids were used for pretreatment reactions and the variables affecting the FFA level were investigated by using the chicken fat with 13.45% FFA. After reducing the free fatty acid level of the chicken fat to less than 1%, the transesterification reaction was completed with an alkaline catalyst. Potassium hydroxide, sodium hydroxide, potassium methoxide and sodium methoxide were used as catalyst and methanol was used as alcohol for transesterification reactions. The effects of catalyst type, reaction temperature and reaction time on the fuel properties of methyl esters were investigated. In terms of high ester yield, the measured fuel properties of the chicken fat methyl ester met EN 14214 and ASTM D6751 biodiesel specifications.

Keywords: Biodiesel, Low cost feedstock, Chicken fat, Transesterification

1. Introduction

Biodiesel which can be produced from vegetable oils and animal fats is an alternative fuel for diesel engines. Biodiesel is nontoxic, biodegradable and environmentally friendly fuel. Biodiesel contains almost no sulfur and does not contribute to greenhouse gases due to its closed carbon cycle [1]. The major component of oils and fats is triglycerides which compose about 90-98% of total mass [2]. Transesterification is a chemical process of reacting triglycerides with alcohol in the presence of a catalyst. If the reaction is not completed, then there will be mono-, di- and triglycerides left in the reaction mixture [3-5]. Alcohols such as methanol, ethanol or butanol can be used in the transesterification [5, 6]. The most preferred alcohol used in biodiesel production. The most commonly preferred catalysts are sulfuric, sulphonic, and hydrochloric acids as acid catalysts, and sodium hydroxide (NaOH), sodium methoxide (NaOMe), potassium hydroxide (KOH) and potassium methoxide (KOMe) as alkaline catalyst [7]. Water is formed when KOH and NaOH are used to produce the methoxide. Water limits the completion of transesterification reaction. Therefore, industrial biodiesel processes run on alkoxides such as NaOMe and KOMe which can be bought as liquid form. They do not contain water and are usually commercially available as ready-to-use methanol solution [8]. NaOMe is offered as a 30% or 25% methanol solution and KOMe as a 32% methanol solution whereas NaOH and KOH are offered as solids and not premixed in methanol [9].

The most common feedstock of biodiesel is rapeseed oil in Europe and soybean oil in the United States of America [10]. The major handicap is the high cost of biodiesel for its commercialization. Chicken fat is a low cost feedstock for biodiesel production compared to high-grade vegetable oils. It is extracted from feather meal which is prepared from chicken wastes such as chicken feathers, blood, offal and trims after rendering process. Feather meal contains significant amount of chicken fat. The fat content of the feather meal varies from 2 to

12% depends on the kind of used feathers [11, 12]. However, they often contain significant amounts of free fatty acid (FFA). The fats with high FFA cannot be converted to biodiesel using alkaline catalysts. FFAs react with an alkaline catalyst and thus soaps are produced by this reaction. Soaps prevent the separation of the ester, glycerin, and wash water [13]. Acid catalysts are too slow to be suitable for converting triglycerides to biodiesel. However, they appear to be quite effective at converting FFAs to esters [14]. For these reasons, an acid catalyst can be used to esterify the FFAs to esters. The acid-catalyzed process is called as pretreatment. FFAs are converted to monoesters through the pretreatment of the feedstock with high FFA and thereby the FFA level reduces. The major handicap for the acid-catalyzed esterification of FFAs is the water formation. The water formation is the primary mechanism limiting the completion of the acid catalyzed esterification reaction with FFAs [13]. After pretreatment, the pretreated feedstock can be transesterified with an alkali catalyst to convert the triglycerides to esters [15-17]. Some researchers [18, 19] stated that the feedstock should not contain more than 1% FFA for alkaline catalyzed transesterification reactions, whereas some researches [1] stated that an alkaline catalyst can be used in the transesterification up to the FFA level of 5%, but it reduces the biodiesel yield.

