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A Study on Biodiesel Production from Sewage Sludge

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ABSTRACT:

The global energy crisis has emerged as one of the most pressing challenges of the 21st century. Rapid industrialization, urbanization, and increasing energy demands have put tremendous pressure on the limited reserves of non-renewable fossil fuels. This issue is particularly severe in developing countries such as India, where the dependency on imported crude oil and petroleum products significantly impacts the national economy and energy security. With fuel consumption steadily rising, and fossil fuel reserves depleting at an alarming rate, the transition to sustainable and renewable sources of energy is no longer a choice but a necessity. The situation calls for urgent exploration of alternative fuels that can not only supplement the existing energy demand but also reduce environmental degradation and greenhouse gas emissions.

Among the various alternatives being explored, biofuels have gained considerable attention due to their renewable nature, environmental benefits, and potential to reduce dependency on fossil fuels. In particular, biodiesel—a clean-burning, biodegradable fuel—has shown promise as a substitute for diesel in transportation and industrial sectors. The Government of India has set an ambitious target of blending 20% biofuel with conventional fuels in the near future, aiming to promote energy diversification, reduce carbon footprint, and enhance rural livelihoods. Currently, biodiesel is predominantly produced from non-edible oil seeds such as jatropha, karanja, and neem. However, large-scale cultivation of these crops is constrained by the high cost of production, limited availability of arable land, and competition with food crops, making the process economically and environmentally challenging.

In light of these constraints, researchers and policymakers are increasingly looking at unconventional and waste-derived sources for biodiesel production. One such potential feedstock is sewage sludge—a by-product generated in massive quantities by sewage treatment plants (STPs) across urban India. These facilities are essential for managing municipal wastewater, and in the process, produce substantial amounts of sludge, which is often regarded as waste. However, this sludge contains lipids and other organic compounds that can be harnessed for biodiesel production through appropriate extraction and transesterification processes. This study aims to evaluate the competitiveness and feasibility of synthesizing biodiesel from sewage sludge collected at a major STP located in Pirana, Gandhinagar, India.

Keywords- Biofuels, renewable sources, biodiesel.

INTRODUCTION:

Energy is a standout amongst the crucial resources for mankind and its sustainable development. Today, the energy crisis has become one of the worldwide issues confronting us. Fuels are of great importance because they can be burned to produce substantial amounts of energy. Many facets of ordinary lifespan rely on fuels, in particular the transportation of goods and people. Principal energy resources come from fossil fuels such as petrol oil, coal and natural gas. Fossil fuel contributes 80%of the world's energy needs [1]. Maximum industries use diesel machines for the production process. In the transportation sector, private vehicles, buses, trucks, and ships also consume significant amounts of diesel and gasoline This circumstance prompts a solid reliance of regular day to day existence on non-renewable energy sources. However, the growth of the population is not covered by domestic crude oil production. Fossil oils are fuels which come from prehistoric animals and microorganisms [2]. Fossil fuel formation requires millions of years. Thus, fossil oils belong to non-renewable energy sources. An increase of the oil price often leads to economic recessions, as well as global and international conflicts. Particularly in some developing countries, the immense improvement in the economy in petroleum derivative assets will be devoured in just 65 more years. Furthermore, the emission generated by the combustion of fossil fuels also contributes to the air pollution and global warming. Most countries also experience more and more international pressure on global warming issues. Consequently, renewable and clean alternative fuels have received increasing attention for current and future utilization [3].

