

IMPACT OF BIOETHANOL ON VCR DIESEL ENGINE PERFORMANCE USING BIODIESEL

Submitted in partial fulfillment of the requirements for the award of a
Bachelor of Engineering degree in MECHANICAL ENGINEERING

By

BADAM NANDA KISHORE REDDY (39150013)

VEGI DHANAJAI SAI SANKAR (39150129)



DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL ENGINEERING

SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY (DEEMED TO BE
UNIVERSITY)**

Accredited with grade "A" by NAAC

JEPPIAAR NAGAR, RAJIV GANDHI SALAI, CHENNAI – 600119

APRIL 2023



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)

Accredited with "A" grade by NAAC | 12B Status by UGC | Approved by AICTE
Jeppiaar Nagar, Rajiv Gandhi Salai, Chennai – 600 119
www.sathyabama.ac.in

DEPARTMENT OF MECHANICAL ENGINEERING

BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of BADAM NANDA KISHORE REDDY (39150013), VEGI DHANANJAI SAI SANKAR (39150129) who carried out the project entitled "IMPACT OF BIOETHANOL ON VCR DIESEL ENGINE PERFORMANCE USING BIODIESEL" under our supervision from December 2022 to April 2023.

Dr.S.Ganesan
Internal Guide

Dr.G.ARUN KUMAR M.E.,Ph.D.,
Head of the Department

Submitted for Viva voce Examination held on 26-04-2023

Internal Examiner

External Examiner

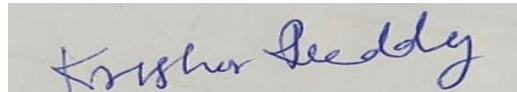
DECLARATION

We BADAM NANDA KISHORE REDDY (39150013) and VEGI DHANANJAI SAI SANKAR (39150129) hereby declare that the Project Report entitled **IMPACT OF BIOETHANOL ON VCR DIESEL ENGINE PERFORMANCE USING BIODIESEL** done by me under the guidance of Dr.S.GANESAN at SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY, CHENNAI is submitted in partial fulfillment of the requirements for the award of Bachelor of Engineering degree SATHYABAMA INSTITUTE OF SCIENCE AND TECHNOLOGY.

DATE: 26-04-2023



PLACE: CHENNAI



SIGNATURE OF THE CANDIDATE

ACKNOWLEDGEMENT

We are pleased to acknowledge my sincere thanks to Board of Management of SATHYABAMA for their kind encouragement in doing this project and for completing it successfully. We are grateful to them.

We convey our thanks to Dr.S.PRAKASH., Dean, School of MECHANICAL ENGINEERING, and Dr.G.ARUN KUMAR, Head of the Department, Dept. of MECHANICAL ENGINEERING for providing us with necessary support and details at the right time during the progressive reviews.

We would like to express my sincere and deep sense of gratitude to my Project Guide Dr. S GANESAN for his valuable guidance, suggestions, and constant encouragement paved way for the successful completion of my project work.

We wish to express our thanks to all Teaching and Non-teaching staff members of the Department of MECHANICAL ENGINEERING who were helpful in many ways for the completion of the project

ABSTRACT

Biodiesel is a fuel extracted from Natural Sources such as vegetable oils using Transesterification. The process of transesterification involves the reaction of a fat or oil with an alcohol to produce esters and glycerol. Transesterification is the easiest and most cost-effective process to produce biodiesel. Since biodiesel is made from a natural source it is renewable. Biodiesel energy is not as efficient as diesel. Biodiesel releases more gases such as CO, HC, and NOX, which are harmful to the environment. In this study, the biodiesel is extracted from a waste cooking oil such that the efficiency of the Biodiesel increases and the emission of harmful gases decreases. The properties of biodiesel such as Calorific value, Viscosity, and Density will be investigated and the performance of biodiesel by testing Brake thermal energy and Specific Fuel Consumption will also be investigated. Bioethanol is added because it has a higher-octane number and decreases the density. Four samples are prepared and mixed with diesel, bioethanol, and 2-Ethylhexyl as catalysts in different proportions. This project shall investigate the biodiesel mixture's properties, efficiency, and emission.

