STUDY OF CALCIUM ALGINATE-SILICA COMPOSITE BEADS IN TRANSESTERIFICATION OF BLEACHED OIL: CATALYST MODIFICATION, OPTIMIZATION AND CONVERSION TO RENEWABLE HYDROCARBON

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by

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LIST OF SYMBOLS

%	Percentage
°	Degree
µL	Microlitre
µm	Micrometer
amu	Atomic mass unit
°C	Degree Celsius
°C/min	Degree Celsius per minute
cm^{-1}	Per centimeter
cm^3/g	Volume
G	Gram
Hr	Hour
K	Kelvin
kg	Kilogram
kg/m^3	Density
kJ mol^{-1}	Activation energy
L	Litre
m^2/g	Specific surface area
meq/kg	Milliequivalents per kilogram
min	Minute
min^{-1}	Per minute
MJ/kg	Energy Content
ml	Millilitre

ml	Mililiter
ml/min	Mililiter per minute
mm^2/s	Viscosity
mol/l	Molarity
P/Po	Relative pressure
ppm	Part Per Millions
rpm	Revolutions per minute
w/v	Weight per Volume
w/w%	Weight by weight percent
wt.%	Weight percentage
θ	Theta

LIST OF ABBREVIATIONS

Alg-SBE/KOH	Alginate beads of Spent bleaching earth doped with potassium hydroxide
ASTM	American Society for Testing and Materials
BET	Brunauer-Emmett-Teller
BO	Bleached oil
C_6H_{14}	N-hexane
Ca	Calcium
$CaCl_2$	Calcium chloride
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon Dioxide
CPO	Crude Palm Oil
Cu	Copper
FAME	Fattyacid methyl ester
Fe_3O_4	Iron oxide
FESEM-EDX	Field Emission Scanning Electron Microscope-Energy Dispersive X-ray
FFA	Free fatty acid
FTIR	Fourier Transform Infrared Spectroscopy
GC-FID	Gas chromatography-flame ionization instrument
GC-MS	Gas Chromatography-Mass Spectrometry
H_2	Hydrogen gas
H_2SO_4	Sulphuric acid
H_3PO_4	Phosphoric acid
HCl	Hydrochloric acid
HDO	Hydrodeoxygenation
JCO	Jatropha curcas L. oil
K_2CO_3	Potassium carbonate
K_2O	Potassium oxide
KOH	Potassium hydroxide
MgO	Magnesium oxide

MOFs	Metal-Organic Frameworks
NaOH	Sodium hydroxide
Ni	Nickel
NO_X	Oxides of Nitrogen
Pd	Palladium
PFAD	Palm Fatty Acid Distillate
POME	Palm Oil Mill Effluent
Pt	Platinum
RPO	Refined palm oil
SAF	Sustainable Aviation Fuel
SBE	Spent Bleaching Earth
SBE/alginate bead	SBE coated with calcium alginate to form a bead
SBE/KOH	Spent bleaching earth doped with potassium hydroxide
SDG	Sustainable Development Global
TGA	Thermogravimetric Analysis
TPD-CO_2	Temperature Programmed Desorption of Carbon Dioxide
UCO	Used Cooking Oil
WAFs	Waste Animal Fats
WCO	Waste Cooking oil
WCoO	Waste Coconut oil
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

KAJIAN KALSIUM ALGINET-SILIKA MANIK KOMPOSIT DALAM TRANSESTERIFIKASI MINYAK PELUNTUR: PENGUBAHSUAIAN MANGKIN, PENGOPTIMUMAN DAN PENUKARAN HIDROKARBON BOLEH DIPERBAHARUI

ABSTRAK

Tanah peluntur terpakai (SBE), sisa pepejal yang dihasilkan oleh industri penapisan minyak sayuran, menimbulkan cabaran alam sekitar dan pelupusan yang ketara akibat kandungan minyak yang tinggi. Kajian ini meneroka pemanfaatan SBE sebagai penyokong mangkin dan bahan suapan bagi penghasilan biodiesel, sekali gus menawarkan penyelesaian pengurusan sisa yang mampan. Pemangkin komposit alginat–SBE yang baru telah disintesis melalui kaedah impregnasi mudah di bawah keadaan optimum, menggunakan nisbah 1:4 antara natrium alginat dan SBE/KOH (25%, 30% & 35%), diikuti dengan kalsinasi pada 600 °C. Pemangkin ini telah dicirikan secara sistematik menggunakan fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), Brunauer–Emmett–Teller Surface Area Analysis (BET), X-ray Diffraction (XRD), Carbon Dioxide Temperature-Programmed Desorption (CO_2-TPD), and Field Emission Scanning Electron Microscopy with Energy Dispersive X-ray Analysis (FESEM-EDX) untuk mengesahkan sifat struktur, tekstur, dan kimianya. Analisis BET dan CO_2-TPD menunjukkan bahawa Alg-SBE/KOH 30 memberikan luas permukaan tertinggi (40.92 m^2/g) dan sifat kealkalian (49.29 mmol/g), yang menunjukkan bahawa penambahan KOH ke dalam komposit alginat-SBE secara signifikan meningkatkan luas permukaan mangkin serta memperkukuhkan sifat kealkaliannya. Transesterifikasi minyak peluntur yang dioptimumkan menggunakan Alg-SBE/KOH 30 mencapai hasil biodiesel maksimum sebanyak 93.35% dalam keadaan optimum: 80°C, nisbah molar metanol kepada minyak 22:1, dan pemuatan mangkin sebanyak 9

wt.% dalam tempoh 2 jam. Mangkin ini menunjukkan kebolehkitaran yang sangat baik, mengekalkan lebih daripada 90% aktiviti asalnya selepas lima kitaran penggunaan. Analisis GC-MS menunjukkan kehadiran metil ester asid lemak utama (FAME) seperti metil laurat (C12), metil miristat (C14), metil palmitoleat (C16:1) dan metil stearat (C18) yang mencadangkan potensi penukaran biodiesel kepada hidrokarbon boleh diperbaharui. Secara signifikan, mangkin alginat-SBE menunjukkan peningkatan ketara dalam perolehan biodiesel berbanding kajian terdahulu yang menggunakan bahan suapan minyak dan pemangkin berasaskan SBE konvensional, sekali gus menyerlahkan keunggulan prestasi mangkin ini. Kajian ini bukan sahaja mengesahkan keberkesanan pengubahsuaian KOH dalam meningkatkan kecekapan pemangkin tetapi juga mengukuhkan potensi pemanfaatan sisa industri bagi penghasilan biodiesel yang mampan.

