Biodiesel: Review on Production Techniques & Raw Material Process Economic Aspects

J. Srinithi[1], M. Thirumarimurugan[2*]

[1]Research Scholar, Department of Chemical Engineering, Coimbatore Institute of Technology
[2]Professor & Head, Department of Chemical Engineering, Coimbatore Institute of Technology*

***Corresponding Author:** J.Srinithi, Research Scholar , Department of Chemical Engineering,Coimbatore Institute of Technology,

Abstract:

Biodiesel is found to be one of the promising alternatives for conventional fuels since lot of researches and steps for practical implementation has been started by numerous countries to meet out the futuristic demands of switching towards new energy sources due to less toxicity and eco-friendly aspects. Diverse feedstock's are being used to produce by means of blending/direct use, micro-emulsion, thermal cracking/pyrolysis and transesterification. Parameters like type of alcohol, type of catalyst & its quantity, alcohol to oil ratio, stirring speed, temperature, pressure, time of reaction and type of source oil plays a major role in the contribution of yield, efficiency and cost. It is really important to study the process economics to understand the aspects in practical implementation. This study entirely deals with biodiesel production methods, parameters associated and process economics behind selection of raw materials.

Keywords: *Biodiesel, Production, Process Economics, Raw materials, Feedstock*

1. INTRODUCTION

Decrease in availability of mineral oils is becoming a biggest concern in terms of energy crisis. Mineral oil also leads a way for global warming, environmental degradation and pollution, green house effect etc.[1] Few statistics reveals that oil and gas will not be available for use after 63 years if it is used consistently in the same pace.[2] Thoughscientists are working hard in doing researches on the areas of wind, geothermal and solar technologies, there is a huge need of alternative renewable energy sources termed as bio fuelswhich is an emerging technique in the field of energy sector.

In recent trends, world is stepping forward for a renewable production source of alternative fuel for diesel which is beneficial to environment, non-toxic and bio-degradable.

In the vision of deficiency towards fossil fuels and a hike in demand of diesel for generation of power, agriculture and transportation [3] in very near future tends to identification and implementation of new alternative to avoid the crisis and an alternative is necessary and unavoidable in current scenario.

Biodiesel is produced from various biological resources which are renewable and non- toxic to environment such as fats and non-edible oils etc. which can be a best alternative for diesel. Biodiesel literally defined as a fuel with long chain fatty acids with mono-alkyl esters from oils and fats.[4] Numerous research studies prove that biodiesel can be a suitable alternative and substitute. Production techniques undergo speedy and comprehensive techno- revolution in academic and industries. Efficiency majorly deals with feedstock nature, catalyst, reaction time, temperature, alcohol type and economic aspects.[5]

In case of switching towards fuel of biodiesel, there records a neutral carbon since the quantity of emitted carbon will be same as adsorbed by plant/animal during its life time during combustion process makes a evidence of minimal emission during green combustion. In recent trends, domination of diesel may be high but for an alternative is truly need when we think in a futuristic approach and we can believe that biodiesel can be such a boon for the cause.

Key Characteristics of Pure Biodiesel

Certain key observation has to be done during the examination of pure biodiesel and the observations are being listed in the Table 1. [6]

Table 1: Biodiesel Characteristics

S. No	Property	Observations
1	Anti-Foaming	Excellent
2	Cetane Number	45 & 70
3	Chemical Structure	Ester of fatty acids C_{22}, C_{16}, C_{12}, C_{14} &C_{18}.
4	Oxygen content	11%
5	Cold flow properties	Solidification become difficult to control and more rapid
6	Conductivity	500 pico S/m
7	Corrosion	Oxygen presence may contribute towards corrosion

Classification of Bio-fuel

Bio-fuels are broadly classified into three major categories based on their feedstock selection for production of bio-fuel named as first, second and third generation bio-fuels. The classification criteria and example of feed-stock is listed in Table 2. [7]

Table 2: Biodiesel Classification

Generation	Definition	Feed-stock
First	Produced from food-crop or cultivated bio-energy Crops	Direct usage of wheat, sorghum etc.
Second	Produced from Non-food feedstock such as agro and forestry stocks	Residues from agro and food stock
Third	Produced from aquatic cultivated feedstock	Algae