Many researchers have investigated the availability of animal fats and waste oils for biodiesel production. However, few researchers have studied on the chicken fat especially with high FFA. Mattingly [20] produced biodiesel from chicken fat with 2.3% FFA. He concluded that it was needed to perform a pretreatment reaction to get high biodiesel yield. Bhatti et al. [21] obtained high ester yields up-to 99% from chicken fat after 24 h in the presence of sulfuric acid. Kondamudi et al. [11] chose the chicken fat for biodiesel production. They used potassium hydroxide to remove FFA in the form of soap. After separating the soap, the optimization of transesterification parameters was researched. They obtained good results and managed to produce biodiesel whose fuel properties were suitable for American Society of Testing and Materials (ASTM) biodiesel standards. Schulte [22] investigated optimum reaction parameters for biodiesel production from chicken fat. He obtained high biodiesel yields up-to 91% by using supercritical methanol. The purpose of the present study was to produce biodiesel from chicken fat with high FFA. Therefore, the optimization of pretreatment reaction was investigated with different acid catalysts to reduce FFA level (below 1%) of chicken fat. The effects of catalyst type, catalyst amount, alcohol molar ratio and reaction time on the FFA level were also analyzed. After the optimum pretreatment parameters were determined, the transesterification reaction was carried out with an alkaline catalyst to produce biodiesel. The optimization of biodiesel production from the chicken fat was investigated with different alkaline catalysts, reaction temperatures and reaction times. The obtained esters were characterized by determining its fuel properties according to the standard test methods. The obtained products were named as chicken fat methyl ester (CFME) because all fuel properties in the standards were not measured.

2. Materials and method

In this study, chicken fat was obtained from Şenpiliç Chicken Slaughterhouse in Sakarya, TURKEY. The chicken fat was subjected to a heating at 110°C for one hour to remove water and then filtered to remove the insoluble materials. The FFA level of the rendering plant feedstock is generally between 5% and 25% [14]. The researchers have suggested that the FFA level of the feedstock should be reduced to less than 1% before using an alkaline catalyst [18, 19]. This was the initial target for the pretreatment. The chicken fat used in this study had an acid value of 26.89 mg KOH/g which corresponds to FFA level of about 13.45%. Because the acid value of the chicken fat was greater than 2 mg KOH/g, it was needed to perform a

pretreatment to the feedstock. Some properties and fatty acid composition of the chicken fat are shown in Tables 1 and 2, respectively.

Table 1. Some properties of chicken fat

Properties	Unit	Chicken Fat
Density (at 15°C)	kg.m ⁻³	932
Viscosity (at 40°C)	mm ² .s ⁻¹	59.2
Acid Number	mg KOH.g ⁻¹	26.89
Heat of Combustion	kJ.kg ⁻¹	39407
Water Content	% mass	0.3

Table 2. Fatty acid composition of chicken fat

Fat	Fatty acid composition (%)						
	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	C20:4
Chicken	19.82	3.06	6.09	37.62	31.59	1.45	0.37

2.1. Pretreatment Process

Sulfuric acid (Merck), hydrochloric acid (Merck) and sulfamic acid (Merck) were used as catalyst and methanol was used as alcohol for the pretreatment of chicken fat. The esterification process of FFAs was repeated for different alcohol molar ratios, amounts of acid catalysts based on the weight of FFAs and reaction times at 60°C. In the calculations, the molecular weight of FFA was obtained from the reference [22]. The experiments were performed in a laboratory scale apparatus. The chicken fat was added into the reaction flask equipped with reflux condenser, magnetic stirrer and thermometer, and then it was heated. When the temperature reached to 60°C, the alcohol/catalyst mixture was added into the fat. The final mixture was stirred for the desired reaction time at 60°C. The mixture was settled overnight and two phases were formed after the pretreatment. The upper phase consists of a mixture of methanol, sulfuric acid and water whereas the lower phase mainly consists of chicken fat and esterified FFAs. The upper phase was removed. After this step, the lower phase was subjected to a heating at 110°C for one hour to remove any remaining alcohol and water. And then, the acid value of the fat-ester mixture was measured and recorded.