Biodiesel is one promising alternative to fossil fuel for diesel engines has become increasingly important due to environmental consequences of petroleum-fueled diesel engines and the decreasing petroleum resources. Biodiesel can be produced by chemically combining any natural oil or fat with an alcohol such as methanol or ethanol [4]. Methanol has been the most commonly used alcohol in the commercial production of biodiesel. Lots of researches on biodiesel have shown that the fuel made by vegetable oil can be used properly on diesel engines. There are several reasons why biofuels are considered relevant technologies by both developing and developed countries. Due to environmental merits, the share of biofuel in the automotive fuel market will raise faster in the next decade. Biodiesel has emerged as a viable and promising alternative to conventional fossil-based diesel fuel. As concerns grow regarding the environmental effects associated with petroleum-powered engines and the finite availability of fossil energy resources, biodiesel presents an attractive substitute [5]. Unlike fossil fuels, biodiesel is derived from renewable biological sources such as vegetable oils and animal fats, which can be replenished over a short period of time. It is gaining attention globally not only for its sustainability but also for its potential to reduce dependence on foreign oil and to foster energy security. The process of producing biodiesel typically involves a chemical reaction known as transesterification. In this reaction, natural oils or fats are reacted with a short-chain alcohol—commonly methanol or ethanol—using a catalyst, often sodium hydroxide or potassium hydroxide. Methanol remains the preferred alcohol in commercial biodiesel production due to its cost-effectiveness and wide availability [6]. This process results in the formation of fatty acid methyl esters (FAME), which is the chemical name for biodiesel, and glycerin as

a byproduct. The biodiesel produced through this method has combustion properties very similar to traditional diesel, making it suitable for use in most
existing diesel engines with little or no modifications [7]. A growing body of research indicates that biodiesel performs efficiently in diesel engines while also reducing the emission of harmful pollutants such as carbon monoxide, particulate matter, and unburned hydrocarbons. Biodiesel combustion is cleaner, contributing to lower levels of air pollution and greenhouse gases such as carbon dioxide. Additionally, since biodiesel is biodegradable and non-toxic, it poses fewer environmental hazards in case of spills compared to petroleum diesel [8]. These ecological benefits make biodiesel a strong candidate for use in transportation, particularly in countries seeking to reduce their carbon footprint and improve air quality in urban areas. Both developing and industrialized nations are investing in biofuel technologies due to their multiple advantages. For developing countries, biodiesel production offers the possibility of using locally available feedstocks such as used cooking oil, non-edible plant oils, or even agricultural waste, which can help stimulate rural economies and create employment. In developed countries, biodiesel serves as part of broader strategies to transition toward low-carbon economies. Forecasts indicate a significant increase in the share of biofuels like biodiesel in the transport energy mix over the coming years. This trend is driven not only by environmental regulations but also by advances in agricultural practices, fuel processing technologies, and a rising commitment to achieving sustainable energy goals

NEED OF THE STUDY:

Over the past 100 years of automobile sectors and automobile technology, there have been a number of different advancements in power, speed, size, power and efficiency. Fossil fuels are in limited sources for supply. The combustion of Fossil fuel generates large amounts of greenhouse gases, in which the major being carbon dioxide, which is contributing world-wide attention for significant environmental problem due to the different uses of fossil fuels. Hence the requirement of fossil fuels need to be replaced with other alternative sources of fuels. In present, the available fuels are Bio-ethanol vegetable oil, biogas & biodiesel. The comparative study of petrodiesel and biodiesel is also available, which justifies it as a better option in any case. The comparative study is as follows:

Properties	*Petrodiesel*	*Biodiesel*
Cetane Number	40 - 55	50 – 65
Energy Density (MJ/Kg)	43	38
Density (g/mL)	0.83-0.85	0.88
Energy Content (BTU/gal)	129 K	118 K
Sulfur Content	<10 ppm	<5 ppm
NOx Emission	Baseline	+10
Cloud Point, C	-5	20
Lubricity	Baseline	Excellent

Source: Difference - Jesse Jin Yoon for Advanced Biofuels

Table 1 - Comparison of Petrodiesel & Biodiesel

Thus, as shown above, there is currently an unprecedented increase in interest and demand for biodiesel and other fuels derived from renewable biomass. However, pure vegetable or seed oils are expensive and constitute between 70% and 85% of the overall biodiesel production cost. Therefore, an alternative fuel necessitates today's demand of sustainable development.