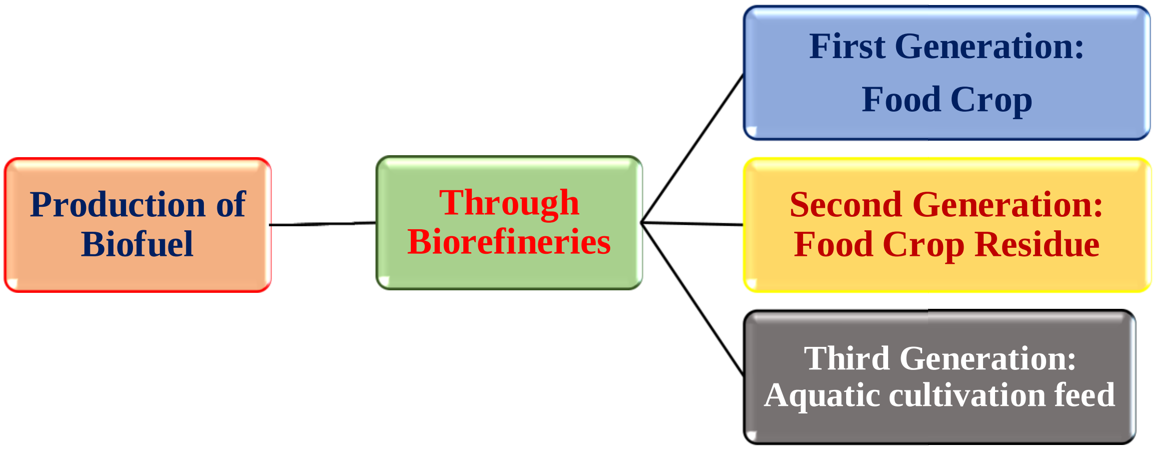

Figure 1: Classification of Biodiesel

2. Production of Biodiesel

The four main approaches for production of bio-diesel are [8]

1) Direct use and Blending

2) Transesterification Process

3) Thermal Cracking/Pyrolysis

4) Microemulsion

Direct use and Blending:

Usage of vegetable oils directly to engines as a fuel consists of numerous practical implementation issues with it. Considering those conditions, an alternative method of blending technique has been adopted and the method helps in obtaining the properties of a fuel to a considerable extent. This method helps us in overcoming the faced issues in practical approach. Blending help in improving quality and reducing consumption thereby play a promising role in approaching the alternatives.

Table 3: Blending

S.NO	Biodiesel	Blender	Key Notes	References
1	*E. sanguinea*	Diesel	40% ES	[9]
2	Jatropha seeds	Diesel	20% JS	[10]
3	Rice bran	Ethanol	2.5 % E	[11]
4	Corn	Diesel	20% C	[12]
5	Soyabean	Diesel	20% S	[13]
6	Safflower oil	ULSD	50% B	[14]
7	Mahua fruit	Mineral diesel	30% MD	[15]

Successful ratio of 1:10 to 2:10 is preferred for running in a short period. Also there is a need of modifications in engine and customized running system for energy production since on usage without modifications lead to high risk and even danger of failure too.[16]

Transesterification Process

Glycerol and Biodiesel produced by combination of alcohol and triglycerides in vegetables leads to a reaction called as transesterification. The process takes place in the presence or absence of the catalyst which is determined by the quantity of feed stock free fatty acid which is directly related to important parameters like efficiency & production. It is a reversible process where reaction takes place usually under temperature/pressure. [17] The following equation depicts the simple transesterification reaction.

$$Triglyceride\ (C_6H_8O_6) + Alcohol(ROH) \xrightarrow{Catalyst} Glycerol\ (C_3H_8O_3) + Free\ fatty\ esters\ (C_2H_3O_2R)$$

Generally transesterification takes place in different steps like acid, base, heterogeneous, lipase, supercritical, nano and ionic liquid catalysed process. [18] All the transesterification process looks similar but the change in catalyst plays a primary role in it.

Acid Catalysed

The reaction requires longer time and higher temperature. Sulphonic, hydrochloric and sulphuric acid are commonly used acid in the process.

Table 4: Acid Catalysed Transesterification

Raw Material	Acid Used	Yield %	References
Refined soybean oil	Trifluoroacetic acid	98.4	[19]
Jatropha curcas oil	H_2SO_4	95	[20]
Waste cooking oil	H_2SO_4	89.6	[20]
Palm oil	$CH_3OH-H_2SO_4$	83.72	[21]
Corn Oil	p-toluenesulfonic acid	100	[22]
Sunflower and Soyabean oil	H_2SO_4	96.6	[23]

Base Catalysed

The reaction is faster over here and corrosion is less but the process economics is higher due to catalyst consumption and issues in separation process. NaOH and KOH are commonly used catalyst in the process.

Table 5: Base Catalysed Transesterification

Raw material	Base used	Yield%	Reference
Jatropha Oil	NaOH	95.5	[24]
Soyabean Oil	NaOH	90	[25]
Cotton seed Oil	NaOH	98.5	[25]
Ceiba pentandra oil	KOH	96.2	[26]
Karanja oil	KOH	98	[27]
Sunflower cooking oil	KOH	99.5	[28]
Waste cooking oil	KOH	93.2	[29]

Heterogeneous catalysed

The reaction holds a great advantage of simpler separation and lower contamination enabling catalyst reusability. Potassium zirconias, Titanium and Amp. zirconia are few of theheterogeneous catalysts.