STUDY OF CALCIUM ALGINATE-SILICA COMPOSITE BEADS IN TRANSESTERIFICATION OF BLEACHED OIL: CATALYST MODIFICATION, OPTIMIZATION AND CONVERSION TO RENEWABLE HYDROCARBON

ABSTRACT

Spent bleaching earth (SBE), a solid waste generated by vegetable oil refining industries, poses significant environmental and disposal challenges due to its high oil content. This study explores the valorization of SBE as both a catalyst support and a feedstock for biodiesel production, offering a sustainable waste management solution. A novel alginate–SBE composite catalyst was synthesized via a simple impregnation method under optimal conditions, using a 1:4 ratio of sodium alginate to SBE/KOH (25%, 30% & 35%), followed by calcination at 600 °C. The catalyst was systematically characterized using fourier transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), Brunauer–Emmett–Teller Surface Area Analysis (BET), X-ray Diffraction (XRD), Carbon Dioxide Temperature-Programmed Desorption (CO_2-TPD), and Field Emission Scanning Electron Microscopy with Energy Dispersive X-ray Analysis (FESEM-EDX) to confirm its structural, textural, and chemical properties. BET and CO_2-TPD analysis revealed that Alg-SBE/KOH 30 gave the highest surface area (40.92 m^2/g) and basicity (49.29 mmol/g) indicated the introduction of KOH into the alginate-SBE composite significantly increased the surface area of the catalyst, while enhancement in basicity. The transesterification of bleached oil optimized using Alg-SBE/KOH 30, achieved a maximum biodiesel yield of 93.35% under optimal conditions: 80°C, a methanol- to-oil molar ratio of 22:1, and a catalyst loading of 9 wt.% within 2 hours. The catalyst exhibited excellent reusability, retaining over 90% of its initial activity after five cycles. GC-MS analysis

indicated the presence of key fatty acid methyl esters (FAMEs), including methyl laurate (C12), methyl myristate (C14), methyl palmitoleate (C16:1) and methyl stearate (C18) suggesting the potential conversion of biodiesel into renewable hydrocarbons. Notably, the alginate-SBE catalyst demonstrated a significant enhancement in biodiesel yield compared to previous studies utilizing the same oil feedstock and conventional SBE-based catalysts, highlighting its superior catalytic performance. This study not only confirms the effectiveness of KOH modification in improving catalyst efficiency but also reinforces the potential of industrial waste valorization for sustainable biodiesel production.

CHAPTER 1

INTRODUCTION

1.1 Background of study

As a signatory to the Paris Agreement, Malaysia has committed to reducing its greenhouse gas (GHG) emissions and transitioning toward a more sustainable energy system. The Paris Agreement, adopted in 2015, aims to limit global temperature rise to well below 2°C above pre-industrial levels while pursuing efforts to keep it below 1.5°C (Zhang et al., 2022). In line with this global initiative, the Malaysian government has intensified efforts to reduce its dependence on fossil fuels by promoting renewable energy sources and sustainable industrial practices (Fernandez et al., 2024). In addition to its commitments under the Paris Agreement, Malaysia is also aligning its energy and environmental policies with the United Nations 2030 Agenda for Sustainable Development. This agenda, which includes the 17 Sustainable Development Goals (SDGs), emphasizes the need for responsible consumption and production (SDG 12), climate action (SDG 13), and affordable and clean energy (SDG 7) (Zhang et al., 2020). Reducing reliance on fossil fuels and adopting renewable biofuels, such as biodiesel from waste materials, are essential steps in achieving these sustainability goals (Hamamre et al., 2024).

Fossil fuels represented more than 95 % of Malaysia's total primary energy mix in the past decade, though her large natural gas reserves have made the country a major exporter of the resource in the ASEAN region (Alam et al., 2024). Fossil fuels such as coal, oil, and natural gas as shown in Figure 1.1 have been the backbone of Malaysia's energy sector, but their continued use contributes to air pollution, greenhouse gas emissions, and climate change. Moving away from fossil fuels can provide significant economic benefits by reducing reliance on imported fuels, stabilizing energy costs, and fostering new green industries. The development of the renewable energy sector can attract foreign investments, and promote technological innovation, ultimately strengthening Malaysia's economy (A. J. A. Aziz et al., 2024). Furthermore, a shift to renewable energy will improve public health by reducing air pollution-related diseases, such as respiratory problems, caused by fossil fuel emissions. By embracing cleaner energy solutions, Malaysia can ensure long-term energy security, enhance environmental sustainability, and improve the overall well-being of its people while positioning itself as a leader in the global transition to a low-carbon economy (Shadman et al., 2021).