CONTENTS

CHAPTER No.	TITLE	PAGE No.
	ABSTRACT	i
	LIST OF FIGURES	iii
	LIST OF ABBREVIATIONS	iv
1	INTRODUCTION	1
2	LITERATURE SURVEY	4
3	AIM AND SCOPE	7
	3.1 AIM	7
	3.2 SCOPE OF THE PROJECT	7
4	EXPERIMENTAL METHODS	8
	4.1 METHODOLOGY	8
	4.2 TRANSESTERIFICATION	9
5	RESULTS AND DISCUSSION	11
6	CONCLUSION	16
	REFERENCES	17

LIST OF FIGURES

FIGURE NO	TITLE	PAGE NO.
1.1	WASTE COOKING OIL	2
1.2	TRANSESTERIFICATION PROCESS	2
4.1	BIOFUEL EXTRACTION PROCESS	8
5.1	1LT OF WASTE COOKING OIL	11
5.2	ISOPROPYL ALCOHOL	11
5.3	FREE FATTY ACID ENDPOINT	12
5.4	METHANOL	12
5.5	CHECKING THE WEIGHT OF NAOH	13
5.6	WCO IS HEATING	13
5.7	BIOFUEL WITH GLYCEROL	14
5.8	CRUDE GLYCEROL	14
5.9	BIOFUEL	15

LIST OF ABBEREVIATIONS

VCR	Variable Compression Ratio
WCO	Waste Cooking Oil
UCO	Used Cooking Oil
WFO	Waste Frying Oil
FAME	Fatty Acid Methyl Ester
FFA	Free Fatty Acid

CHAPTER - 1

INTRODUCTION

Biodiesel from renewable resources is one of the most attractive alternative fuels, present it's been producing because of its low emissions and its desired chemical features, such as being non-toxic, sustainable, and having high-quality engine performance. Any conventional diesel engine may run on biodiesel fuel. Biodiesel base materials are plant-based lipids, such as corn oil, coconut oil, palm oil, olive oil, soybean oil, grape seed oil, and canola oil, or animal-based lipids, such as butter, ghee, and fish oil. These lipids are transesterified to make biodiesel. But edible oil cost increases 2-3 times of waste cooking oil and there is huge criticism from nongovernmental organizations (NGOs) for using edible oils as fuels because millions of people are suffering from hunger. If Waste Cooking Oil is recycled and used as cooking oil it causes cancer because of the toxic contents produced when the oil is oxidized. Waste Cooking Oil leads to water pollution and blockage in drainage systems which leads to extra work. So If Waste Cooking Oil is collected from homes and restaurants using a special bin it helps the environment from pollution, the collected Waste Cooking Oil will be used to make Biodiesel. Waste Cooking Oil collected can also prepare soaps and additives for lubricating oil using glycerine, a by-product of biodiesel production. Waste Cooking Oil requires several pre-treatment steps to eliminate solid impurities and reduce Free Fatty Acids and water contents. From the transesterification process, the fuel will be extracted. Before doing the transesterification process Free Fatty Acid test has to be taken. If the Free Fatty Acid value is less than or equal to 2, then it is a transesterification process. If not, we must take it into the Esterification process to reduce the Free Fatty Acid content (mg KOH/g) to a value less than or equal to 2. However, the transesterification is dependent on the molar ratio of alcohol and the weight basis of KOH that we use as the catalyst, Widely used catalysts are acids and bases. (Arachchige et al., 2021) (Yaakob et al., 2013) (Zhang et al., 2003b)

Waste oil generated in food processing industries is directly transferred to biodiesel production units. In some cases, the same sector utilizes its waste oil



Fig:1.1: Waste cooking oil

to produce biodiesel and uses biodiesel to run its plant machinery. Waste oils produced from fast food stores or restaurants are collected by local collecting agents. The use of cooking oil over and over for frying operations increases the viscosity, acidity, specific heat, and unpleasant smell. Foodstuff's water mixes with oil during the frying process at high temperatures. This water in oil caused hydrolysis of triglycerides and forms more FFAs. To perform further biodiesel production steps, these amounts should be lowered to desired values.