2.2. Transesterification Process

In this study, potassium methoxide solution (32% in methanol) and sodium methoxide solution (30% in methanol) were supplied from Evonik Industries in Germany. These alkoxides, potassium hydroxide (Carlo Erba) and sodium hydroxide (Merck) were used as the catalysts for transesterification reactions to investigate the effect of catalyst type on the fuel properties of biodiesel. Molar ratio between alcohol and fat-ester mixture was 6:1 for the transesterification reaction. The catalyst amount was selected as 1% of the weight of the initial amount of fat in the chicken fat and the neutralization amount which was calculated from the reference [3] for KOH and NaOH catalyst whereas the catalyst amounts were (FFA% x 0.64) + 1.7% and (FFA% x 0.78) + 2.0% for NaOMe and KOMe catalysts, respectively. The catalyst amounts for NaOMe and KOMe were calculated according to the manufacturer recommendation. In the calculations for transesterification, the molecular weight of chicken fat was obtained from the reference [22]. The transesterification process and laboratory apparatus were the same as those of pretreatment experiments except for catalyst. The reaction temperature was selected as 25°C and 60°C, and reaction time was selected as one, two and four hours. After the transesterification reaction, the glycerin layer was separated in a separating funnel and the ester layer was washed with warm water. After

washing, the methyl ester was subjected to a heating at 110°C to remove excess alcohol and water, and then filtered. The obtained methyl esters were characterized in the Fuel Laboratory of the Department of Automotive Engineering Technologies and Alternative Fuels R&D Center in Kocaeli University.

3. Results and discussion

Some researchers [14, 16] tried to reduce high FFA level of the feedstock by two step pretreatment process. After the first treatment, the reaction mixture is allowed to settle. Since the water formation when the FFAs are converted to esters inhibits the reaction, the methanol-water mixture is separated from the oil phase. Then, additional methanol and acid catalyst can be added and the reaction continued for the second step. Increasing the number of pretreatment steps reduces the ester yield due to the solubility of the fat and ester in methanol [15]. Therefore, in this study, it was tried to reduce the FFA level by one step pretreatment to get high ester yield and save time for producing biodiesel.

3.1. Pretreatment of the Chicken Fat with Sulfuric Acid

Sulfuric acid was selected as reference catalyst. The esterification process was repeated for different alcohol molar ratios (10:1, 15:1, 20:1, 25:1, 30:1) and amounts of sulfuric acid (3%, 6%, 15%, 20%, 35%) based on the FFA level of the chicken fat for one hour reaction at 60°C. The initial experiments were performed with 3% and 6% catalyst at different methanol molar ratios. Good results were not obtained when using 3% and 6% sulfuric acid, and methanol molar ratios from 10:1 to 30:1 for one hour reaction at 60°C. The FFA level was only reduced to 11.25% when using 6% sulfuric acid and methanol molar ratio of 30:1. Therefore, greater amount of sulfuric acid and methanol molar ratio were used. The reaction conditions of the next pretreatments were two different methanol molar ratios of 20:1 and 30:1, and three different sulfuric acid amounts of 15%, 20% and 35% for one hour reaction at 60°C. The FFA level of the chicken fat decreased with rising of sulfuric acid amount and methanol ratio in the pretreatment reaction. The FFA level was reduced to 6.26%, 2.27% and 1.20% for 15%, 20% and 35% sulfuric acid with methanol molar ratio of 20:1, respectively. The aim of the pretreatment reaction was to decrease the FFA level from 13.45% to less than 1%. Therefore, the methanol ratio was raised to 30:1. In this case, the FFA level decreased to 4.92%, 1.40% and 1.04% for 15%, 20% and 35% sulfuric acid, respectively.