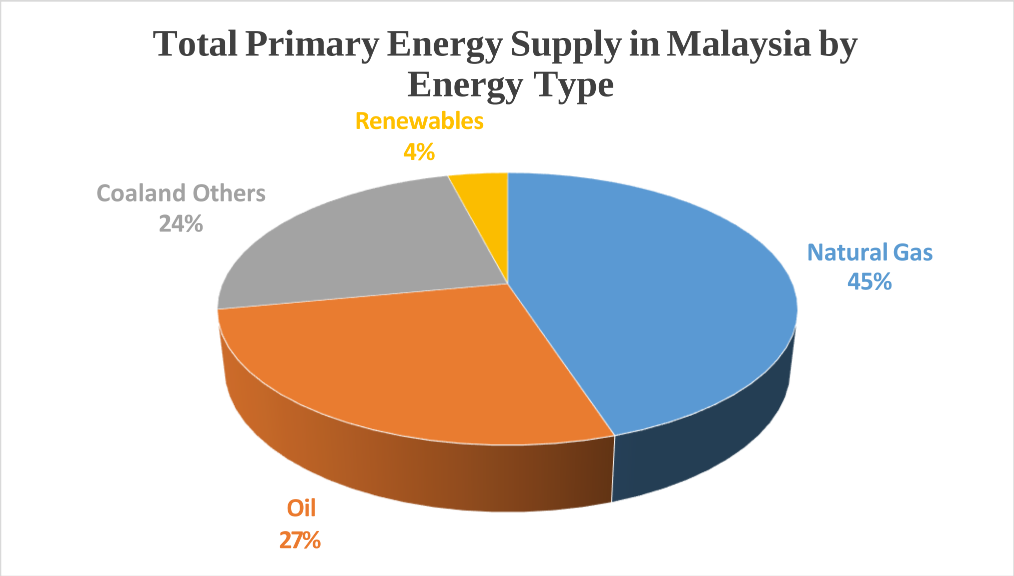

Figure 1.1 Malaysia's total primary energy supply by different energy types (Alam et al., 2024)

One of the key areas of focus in Malaysia's renewable energy transition is the development of biofuels, particularly biodiesel and bioethanol. The Malaysian government has actively promoted biodiesel adoption through initiatives such as the B20 biodiesel program, which mandates a 20% palm biodiesel blend in diesel fuel for the transportation sector (Abdullah et al., 2022, Kumar et al., 2022). Additionally, Malaysia's National Energy Policy 2022-2040 and the Renewable Energy Roadmap (MyRER) outline long-term strategies to increase renewable energy integration, enhance energy security, and drive sustainable economic growth (Christopheret al., 2022). Figure 1.2 show the trend of biodiesel production in Malaysia from 2020 to 2024. Production is expected to increase by 2025 as the country is likely to maintain a B10 blend rate, with limited progress in advancing B20 and B30 mandate goals (Foreign Agricultural Service., 2023). In this context, biodiesel research is crucial for optimizing production efficiency, improving feedstock utilization, and reducing costs, making it a more viable option for large-scale adoption. Biodiesel, derived from plant oils, animal fats, and used cooking oil contains free oxygen in its molecular structure, distinguishing it from traditional fossil fuels, leading to cleaner combustion and lower emissions of CO_2 and CO compared to petroleum diesel (Kukana et al., 2021; Zhang et al., 2021). Besides that, it emits fewer pollutants and greenhouse gases, thus reducing air pollution and combating climate change. It can also be used in existing diesel engines with minimal modifications, providing a practical option for reducing transportation emissions (Ciolkosz. 2024). This transition is vital for mitigating rising fuel costs and addressing the environmental impacts of global warming, ensuring a sustainable future for the next generation.

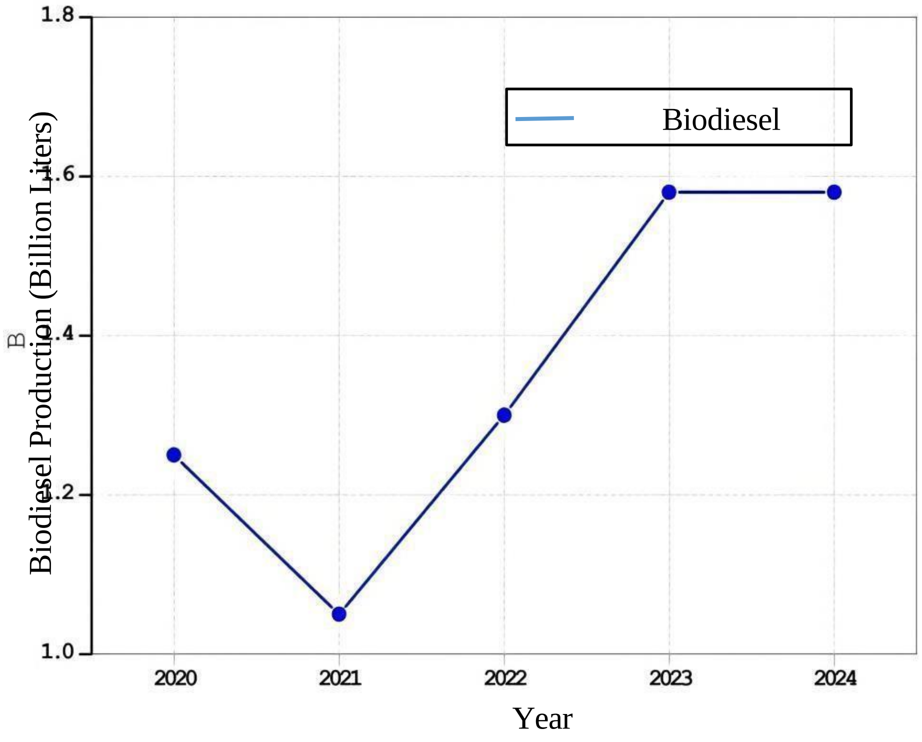

Figure 1.2 The trend of biodiesel production in Malaysia from 2020 to 2024 (Foreign Agricultural Service., 2023)

Biodiesel production commonly relies on palm oil as a primary feedstock due to its high oil content and availability. As Malaysia is one of the world's largest palm oil producers, the industry plays a crucial role in the economy (Kadir, 2024). However, the sector faces challenges such as fluctuating palm oil prices, which directly impact biodiesel profitability, as well as growing concerns over sustainability issues, including land use changes and deforestation (Q. Lin & Zhou, 2024). To address these challenges, there is a growing need to explore alternative feedstocks, particularly those derived from industrial waste. One promising solution is the utilization of spent bleaching earth (SBE), a waste material from the oil refining industry, which not only reduces reliance on virgin oils but also enhances the sustainability of biodiesel production through waste valorization. By utilizing waste materials as feedstock, biodiesel production aligns with the principles of a circular economy, promoting resource efficiency and waste reduction.