Fig:1.2: Transesterification process

Several pre-treatment methods can be used for WCO like steam and sedimentation, injection of steam, neutralization, vacuum filtration, ion exchange resin method, film vacuum evaporation, and glycerin with catalyst reaction (Kulkarni and Dalai, 2006). These processes reduce the viscosity, water, and FFA contents of oil. Pre-treatment of WCO also removes the solid impurities that are added during cooking and handling operation (Yaakob et al., 2013). The high amount of water content can remove by heating at 100 °C (Li et al., 2014).

CHAPTER – 2

LITERATURE SURVEY

(Suresh et al., 2018) Researchers have reviewed and promulgated on the use of waste cooking oil, and their esters for the purpose of blending/complete substitution for standard diesel fuel. This biodiesel can be used as an alternative to diesel in the VCR engine without any modification. Switching over to VCR engine gives good performance, a lesser emission of harmful gasses such as HC, CO, CO₂, and NO_x at all loads and provides better combustion rate. It was clearly shown that VCR engine offers the potential to increase the combustion efficiency and reduces the ignition delay under varying loads and provide higher compression ratios. From all the above re-views, it was found that VCR engine has better control at peak cylinder pressure and it results in the reduction of fuel consumption. Using biodiesel in the VCR engine also has other advantages such as it reduces the power consumption, noises and so forth.

(Channappagoudra et al., 2020) For biodiesel and ethanol additive added blends in a diesel engine, the BTE increased with increased blend ratio of ethanol in diesel up to 6%. However, BTE, cylinder pressure and HRR are decreased and BSFC is increased beyond 6% ethanol addition in the B20 as they have lower calorific value and ignition delay hence more time will take to burn in the premixed combustion cause poor combustion. HC emission is increased with increased ethanol concentration in B20 because ethanol cooling effect tends to incomplete combustion hence there will be lack of auto-ignition temperature for unburned gases in the combustion chamber. For higher ethanol concentrations the CO emission is increased it could be due to more latent heat evaporation and lesser time for better mixing of air-fuel and results in poor combustion. Rapid burning of vapourized ethanol and subsequent charge leads reduced cylinder temperature which causes the poor oxidation of CO to CO₂ hence increases the CO. The addition of ethanol into biodiesel has shown the slightly higher HC, CO emission with improved BTE, BSFC, NO_x and CO₂ than sole B20. Among all three (3%, 6% and 9%) ethanol additive ratios E6% (6%) ethanol additive exhibits slightly better BTE, BSFC, and cylinder pressure.

(Arachchige et al., 2021) If we reused more than one-time fried waste cooking oil, it could become a carcinogen enzyme. Any chemical, radionuclide, or radiation that promotes carcinogenesis, or the production of cancer, is referred to as a carcinogen Biodiesel is named as a renewable and alternative fuel for diesel engines. If this FFA value is less than or equal to 2, conduct the transesterification process directly. If not, we must take it into the Esterification process to reduce the FFA content (mg KOH/g) to a value less than or equal to 2. Transesterification is commonly used to reduce the viscosity during the production of biodiesel. Widely used catalysts are acids and bases. However, the transesterification is dependent on the molar ratio of alcohol and the weight basis of KOH that we use as the catalyst