Table 6: Heterogeneous Catalysed Transesterification

Raw material	Catalyst used	Yield%	Reference
Soyabean Oil	Titanium	95	[30]
Soyabean oil	Al doped Zirconias	95	[30]
Jatropha curcas oil	Solid Super Base CaO	93	[31]
Jojoba oil	CaO	96.3	[32]
Waste Cooking Oil	SO_4^{2-}/TiO_2-ZrO_2	96.7	[33]
PFAD	SO_4^{2-}/TiO_2-ZrO_2	98.9	[34]
Decanter Cake	SO_4^{2-}/TiO_2-ZrO_2	91	[35]

Lipase catalysed

Though the cost and reaction time are quite more, utilizing enzymes become a recent trend as it help to produce a high purity product and supporting quite easier separation. Pseudomonas species, Rhizopus oryza, Novozym 435, Lipozyme TL are few enzymes utilized in the process.

Table 7: Lipase Catalysed Transesterification

Raw material	Catalyst used	Yield%	Reference
Jatropha oil	Pseudomonas fluorescens	72	[36]
Virgin Oil	Rhizopus oryzae	75	[37]
Waste vegetable oil	Rhizopus oryzae	80	[38]
Soyabean Oil	Rhizopus oryzae	92	[39]
Rapeseed Oil	Lipozyme TL	95	[40]
Jatropha Oil	Chromobacterium viscosum	71	[41]
Soyabean Oil	Candida antarctica	80	[42]

Supercritical Reaction

Considering immiscibility constraints, this type of reaction takes place under high temperature and pressure. It is non catalytic but takes very lesser time for reaction. Though methanol consumption and cost are higher, purity is good, separation is easier and it an eco friendly process.

Table 8: Supercritical Catalysed Transesterification

Raw material	Optimum Conditions	Yield%	Reference
Rapeseed Oil	350^{o}C & 14 MPa	95	[43]
Coconut Oil	350^{o}C & 19 MPa	95	[44]
Palm Kernel Oil	350^{o}C & 19 MPa	96	[44]
Sunflower seed oil	252^{o}C & 24 MPa	95	[45]
Vegetable Oil	200^{o}C & 20 MPa	80	[46]
RBD Palm oil	350^{o}C & 40 MPa	95	[47]
Jatropha Oil	320^{o}C & 8.4 MPa	100	[48]

Nano Catalysed

This type of advanced catalyst enhances the catalytic activity due to its enormous advantages. It can be concluded as a promising one for effective production. Few of the nano catalysts are CaO/CaN, CaO/SS, CaO-Al2O3 etc.

Table 9: Nano Catalysed Transesterification

Raw material	Catalyst used	Yield%	Reference
Palm Oil	$SrO–CaO–Al_2O_3$	98.16	[49]
Soyabean Oil	CaO/CaN	93	[50]
Soyabean Oil	CaO/SS	96	[50]
Waste Cooking Oil	CaO	94.4	[51]
Waste Cooking Oil	CaO & MgO	98.95	[51]
Stillingia oil	$KF/CaO–Fe_3O_4$	95	[52]
Chinese tallow seed oil	KF/CaO	96.8	[53]

Ionic Liquid Catalysed

This type of catalyst helps us in formation of biphasic product at the end enabling quick separation. The process takes very less time compared to others and also helps us in reusability. 1-n-butyl-3-methylimidazolium is one of the ionic liquid studied by many researchers.

Table 10: Ionic Catalysed Transesterification

Raw Material	Catalyst Used	Yield %	Reference
Rapeseed oil	1-butyl-3-methylimidazolium hydrogen sulfate	8.89	[54]
Soyabean Oil	Chloroaluminate	98.5	[55]
Cottonseed Oil	1-(4-Sulfonic acid) butylpyridinium hydrogen sulfate	92	[56]
Rapeseed oil	1-butylsulfonate-3-methyl imidazolium hydrogen sulfate	100	[54]
Soyabean Oil	Brønsted acidic ionic liquid	93.2	[57]
Waste Palm Cooking Oil	butyl-methyl imidazolium hydrogensulfate	95.7	[58]

Thermal Cracking/ Pyrolysis

Numerous small molecules formed due to breakage of bonds using heat between 400 – 600 °C with/without oxygen or with/without catalyst named as a chemical change called Pyrolysis. Among the different classes of production, fast pyrolysis is found to be best suited one for the production of bio-diesel due to its simplicity and efficiency. The process should be made with at most care since small deviations may lead to different products and uncertainty in purity of the product. Also separation technique in post production is yet a challenging milestone in this type of process. Zeolites, Red-mud and Alumina are the commonly used catalyst in pyrolysis process.