SBE is a byproduct generated during the refining of edible oils, where activated clays are used to remove impurities, colorants, and other undesirable components. After this bleaching process, the resultant SBE contains residual oil, making it a potential feedstock for biodiesel production (Sales et al., 2022; Farouk et al., 2024). Utilizing SBE for biodiesel not only offers a method to recover valuable oil but also addresses waste management challenges by reducing the environmental impact associated with its disposal (Sujin et al., 2024).

As shown in Table 1.1, Malaysia is the second-largest producer of SBE waste. Managing SBE waste in the country poses significant challenges, including high treatment costs and the risk of illegal dumping. Disposing of SBE in landfills poses environmental risks, including potential spontaneous combustion due to its residual oil content, which can lead to fires and air pollution (Zamri et al., 2019; Fadhullah et al., 2022). Additionally, the decomposition of SBE in landfills can contribute to the generation of leachate, which may contaminate soil and groundwater resources. By repurposing SBE as a feedstock for biodiesel production, these environmental hazards can be mitigated. This approach can help government in handling industrial waste management, aligning with global efforts to promote environmental sustainability (Yatoo et al., 2024; Matthews et al., 2024).

Table 1.1 Quantity of spent bleaching earth produces in selected countries. (Sigauke et al., 2024; Hasibuan, 2023)

Country	Quantity (tonnes/year)
Saudi Arabia	5,200
Japan	80,000
Indonesia	2.5 million
Thailand	0.5 million
Malaysia	1.2 million

SBE often discarded in landfills, contains about 20-40% crude oil that can be converted into biodiesel through transesterification (PASPI, 2020). SBE is mainly composed of clay minerals, particularly montmorillonite, an alumino-silicate mineral with a large surface area and high cation exchange capacity, making it effective in adsorbing impurities during oil refining (Abdelbasir et al., 2023). Acidic sites on montmorillonite also have potential to act as catalysts in transesterification and esterification for biodiesel production (Sigauke et al., 2024). In 2023, Keasavan et al. investigated SBE's potential for biodiesel production, enhancing its catalytic activity by doping it with potassium hydroxide (KOH) and calcining at 600°C, achieving a biodiesel yield of 80.3%. However, these study identified certain limitations, particularly concerning catalyst reusability and stability. Catalysts used in the transesterification process are often in powder form, which enhances their effectiveness due to their separation from the liquid reactants. However, powder catalysts pose practical challenges: they are difficult to recover, and significant material loss can occur during recycling, especially during washing steps (Kishore et al., 2022). To address these limitations, researchers have increasingly explored the use of alginate composites as catalyst supports. Alginate composites have been shown to significantly reduce material loss during reuse, making them a more sustainable alternative (Y. Wang & Lu, 2023).

Unlike traditional powder catalysts, alginate composites feature a three-dimensional network structure formed through hydrophilic interactions or copolymer crosslinking. This structure offers several advantages, including ease of handling, high adsorption capacity, reusability, and good porosity (Kavand et al., 2024). As a result, immobilizing powder catalysts within alginate-based beads can enhance catalyst stability and performance, contributing to more efficient and sustainable biodiesel production processes (Al-Sakkari et al., 2021).

Beyond biodiesel production, the conversion of SBE oil into other renewable hydrocarbons through catalytic processes remains unexplored. According to T. Kumar et al., (2023) Malaysia is set to commence the production of Sustainable Aviation Fuel (SAF) in 2027, targeting an initial output of one million metric tons annually. This initiative aligns with the nation's National Energy Transition Roadmap (NETR) that includes a SAF blending mandate, starting at 1% and aiming for a 47% blend by 2050 (Rani et al., 2025; The Energy Year. 2024). To support this initiative, substantial investments are being made in Malaysia’s sustainable aviation fuel (SAF) sector. EcoCeres Renewable Fuels Sdn Bhd and Petronas, in collaboration with Enilive and Euglena, are developing state-of-the-art production facilities with annual capacities of 350,000 and 650,000 metric tons, respectively (Osman et al., 2024). These advancements position Malaysia as a leading in the global SAF market, driving innovation and sustainability in aviation. Furthermore, this growth presents significant opportunities for scientists to explore cutting-edge research, particularly in biojet fuel development, enhancing Malaysia’s role in the renewable energy landscape (The Star., 2024). Converting biodiesel into biojet fuel presents a viable option for significantly reducing greenhouse gas emissions compared to conventional jet fuels, thereby supporting global carbon-neutral aviation goals set by organizations like the International Civil Aviation Organization (ICAO). The demand for biojet fuel is projected to increase, potentially reaching nearly 1% of global jet fuel supplies by 2028, with estimates suggesting it could rise to 3.5% under favorable policy conditions, particularly in the U.S., Europe, and Japan (Fitriasari et al., 2023; IEA., 2024).

Building upon the aforementioned concerns, this study designed alginate-SBE composite catalyst with derived from waste for biodiesel production. Utilizing SBE as catalyst and feedstock for biodiesel provide sustainable approach to enhance biodiesel production, while also offering the potential to convert into renewable hydrocarbons.

1.2 Problem Statement

The growing global demand for sustainable energy has intensified efforts to identify eco-friendly feedstocks for biodiesel production. In Malaysia, the palm oil refining industry generates an estimated 120,000 to 170,000 tonnes of spent bleaching earth (SBE) annually, a figure expected to rise in tandem with increasing palm oil production. However, the disposal of SBE presents significant environmental challenges, including high disposal costs, landfill accumulation, and the risk of soil and water contamination. Despite these concerns, SBE holds untapped potential, as it contains residual oils and catalytic components that can be repurposed to enhance biodiesel synthesis. By utilizing SBE as a catalyst, this approach not only mitigates waste disposal issues but also aligns with the principles of waste valorization and the circular economy, promoting a more sustainable and resource-efficient biofuel industry. Traditional catalysts used in transesterification processes, such as homogeneous alkali catalysts like sodium hydroxide ($NaOH$) and potassium hydroxide (KOH), often face challenges such as leaching, low stability, high energy consumption, and limited reusability, underscoring the need for cost-effective and sustainable alternatives. This study investigates the catalytic potential of SBE-calcium alginate composite beads as a novel heterogeneous catalyst for biodiesel production, aiming to optimize reaction parameters, improve catalyst reusability, and enhance catalytic efficiency.