(Singh et al., 2021) WCO belongs to the 3rd generation of biodiesel. Approximately 30% of per capita edible oil consumption is generated as waste. The use of WCO reduces the cost of biodiesel production and reduces the load on waste disposal plants. WCO can be collected from food processing industries, restaurants, and houses. This collected WCO has high water and FFA contents. In order to reduce these values, pre - treatment of oil is required before biodiesel production. Oleic acid (45.15%) and linoleic acid (39.74%) are the main fatty acids content of WCO. Two -step transesterification is the most suitable method for industrial -scale biodiesel production with high biodiesel yield and low cost. Yield of biodiesel produced from transesterification reaction is highly influenced by the reaction parameters in order of; catalyst type >catalyst concentration >alcohol to oil molar ratio >reaction pressure and temperature >time of reaction. The physico chemical properties of WCO biodiesel are comparable with conventional diesel fuel. An increase in BSFC and decrease in BTE and BP are observed when WCO biodiesel is used in CI engines. Poor atomization of fuel in-side the combustion chamber and lower heating value of fuel are the reasons behind these variations. With the increase in the percentage of pure WCO biodiesel in the biodiesel diesel blend, BTE decreases, and BSFC increases. CO, HC, PM, and smoke emissions are significantly reduced with the use of WCO biodiesel in CI engines.

(Sahar et al., 2018) The FFAs of WCO were esterified using mineral acid pretreatment. Among the different mineral acids, H₂SO₄ was found to be promising for the efficient esterification of FFAs with 88% conversion efficiency. The acid-pretreated WCO was subjected to base catalyzed transesterification to produce biodiesel. 94% FAME yield was achieved with 1:3 methanol to oil ratio, 1% catalyst dose and 60 °C reaction temperature. The quality of biodiesel was evaluated through various physicochemical properties and compared with ASTM standards for biodiesel. Oleic acid, linoleic acid, palmitic acid and stearic acid were the main components of bio-diesel produced. Results revealed that acid pretreatment followed by base catalyzed reaction of WCO is viable process for biodiesel production as well as utilization of waste oil to lessen the energy crises and environmental pollution issues.

CHAPTER – 3

AIM AND SCOPE

3.1 AIM

The aim is to extract biodiesel from a waste cooking oil such that the efficiency of the Biodiesel increases and the emission of harmful gases decreases.

3.2 SCOPE

Biodiesel releases more gases such as CO, HC, and NOX, which are harmful to the environment. In this study, the biodiesel is extracted from a waste cooking oil such that the efficiency of the Biodiesel increases and the emission of harmful gases decreases.

