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Palm Oil Biodiesel Production: An Overview of Opportunities and Challenges

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ABSTRACT: The utilization of palm oil for the preparation of biodiesel is proposed as a promising alternative to petroleum and diesel and in this review, we examined how palm oil can be utilized to create biodiesel through various methods such as transesterification, supercritical methods, blending, and thermal cracking. By this, we found out that there is a high yield and purity associated with palm oil. The usage of different catalysts and their results have been discussed thoroughly, and different quantification tools, such as NMR, gas chromatography, and simulation and statistical tools ASPEN, SUPERPRO, and JMP can be used to simulate and amplify our results. Lastly, the future and difficulties of harnessing palm oil as a vegetable oil to make biodiesel have also been examined.

I. INTRODUCTION

Since the beginning of the Industrial Revolution, there has been a rise in the world's energy consumption as a result of the quick population growth. The depletion of the ozone layer, inappropriate waste management, environmental pollution, global warming, and other environmental issues have all been brought on by this, including deforestation and the exhaustion of natural resources. These issues are associated with both predictable and unpredictable disasters, such as economic crises, and human health problems. About 11 billion tons per year of fossil fuel is consumed and is expected to be depleted soon. The significance of energy demands that have grown exponentially over the past century has prompted the need to find other ideal, powerful, yet environmentally friendly solutions with lower emissions and abundance in nature as the potential replacement alternative to conventional fossil fuel. As a result, the usage of clean energy sources such as biodiesel is critical. As a result, the usage of clean energy sources such as biodiesel is critical. As a result, the usage of clean energy sources such as biodiesel is critical considering the environmental problems arising from the rising greenhouse gas and hazardous pollution emissions.

Transesterification is a common method for producing biodiesel from a limitless supply of natural resources. The American Society for Testing Materials (ASTM) defines biodiesel as a mono-alkyl ester that is created using a variety of lipid feedstocks, including vegetable oils and animal fats. In more than 80 different countries, using biodiesel as a fuel as a fuel additive is permitted [1]. The utilisation in terms of biodiesel in diesel engines has garnered a lot of interest due to concerns about energy security, petroleum supply, and the recent rise in petroleum costs. Vegetable and animal oils have a high kinematic viscosity, moderate volatility, and a large molecular mass when utilised directly as diesel fuel causing issues with the oil thickening, gelling, and sticking [2]. Several techniques, including blending with petrol-diesel, transesterification, micro-emulsification, and pyrolysis [3, 4], can be used to solve these issues and enable its usage as fuel.

In addition to the production of biodiesel, the glycerin by-product can also be used in various industries, such as in producing soaps and cosmetics. It is worth noting that the large-scale production of palm oil has raised concerns about its impact on the environment, particularly about deforestation and loss of biodiversity. However, sustainable palm oil production practices are being developed and implemented to minimise these impacts, and using used or waste palm oil is valued for use in biodiesel manufacture.

II. LITERATURE REVIEW

2.1 Palm oil used as a biodiesel fuel:

The result of the biodiesel synthesis process depends on a variety of variables, including the kind of reactor, agitation rate, time of reaction, catalyst type and concentration, temperature, fluid-to-oil ratio, solvent type, and raw material kinds. Because various raw materials include varying kinds and compositions of free fatty acids (FFA), impurities, etc., the choice of these parameters, notably catalyst and solvent types, is primarily impacted by the kind of raw materials chosen. To manufacture high-quality biodiesel, raw materials should be carefully chosen. Additionally, it

needs to be affordable and abundant in nature. Because of its reusability, sustainability, high energy content, and energy security [5], vegetable oil has been recognized as the right raw material.