Furthermore, the aviation industry is a significant contributor to greenhouse gas emissions, accounting for approximately 5% of global emissions. Traditional jet fuels are derived from fossil fuels, leading to substantial carbon footprints. Sustainable aviation fuels (SAFs), produced from renewable resources like biomass and waste oils, offer a promising alternative but currently account for less than 0.1% of all aviation fuels consumed. Challenges such as high production costs, limited availability, and the need for technological advancements have hindered widespread adoption. This research explores the conversion of biodiesel into renewable hydrocarbons suitable for aviation, addressing key challenges in sustainable fuel production while contributing to the development of greener aviation fuels and advancing the transition toward a circular bioeconomy. To achieve this, a base catalyst doped with KOH, supported by an SBE/alginate composite, was synthesized and investigated for its efficacy in biodiesel production through the transesterification of bleached SBE oil. Furthermore, the physicochemical properties of the catalyst were systematically analyzed to assess its performance.

1.3 General Objectives

This study investigates the production of biodiesel from bleached oil as feedstock using alginate composite catalysts in a transesterification.The specific objectives of the study were:

a) To synthesize the SBE-alginate composite catalyst for transesterification of bleached oil.

b) To characterize the physicochemical properties of the potential catalyst and biodiesel using several characterization techniques.

c) To optimise the performance of catalysts in transesterification reaction under hydrothermal condition.

d) To study the feasibility of converting biodiesel into renewable hydrocarbon.

1.4 Scope of study

The goal of this study was to increase biodiesel production from SBE oil by utilizing the Alg-SBE/KOH catalysts. The oil was extracted from SBE using Soxhlet extraction method, and the catalyst was prepared using wet impregnation method. Given the abundant availability of SBE, it is an ideal feedstock for this process, addressing the issue of mass waste production and promoting eco-friendly practices. The transesterification process was carried out using SBE oil and methanol as solvent to produce fatty acid methyl esters (FAME) as biodiesel and glycerol. The FAME was tested by gas chromatography with flame ionization detection (GC-FID) to identify the compounds present. From the transesterification reaction, the best catalyst which yields higher biodiesel production was chosen and optimized based on the KOH loading, catalyst dosage, oil-to-methanol molar ratio, reaction time, and reaction temperature. The potential catalysts were characterized using several advanced techniques, including Thermogravimetric analysis (TGA) was carried out to calculate the mass loss of the catalyst while the surface morphology and elemental composition of the catalysts were determined by field emission scanning electron microscopy-energy dispersive X-ray (FESEM-EDX) analysis. Temperature programmed desorption of CO_2 (TPD-CO_2) were used to investigate the surface basicity and acidity of the catalysts, respectively. The surface area, pore volume, and pore size of the catalysts were determined through Brunauer-Emmett-Teller (BET) analysis, while their functional groups were examined using Fourier Transform Infrared Spectroscopy (FTIR). Next, the potential conversion of biodiesel into renewable hydrocarbons was investigated through a deoxygenation process carried out in a stainless steel autoclave reactor, utilizing a 10 wt% Co/γ-Al_2O_3 catalyst. The resulting hydrocarbon products were then analyzed using gas chromatography-mass spectrometry (GC-MS) to evaluate their hydrocarbon composition as renewable fuel alternatives.

1.5 Significance of study

The market competitiveness of biodiesel is heavily dependent on feedstock costs. The disposal of spent bleaching earth (SBE) waste poses significant challenges. The production of catalysts often involves the use of numerous chemicals, resulting in high costs and negative environmental impacts. Using readily available waste materials offers a sustainable approach to reduce biodiesel production costs. This study employs a two-pronged approach to repurpose spent bleaching earth (SBE) from the palm oil refining industry, evaluating its suitability both as a second-generation biofuel feedstock and as a catalyst. Additionally, the research explores the application of alginate composites in enhancing catalytic performance and investigates the potential conversion of biodiesel into renewable hydrocarbons. The study's novel contributions are outlined below:

1. Enhancement of catalytic performance with alginate composites.
2. Exploration of renewable hydrocarbon production.
3. Promotion of circular economy principles.

CHAPTER 2

LITERATURE REVIEW

2.1 Need for cleaner biodiesel

The increasing global focus on environmental sustainability and energy security has prompted many nations, including Malaysia, to explore alternative and cleaner energy sources (Sharma et al, 2020). Biodiesel, a renewable and biodegradable fuel derived from vegetable oils or animal fats, has emerged as a promising substitute for conventional fossil fuels. While biodiesel offers several advantages, concerns over emissions, feedstock sustainability, and production efficiency highlight the need for cleaner biodiesel solutions.

As one of the world's leading palm oil producers, Malaysia has naturally turned to palm oil-based biodiesel as a key component of its biofuel industry (Atabani et al., 2019). To support this initiative, the Malaysian government has introduced policies such as the National Biofuel Policy (NBP) and the B20 biodiesel mandate, which requires a 20% blend of palm biodiesel with conventional diesel (Ahmad et al., 2021). However, despite these efforts, the combustion of palm-based biodiesel has been found to produce higher nitrogen oxides (NOx) emissions, contributing to air pollution and smog formation (Yusoff et al., 2022). In Malaysia, the transportation sector is a significant contributor to greenhouse gas (GHG) emissions. As of 2018, transportation accounted for approximately 36.4% of the country's total final energy demand, with carbon dioxide (CO_2) comprising 96% of the GHG emissions from this sector (Solaymani et al., 2022). Within the transportation sector, road transport is the predominant source of emissions, contributing about 85.2% of the total transportation-related emissions. Passenger cars are the largest contributors, accounting for approximately 59% of these emissions, while freight transport contributes around 27% (Romanello et al., 2023; IPCC. 2022). As shown in Figure 2.1 the CO_2 emissions from fuel combustion keep increasing by year. These statistics underscore the critical need for cleaner biodiesel alternatives in Malaysia. Transitioning to low-emission fuels can significantly reduce CO_2 emissions from the transportation sector, thereby mitigating environmental impact and promoting public health.