3.2. Pretreatment of the Chicken Fat with Hydrochloric Acid

The pretreatments were repeated with 6%, 15% and 20% hydrochloric acid and methanol molar ratio of 20:1 and 30:1 for one hour reaction at 60°C. Six percent of hydrochloric acid was not effective in decreasing the FFA level of the chicken fat with methanol molar ratios 20:1 and 30:1 for one hour reaction at 60°C such as in sulfuric acid experiments. The FFA level was only reduced to 12.99% and 12.46% with using 6% hydrochloric acid for methanol molar ratio of 20:1 and 30:1, respectively. Consequently, the catalyst amount was raised to 15% and 20%. The FFA level of the chicken fat was reduced to 5.26% and 2.83% for 15% and 20% hydrochloric acid at methanol molar ratio of 20:1, respectively. The FFA level of the chicken fat was strongly affected by the molar ratio of methanol. With using methanol molar ratio of 30:1, the FFA level was reduced to 3.89% and 1.67% for 15% and 20% hydrochloric acid, respectively. The FFA level of the chicken fat was decreased to about 1% when using 20% hydrochloric acid and methanol molar ratio of 30:1. The pretreatment results with sulfuric and hydrochloric acids were very close to each other. The differences of FFA level were only 0.56% and 0.27% for 20% acid catalyst with methanol molar ratio of 20:1 and 30:1, respectively.

3.3. Pretreatment of the Chicken Fat with Sulfamic Acid

The third acid catalyst which was used for esterification of FFAs was sulfamic acid in this study. Sulfamic acid is slightly soluble in methanol. For this reason, it needs to be heated to prepare a mixture of alcohol-acid catalyst. The esterification process was repeated for 6% sulfamic acid and alcohol molar ratios of 20:1 and 30:1. Six percent of sulfamic acid did not affect the FFA level of the chicken fat significantly with methanol molar ratios of 20:1 and 30:1 for one hour reaction at 60°C. The FFA level was only reduced to 12.78% and 12.32% when using 6% sulfamic acid for methanol molar ratio of 20:1 and 30:1, respectively. Therefore, the catalyst amount was raised to 15% with methanol molar ratio of 30:1 for one hour reaction at 60°C. But, satisfactory results were not reached with 15% sulfamic acid. The FFA level was only reduced to 11.97%. For this reason, the pretreatment was not continued with sulfamic acid.

3.4. Effect of Reaction Time on the FFA Level of Chicken Fat with Sulfuric Acid

According to the results, sulfuric acid gave the best results among the three acid catalysts used in this study. The initial target was to reduce the FFA level of the chicken fat less than 1%. Thirty-five percent of sulfuric acid was better than 20% for converting FFAs to monoesters. However, the loss of feedstock after the pretreatment was the highest for 35% sulfuric acid. Lower feedstock amount means lower biodiesel yield after transesterification. For this reason, 20% sulfuric acid was selected as acid catalyst amount. Beside, methanol molar ratio was raised to 40:1 to decrease the FFA level below 1%. The effect of reaction time on the FFA level of the chicken fat was investigated. Reaction time was chosen as 60, 70 and 80 minutes at 60°C in these pretreatments. The FFA levels of the chicken fat were 0.93%, 0.80% and 0.67% for 60, 70 and 80 minutes with 20% sulfuric acid and methanol molar ratio of 40:1, respectively. The FFA level decreased below 1% for these three experiments. The pretreatment with 20% sulfuric acid and methanol molar ratio of 40:1 for 80 minutes at 60°C was thought to be sufficient for reducing FFA level less than 1% to get high ester yield after transesterification. Thus, these reaction parameters were selected for pretreatment.

3.5. Characterization of Fuel Properties after Transesterification

After pretreatment reaction, the FFA level of the chicken fat was 0.67% which is sufficient to complete the reaction with alkaline catalysts. The effects of variables such as catalyst type, reaction temperature and reaction time on the fuel properties of the CFMEs were investigated. The gathered ester yield results are shown in Table 3. The ester yield increased with the increasing reaction temperature from 25°C to 60°C for all esters. But the ester yield did not change significantly with the increasing reaction time. In this study, the minimum and maximum ester yields were 71.3% (at four-hour, 25°C and NaOH catalyzed reaction) and 88.5% (at one-hour, 60°C and KOMe catalyzed reaction), respectively. The total-free glycerin, mono-, di- and triglyceride results are illustrated in Table 3. Standard total glycerin results were obtained only when using KOH and NaOH in the transesterification. Better total glycerin results were determined for NaOH catalyzed reactions compared to KOH. However, the ester yield was significantly lower for NaOH catalyzed reactions. Free glycerin results show that it is not directly affected by reaction parameters. Mono-, di and triglyceride values generally reduced with increasing reaction time at 25°C. But, these values show different changes at 60°C because of reversible reaction.