Over the past century, the automobile industry has witnessed remarkable advancements in power, speed, size, and efficiency. However, the continued reliance on fossil fuels—a finite resource—poses significant environmental concerns. The combustion of fossil fuels releases large quantities of greenhouse gases, particularly carbon dioxide, which is a major contributor to global climate change. This growing environmental impact has led to a pressing need for alternative fuel sources. Currently, several renewable options such as bioethanol, vegetable oil, biogas, and biodiesel are being explored. Comparative studies between Petro diesel and biodiesel have shown that biodiesel offers numerous advantages, making it a more sustainable and environmentally friendly option. As a result, there is a growing global interest in biodiesel and other fuels derived from renewable biomass. However, the high cost of pure vegetable or seed oils—accounting for 70% to 85% of biodiesel production expenses—poses a challenge [9]. To meet the demands of sustainable development, it is essential to explore cost-effective and efficient alternative fuels that can replace traditional fossil fuels.

SCOPE AND METHODOLOGY APPROACH:

The scope of research work is to study the quality comparisons of biodiesel generated from sludge, vegetable oil and petro diesel. The research will also cover the examination of molecular structure, composition, viscosity, moisture content, iodine value, emissions led due to its combustion and such other crucial parameters. The study will depict earnest use of municipal sludge containing higher organic content. The experiments for generation of biodiesel from municipal sludge will illustrate possible complications like interference of other compounds, contamination on exposure, etc. The study has been solely carried out in order to come up with a judicious, economic and worthy solution to meet the increasing demand of fossil fuel keeping in mind the sustainable development for the conventional resources. The objective of this research is to compare the quality of biodiesel produced from municipal sludge, vegetable oil, and conventional Petro diesel. The study will analyse key parameters such as molecular structure, chemical composition, viscosity, moisture content, iodine value, and emissions resulting from combustion. A significant focus will be placed on the utilization of municipal sludge, particularly due to its high organic content. The research will also investigate the challenges involved in biodiesel production from sludge, including potential interference from other compounds and contamination risks during exposure. This work aims to develop a practical, cost-effective, and environmentally responsible solution to address the growing demand for fossil fuels, with an emphasis on promoting sustainable alternatives to conventional energy sources.

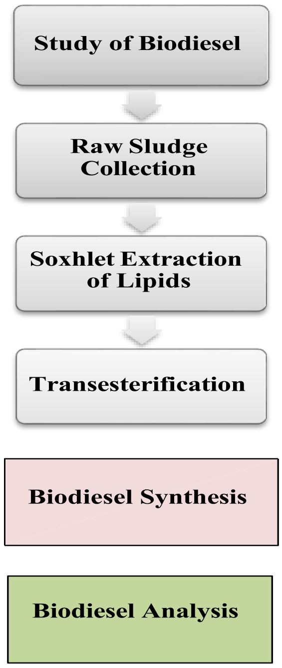

Figure 1: Plan of Research

EXPERIMENTAL METHODOLOGY:

MATERIALS

All materials required for conducting the experiment and analyzing the results were readily available at the laboratory scale. The experimental procedure primarily involved Soxhlet extraction of lipids, followed by transesterification and subsequent analysis. Sludge samples collected from both Primary and Secondary Treatment processes served as the primary feedstock for the study. Hexane was utilized as the solvent to extract lipids from the sludge samples, while HPLC-grade methanol was employed in the transesterification process, using potassium hydroxide as a catalyst. To dry the resulting methyl esters, magnesium sulfate monohydrate ($MgSO_4 \cdot H_2O$) was used. Key laboratory instruments used in the study included a desiccator, Soxhlet extractor, condenser, muffle furnace, separating funnel, vacuum filter, and gas chromatograph, which was employed for the final analysis of the biodiesel composition.

Municipal sludge samples were collected from the Sewage Treatment Plant located at Pirana, Gandhinagar. One sample was obtained directly from the outlet valve of the sludge digester, prior to its transfer to the thickener. A second sample was collected from freshly deposited sludge on the sludge drying
beds. A third composite sample was prepared by mixing equal proportions of sludge from both collection points.

SAMPLE PREPARATION

Parameters such as pH, moisture content, and total organic and inorganic content were analyzed for each sludge sample. As the sludge was found to be basic in nature, it was acidified using hydrochloric acid (HCl). For the analysis, 30 grams of sludge were used per sample. Since the sludge was in a semi-liquid state, it needed to be fully dried to remove all moisture. To achieve complete drying, magnesium sulfate monohydrate was added to effectively absorb and trap the remaining moisture. The acidified sludge was allowed to stand until its paste-like consistency became sufficiently moisture-free. The solidified sludge was then placed in a desiccator overnight to ensure complete removal of any remaining water content. Once dried, the sample was finely powdered using a mortar and pestle to maximize surface area for extraction. Pre-weighed samples were then carefully packed into cellulose thimbles, with the top sealed using glass wool to prevent any exchange of sludge particles with the solvent during the extraction process.