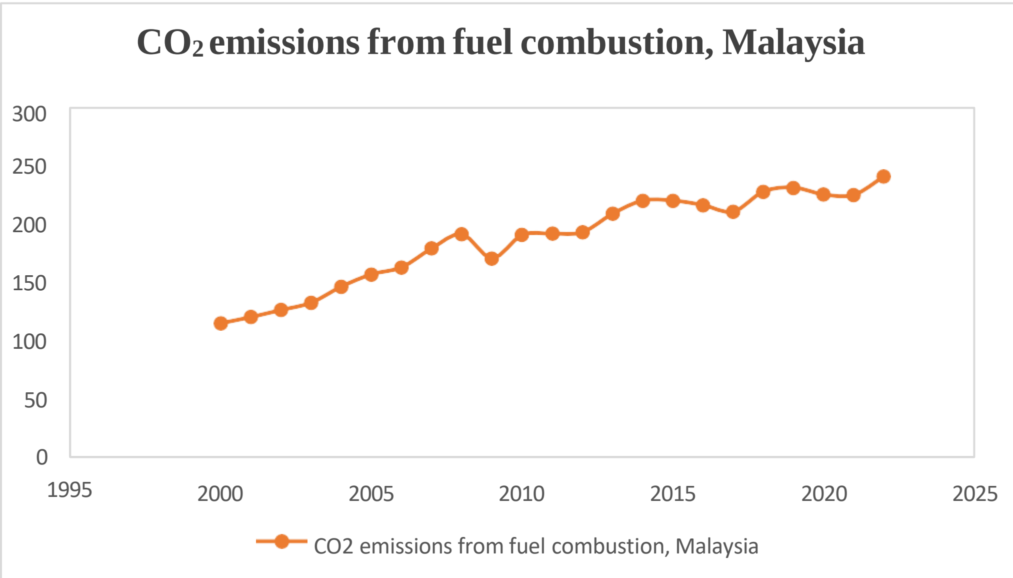

Figure 2.1 CO_2 emissions from fuel combustion, regional ranking, 2022 (International Energy Agency. 2022)

Beyond emissions, the economic feasibility of large-scale cleaner biodiesel production remains a challenge. Although Malaysia possesses substantial palm oil reserves, fluctuating palm oil prices and concerns over deforestation and land use changes have raised sustainability issues. As a result, researchers have explored alternative feedstocks such as waste cooking oil, algae, and Jatropha curcas as more sustainable options (Lim et al., 2018). However, transitioning to these alternatives requires significant investment in upgrading production facilities and refining processes to meet cleaner fuel standards, posing financial constraints for the industry.

To enhance the sustainability of biodiesel, researchers have investigated various methods to improve fuel quality. Advanced catalytic processing, blending with cleaner additives, and the development of second and third generation biofuels have shown promise in reducing emissions and improving overall efficiency (Rajaeifar et al., 2020). Additionally, improved feedstock management such as prioritizing non-food-based bio oils can help mitigate the environmental impact of biodiesel production.

Ultimately, while biodiesel presents a viable alternative to fossil fuels, ensuring its long-term sustainability requires continuous innovation and policy support. By addressing emissions, diversifying feedstocks, and refining production processes, Malaysia can strengthen its position in the global biofuel industry while contributing to a cleaner and more sustainable energy future.

2.1.1 Advantages of Biodiesel Over Petroleum

Biodiesel offers numerous advantages over petroleum diesel, making it a more sustainable and environmentally friendly alternative. One of its most significant benefits is its renewability, as it is derived from natural sources such as vegetable oils, animal fats, and algae (Zhang et al., 2022). Unlike petroleum diesel, which depends on finite fossil fuel reserves, biodiesel provides a more sustainable energy option that enhances energy security (Atabani et al., 2019). Additionally, biodiesel is biodegradable and non-toxic, reducing environmental risks in the event of spills (Sharma et al., 2020).

Beyond its renewability, biodiesel exhibits fuel properties that contribute to lower emissions and improved engine performance. Compared to petroleum diesel, biodiesel significantly reduces greenhouse gas (GHG) emissions. Studies indicate that over its life cycle, biodiesel can lower carbon dioxide (CO_2) emissions by up to 78%, making it a key contributor to climate change mitigation (U.S. Department of Energy, 2023). Furthermore, biodiesel contains little to no sulfur (<10 ppm in B100), preventing the formation of sulfur oxides (SOx), which are major contributors to acid rain and respiratory illnesses (Lim et al., 2018).

In addition to its environmental benefits, biodiesel has superior fuel characteristics compared to conventional diesel, as shown in Table 2.1. One key advantage is its higher cetane number (48–65), which enhances combustion efficiency, reduces engine knocking, and improves overall engine performance (Rajaeifar et al., 2020). Moreover, biodiesel has a higher flash point, making it safer for storage and handling. It also offers superior lubricity, which helps reduce engine wear and can extend the lifespan of diesel engines by up to 30% (Ahmad et al., 2021).

However, biodiesel does have some limitations, such as slightly higher viscosity and lower energy content compared to petroleum diesel, which can affect fuel economy and engine performance. Despite this, biodiesel significantly reduces harmful emissions, including particulate matter (PM) by up to 47%, hydrocarbon (HC) emissions by 67%, and carbon monoxide (CO) emissions by 48% compared to petroleum diesel (Yusoff et al., 2022). The main challenge lies in its slightly higher nitrogen oxides (NOx) emissions, which necessitate mitigation strategies such as exhaust gas recirculation (EGR) and catalytic converters (Sharma et al., 2020).