Table 3. Fuel properties of produced CFMEs *

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
a	25	1	886	1	170	0.04	4	40.1	0.49	0.03	0.71	0.82	1.50	0.30	5.4	80.2	
a	25	2	885	1	171	0.11	3	40.3	0.35	0.03	0.56	0.54	0.90	0.29	5.2	82.1	
a	25	4	884	1	172	0.13	3	40.3	0.16	0.03	0.40	0.03	0.20	0.25	5.1	84.8	
a	60	1	885	1	171	0.01	2	40.2	0.20	0.03	0.55	0.03	0.27	0.25	5.1	88.1	
a	60	2	884	1	171	0.01	2	40.2	0.19	0.04	0.45	0.11	0.14	0.24	5.0	87.6	
a	60	4	883	1	172	0.01	2	40.2	0.19	0.02	0.56	0.09	0.12	0.22	4.9	87.4	
b	25	1	885	1	170	0.12	3	40.1	0.05	0.02	0.01	0.13	0.06	0.30	5.4	72.8	
b	25	2	885	1	172	0.06	2	40.1	0.08	0.03	0.16	0.01	0.04	0.29	5.3	71.7	
b	25	4	884	1	172	0.03	2	40.2	0.07	0.02	0.16	0.01	0.03	0.24	5.2	71.3	
b	60	1	885	1	171	0.20	2	40.1	0.10	0.02	0.31	0.01	0.02	0.28	5.2	79.1	
b	60	2	884	1	172	0.08	2	40.2	0.12	0.01	0.41	0.01	0.01	0.24	5.1	78.4	
b	60	4	883	1	172	0.09	2	40.3	0.15	0.01	0.55	0.01	0.02	0.23	4.9	77.3	
c	25	1	891	1	170	0.02	4	40.0	NT	NT	NT	NT	NT	0.30	6.7	84.6	
c	25	2	890	1	172	0.01	3	40.1	1.10	0.02	1.99	2.81	1.57	0.27	6.3	82.7	
c	25	4	888	1	172	0.01	3	40.1	0.68	0.01	1.30	1.08	1.74	0.25	5.8	81.9	
c	60	1	887	1	171	0.01	3	40.1	0.55	0.01	0.90	0.84	1.81	0.29	5.6	88.5	
c	60	2	886	1	172	0.01	3	40.1	0.49	0.01	0.99	0.15	2.04	0.26	5.6	85.2	
c	60	4	886	1	172	0.01	3	40.1	0.72	0.01	1.02	1.25	2.56	0.24	5.6	86.2	
d	25	1	891	1	171	0.03	4	39.9	NT	NT	NT	NT	NT	0.30	6.8	75.8	
d	25	2	890	1	171	0.12	3	40.1	1.07	0.02	1.50	2.23	3.31	0.28	6.2	79.1	
d	25	4	888	1	172	0.05	3	40.1	0.71	0.04	1.23	1.58	1.18	0.25	5.9	80.3	
d	60	1	886	1	171	0.20	2	40.2	0.50	0.02	0.96	0.70	1.32	0.26	5.4	85.9	
d	60	2	886	1	173	0.12	2	40.2	0.58	0.01	0.94	0.91	1.94	0.25	5.5	85.3	
d	60	4	885	1	173	0.15	2	40.1	0.44	0.01	1.52	0.04	0.34	0.22	5.5	88.3	

