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GREENFUSION: SYNTHESIS OF NEXT-GENERATION GREEN DIESEL FUEL THROUGH HYDRODEOXYGENATION OF NYAMPLUNG AND UCO

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Abstract. *The urgency of the energy transition in Indonesia is becoming increasingly pressing due to the country's high dependence on fossil fuels and the presence of 5 million diesel vehicles. This research introduces "GreenFusion," a method for synthesizing green diesel to overcome the limitations of conventional biodiesel. The objective is to investigate the hydrodeoxygenation of a dual non-food feedstock mixture, specifically Calophyllum inophyllum (Nyamplung) oil and used cooking oil (UCO). The approach involves synthesizing a nickel-silver catalyst on natural zeolite (NiAg/ZH) and conducting the hydrodeoxygenation process in a batch reactor at temperatures between 325°C and 375°C. The results confirm the successful synthesis of high-quality green diesel with an estimated yield of 91,2% and a cetane number of 75. Environmental impact projections at the pilot scale indicate significant potential for reducing UCO waste and lowering CO2 emissions by over 1,200 tons per year. Therefore, GreenFusion presents a technically viable and environmentally superior pathway for producing drop-in fuel, supporting Indonesia's goal of achieving the 2060 Net Zero Emissions (NZE) target.*

Keywords: *green diesel, hydrodeoxygenation, nyamplung seeds, nze 2060, used cooking oil*

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 2019) explained that the global surface temperature would increase by 1.1 to 6.4°C between 1990 and 2100. The increase in average global temperatures is primarily due to the rising concentrations of greenhouse gases in the atmosphere, which are largely driven by human activities. Indonesia is a country that heavily relies on fossil fuels, such as coal, oil, and natural gas. The use of fossil energy contributes significantly to greenhouse gas emissions, which in turn contribute to global climate change (Aprianto *et al.*, 2024). According to the Ministry of Energy and Resources of Indonesia (2023), Indonesia's crude oil consumption reached 319,664 barrels in 2023, reflecting a 4.15% increase from 2019 (Fig. 1). Based on the IESR (2021), Indonesia has become the second-largest emitter in the energy sector. In 2019, the energy sector accounted for up to 34% of total emission.

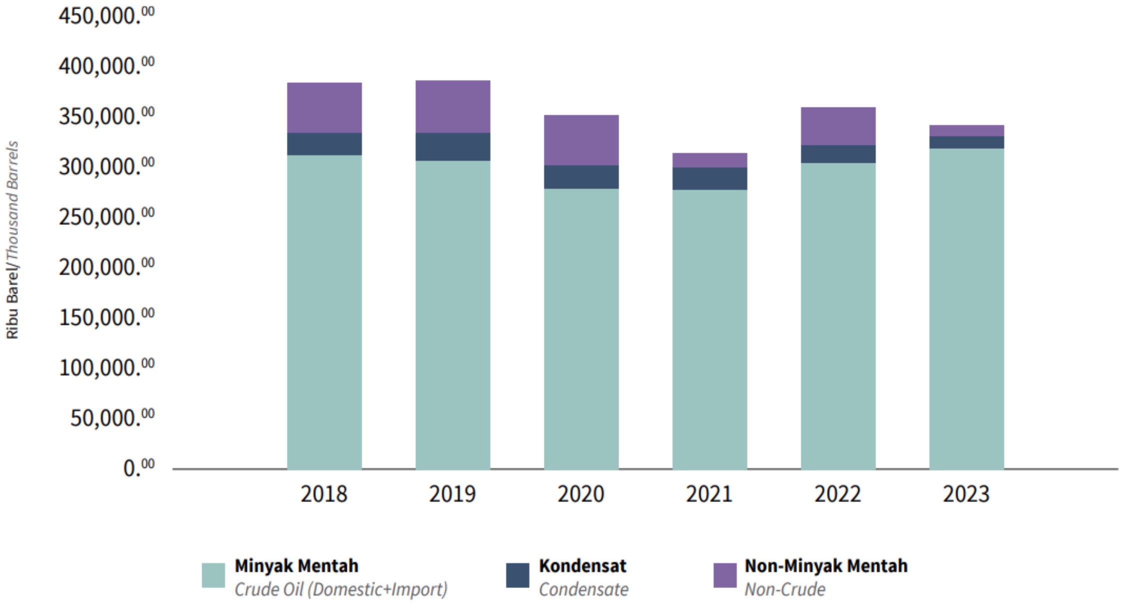

Figure 1. Processing of Crude Oil 2018–2023 (Ministry of Energy and Mineral Resources Republic of Indonesia, 2023)

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The transportation sector accounts for 33% of final energy consumption, with 95% of the demand met through oil. Strong policies to decarbonize the transport sector are necessary to help Indonesia achieve its Net-Zero Emissions (NZE) target (Climate Transparency Report, 2022). Among transportation modes, diesel-powered vehicles are the primary users of oil as fuel. Vehicle sales in Indonesia reached 1,050,000 units, with 23% of these being diesel-powered vehicles. Meanwhile, the number of diesel vehicles in operation is approximately 5 million units (GAIKINDO, 2022). Diesel fuel generates significant emissions when burned, contributing to air pollution (EIA, 2024).