Figure 2: Dried Sludge

Figure 3: Powdered Sludge Sample

SOXHELET EXTRACTION

Lipids were extracted from the solid sludge samples using a Soxhlet extractor, a device developed by Franz von Soxhlet in 1879. This apparatus is particularly effective for extracting lipids from sewage sludge using hexane as the solvent. Hexane was selected due to its ability to dissolve lipids while the other components of sludge remain insoluble, ensuring selective extraction.

Pre-weighed powdered sludge samples were placed into cellulose thimbles and sealed with glass wool to prevent particle exchange during the process. The experiment followed Standard Method 5520E [14]. The Soxhlet apparatus was assembled, and the thimble was inserted into the chamber. Initially, 120 mL of hexane was measured into a 250 mL round-bottom flask. A bubble condenser was used to condense the solvent vapours. The extraction was conducted at approximately 70°C, with 80 continuous cycles performed over 5.5 hours to ensure efficient lipid extraction. During each cycle, lipids were gradually dissolved in hexane and collected in the flask below. To assess any potential influence of solvents on the sludge or lipid composition, a parallel set of experiments was conducted using methane as an alternative solvent. Given that hexane has a boiling point of 68°C, it was evaporated after extraction to separate it from the lipids. The evaporated hexane was condensed and recovered for reuse. The extracted lipids, now free from solvent, were collected in vials, re-dissolved in hexane, and stored at –20°C for preservation and further analysis.

TRANSESTERIFICATION

Transesterification is a widely used chemical process, particularly in the detergent and soap manufacturing industries, and is the primary method for producing biodiesel. Nearly all biodiesel is synthesized through this process, which typically involves the use of a base catalyst. Base-catalyzed transesterification is considered the most economical method, as it can achieve up to 98% conversion efficiency under relatively mild conditions of low pressure and temperature. In this process, triglycerides—found in fats, oils, and lipids—react with an alcohol to produce glycerol and esters (biodiesel).

A triglyceride molecule consists of a glycerol backbone bonded to three long-chain fatty acids. The specific nature of these fatty acids determines the properties of the fat or oil and, subsequently, affects the characteristics of the resulting biodiesel. During biodiesel production, the triglycerides are typically reacted with alcohols such as methanol, ethanol, or isopropyl alcohol in the presence of a catalyst, which is usually a strong base like sodium hydroxide (NaOH) or potassium hydroxide (KOH). The reaction breaks down the triglycerides, allowing the alcohol to bond with the fatty acids, forming mono-alkyl esters (biodiesel) and crude glycerol as a byproduct.

In the conducted experiment, the extracted lipid samples were first dissolved in 1 mL of hexane. To this, 2 mL of 1% sulfuric acid in methanol was added. The vials were then sealed and gently heated in a muffle furnace at 50°C to initiate the transesterification reaction.

Following the heating process, 5 mL of 5% sodium chloride solution was thoroughly mixed into the vial to facilitate phase separation. The mixture was then transferred to a separating funnel, where two distinct layers formed—crude glycerol and methyl ester (biodiesel). The methyl ester layer was separated and washed twice with 10 mL of hexane to remove any residual impurities. The glycerol layer was discarded, and the methyl ester was dried using magnesium sulphate monohydrate ($MgSO_4 \cdot H_2O$) to eliminate any remaining moisture. The biodiesel, initially viscous, was then gently heated to 60–70°C to reduce its viscosity. To remove the $MgSO_4$, suction filtration was performed, with the drying agent retained on the filter paper, ensuring the biodiesel was free of moisture. The purified methyl ester was then collected in a clean vial for final analysis. For compositional analysis, the biodiesel was subjected to Gas Chromatography using an Agilent 6890GC equipped with a Flame Ionization Detector (FID). Helium was used as the carrier gas. The injector and detector were both maintained at 260°C, and the injection volume was 1.5 µL with a split ratio of 20:1. The oven temperature program started at 150°C (held for 1 minute), then increased at a rate of 2.9°C per minute until reaching 230°C, where it was held for an additional minute.