Understanding these differences is essential for optimizing biodiesel use in existing diesel engines while ensuring compliance with fuel standards. Overall, biodiesel's renewable nature, lower emissions, and favorable fuel properties position it as a promising alternative to conventional diesel, supporting the transition toward cleaner and more sustainable energy sources.

Table 2.1 Properties of biodiesel and conventional fossil fuels (Zhang et al., 2022; Bousbaa et al., 2024)

Property	Biodiesel (100)	Conventional Fossil Fuels (Petroleum Diesel)
Density (kg/m^3)	860-900	820-860
Viscosity (mm^2/s at 40°C)	3.5-5.0	2.0-4.5
Cetane Number	48-65	40-55
Flash Point (°C)	37-40	42-45
Energy Content (MJ/kg)	37-40	42-45
Oxygen Content (%)	10-12	0
Sulfur Content (ppm)	<10	Varies (Ultra-low sulfur <15 ppm)
Carbon Residue (%)	Lower than diesel	Higher carbon content
Lubricity	Higher (better for engine components)	Lower
Cold Flow Properties	Poor (prone to gelling at low temperatures)	Better cold flow properties

2.2 Biodiesel Feedstock

Biodiesel has emerged as a sustainable alternative to fossil fuels, with its production largely dependent on the availability of suitable feedstocks. In Malaysia, palm oil remains the primary feedstock due to its abundance and high oil yield, contributing significantly to the country's biodiesel industry (Mahayuddin et al., 2022). However, to improve sustainability and reduce reliance on edible oil sources, researchers have explored various alternative feedstocks.

In addition to palm oil, Malaysia has been investigating the potential of non-edible oils, waste oils, and other renewable sources for biodiesel production. Non-edible oils, such as Jatropha and rubber seed oil, present viable alternatives that do not compete with food supply (Shaah et al., 2021). Similarly, waste oils, including used cooking oil (UCO) and palm fatty acid distillate (PFAD), offer an environmentally friendly solution by repurposing industrial and household waste (Osman et al., 2024). Furthermore, algae-based biodiesel has gained attention due to its high oil yield and ability to grow in non-arable land, making it a promising long-term option (Nirmala et al., 2025).

Palm oil remains the dominant feedstock, while non-edible and waste oils play a growing role in diversification efforts as shown in Table 2.2. Palm oil exhibits the highest oil content, making it the most economically viable option as illustrates in Figure 2.2, highlighting the significant differences in yield. However, alternative feedstocks such as Jatropha and rubber seed oil also show considerable oil percentages, supporting their potential as supplementary sources.

Table 2.2 Biodiesel feedstock in Malaysia (Ong et al., 2024; Mahayuddin et al., 2022; Hamzah et al., 2020)

Feedstock Type	Percentage Contribution (%)	Category	Remarks
Crude Palm Oil (CPO)	80	Primary Feedstock	Main biodiesel feedstock, used for B7 & B10 blends.
Palm Oil Mill Effluent (POME)	15	Waste-Based Feedstock	Increasing use due to sustainability and EU export demand.
Used Cooking Oil (UCO)	4-5	Waste-Based Feedstock	Collected from households/restaurants, mainly for exports.
Palm Fatty Acid Distillate (PFAD)	<1	Byproduct Feedstock	Byproduct of palm oil refining, limited biodiesel use.
Other Feedstocks (Jatropha, Algae, Rubber Seed Oil, etc.)	<1	Emerging Feedstock	Mostly in research and pilot stages, not widely commercialized.

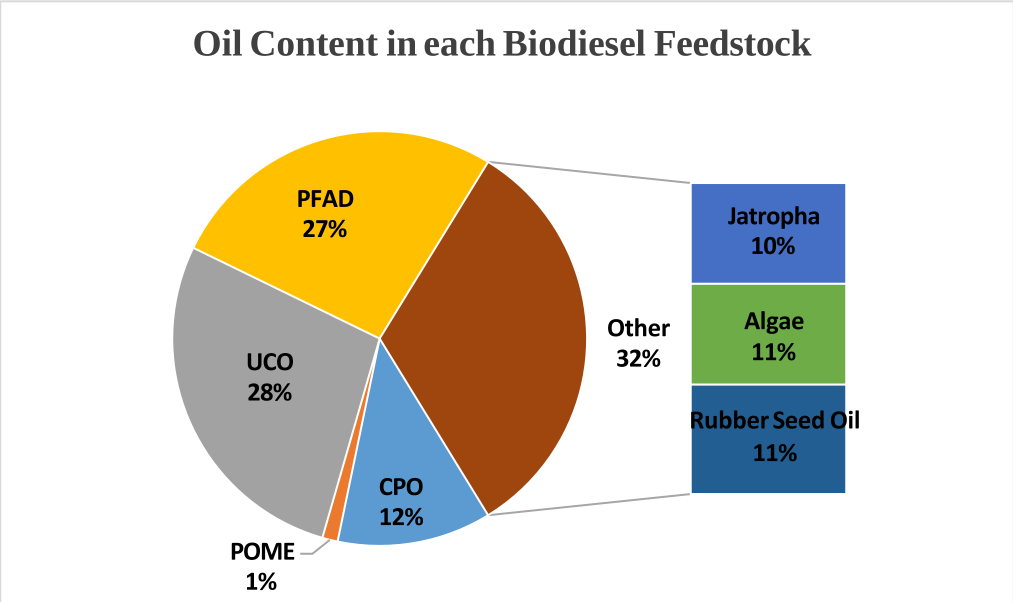

Figure 2.2 Oil Content in each feedstock (Maliki et al., 2020)

Beyond oil yield, the fatty acid composition of biodiesel significantly influences its fuel properties, including oxidation stability, cetane number, and cold flow performance. As shown in Table 2.3, studies by B. Singh et al. (2023); Ikram et al. (2019); and Azad et al. (2019) have examined the fatty acid profiles of different biodiesel feedstocks, revealing variations in saturated and unsaturated fatty acid content. These differences impact fuel quality and usability in various climatic conditions. The diversification of biodiesel feedstocks is crucial for ensuring long-term sustainability in Malaysia's biofuel sector. By integrating multiple feedstocks, strengthening supply chains, and investing in advanced biotechnologies, biodiesel production can become more efficient and environmentally friendly. Additionally, policy interventions such as incentives for waste-based biodiesel and sustainable land management will further support the transition toward cleaner and more sustainable biodiesel solutions (Rajaeifar et al., 2020).