The highest concentration of palmitic and oleic acids among all currently used vegetable oils is found in palm oil, which has long been recognized as the ideal crude material for biodiesel production. Due to its geographical positioning, palm oil has become a primary source of biodiesel in most Asian nations. The world's biggest consumer of palm oil is India and its demand is expected to rise in the coming years. Unlike other types of oil, palm oil is a perennial crop, and as a result, it is continuously produced all year round [6]. Additionally, palm oil has many benefits due to its elevated oil content [7], cost-effectiveness, abundance, and high production capacity. It accounts for nearly a third of all vegetable oil produced globally and requires less planting area than other oil crops, about 19 million hectares for 81 Million Tonnes of oil [6,8,9,10]. Two key constituents of its fruits include oil extracted from the outer mesocarp and oil derived from the inner part of the nut. [6,11]. Their fatty acid composition sets the two products apart. While palm kernel oil contains a significant amount of lauric acid (more than 89% saturated fat), the oil obtained from the outer mesocarp consists mainly of palmitic and oleic acids, comprising approximately 50% saturated fat. These fatty acids are particularly valuable for biodiesel production. In particular, the cetane number and iodine value of palm oil biodiesel were superior to those of other forms of biodiesel (Table 1). In terms of clean emissions and engine efficiency, a higher cetane number is advantageous.

Type of oil-biodiesel	Palm oil	Soybean oil	Sunflower oil	Peanut
Kinematic viscosity (40 °C; mm ² /s)	4.42-4.76	4.08-4.42	4.38-4.90	4.42-5.25
Iodine Number	35-61	117-143	110-143	67.45
Cetane Number	59.9-62.8	37-52	45-51	54
Saponification Number	186-209	201	200	200
High Heating Value (HHV)	37.2-39.91	37.3-39.66	37.5-39.95	39.7

Table 1: Physical properties of a few commonly used oils for biodiesel production [3].

2.2 Methods:

2.2.1. Transesterification:

Biodiesel is typically produced by transesterification. To form fatty acids, the triglycerides in this method react with alcohol (Methanol or ethanol) [3]. Since transesterification can diminish the highly viscous quality of vegetable oil, ignition engines are not used. Additionally, the alcohol-to-oil molar ratio is crucial, by Le Chatelier's principle, the more the alcohol component, the stronger the reaction will be. Alkali and acid catalysts are generally employed in this procedure. Acid catalysts and a greater ratio of alcohol to oil are needed when there's a higher concentration of fatty acids present, the reaction will be inactive. Base catalysts and decreasing the molar ratio of alcohol to oil can be utilised whenever the concentration of fatty acids is less [12]. In some cases, lipases are used and this is because they have high selectivity and also it is less sensitive to high levels of free fatty acids. [13]. Methanol can be utilized since it has lower viscosity however it is ineffective, though, when lipase is used as a catalyst. In most cases, after adding alcohol and triglycerides to the mixture with the catalysts, it is heated at a particular temperature for a specific duration of time to produce biodiesel in the upper phase and glycerol and a few salts in the lower phase. Catalysts that are still present are neutralized and cleaned. Then these components are separated using a decanter, usually to separate the glycerol, according to the differences in their densities [14]. When base catalysts are used there is a problem of soap formation. [12,15]. If there is soap formation we will have to wash the product repeatedly and this complicates the reaction.

2.2.2. Other Methods:

2.2.2.1 Supercritical method:

Another method for producing biodiesel that does not involve catalysts is the supercritical method. A substance becomes a supercritical fluid when it surpasses its critical point in terms of temperature and pressure. As a supercritical fluid, water, carbon dioxide, or alcohol is used. Compared to traditional solvents, these fluids offer distinct features that allow them to efficiently dissolve and transport the reactants. Studies have shown that the traditional approach utilizing a catalyst with basic properties does not produce as much methyl ester as the supercritical methanol method does. This is because methanol in its liquid form is a polar solvent, and forms methanol clusters through hydrogen bonding. In contrast, supercritical methanol has a lower dielectric constant and a hydrophobic nature. Consequently, supercritical methanol can solvate nonpolar triglycerides, resulting in a unified oil/methanol mixture. These fluids are cost-effective and safe for the environment. The substance that will be employed as a supercritical fluid is heated above its critical point and pressured before being added to the reaction mixture; this fluid's solvating qualities improve its capacity to interact with the triglycerides and alcohol and dissolve them, leading to the production of biodiesel [14].