Table 11: Thermal Cracking/Pyrolysis

Raw Material	Catalyst Used	Yield %	Reference
Waste olive oil	Dolomite	93	[59]
Rapeseed oil	ZSM-5	95	[60]

Biomass tar	ZSM-5	75.56	[61]
Soybean oil	Bauxite	93	[62]
Vegetables oil	Sulfated zirconia	97.08	[63]
Sunflower oil	HZSM-5	83.13	[64]
Woody oil	Al_2O_3/MCM-41/CaO	90.1	[65]

Micro emulsions

Certain oil cannot be directly used as a fuel and viscosity might be one of the reasons for the particular cause. In this regard, micro-emulsions can be a best suitable one to overcome the cause. It really consists of oil, water and a surfactant which helps in incrementing the Cetane number and lowering the viscosity. This type of biodiesel cannot be used for a long time in a engine because it may cause damage to the engines. But literally thistype of fuel possesses best spray property when compared to others.

Table 12: Micro emulsions

S.No	**Micro-emulsions**	**Reference**
1	Ethanol – Vegetable Oil – Carboxylate	[66]
2	Ethanol – Palm Oil – Diesel	[67]
3	Ethanol – Jatropha Oil – Diesel	[68]
4	Ethanol – Jatropha Oil – Sorbitane Fatty esters	[69]
5	Rhamnolipid – Crude Glycerine – Diesel	[70]

3. Discussion of Key Variables involved in Biodiesel Characteristics

Key variables associate with Biodiesel production are selection of type of alcohol needed, Alcohol to Oil Ratio, Time of the reaction, Temperature needed, Necessity of mixing, type of catalyst and its quantity, pressure etc. Each variable has its own characteristic contribution towards the economical, simple and quicker process for biodiesel production.

Selection of Oil

The most important entity required for the biodiesel production is Oil source. Selection of oil is done based on analyzing its physicochemical characteristics like viscosity, calorific value etc. which help us to identify the suitable oil which as a primary base raw material for biodiesel production. Also few parameters like iodine index, acidity, phosphorous index and oxidation stability are quality based parameters studied before selection of oil source. Also fatty acid content deals with the production process in a major extent since catalyst selection greatly deals with it. [71] Jatropha, rapeseed, sunflower, palm, soybean, cotton etc. are the most commonly used raw material for producing oil.

Type of Alcohol

As we are aware that alcohol reacts with triglycerides to form free fatty acids. Thus alcohol is a major raw material required for the process to complete the reaction.[72] Ethanoland Methanol are most commonly used alcohols in the production process due to its availability physical & chemical advantages and low cost. There are other few alcohols used in process like butanol, octanol, branched alcohols etc. but they are costly. Also few co- solvent with alcohol for better yield purpose has been reported in few researches but majorly Methanol is using by extensive researchers in their research.

Alcohol to Oil Ratio:

An important parameter associated with yield, cost and conversion is alcohol to oil ratio. Literally when conversion needs to occur in a shorter time, alcohol to oil ratio should be higher and it may be lead to higher to purity of biodiesel.[73] The alcohol to oil ratio reported in various literatures vary from 1:1 to 45:1 in different methods of production of biodiesel. This ratio selection makes a huge impact until the biodiesel refining process.

Time of reaction, Stirring speed, Temperature and Pressure

All the parameters are interlinked with each other and we can infer that the above parameters deal with overall production time, quantity and cost. Reaction time is one which deals with quantity of production and cost of production. Only few process required stirring when viscosity variance occurs during the reaction. Temperature and Pressure is varied only when the reaction is too low and this type of reaction occurs under special category only. Also all these parameters deal with yield, conversion efficiency & purity of production.[74]

Type of Catalyst and Quantity

Quantity of catalyst and the type of the catalyst used for the reaction is directly proportional to biodiesel yield and conversion efficiency since the catalyst increase the speed of the reaction thereby enabling increase in yield. There are several type of catalyst available like acid, basic, ionic, nano etc. and the catalyst is selected for the reaction on the basis of oil source characteristics.[75]

Other parameters

Selection of appropriate blend quantity and the selection of required quantity of emulsions for the preparation of biodiesel play a major role in blending and micro-emulsions techniques respectively in which those parameters meant to deal with yield and efficiency aspects.