CHAPTER – 4

4.1 METHODOLOGY

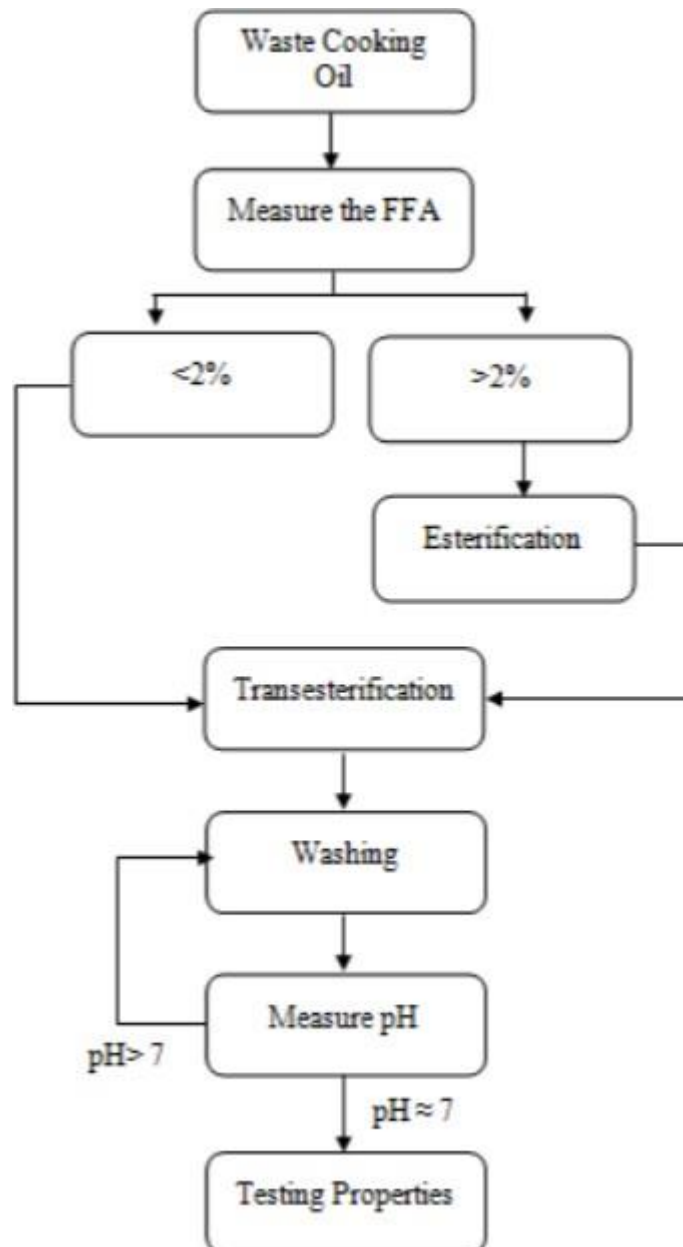


Fig:4.1: Biofuel extraction process

4.2 TRANSESTERIFICATION

Viscosity, free fatty acid content, density, water content, etc factors should be checked before using biofuel in the engine because if the water content is high then the engine will get corrosion and high viscosity will affect the injection system and combustion chamber because of gum formation. The high acidity of fuel also reduces the life of the engine (de Araújo et al., 2013). To avoid these failures several approaches should be used to produce biodiesel from waste cooking oils. Biodiesel of waste cooking oil will extract from used cooking oil by the Transesterification Process to reduce the viscosity of waste cooking oil. In the transesterification process, waste cooking oil will react with ethanol alcohol. In this process, a catalyst should be used because it will improve the reaction rate and yield, as a catalyst Sodium Hydroxide (NaOH) or Potassium Hydroxide (KOH) is used to increase reaction speed, increase product weight and increase the yield of the final product. In this process, one mole of triglyceride reacts with three moles of alcohol to produce three moles of mono-alkyl ester and one mole of glycerol. Transesterification is the process by which fats or vegetable oils are transformed into FAME and glycerol at a specific temperature while being in the presence of a specific quantity of alcohol and catalyst. The process is also known as alcoholysis. Transesterification is commonly used to reduce the viscosity during the production of biodiesel. If this FFA value is less than or equal to 2, conduct the transesterification process directly. If not, we must take it into the Esterification process to reduce the FFA content (mg KOH/g) to a value less than or equal to 2. For the production of biodiesel, the transesterification reaction is used using fats or waste/vegetable oils. It is preferred to use a lot of alcohol to increase biodiesel production. The choice of catalysts is crucial since the reaction will result in greater soap formation if an appropriate catalyst with a defined amount is not employed. Different kinds of catalysts, including acid, base, enzyme, and nanocatalysts, can be utilized in this reaction. Al-kali acid and base catalysts can be homogeneous or heterogeneous. The third generation of biodiesel includes WCO. Approximately 30% of the edible oil consumed by each person is wasted. The yield of biodiesel produced from transesterification reaction is highly influenced by the reaction parameters in order of; catalyst type >catalyst concentration >alcohol to oil molar ratio >reaction pressure and temperature >time of reaction. The physicochemical properties of WCO biodiesel are

comparable with conventional diesel. The most effective technology for industrial-scale biodiesel synthesis with a high biodiesel output and low cost is two-step transesterification. The most effective technology for industrial-scale biodiesel synthesis with a high biodiesel output and low cost is two-step transesterification. (Singh et al., 2021), (Arachchige et al., 2021), (Abed et al., 2019).

CHAPTER – 5

RESULT AND DISCUSSION

The transesterification process has been completed by using Waste Cooking Oil, before processing into the transesterification process Free Fatty Acid content should be checked.