2.2.2.2 Microemulsion:

The microemulsion method involves the use of surfactants or co-surfactants to stabilise immiscible liquids like water and oil, resulting in biodiesel [4]. The surfactant utilised has a hydrophilic head and a hydrophobic tail, which together create a higher interfacial area and lower interfacial tension while increasing the rate. Surfactants include Span 80, Tween 80, and Triton X-100., and AOT [16].

2.2.2.3 Pyrolysis (Thermal cracking):

Thermal cracking, or pyrolysis, involves heating vegetable oil without oxygen and potentially with a catalyst. This process produces a variety of substances and Alkanes, alkenes, alkadienes, aromatics, and carboxylic acids are some examples. This method doesn't give rise to different contaminants due to its high temperature conditions and this is what makes it popular. The behavior of the mixture must be examined using thermo-gravimetric analysis before employing the furnace in this approach. The reaction is aided by the use of a porous media, such as silica. Typically, the variables are the silica-to-oil and methanol-to-oil ratios. Dichloromethane is a solvent that is employed, and it is unique since it can dissolve biodiesel only in certain places. Silica and other materials are still insoluble. After that, they are separated by phase separation [17]. Thermal cracking is not employed in the manufacturing of biodiesel since it is more expensive and difficult to control the end product. [4].

2.2.2.4 Blending(dilution):

In blending the first step may employ transesterification, the Supercritical technique, or microemulsion, but it always includes combining biodiesel and petro-diesel in a variety of weight ratios, often between 10% and 40%. An oil-diesel combination is created as a result, and diesel engine fuel is subsequently utilized. The goal is to produce a mixture that includes both conventional petro-diesel and a part of renewable, non-petroleum-based fuel (vegetable or animal oil) [17]. B5 (5% biodiesel), B10 (10% biodiesel), B20 (20% biodiesel), and various biodiesel are available. blend ratios are examples of blends of biodiesel. High quality is assured through this procedure [15, 18].

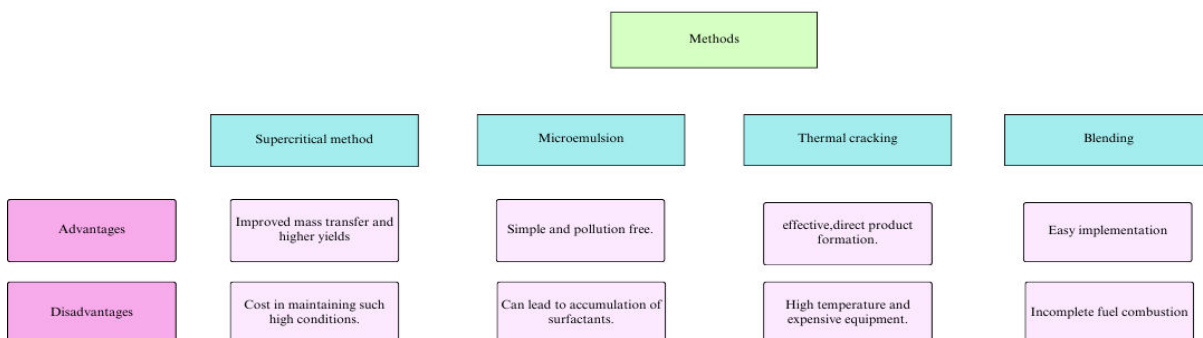


Fig 1: Advantages and disadvantages of different methods for biodiesel production.