4. Process Economics dealing with Raw Material

Process Economics is one of the important aspects to be studied in all the areas of engineering, science and technology as it paves a successful way for the practical implementation of the idea or research aspects. [76] World due to its adverse effects facing in the areas of environment protection and its related health hazards taking a joint initiative to save the earth. Also Government has started using blending technique as a miniature alternative for this futuristic idea. But a prominent alternative really needed and Biodiesel found to be a boon for the conventional fossil fuels. In this regard, it should be economical tobring out for human consumption in daily needs.

Oil, Alcohol and Catalyst are the primary raw materials involved in this process. As discussed earlier in this study, Methanol is commonly used as an alcohol due to its availability and low cost in several processes.[72] Though co-solvents used in few studies, it is added in a very minimal amount and it does not make a much variation. Catalyst is anotherchallenge but numerous studies worked up in biodiesel production consumes very less amount of catalyst and also the most of the catalyst used as easily available and of considerable cost.[75]

The only thing we need to study is the oil source and its availability for its implementation in practical applications. Jatropha, rapeseed, cottonseed, palm, vegetable, sunflower, soybean and waste cooking oil are commonly used source for oil.[77] In this area,cottonseed, palm, sunflower, vegetable, rapeseed and soybean oil are being used in the areas of cooking and wide extensive use of those oils in production of biodiesel may make a huge impact on the food market chain and oil price may reach a hike. Also collection of waste cooking oil is really a challenging task in preparing biodiesel. Thus we can infer that

Jatropha oil, non edible oil found to be a boon for the biodiesel production industry. Also statistics says that Jatropha cultivation has been increased gradually to a great extent in past 10 years giving a hope towards switching an alternative fuel for usage.

Jatropha oil cost around Rs. 8-10 per litre and NaOH can be used a catalyst since the research stated the highest yield using the same in adding methanol in the ratio of 5:1. We can conclude in the aspects of raw material process economics that Jatropha Oil found to be aboon to biodiesel production.

5. Conclusion

The following points were inferred during this study in the process economic aspects of biodiesel production:

1) As we are aware, Methanol can be used a alcohol in the process considering availability and low cost
2) Base Catalyst is preferred due to its low cost and availability
3) Jatropha Oil is economical for this process and can be used in biodiesel production to meet out the problems which we are going to face in our future.
4) Since methanol to oil ratio is low while using base catalysts, overall process cost is also low enabling the public to change their mind towards quick shift for the biodiesel usage as an alternative fuel.
5) Also there is no need of making quite huge modifications in engine system while implementation for practical use.
6) Production process in simpler proving high purity and easier separation of the components.

REFERENCES

1. *Bünger, J., et al. "Cytotoxic and mutagenic effects, particle size and concentration analysis ofdiesel engine emissions using biodiesel and petrol diesel as fuel." Archives of toxicology 74.8 (2000): 490-498.*
2. *Global Reports and Publications. Statistical review of world energy; June 2007.*
3. *Birol F (2014) world energy outlook 2013–2035. Rotterdam: International Energy Agency, IEA.*
4. *Pinto, Angelo C., et al. "Biodiesel: an overview." Journal of the Brazilian Chemical Society 16.6B (2005): 1313-1330.*
5. *Van Gerpen, Jon. "Biodiesel processing and production." Fuel processing technology 86.10 (2005): 1097-1107.*