*1: catalyst (a: KOH, b: NaOH, c: KOMe, d:NaOMe), 2: reaction temperature (°C), 3: reaction time (hour), 4: density (15°C, kg.m⁻³), 5: copper strip corrosion (degree of corrosion), 6: flash point (°C), 7: methanol content (%), 8: pour point (°C), 9: heat of combustion (MJ.kg⁻¹), 10: total glycerin (%), 11: free glycerin (%) 12: monoglyceride (%), 13: diglyceride (%); 14: triglyceride (%), 15: acid number (mg KOH.g⁻¹), 16: viscosity (40°C, mm².s⁻¹), 17: ester yield (%), NT: not tested.

Generally, the density of CFME decreases with increasing of reaction time and reaction temperature. There is no significant difference among the densities for transesterification reactions catalyzed with KOMe and NaOMe compared to KOH and NaOH. In general, the viscosity of CFME decreases with the increasing reaction time and reaction temperature. However, there is a significant difference among the viscosities when using KOMe and NaOMe catalysts compared to KOH and NaOH. The viscosities of CFMEs are higher for transesterification reactions catalyzed with KOMe and NaOMe. This situation can be explained with incomplete transesterification reaction. The methanol contents of CFMEs vary from 0.01% to 0.20% as seen in Table 3. It clearly shows that the methanol content values of biodiesel do not directly depend on transesterification reaction parameters. The flash points of CFMEs do not change mostly and range from 170°C to 173°C. The CFMEs produced in this study have high pour point. The minimum and maximum pour point is 2°C and 4°C, respectively. The acid value of pretreated chicken fat was 1.34 mg KOH.g⁻¹ and this value was reduced to 0.22 mg KOH.g⁻¹ after transesterification reaction. The maximum acid value was measured to be 0.30 mg KOH.g⁻¹ which is much below the required biodiesel standards.

The heat of combustion results are around 40 MJ.kg^{-1} and they are slightly lower than those of petroleum diesel fuels. According to the results, there is no significant difference among the heat of combustion results depending on transesterification reaction parameters. The copper strip corrosion results gathered with each of CFME are the lowest level of corrosiveness (No 1a). This means that corrosion would not be a problem for CFMEs.

4. Conclusion

The objective of this study was to produce biodiesel from low-cost chicken fat with high FFA. The FFA level of the feedstock should be reduced to less than 1% before using the alkaline catalysis. For this aim, three acid catalysts were used in the pretreatment reactions and the variables affecting the acid value including alcohol molar ratio, acid catalyst amount and reaction time were investigated. After determining the optimum pretreatment conditions to reduce the FFA level of the chicken fat below 1%, the process was completed by using the alkaline catalysts. The effects of the variables on the fuel properties such as catalyst type, reaction temperature and reaction time were investigated. According to the results, the following conclusions can be drawn:

- The acid catalyst type and amount have effect to reduce the FFA level of the chicken fat in the pretreatment reaction. Sulfuric acid is the best catalyst for reducing FFA level among the acid catalysts used in this study. Low amount of acid catalyst (3% and 6%) is not effective for reducing FFA level of the feedstock for all acid catalysts.
- The FFA level of the chicken fat is strongly affected by the molar ratio of methanol, acid catalyst amount and reaction time. Sulfuric and hydrochloric acids give similar pretreatment results.
- Sulfamic acid does not have significant effect on the reduction of acid value of the chicken fat. The FFA level of the chicken fat with about 15% FFA may be reduced to below 1% when using 20% sulfuric acid and methanol molar ratio of 40:1 for 60, 70 and 80 minutes at 60°C . The ester yield increased with increasing reaction temperature.
- The viscosity and glyceride values of CFME decreased with increasing reaction temperature. The catalyst type especially affects viscosity and glyceride values.
- The fuel properties such as density, flash point, methanol content, pour point, heat of combustion, acid value and copper strip corrosion values did not change significantly with the reaction parameters.
- The required viscosity for EN 14214 standards was only obtained using KOH and NaOH at 60°C . KOH and NaOH are superior to KOMe and NaOMe with the catalyst amounts used in this study. But, the effect of catalyst amounts for KOMe and NaOMe on the fuel properties should be investigated for further studies.
- The measured fuel properties of the CFME met both the ASTM D6751 and EN 14214 biodiesel standards when using KOH and NaOH at 60°C for a four-hour reaction.