Fig:5.1: 1lt of waste cooking oil from sathyabama cafeteria

The Free Fatty Acid procedure is to take 5gm of waste cooking oil, 25ml of Isopropyl alcohol, and 4 drops of 0.1 normality NaOH. It should be heated to 60 degrees temperature and allowed the room temperature.



Fig:5.2: Isopropyl alcohol for FFA

After allowing it at room temperature add 2 drops of phenolphthalein indicator and keep stirring, pink color appearance will appear at the endpoint.



Fig:5.3: Free Fatty Acid endpoint

Once FFA content reading shows $2\% <$ then it is the Transesterification process.

For the Transesterification process take 1lt of WCO heated at 60 deg temperature and add methoxide in the ratio of 1:3



Fig:5.4: Methanol

1lt of WCO, 182 ml of methanol, and 5gm of NaOH are the apparatus required for the Transesterification process.



Fig:5.5: Checking the weight of NaOH

1lt of oil will be placed on the hot plate with a stirrer magnetic palate will be placed inside the oil for the stirring process and the thermometer will also be placed to know the temperature of the oil. The temperature should be 60 degrees. The stirrer is used to circulate the temperature of the oil.



Fig:5.6: WCO is heating

After the temperature reached 60 degrees add the catalyst. After adding the catalyst condenser equipment will be fixed to maintain the oil temperature stable at 60 degrees.



Fig:5.7: Biofuel with glycerol

When it reached 60 degrees temperature we added methoxide maintain it at 60 degrees and allow the time for 90 minutes. Transferring to the separating funnel 2 layers will form.

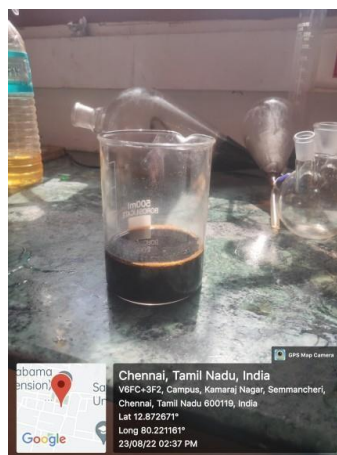


Fig:5.8: Crude glycerol

The top layer is crude biofuel and the bottom layer is crude glycerol. The Crude glycerol will be separated and it is the byproduct it can be used in many products such as toothpaste, mouthwashes, shaving cream, and soaps



Fig:5.9: Biofuel

The extraction of Biofuel from Waste cooking oil has been extracted with the transesterification process.

CHAPTER – 6

SUMMARY AND CONCLUSION

Waste Cooking Oil was filtered to remove food residues and other suspended matters to complete the filtration process. Then it was heated at a high temperature to remove the soluble impurities and moisture. The acid number of the Waste Cooking Oil should be measured to get the Free Fatty Acid value. We aimed to reduce the FFA value of WCO to a value of less than or equal to 2%. The transesterification process has been completed and further processes are to be carried out like property check of the biofuel.