6. *Atabani, Abdelaziz E., et al. "A comprehensive review on biodiesel as an alternative energy resource and its characteristics." Renewable and sustainable energy reviews 16.4 (2012): 2070-2093.*
7. *Hao, Han, et al. "Biofuel for vehicle use in China: Current status, future potential and policy implications." Renewable and Sustainable Energy Reviews 82 (2018): 645-653.*
8. *Oh, Pin Pin, et al. "A review on conventional technologies and emerging process intensification (PI) methods for biodiesel production." Renewable and Sustainable Energy Reviews 16.7 (2012): 5131-5145.*
9. *Papu, Nabam Hina, Pradip Lingfa, and Santosh Kumar Dash. "Euglena Sanguinea algal biodiesel and its various diesel blends as diesel engine fuels: a study on the performance and emission characteristics." Energy Sources, Part A: Recovery, Utilization, and Environmental Effects (2020): 1-13.*
10. *Chauhan, Bhupendra Singh, Naveen Kumar, and Haeng Muk Cho. "A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends." Energy 37.1 (2012): 616-622.*
11. *Venkata Subbaiah, G., and K. Raja Gopal. "An experimental investigation on the performance and emission characteristics of a diesel engine fuelled with rice bran biodiesel and ethanol blends." International Journal of Green Energy 8.2 (2011): 197-208.*
12. *Manigandan, S., et al. "Emission and injection characteristics of corn biodiesel blends in diesel engine." Fuel 235 (2019): 723-735.*
13. *Candeia, R. A., et al. "Influence of soybean biodiesel content on basic properties of biodiesel–diesel blends." Fuel 88.4 (2009): 738-743.*
14. *Aydın, Selman. "Detailed evaluation of combustion, performance and emissions of ethylproxitol and methyl proxitol-safflower biodiesel blends in a power generator diesel engine." Fuel 270 (2020): 117492.*
15. *Acharya, N., et al. "Analysis of properties and estimation of optimum blending ratio of blended mahua biodiesel." Engineering Science and Technology, an International Journal 20.2 (2017): 511-517.*
16. *Ghazali, Wan Nor Maawa Wan, et al. "Effects of biodiesel from different feedstocks on engine performance and emissions: A review." Renewable and Sustainable Energy Reviews 51 (2015): 585-602.*
17. *Fukuda, Hideki, Akihiko Kondo, and Hideo Noda. "Biodiesel fuel production by transesterification of oils." Journal of bioscience and bioengineering 92.5 (2001): 405-416.*
18. *Ma, Fangrui, and Milford A. Hanna. "Biodiesel production: a review." Bioresource technology 70.1 (1999): 1-15.*
19. *Miao, Xiaoling, Rongxiu Li, and Hongyan Yao. "Effective acid-catalyzed transesterification for biodiesel production." Energy Conversion and Management 50.10 (2009): 2680-2684.*
20. *Patil, Prafulla D., Veera Gnaneswar Gude, and Shuguang Deng. "Biodiesel production from Jatropha curcas, waste cooking, and Camelina sativa oils." Industrial & Engineering Chemistry Research 48.24 (2009): 10850-10856.*
21. *Patle, Dipesh S., and Zainal Ahmad. "Techno-economic analysis of an alkali catalyzed biodiesel production using waste palm oil." Applied Mechanics and Materials. Vol. 465. Trans Tech Publications Ltd, 2014.*
22. *Guan, Guoqing, et al. "Transesterification of vegetable oil to biodiesel fuel using acidcatalysts in the presence of dimethyl ether." Fuel 88.1 (2009): 81-86.*
23. *Gebremariam, Shemelis Nigatu, and Jorge Mario Marchetti. "Biodiesel production through sulfuric acid catalyzed transesterification of acidic oil: Techno economic feasibility of different process alternatives." Energy Conversion and Management 174 (2018): 639-648.*
24. *Ojolo SJ OBS, Adelaja AO, Ogbonnaya M (2011) Study of an effective technique for the production of biodeseal. JETEAS 2: 79–86.*
25. *Keera ST, El Sabagh SM, Taman AR (2011) Transesterification of vegetable oil to biodiesel fuel using alkaline catalyst. Fuel 90: 42–47.*