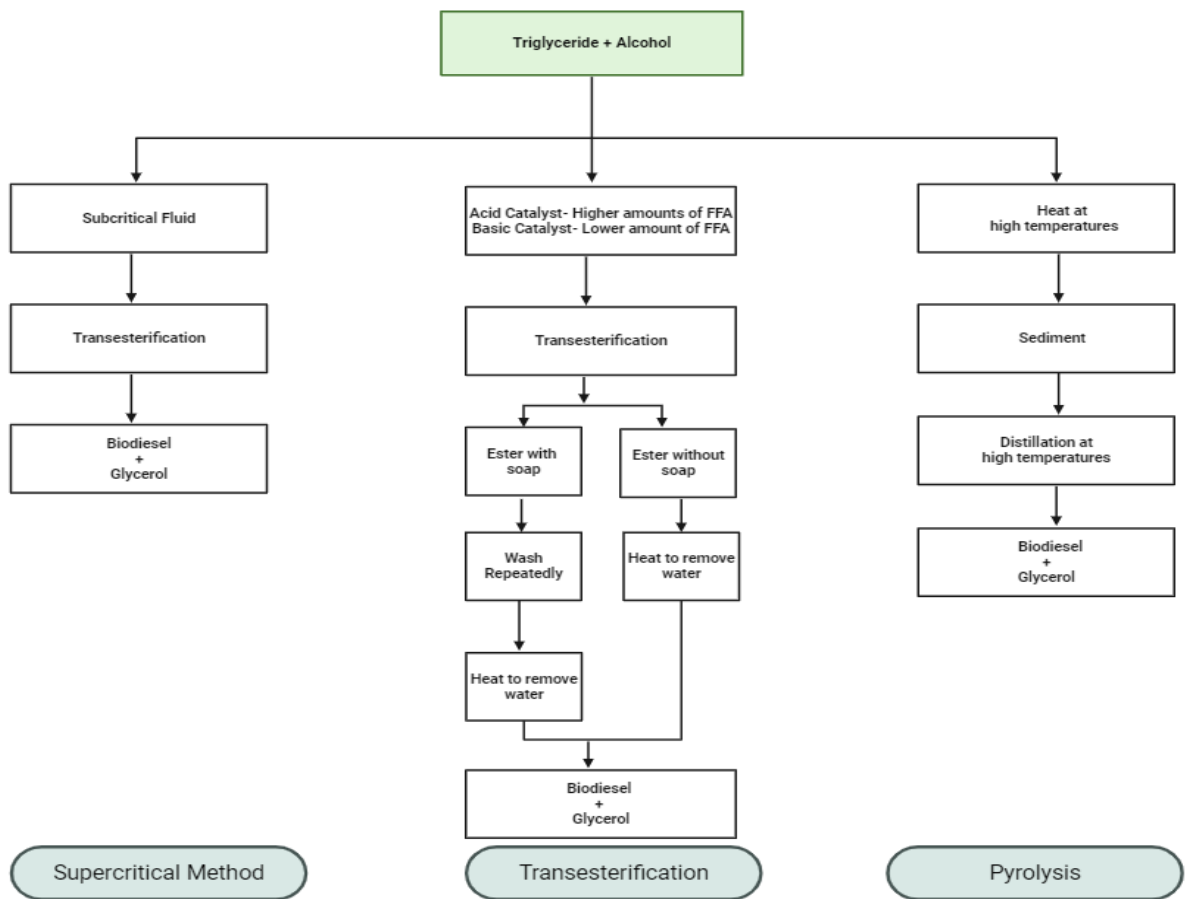


Fig 2: Process flow diagram for production of Biodiesel.