Figure 4: Separation of Glycerol and Methyl Ester

RESULTS:

The fatty acid methyl esters (FAMEs) produced through the transesterification process were analyzed using Gas Chromatography equipped with a Flame Ionization Detector (FID). The percentage yield of biodiesel was calculated based on the analysis results. During the experiment, lipid extraction from 20–30 grams of powdered sludge yielded the following quantities: 0.951 g, 0.22 g, 0.684 g, and 0.710 g, respectively. The sludge samples exhibited a high moisture content, ranging between 70% and 90%. The pH of the samples was found to be basic, varying between 8.0 and 9.5. The total organic content ranged from 9% to 14%, with the remaining portion consisting of inorganic matter.

Parameters	*Unit*	*Result*	*ASTM Standards*
Density @ 15 ºC	Kg/m³	891	--
Kinematic Viscosity mm²/s	CP	13.53 (40ºC),	**1.9 – 6.0**
Flash Point	ºC	129	**130 min**
Sulphur Content	% by Mass	0.001	**0.0015 (max) (S15);** **0.05 max (S500)**
Carbon Residue Content	% by Mass	0.016	**0.050 (max)**
Water Content	% by Volume	0.065	**0.050 (max)**
Total Contamination	% by Mass	0.13	**-**

Parameters	*Unit*	*Result*	*ASTM Standards*
Copper Strip Corrosion at 3 hours at 50 ºC	--	Nil	**No. 3 (max)**
Cetane Number	**--**	**58**	**47 min**
Acid Number	Mg KOH/g	0.401	**1.00 (max)**
Methanol Content	% by Mass	0.14	**--**
Ethanol Content	% by Mass	0.18	**--**
Total glycerol Content	% by Mass	0.16	**0.240**
Iodine Value	-	123	
Viscosity Index	--	101	**>90**
Gross Calorific Value **(By Bomb Calorimeter)**	MJ/Kg	35.44	**50**
Fire Point	ºC	125	**150 (max)**
Iron	ppm	8	**25 (max)**
Chromium	ppm	2.22	**15 (max)**
Aluminium	ppm	2.53	**15 (max)**
Manganese	ppm	0.77	**5.0 (max)**
Calcium	ppm	7.43	**10.0 (max)**
Phosphorous	ppm	19	**50.0 (max)**

Table 2 – Observations and Results

COST BENEFIT ANALYSIS

A comparative study of the fuel properties of conventional diesel, a biodiesel blend (B20), and biodiesel synthesized from sewage sludge in this study reveals some notable differences. The biodiesel produced from sewage sludge exhibited the highest cetane number at 61, compared to 47.5 for diesel and approximately 52 for the B20 blend. In terms of density, the values recorded were 839 kg/m³ for diesel, 847 kg/m³ for the B20 blend, and 894 kg/m³ for the synthesized biodiesel. Importantly, the sulphur content—an environmental concern—was found to be significantly lower in the synthesized biodiesel (0.001% by mass) compared to diesel (0.034%) and B20 (0.031%). Currently, diesel prices in India range between ₹51 and ₹59 per litre. To meet the national renewable energy goals, India had set a target of replacing 20% of fossil fuel consumption with biofuels by 2017, requiring approximately 3.5

million tonnes of biofuel annually. However, only about 45% of this target has been achieved, mainly due to technical, financial, and political challenges. While government initiatives have promoted the cultivation of non-edible oilseeds such as jatropha and pongamia for biodiesel production, the high cost of land (even wasteland), crop cultivation, and ongoing maintenance have made these options less economically viable. In contrast, sewage sludge—a byproduct of wastewater treatment—offers a promising and underutilized alternative. At the Pirana Sewage Treatment Plant in Gandhinagar, sewage sludge is currently sold as manure at ₹285 per cubic meter. While this represents a fair market value, the sludge is being used for a relatively low-value purpose, despite its potential for biodiesel production. Given the abundance of other organic alternatives for manure and fertilizers, the higher-value application of sludge for biodiesel synthesis should be prioritized to fully exploit its potential.