26. *Kusumaningtyas, Ratna Dewi, et al. "Synthesis of biodiesel from kapok (Ceiba pentandra L.) seed oil through ultrasound-enhanced transesterification reaction." AIP Conference Proceedings. Vol. 2217. No. 1. AIP Publishing LLC, 2020.*
27. *Meher L, Dharmagadda VS, Naik S (2006) Optimization of alkali-catalyzed transesterification of Pongamia pinnata oil for production of biodiesel. Bioresource technol 97: 1392–1397*
28. *Boyce ABMSHaAN (2009) Biodiesel Production from Waste Sunflower Cooking Oil as an Environmental Recycling Process and Renewable Energy. Bulgarian J Agricul Sci 15: 312– 317.*
29. *Ouanji F, Kacimi M, Ziyad M, et al. (2016) Production of biodiesel at small-scale (10 L) for local power generation. Int J Hydrogen Energ 42: 8914–8921.*
30. *Furuta S, Matsuhashi H, Arata K (2006) Biodiesel fuel production with solid amorphouszirconia catalysis in fixed bed reactor. Biomass Bioenerg 30: 870–873.*
31. *Zhu H, Wu Z, Chen Y, et al. (2006) Preparation of Biodiesel Catalyzed by Solid Super Base of Calcium Oxide and Its Refining Process. Chinese J Catal 27: 391–396.*
32. *Sánchez M, Avhad MR, Marchetti JM, et al. (2016) Enhancement of the jojobyl alcohols and biodiesel production using a renewable catalyst in a pressurized reactor. Energ Convers Manage 126: 1047–1053.*
33. *Zhou, Hou Bo, Yang Cao, and Jin Li. "Research of Preparation of SO42-/TiO2-ZrO2 and its Application on Synthesis of Biodiesel from Waste Cooking Oil." Applied Mechanics and Materials. Vol. 316. Trans Tech Publications Ltd, 2013.*
34. *Syazwani, Osman Nur, et al. "Esterification of palm fatty acid distillate (PFAD) to biodiesel using Bi-functional catalyst synthesized from waste angel wing shell (Cyrtopleura costata)." Renewable Energy 131 (2019): 187-196.*
35. *Hindryawati, Noor, Erwin, and Gaanty Pragas Maniam. "Esterification of oil adsorbed on palm decanter cake into methyl ester using sulfonated rice husk ash as heterogeneous acid catalyst." AIP Conference Proceedings. Vol. 1813. No. 1. AIP Publishing LLC, 2017.*
36. *Devanesan, M. G., T. Viruthagiri, and N. Sugumar. "Transesterification of Jatropha oil using immobilized Pseudomonas fluorescens." African Journal of biotechnology 6.21 (2007).*
37. *Zeng, Jing, et al. "Study on the effect of cultivation parameters and pretreatment on Rhizopus oryzae cell-catalyzed transesterification of vegetable oils for biodiesel production." Journal of Molecular Catalysis B: Enzymatic 43.1-4 (2006): 15-18.*
38. *Lopresto, C. G., et al. "Enzymatic transesterification of waste vegetable oil to produce biodiesel." Ecotoxicology and environmental safety 121 (2015): 229-235.*
39. *Hama, Shinji, et al. "Biodiesel-fuel production in a packed-bed reactor using lipase- producing Rhizopus oryzae cells immobilized within biomass support particles." Biochemical Engineering Journal 34.3 (2007): 273-278.*
40. *Li L, Du W, Liu D, et al. (2006) Lipase-catalyzed transesterification of rapeseed oils for biodiesel production with a novel organic solvent as the reaction medium. J Mol Catal B Enzym 43: 58–62.*
41. *Shah, Shweta, Shweta Sharma, and M. N. Gupta. "Biodiesel preparation by lipase-catalyzed transesterification of Jatropha oil." Energy & Fuels 18.1 (2004): 154-159.*
42. *Tan, Tianwei, et al. "Biodiesel production with immobilized lipase: a review." Biotechnology advances 28.5 (2010): 628-634.*
43. *Kusdiana D, Saka S (2001) Kinetics of transesterification in rapeseed oil to biodiesel fuel as treated in supercritical methanol. Fuel 80: 693–698.*
44. *Bunyakiat K, Makmee S, Sawangkeaw R, et al. (2006) Continuous Production of Biodiesel via Transesterification from Vegetable Oils in Supercritical Methanol. Energ Fuel 20: 812– 817.*
45. *Demirbas A (2007) Biodiesel from sunflower oil in supercritical methanol with calcium oxide. Energ Convers Manage 48: 937–941.*