2.3. Tools used in biodiesel production:

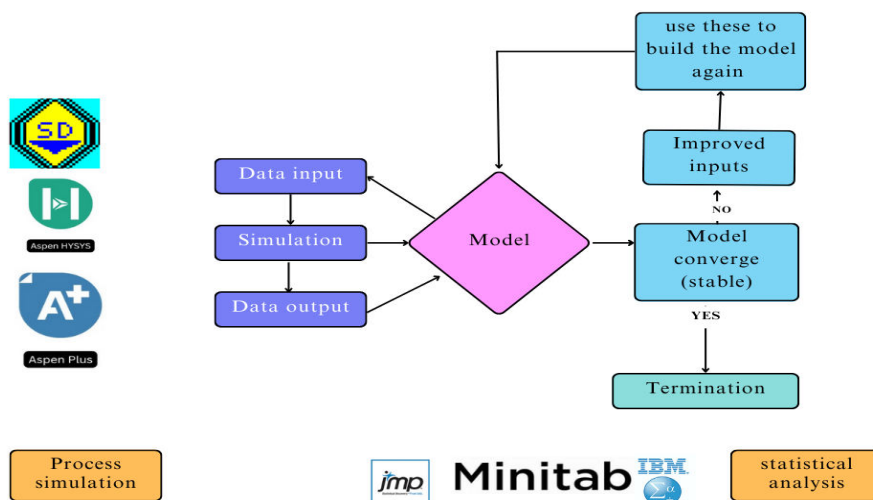


Fig 3: Common tools used in Biodiesel Production.

2.3.1. Quantification and identification tools:

There are many tools for quantifying and finding out what compounds are present in the mixture some of them are discussed below:

2.3.1.1 GC (Gas Chromatography):

Gas chromatography is an analytical technique for isolating and quantifying mixture components. After injecting the sample solution into the equipment, a gas stream transports it through a column-shaped separation tube. Helium or nitrogen are the approved transport gases. The different components are split within the column. The column's output is monitored by the detector. To analyze an unknown sample's concentration, a standard sample of known concentration is introduced into the equipment. Concentration is calculated by comparing the retention time (arrival time) and peak area between the reference and test samples.[13, 19, 20].

2.3.1.2 TLC (Thin Layer Chromatography):

Thin-layer chromatography (TLC) is a method employed for the separation and identification of components within a mixture. A sample is applied to a thin layer of adsorbent material through a process known as spotting, after which the plate is immersed in a solvent to initiate its development. Typically, silica gel plates serve as the adsorbent or stationary phase. Identification is possible because different chemicals travel across the plate at various rates [20, 21].

2.3.1.3 ¹³C-NMR Spectroscopy:

By examining how molecules' carbon atoms resonate in a magnetic field, a technique called carbon-13 nuclear magnetic resonance spectroscopy can be used to ascertain the composition of a mixture. It is especially helpful for examining methyl ester, triacylglycerol, and fatty acid combinations [22].

2.3.1.4 HPLC (High-performance liquid chromatography):

HPLC is a method utilised for separating, detecting, and measuring elements in a mixture. In the first approach, methyl esters and triacylglycerols are analyzed using a u-Porosil HPLC column and a particular solvent mixture. A C18 reverse-phase HPLC column is used in the second method to measure methyl esters, monoacylglycerols, diacylglycerols, and triacylglycerols [21,22].

2.3.1.5 FTIR (Fourier-transform infrared spectroscopy):

Biodiesel compounds are identified using FTIR by infrared light absorption, which reveals functional groups and compounds. Attenuated Total Reflectance (ATR) is used to directly analyze solid and liquid samples, which reveals the composition and qualities of the materials. FTIR collects absorption and transmission information, providing spectrum insights into the molecules that make up biodiesel. Understanding the links between the components of biodiesel is facilitated using Principal Component Analysis (PCA), which streamlines data by spotting patterns and correlations [4].

2.3.2. Statistical tools:

Statistical tools are used for analysing and interpreting data to understand patterns, relationships, and trends [23].

2.3.2.1 Java memory profiler (JMP):

This is a SAS-created statistics tool. These software's primary two functions are regression analysis and statistical modeling. p-values, parameter estimations, and energy performance can be discovered.[24, 25].