REFERENCES

- [1] Abed, K. A., el Morsi, A. K., Sayed, M. M., Shaib, A. A. E., & Gad, M. S. (2018). Effect of waste cooking oil biodiesel on performance and exhaust emissions of a diesel engine. *Egyptian Journal of Petroleum*, 27(4), 985–989. <https://doi.org/10.1016/j.ejpe.2018.02.008>
- [2] Abed, K. A., Gad, M. S., el Morsi, A. K., Sayed, M. M., & Elyazeed, S. A. (2019). Effect of biodiesel fuels on diesel engine emissions. *Egyptian Journal of Petroleum*, 28(2), 183–188. <https://doi.org/10.1016/j.ejpe.2019.03.001>
- [3] Ali, O. M., Mamat, R., & Faizal, C. K. M. (2013). Review of the effects of additives on biodiesel properties, performance, and emission features. *Journal of Renewable and Sustainable Energy*, 5(1). <https://doi.org/10.1063/1.4792846>
- [4] Arachchige, U., Weerasekara, N. A., Thilakarathne, D., Miyuranga, K. A. V., Arachchige, U. S. P. R., Weerasekara, N. A., & Jayasinghe, R. A. (2021). Production of Biodiesel from Waste Cooking Oil in Laboratory Scale: A Review. In *Article in International Journal of Scientific and Engineering Research* (Vol. 5, Issue 6). <http://ijses.com/>
- [5] Bilgin, A., Gülüm, M., Koyuncuoglu, İ., Nac, E., & Cakmak, A. (2015). Determination of Transesterification Reaction Parameters Giving the Lowest Viscosity Waste Cooking Oil Biodiesel. *Procedia - Social and Behavioral Sciences*, 195, 2492–2500. <https://doi.org/10.1016/j.sbspro.2015.06.318>
- [6] Channappagoudra, M., Ramesh, K., & Manavendra, G. (2020). Bio-ethanol additive effect on direct injection diesel engine performance, emission and combustion characteristics—an experimental examination. *International Journal of Ambient Energy*, 41(12), 1342–1351. <https://doi.org/10.1080/01430750.2018.1517665>
- [7] Chen, H., Xie, B., Ma, J., & Chen, Y. (2018). NO_x emission of biodiesel compared to diesel: Higher or lower? *Applied Thermal Engineering*, 137, 584–593. <https://doi.org/10.1016/j.applthermaleng.2018.04.022>
- [8] Demirbas, A. (2008). Relationships derived from physical properties of vegetable oil and biodiesel fuels. *Fuel*, 87(8–9), 1743–1748. <https://doi.org/10.1016/j.fuel.2007.08.007>
- [9] Giakoumis, E. G., & Sarakatsanis, C. K. (2018a). Estimation of biodiesel

- cetane number, density, kinematic viscosity and heating values from its fatty acid weight composition. *Fuel*, 222, 574–585. <https://doi.org/10.1016/j.fuel.2018.02.187>
- [10] Hoekman, S. K., & Robbins, C. (2012). Review of the effects of biodiesel on NO_x emissions. In *Fuel Processing Technology* (Vol. 96, pp. 237–249). <https://doi.org/10.1016/j.fuproc.2011.12.036>
- [11] Kassem, Y., Çamur, H. A Laboratory Study of the Effects of Wide Range Temperature on the Properties of Biodiesel Produced from Various Waste Vegetable Oils. *Waste Biomass Valor* 8, 1995–2007 (2017). <https://doi.org/10.1007/s12649-016-9753-4>
- [12] Knothe, G., & Steidley, K. R. (2005a). Kinematic viscosity of biodiesel fuel components and related compounds. Influence of compound structure and comparison to petrodiesel fuel components. *Fuel*, 84(9), 1059–1065. <https://doi.org/10.1016/j.fuel.2005.01.016>
- [13] Kulkarni, M. G., & Dalai, A. K. (2006). Waste cooking oil - An economical source for biodiesel: A review. In *Industrial and Engineering Chemistry Research* (Vol. 45, Issue 9, pp. 2901–2913). <https://doi.org/10.1021/ie0510526>
- [14] Martínez, G., Sánchez, N., Encinar, J. M., & González, J. F. (2014). Fuel properties of biodiesel from vegetable oils and oil mixtures. Influence of methyl esters distribution. *Biomass and Bioenergy*, 63, 22–32. <https://doi.org/10.1016/j.biombioe.2014.01.034>
- [15] Nguyenthi, T. X., Bazile, J. P., & Bessi res, D. (2018a). Density measurements of waste cooking oil biodiesel and diesel blends over extended pressure and temperature ranges. *Energies*, 11(5). <https://doi.org/10.3390/en11051212>
- [16] Palash, S. M., Kalam, M. A., Masjuki, H. H., Masum, B. M., Rizwanul Fattah, I. M., & Mofijur, M. (2013). Impacts of biodiesel combustion on NO_x emissions and their reduction approaches. In *Renewable and Sustainable Energy Reviews* (Vol. 23, pp. 473–490). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2013.03.003>
- [17] Ram rez-Verduzco, L. F., Garc a-Flores, B. E., Rodr guez-Rodr guez, J. E., & del Rayo JaramilloJacob, A. (2011a). Prediction of the density and viscosity in biodiesel blends at various temperatures. *Fuel*, 90(5), 1751–1761.