46. *Santana A, Maçaira J, Larrayoz MA (2012) Continuous production of biodiesel using supercritical fluids: A comparative study between methanol and ethanol. Fuel Process Technol 102: 110–115.*
47. *Song ES, Lim JW, Lee HS, et al. (2008) Transesterification of RBD palm oil using supercritical methanol. J Supercrit Fluid 44: 356–363*
48. *Hawash S, Kamal N, Zaher F, et al. (2009) Biodiesel fuel from Jatropha oil via non-catalytic supercritical methanol transesterification. Fuel 88: 579–582.*
49. *Zhang, Yujiao, et al. "Synthesis of the SrO–CaO–Al2O3 trimetallic oxide catalyst for transesterification to produce biodiesel." Renewable Energy 168 (2021): 981-990.*
50. *Gupta J, Agarwal M (2016) Preparation and characterizaton of CaO nanoparticle for biodiesel production. 2nd International Conference on Emerging Technologies. Jaipur, 302017, India: American Institute of Physics*
51. *Tahvildari K, Anaraki YN, Fazaeli R, et al. (2015) The study of CaO and MgO heterogenic nano-catalyst coupling on transesterification reaction efficacy in the production of biodiesel from recycled cooking oil. J Environ Health Sci Eng 13: 73–81.*
52. *Hu S, Guan Y, Wang Y, et al. (2011) Nano-magnetic catalyst KF/CaO–Fe3O4 for biodiesel production. Appl Energ 88: 2685–2690.*
53. *Wen L, Wang Y, Lu D, et al. (2010) Preparation of KF/CaO nanocatalyst and its application in biodiesel production from Chinese tallow seed oil. Fuel 89: 2267–2271.*
54. *Fan P, Xing S, Wang J, et al. (2017) Sulfonated imidazolium ionic liquid-catalyzed transesterification for biodiesel synthesis. Fuel 188: 483–488.*
55. *Fan, Mingming, et al. "Biodiesel production by transesterification catalyzed by an efficient choline ionic liquid catalyst." Applied energy 108 (2013): 333-339.*
56. *Wu Q, Chen H, Han M, et al. (2007) Transesterification of cottonseed oil catalyzed by brønsted acidic ionic liquids. Ind Eng Chem Res 46: 7955–7960.*
57. *Yanfei, He, et al. "Transesterification of soybean oil to biodiesel by brønsted-type ionic liquid acid catalysts." Chemical Engineering & Technology 36.9 (2013): 1559-1567.*
58. *Ullah, Zahoor, Mohamad Azmi Bustam, and Zakaria Man. "Biodiesel production from waste cooking oil by acidic ionic liquid as a catalyst." Renewable Energy 77 (2015): 521-526.*
59. *Encinar, J. M., et al. "Catalytic pyrolysis of exhausted olive oil waste." Journal of Analytical and Applied Pyrolysis 85.1-2 (2009): 197-203.*
60. *Omar, Rozita, and John P. Robinson. "Conventional and microwave-assisted pyrolysis of rapeseed oil for bio-fuel production." Journal of analytical and applied pyrolysis 105 (2014):131-142.*
61. *Laksmono, Nino, et al. "Biodiesel production from biomass gasification tar via thermal/catalytic cracking." Fuel processing technology 106 (2013): 776-783.*
62. *Prado, Cinara MR, and Nelson R. Antoniosi Filho. "Production and characterization of the biofuels obtained by thermal cracking and thermal catalytic cracking of vegetable oils." Journal of Analytical and Applied Pyrolysis 86.2 (2009): 338-347.*
63. *Dehghani, Sahar, and Mohammad Haghighi. "Sono-sulfated zirconia nanocatalyst supported on MCM-41 for biodiesel production from sunflower oil: influence of ultrasound irradiation power on catalytic properties and performance." Ultrasonics sonochemistry 35 (2017): 142- 151.*
64. *Chaihad, Nichaboon, et al. "In-situ catalytic upgrading of bio-oil derived from fast pyrolysis of sunflower stalk to aromatic hydrocarbons over bifunctional Cu-loaded HZSM-5." Journal of Analytical and Applied Pyrolysis 155 (2021): 105079.*
65. *Xu, Junming, et al. "Biofuel production from catalytic cracking of woody oils." Bioresource technology 101.14 (2010): 5586-5591.*
66. *Attaphong, Chodchanok, and David A. Sabatini. "Phase behaviors of vegetable oil-based microemulsion fuels: the effects of temperatures, surfactants, oils, and water in ethanol." Energy & fuels 27.11 (2013): 6773-6780.*
67. *Arpornpong, Noulkamol, et al. "Ethanol-in-palm oil/diesel microemulsion-based biofuel: Phase behavior, viscosity, and droplet size." Fuel 132 (2014): 101-106.*

68. *Sankumgon, Akechai, et al. "Properties and performance of microemulsion fuel: blending of jatropha oil, diesel, and ethanol-surfactant." Renewable Energy Focus 24 (2018): 28-32.*
69. *Patidar, Vivek, et al. "Physiochemical and phase behaviour study of jatropha curcus oil– ethanol microemulsion fuels using sorbitane fatty esters." Int J Renewable Sustainable Energy 3 (2014): 13-19.*
70. *Leng, Lijian, et al. "Rhamnolipid based glycerol-in-diesel microemulsion fuel: Formation and characterization." Fuel 147 (2015): 76-81.*
71. *Sharma, Mahendra Pal. "Selection of potential oils for biodiesel production." Renewable and Sustainable Energy Reviews 56 (2016): 1129-1138.*
72. *Verma, Puneet, M. P. Sharma, and Gaurav Dwivedi. "Impact of alcohol on biodiesel production and properties." Renewable and Sustainable Energy Reviews 56 (2016): 319-333.*
73. *Musa, Idris Atadashi. "The effects of alcohol to oil molar ratios and the type of alcohol on biodiesel production using transesterification process." Egyptian Journal of Petroleum 25.1 (2016): 21-31.*
74. *Günay, M. Erdem, Lemi Türker, and N. Alper Tapan. "Significant parameters and technological advancements in biodiesel production systems." Fuel 250 (2019): 27-41.*
75. *Math, M. C., Sudheer Prem Kumar, and Soma V. Chetty. "Technologies for biodiesel production from used cooking oil—A review." Energy for sustainable Development 14.4 (2010): 339-345.*
76. *Towler, Gavin, and Ray Sinnott. Chemical engineering design: principles, practice and economics of plant and process design. Elsevier, 2012.*
77. *Barnwal, B. K., and M. P. Sharma. "Prospects of biodiesel production from vegetable oils in India." Renewable and sustainable energy reviews 9.4 (2005): 363-378.*