References

- [1] Van Gerpen JH. Biodiesel processing and production. *Fuel Processing Technology* 2005;86:1097-1107.
- [2] Srivastava A, Prasad R. Triglycerides-based diesel fuels. *Renewable Sustain. Energy Rev.* 2000;4:111-33.
- [3] Van Gerpen JH, Shanks B, Pruszko R, Clements D, Knothe G. Biodiesel production technology. National Renewable Energy Laboratory Report, NREL/SR-510-36244, 2004.

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- [4] Darnoko D, Cheryan M. Kinetics of palm oil transesterification in a batch reactor. *JAACS* 2000;77(12):1263-67.
- [5] Canakci M. The potential of restaurant waste lipids as biodiesel feedstocks. *Bioresource Technology* 2007;98:183-90.
- [6] Sanli H, Canakci M. Effects of different alcohol and catalyst usage on biodiesel production from different vegetable oils. *Energy and Fuels* 2008;22:2713-19.
- [7] Sridharan R, Mathai MI. Transesterification reactions. 1974;33(4):178-87.
- [8] Van Gerpen JH, Peterson CL, Goering CE. Biodiesel: An alternative fuel for compression ignition engines. *American Society of Agricultural and Biological Engineers Distinguished Lecture Series* 2007;31:1-22.
- [9] Ruwwe, J. Metal alkoxides as catalysts for the biodiesel production. *Chemistry Today* 2008;26(1);26-28.
- [10] Canakci M. Combustion characteristics of a turbocharged DI compression ignition engine fueled with petroleum diesel fuels and biodiesel. *Bioresource Technology* 2007;98:1167-75.
- [11] Kondamudi N, Strull J, Misra M, Mohapatra SK. A green process for producing biodiesel from feather meal. *J. Agric. Food Chem.* 2009;57:6163-66.
- [12] Dale N. True metabolizable energy of feather meal. *J. Appl. Poult. Res.* 1992;1:331-34.
- [13] Canakci M, Van Gerpen JH. Biodiesel production via acid catalysis. *Trans. of ASAE* 1999;42(5):1203-10.
- [14] Canakci M, Van Gerpen JH. Biodiesel production from oils and fats with high free fatty acids. *Trans. of ASAE* 2001;44(6):1429-36
- [15] Canakci M. Production of biodiesel from feedstocks with high free fatty acids and its effect on diesel engine performance and emissions. Ph.D. Dissertation, Iowa State University (2001).
- [16] Ghadge SV, Raheman H. Biodiesel production from mahua (*madhuca indica*) oil having high free fatty acids. *Biomass and Bioenergy* 2005;28:601-5.
- [17] Tiwari AK, Kumar A, Raheman H. Biodiesel production from jatropha oil (*jatropha curcas*) with high free fatty acids: an optimized process. *Biomass and Bioenergy* 2007;31:569-75.
- [18] Freedman B, Pryde EH, Mounts TL. Variables affecting the yields of fatty ester from transesterified vegetable oils. *JAACS* 1984;61(10):1638-43.
- [19] Liu K. Preparation of fatty acid methyl esters for gas-chromatographic analysis of lipids in biological materials. *JAACS* 1994;71(11):1179-87.
- [20] Mattingly BG. Production of biodiesel from chicken fat containing free fatty acids. Master of Science Thesis, University of Arkansas (2006).
- [21] Bhatti HN, Hanif MA, Qasim M, Rehman A. Biodiesel production from waste tallow. *Fuel* 2008;87:2961-66.
- [22] Schulte WB. Biodiesel production from tall oil and chicken fat via supercritical methanol treatment. Master of Science Thesis, University of Arkansas (2007).