<https://doi.org/10.1016/j.fuel.2010.12.032>

[18] Sahar, Sadaf, S., Iqbal, J., Ullah, I., Bhatti, H. N., Nouren, S., Habib-ur-Rehman, Nisar, J., & Iqbal, M. (2018). Biodiesel production from waste cooking oil: An efficient technique to convert waste into biodiesel. *Sustainable Cities and Society*, 41, 220–226. <https://doi.org/10.1016/j.scs.2018.05.037>

[19] Simsek, S., Uslu, S., Simsek, H., & Uslu, G. (2021). Multi-objective-optimization of process parameters of diesel engine fueled with biodiesel/2-ethylhexyl nitrate by using Taguchi method. *Energy*, 231. <https://doi.org/10.1016/j.energy.2021.120866>

[20] Singh, D., Sharma, D., Soni, S. L., Inda, C. S., Sharma, S., Sharma, P. K., & Jhalani, A. (2021). A comprehensive review of biodiesel production from waste cooking oil and its use as fuel in compression ignition engines: 3rd generation cleaner feedstock. In *Journal of Cleaner Production* (Vol. 307). Elsevier Ltd. <https://doi.org/10.1016/j.jclepro.2021.127299>

[21] Suresh, M., Jawahar, C. P., & Richard, A. (2018). A review on biodiesel production, combustion, performance, and emission characteristics of non-edible oils in variable compression ratio diesel engine using biodiesel and its blends. In *Renewable and Sustainable Energy Reviews* (Vol. 92, pp. 38–49). Elsevier Ltd. <https://doi.org/10.1016/j.rser.2018.04.048>

[22] Vijay Kumar, M., Veeresh Babu, A., & Ravi Kumar, P. (2018). The impacts on combustion, performance and emissions of biodiesel by using additives in direct injection diesel engine. In *Alexandria Engineering Journal* (Vol. 57, Issue 1, pp. 509–516). Elsevier B.V. <https://doi.org/10.1016/j.aej.2016.12.016>

[23] Wang, X., Ge, Y., Yu, L., & Feng, X. (2013). Comparison of combustion characteristics and brake thermal efficiency of a heavy-duty diesel engine fueled with diesel and biodiesel at high altitude. *Fuel*, 107, 852–858. <https://doi.org/10.1016/j.fuel.2013.01.060>

[24] Yaakob, Z., Mohammad, M., Alherbawi, M., Alam, Z., & Sopian, K. (2013). Overview of the production of biodiesel from Waste cooking oil. In *Renewable and Sustainable Energy Reviews* (Vol. 18, pp. 184–193). <https://doi.org/10.1016/j.rser.2012.10.016>

[25] Zhang, Y., Dubé, M. A., McLean, D. D., & Kates, M. (2003a). Biodiesel

production from waste cooking oil: 1. Process design and technological assessment. In *Bioresource Technology* (Vol. 89, Issue 1, pp. 1–16). Elsevier Ltd. [https://doi.org/10.1016/S0960-8524\(03\)00040-3](https://doi.org/10.1016/S0960-8524(03)00040-3)

[26] Zhang, Y., Dubé, M. A., McLean, D. D., & Kates, M. (2003b). Biodiesel production from waste cooking oil: 2. Economic assessment and sensitivity analysis. *Bioresource Technology*, 90(3), 229–240. [https://doi.org/10.1016/S0960-8524\(03\)00150-0](https://doi.org/10.1016/S0960-8524(03)00150-0)