2.3.2.2 Minitab:

For experimental design and data analysis, response surface methodology ie., RSM is applied. RSM is used to evaluate systems where an output, or response, is influenced by several different variables. By examining their interactions, this methodology helps to optimize results [26]. For instance, it helps examine the effects of different



temperatures and time periods. A Box-Behnken design [BBD] is used by RSM to organize tests. BBD employs a small number of experimental trials to methodically investigate the range of variables. Establishing a mathematical model that depicts the purpose of RSM is to determine the correlation between the independent variables (A, B, C, and D) and the dependent variable (Y). A second-order polynomial equation is used to do this because it approximates the centre points as well as the ranges. It aids in the analysis of t-tests, ANOVA, and regression studies. Box plots, scatter plots, histograms, and other data visualisation tools are also made easier by it [27].

2.3.2.4 IBM SPSS (Statistical package for the social sciences):

For explanatory as well as conclusive statistical analysis, this is utilized. Using Pearson's approach, we investigate the linear correlation. It is possible to calculate the ANOVA, overall uncertainty, and sample distribution [28].

2.3.3 Simulation tools:

Aspen Plus:

It is one of the most widely used tools, enabling the process design of different pieces of equipment as well as process flow diagrams. Additionally, thermodynamic, chemical and even mass and energy modeling are all possible [29].

2.3.3.1 Aspen HYSYS:

Similar to Aspen, it is used to optimize single units, and it also aids in processing models, including steady-state and dynamic simulations. It supports our work on chemical and thermodynamic modeling. The primary distinction is that Aspen Plus is best suited for simulation, whereas Aspen HYSYS is concentrated on planning and optimizing unit operations [30, 31].

2.3.3.2 Superpro:

The entire procedure, from the preparation of the feedstock to the final product separation, can be modeled using SuperPro Designer. It offers the capability to perform optimization studies to find the optimal operating conditions and design parameters that satisfy multiple objectives. It has premodeled operation studies which we can refer to. The software may also support integration with optimization algorithms to perform multi-objective optimization, considering factors such as profit, environmental impact, and social considerations. This is used in a wider range of industries and is the most common and simple one [32, 33].

2.4 Effect of catalyst in transesterification:

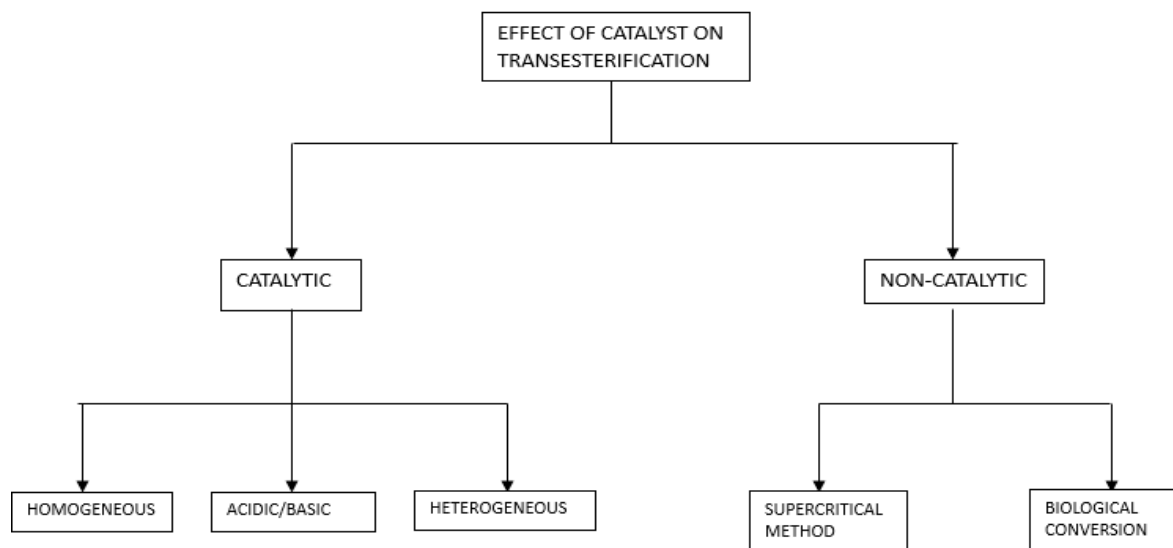


Fig 4: Classification of Catalysts generally used in the Transesterification Process.