The main resource required for converting sewage sludge to biodiesel is electricity. Other materials, such as solvents used during lipid extraction, can be recovered with up to 97% efficiency. Water used in the condensation process is also recoverable, and the consumption of other reactants is minimal. With electricity priced between ₹3.20 and ₹3.90 per unit, and assuming a total consumption of around 20 units for Soxhlet extraction, vacuum filtration, and gas chromatography, the production cost for 200 mL of biodiesel from 500 mg of sludge would be approximately ₹60–₹70. When scaled up, the production of biodiesel from sewage sludge becomes not only a technically viable solution but also a cost-effective and sustainable alternative to conventional diesel.

CONCLUSION

The lipid yield from primary sludge and secondary sludge was found to be 17% and 14%, respectively, while the combined sample of both sludge types yielded 21%. It was also observed that lipid extraction from primary sludge was more efficient when methanol was used as the solvent compared to hexane.

This study demonstrates that biodiesel production from sewage sludge is comparable in efficiency and quality to biodiesel derived from non-edible oil sources such as jatropha. Furthermore, it presents a cost-effective alternative, as the primary resource consumed is electricity, while solvents, water, and other reagents used in the process can be largely recovered and reused. This approach offers a promising and sustainable solution for energy generation from waste, establishing a new model for converting waste materials into valuable biofuels.

REFERENCES:

[1] T. M. Gür, "Review of electrical energy storage technologies, materials, and systems: challenges and prospects for large-scale grid storage," Energy & Environmental Science, 9(10), pp. 3453-3479., 2016.

[2] S. A. A. R. M. A. S. H. M. H. G. J. A. &. R. P. Jambo, "A review on third-generation bioethanol feedstock," Renewable and Sustainable Energy Reviews, 65, pp. 756-769., 2016.

[3] J. H. R. L. T. Z. J. &. C. K. Cheng, "Biodiesel production from wet microalgae by using graphene oxide as a solid acid catalyst," Bioresource Technology, 245, pp. 37-44., 2017.

[4] J. &. C. Y. Ren, "Biofuel production and consumption in China: national and regional perspectives.," Renewable and Sustainable Energy Reviews, 69, pp. 970-977., 2017.

[5] R. S. S. &. S. O. V. Kumar, "Bioconversion of lignocellulosic biomass: Biochemical and molecular perspectives," Journal of Industrial Microbiology & Biotechnology, 45(5), pp. 753-772. , 2018.

[6] S. I. D. G. G. P. M. R. S. J. P. A. C. L. M. R. I. C. .. &. T. J. A. Mussatto, "Technological trends, global market, and challenges of bio-ethanol production," Biotechnology Advances, 34(5), pp. 601-616. , 2016.

[7] R. E. M. W. S. J. N. &. T. M. Sims, "An overview of second-generation biofuel technologies," Bioresource Technology, 101(6), pp. 1570-1580. , 2017.

[8] J. L. Z. H.-R. M. &. F. M. Popp, "The effect of bioenergy expansion: Food, energy, and environment," Renewable and Sustainable Energy Reviews, 32, pp. 559-578. , 2016.

[9] I. d. C. C. &. A. I. Capellán-Pérez, "Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% renewable energy supply scenarios," Renewable and Sustainable Energy Reviews, 77, pp. 760-782. , 2017.

[10] J. C. L. E. E. S. V. O. J. Y. E. E. P. C. E. F. &. A. O. Escobar, "Biofuels: Environment, technology, and food security," Renewable and Sustainable Energy Reviews, 13(6-7), pp. 1275-1287., 2017.

[11] M. Balat, "Historical development of liquid biofuels from biomass," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 38(6), pp. 754-762. , 2016.

[12] D. L. N. O. M. &. W. M. Bacovsky, "Status of advanced biofuels demonstration facilities in 2016: A report to IEA Bioenergy Task 39," IEA Bioenergy, 10, pp. 1-22., 2016.