Table 2.3 The Fatty Acid composition (%) of biodiesel (B. Singh et al., 2023; Ikram et al., 2019; Azad et al., 2019)

Fatty acid	Palm Oil (CPO)	POME	UCO	PFAD	Jatropha Oil	Algae Oil	Rubber Seed Oil
Palmitic Acid (C16:0)	40–45%	30–40%	15–25%	30–50%	10–20%	10–25%	8–12%
Stearic Acid (C18:0)	4–6%	3–5%	2–5%	4–8%	6-9%	1–5%	7–12%
Oleic Acid (C18:1)	38–45%	40–50%	40–50%	35–45%	40–50%	25–40%	24–30%
Linoleic Acid (C18:2)	10–12%	5–10%	20–30%	10–20%	30–40%	10–30%	35–45%
Linolenic Acid (C18:3)	<1%	<1%	<1%	<1%	5–10%	30–60%	10–15%

2.3 Industrial Waste as Feedstock in Biodiesel Production

The use of food-based oils raises concerns about food security and land use competition. In response, waste-based feedstocks have gained significant attention due to their cost-effectiveness, sustainability, and potential to mitigate environmental pollution. Waste-derived biodiesel helps in reducing waste disposal issues, lowering production costs, and contributing to a circular economy by repurposing waste materials (Damian et al., 2024).

2.3.1 Used Cooking Oil (UCO)

Used cooking oil (UCO) is one of the most widely studied waste feedstocks for biodiesel production. It is collected from households, restaurants, and food industries, helping to reduce waste disposal issues while lowering production costs. Studies have shown that UCO-based biodiesel exhibits fuel properties comparable to conventional biodiesel (Pelemo et al., 2022).

According to Rajesh et al., (2025), mixed seashell waste (MSW) was successfully converted into a nanocatalyst and used to produce biodiesel from UCO. By applying a statistical Box-Behnken design (BBD), the conversion efficiency was optimized to 93.18 ± 1.31% using an 11.3:1 methanol-to-WCO molar ratio, 4.28 wt% nanocatalyst, and a reaction time of 360 minutes all without requiring pretreatment of the UCO. However, despite its potential, UCO still presents challenges in social aspect. Different cooking practices (e.g., frying meat vs. vegetables) result in inconsistent levels of FFAs, water content, and oxidation by-products. Repeated heating cooking oil for a long time will cause the oxidation and polymerization of fatty acids, which produce free radicals and peroxide compounds that are toxic to body cells (A. Rahman et al., 2024). Malaysian national standards set requirements for the peroxide numbers in cooking oil at a maximum of 10 meq/kg of oil. Meanwhile, repeated use of cooking oil in the household has a peroxide value of 20–40 meq/kg (Aziz et al., 2018).

2.3.2 Palm Oil Mill Effluent (POME)

Palm oil mill effluent (POME) is a widely available waste product generated during palm oil processing. Due to its high organic content and residual oil, it has been investigated as a potential feedstock for biodiesel production. Recent studies emphasize the need for advanced extraction and purification techniques to improve biodiesel yield and quality from POME-derived feedstocks (Tang et al., 2023).

Research by Zulqarnain et al., (2021) demonstrated that an oil extraction yield of 90% was achieved from POME under optimized conditions, including an agitation speed of 500 rpm, a pH of 10, and a mixing time of 25 minutes. Further optimization for biodiesel synthesis was conducted using an oil-to-alcohol molar ratio of 1:10, a reaction time of 2.5 hours, a reaction temperature of 60°C, and a catalyst loading of 1.5 wt%. These conditions resulted in an experimental biodiesel yield of 93% and a simulation yield of 91%.

This study highlights the potential of POME as a cost-effective feedstock for biodiesel production. However, despite this potential, POME contains only a small fraction of recoverable oil, typically around 1-3%, making it a less viable option for large-scale biodiesel production (Leela et al., 2018).

2.3.3 Animal Fats and Waste Grease

Tallow, lard, and yellow grease from meat processing industries provide a viable alternative to vegetable oil-based biodiesel. These feedstocks have high saturated fatty acid content, resulting in biodiesel with better oxidative stability but higher viscosity and cloud points. Effective pretreatment techniques such as hydrolysis and esterification are crucial to processing animal fat-based biodiesel efficiently (Mandari & Devarai, 2021). Different types of waste animal fats (WAFs) consist of various and mostly high amount of SFA (sum of myristic, palmitic and stearic acids).

Usually, tallow and pork lard consist of more than 40% SFA. According to Mwenge et al., (2025), the SFA content in beef tallow is 45.6%, mutton tallow 61.1%, lard 39.3% and chicken fat 32% (Osman et al., 2024). As a result, the synthesis of biodiesel from WAFs should be conducted at higher temperature which is unlike the conversion processes of used cooking oils. Recycled greases are also waste greases and generally can be classified on the basis of the FFA level in two categories, yellow grease and brown grease. Yellow greases have FFA content of less than 15% (w/w) (Toldrá-Reig et al., 2020). They are produced from heated animal fats and vegetable oils which are collected from commercial and industrial cooking business. Brown greases refer to waste materials in which the amount of FFA exceeds 15%. Sometimes they are named as trap greases, i.e. materials that are collected in special traps in restaurants to prevent the grease from entering the sanitary sewer system (Hájek et al., 2021). They are very cheap materials in comparison with edible vegetable oils and often used as potential feedstocks for biodiesel production. However, waste grease and animal fats contain impurities,