2.4.1. Catalytic

2.4.1.1. Homogeneous:

A homogeneous catalyst is a type of catalyst in which both catalyst and reactants exist in the same phase. They are often used to accelerate the transesterification reactions and lower the activation energy which helps in increasing the rate of the reactions. Homogeneous catalysts interact with the reactants to form reactive intermediates. These intermediates then take part in the reaction and regenerate the catalyst eventually. They enhance the selectivity of the reaction which increases the formation of desired products, in this case, biodiesel. The use of sulfuric acid and hydrochloric acid in the transesterification process can be considered as examples.

2.4.1.2. Acidic/basic:

An acidic catalyst donates protons(H^+ ions) to reactant molecules in a reaction. These increase the concentration of positive charges. They attack electron-rich molecules to break bonds or form new ones. The process of generating biodiesel using an acid catalyst transesterification is the second most commonly used method. Though these catalysts produce a great yield of esters, the reaction is extremely slow. Examples are sulfuric acid, hydrochloric acid, and many more.

A basic catalyst accepts protons(H^+ ions) from reactant molecules. They attack electron-deficient molecules in a reaction. Either sodium hydroxide(NaOH) or potassium hydroxide(KOH) is used with ethanol or methanol in transesterification. They accelerate the rate of transesterification reaction by providing a pathway with minimum activation energy requirements.

2.4.1.3. Heterogeneous:

A heterogeneous catalyst exists in a phase that is different from that of the reactants in a given chemical reaction. A major advantage of using this is that it doesn't get consumed in the reaction. So they help in procuring pure biodiesel without catalyst contamination. These provide a larger surface area that helps in the reaction between reactants and active sites. Heterogeneous catalysts are easily removed through filtration or decantation. Transition metal catalysts, Zeolites, and metal oxides are some examples.

2.4.2 Non-catalytic

2.4.2.1. Supercritical Method:

The supercritical method involves the use of supercritical fluids. Substances that are above their critical temperature and pressure, and exhibit features that are intermediate between liquids and gases are called Supercritical fluids. These have properties like high solvating power, low viscosity, and high diffusivity leading to high reaction rates and selectivity. This method has a lot of effects on transesterification, like improved mass transfer (higher than those with liquid solvents), reduced reaction time, selectivity of product gets improved (without waste side products), reduced catalyst requirements, and product simplification. [14]

2.4.2.2. Biological Conversion:

This method involves enzymes and microbial approaches to carry out transesterification reactions.

a. Enzymatic catalysts:

Biological catalysts like lipases are used for transesterification reactions in biodiesel production, by breaking ester bonds in triglycerides and promoting the production of biodiesel and glycerol. Enzymes function to their maximum when in mild temperatures and pressures, tend to be highly specific in their reactions, produce fewer waste products, and separation of products tends to be easier. [34]

b. Microbial catalysts:

Microorganisms are cultivated using renewable feedstocks, like waste agricultural residues, thus reducing competition, and can act as whole-cell catalysts, simplifying the process. The microorganisms can directly be added to feedstock, wherein reduces the need for chemical catalysts and is more environmentally friendly. These reactions have slower kinetics and may be difficult to scale up for optimum conditions.