[13] M. I. Y. T. &. S. A. Khan, "A comprehensive review of biodiesel as an alternative fuel for compression ignition engines," Renewable and Sustainable Energy Reviews, 71, pp. 12-23., 2016.

[14] C. D. H., M. S. N., A. J. S., and V. L. C, "Indian vegetable fuel oils for diesel engine," 1942.

[15] P. S. &. S. A. Nigam, "Production of liquid biofuels from renewable resources," Progress in Energy and Combustion Science, 37(1), pp. 52-68. , 2016.

[16] Y. A. L, " Biotechnology for food, energy, and industrial products.," 2003.

[17] E. M. Aro, "From first generation biofuels to advanced solar biofuels," Ambio, 45(S1), pp. 24-31., 2016.

[18] B. G. P. &. N. A. Karmakar, "Recent developments on biofuels production from lignocellulosic biomass in the Indian context," Bioresource Technology, 297, p. 122481. , 2020.

[19] A. K. &. G. V. K. Chandel, "India's biofuel roadmap: Current status and future trends," Biofuels, 12(6), pp. 705-720., 2021.

[20] A. E. S. A. S. B. I. A. M. T. M. I. M. H. H. &. M. S. Atabani, "A comprehensive review on biodiesel as an alternative energy resource and its characteristics," Renewable and Sustainable Energy Reviews, 16(4), pp. 2070-2093. , 2015.

[21] S. K. B. A. R. C. C. E. &. N. M. Hoekman, "Review of biodiesel composition, properties, and specifications," Renewable and Sustainable Energy Reviews, 42, pp. 1257-1268., 2016.

[22] M. A. R. &. S. C. Kandasamy, " Effects of biodiesel characteristics on engine performance and emissions using artificial neural network modeling," Fuel, 208, pp. 828-836. , 2017.

[23] M. N. H. S. M. N. &. R. M. M. Nabi, "Characteristics of biodiesel and its blending with diesel and ethanol on engine performance and exhaust emissions: An experimental study," Energy Conversion and Management, 195, pp. 259-267. , 2019.

[24] R. S. M. S. S. &. M. R. K. Sarin, " Jatropha-palm biodiesel blends: An optimum mix for Asia," Fuel, 86(10-11), pp. 1365-1371., 2016.

[25] A. &. B. V. Patel, "Production of Biodiesel from Microalgae via Various Bio-chemical Methods: A Comparative Study," Bioresource Technology, 206, pp. 45-52. , 2016.

[26] A. E. S. A. S. O. H. C. M. T. M. I. M. H. H. B. I. A. &. F. H. Atabani, "Non-Edible Vegetable Oils: A Critical Evaluation of Oil Extraction, Fatty Acid Compositions, Biodiesel Production, Characteristics, Engine Performance, and Emissions Production," Renewable and Sustainable Energy Reviews, 40, pp. 1130-1158. , 2016.

[27] B. H. G. &. B. S. Karmakar, "Biodiesel Production from Palm Oil and Its By-Products: A Review," Materials Science for Energy Technologies, 1(2), pp. 151-157. , 2018.

[28] G. &. R. L. F. Knothe, "Biodiesel Fuels," Progress in Energy and Combustion Science, 58, pp. 36-59. , 2017.

[29] R. V. O. H. C. &. K. J. Quah, "Advancements in Solid Catalysts for Biodiesel Production: A Critical Review," Renewable Energy, 158, pp. 47-65., 2020.

[30] S. A. H. M. A. &. Z. H. Dawood, "Optimization and Kinetics of Biodiesel Production from Waste Cooking Oil Using Heterogeneous Catalyst," Journal of Environmental Chemical Engineering, pp. 5(3), 2978-2986., 2017.

[31] G. A. R. &. B. B. Baskar, "Biodiesel Production from Waste Cooking Oil Using CaO Nanocatalyst: An Efficient Technique for Quality Improvement," Renewable Energy, 143, pp. 1054-1067., 2019.

[32] F. W. Y. X. Z. &. F. Z. Guo, "Transesterification Mechanisms for the Production of Biodiesel," Catalysis Reviews, 57(4), pp. 402-437., 2015.