2.5 Result

Catalyst	Solvent	Optimum catalyst loading (%wt/wt oil)	Optimum alcohol to molar ratio	Reactor Temperature (°C)	Optimum reaction time (h)	Yield (%)	Reference
KOH	Methanol	0.15	12:1	60	3	-	[4]
NaOH/KOH	Methanol	0.005	3:1	30	3.5	99.1	[13]
H ₂ SO ₄	Methanol	0.5-1	6:1	60	-	98	[14]
KOH	-	-	6:1	60	2	98.69	[19]
ZnO	Methanol	-	-	65	9.72	89.23	[26]
CaO, HCl	Methanol	0.5	12:1	800	2	90	[34]
KOH	Methanol	0.2	14:1	80	1	97.6	[35]
KOH	Methanol	-	6:1	63.3	1	98	[36]
KOH/NaOH	Methanol	-	-	38	-	99	[37]
p-toluenesulfonic acid (PTSA)	Methanol	1	10:1	60	24	96	[38]
NaOH	Methanol	1	6:1	60	1	-	[39]
Transferred Kaolin (TK)	Methanol	10	10:1	63	-	95.6	[40]
KOH	Methanol	1.25	10.5:1	60	1.5	97.9	[41]
HCl, H ₂ SO ₄	-	-	-	110	1	-	[42]
SiO ₂ -Rich Sugar Cane Bagasse Ash	Methanol	-	-	65	-	87	[43]
Waste obtuse horn shell-derived CaO catalyst	Methanol	-	-	50-1000	1..58	86.75	[44]
Zeolite, KOH	Methanol	3	1.7:1	60	1	95.09	[45]
Cs-doped silica	Methanol	10-30	20:1	65	3	90	[46]
NaOH	Methanol	1	12:1	65	0.1163	89.7 & 88.63 for jatropa and WFPO	[47]

Table 2: Parameters and their respective yields for optimised biodiesel production

2.5 Challenges and Future Approach:

Currently, palm oil has become the least expensive vegetable oil to be manufactured. This multibillion-dollar business has a poor image and has been accused of, among other things, destroying rainforests, driving creatures to extinction, and upsetting the balance of the planet's environment. Plantations of palm trees are among the main employment and job provider sources in various nations, such as Malaysia and Indonesia. The progress and fast growth of palm biodiesel demand and production increases crop yields. Human land acquisition and exploitation for agricultural purposes cause environmental devastation.

LCA, or life-cycle assessment, is a method used to evaluate sustainability. A commercial product, process, or service's environmental consequences are evaluated using a technique called life cycle assessment (LCA). In essence, the palm oil business entails several significant procedures, including planting, the gathering of oil dates, oil production, and the valorization of wastes and by-products. According to Yung et al. [10], switching from fossil-based to bio-based methanol led to a 63% decrease in the use of fossil fuels and a 22% decrease in global warming.

It is without a doubt advantageous to society and the community for the palm biodiesel sector to flourish effectively, particularly in the rural regions where palm trees are planted. We can use transgenic palm oil to yield more than conventional methods, which helps raise the oleate and lauric acid in the production of palm oil, then the future goal of making the palm oil industry sustainable and safer might turn into a reality [11]. A rapid expansion of high-intensity commercial plantations in new regions plus climatic changes may cause new pests and pathogens to emerge. Thus the public sector and industry must work together to develop methods of early detection and surveillance.

III. CONCLUSION

Biodiesel, a renewable fuel, holds great promise for reducing greenhouse gas emissions and enhancing air quality. However, its production faces challenges such as feedstock purity, high costs, and environmental concerns, particularly related to palm oil production. To address these issues, future strategies include the development of more efficient production methods like supercritical and enzymatic processes, exploring alternative feedstocks such as algae and waste vegetable oils to reduce competition with food crops, utilizing government incentives like tax breaks and regulations, and promoting biodiesel blends to lower environmental impact and improve fuel economy. With ongoing research and development, biodiesel is poised to perform a pivotal role in the global energy mix as a more sustainable and eco-friendly alternative to petroleum diesel.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors have contributed to the study's conception, read, and approved the final manuscript.

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