Indonesia has established national development priorities through the Indonesian government’s strategic direction, known as Asta Cipta, to achieve the country's vision and mission. One of the Asta Cipta priorities that supports renewable energy is Asta Cipta Point 2 – Energy Self-Sufficiency, which highlights Indonesia's efforts to reduce its dependence on fossil fuels and position the country as a global leader in green energy (Subianto & Raka, 2023). This goal is further supported by the vision of Pertamina New & Renewable Energy (PNRE), which aims to become a world-class green energy company, with the mission to accelerate Indonesia's energy transition toward NZE by 2060 (PNRE, n.d.).

Indonesia requires an alternative fuel source that is both sustainable and environmentally friendly. Plant-based fuels present a viable solution to substitute fossil fuels, such as Biodiesel. In Indonesia, biodiesel is commonly blended with fossil fuels to reduce carbon emissions, with blends such as B5 (95% diesel, 5% biodiesel) and the widely used B20 (80% biodiesel, 20% diesel). However, biodiesel is highly dependent on blending with fossil fuels, as even B100 (100% biodiesel) cannot be used directly in diesel engines without modifications. This is due to its high viscosity, low volatility, and lower cetane number, which can lead to engine oil contamination and incomplete combustion (Sonthalia & Kumar, 2019). Additionally, biodiesel has a high cloud point and pour point, which can cause it to thicken at low temperatures, leading to operational issues (Osman *et al*., 2024).

Therefore, it is essential to use 100% natural resources for clean energy, such as Green Diesel. Green Diesel is a next-generation biofuel. It is a straight-chain hydrocarbon fraction similar to conventional diesel, produced through the hydrogenation of triglycerides. Green diesel is considered commercially viable because, unlike previous biofuels, it can be used in conventional transportation without requiring modifications to the diesel engine (Yudhistira & Wibowo, 2022). The first Green Diesel in Indonesia was introduced by PT Pertamina, known as Pertamina Renewable Diesel D100 (Pertamina RD).

Produced through a hydrotreating process using palm oil as feedstock, Pertamina RD has received ISCC certification and is recognized for reducing carbon emissions by 65–70% compared to conventional fuels (Pertamina, 2024).

The use of palm oil as a raw material for Green Diesel continues to raise concerns due to its contribution to deforestation. Oil palm plantations cannot replace primary forests and oil palm plantations, leading to the degradation of soil nutrients, making it unsuitable for growing other plants (Effendi *et al*., 2016). Another promising feedstock for green diesel is *Calophyllum inophyllum* (Nyamplung), a non-edible oil plant. The oil content in Nyamplung seeds is relatively high, ranging from 50% to 73% (Prasetyo *et al.*, 2018). Nyamplung thrives in marginal areas, with significant cultivation in regions across West Borneo, Central Kalimantan, Sulawesi, West Sumatra until NTT. The total land area used for Nyamplung cultivation in Indonesia is 255,350 Ha (BPPH, 2008). In its natural habitat of coastal sandy soils characterized by high porosity and low water retention, nyamplung is highly tolerant to saltwater inundation, whereas in mineral and ultisol soils, where it demonstrates a survival rate of over 90%, this plant responds to waterlogging stress by undergoing morphological adaptations, such as the formation of adventitious roots and lenticel hypertrophy, to maintain oxygen circulation (Fatonah et al., 2023). Conversely, in peatlands, which possess a high cation exchange capacity but low base saturation, nyamplung is still able to survive at rates of 81–82% in degraded areas such

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as Buntoi, Kalimantan. However, it becomes highly susceptible to mortality if continuously waterlogged due to high exposure to phytotoxic phenolic acids (Leksono et al., 2021).

Geographically, the differences between islands contribute to distinct genetic and ecophysiological variations. For instance, the provenance from Ketapang, West Kalimantan, has been proven to exhibit the most superior vegetative growth performance (seedling height, diameter, and sturdiness) with a survival rate above 90% and it has been successfully tested on bioenergy trial plots in East Kalimantan (Hasnah & Windyarini, 2014). On Java Island, nyamplung grows not only at an elevation of 0 meters above sea level (masl) but is also adaptable to mountainous regions up to 600 masl in Majalengka and it grows optimally in type C climate regions such as the Special Purpose Forest Area (KHDTK) in Wonogiri, where its superior clones possess excellent outcrossing traits ideal for tree breeding (Adinugraha et al., 2021). Furthermore, the geographical location of the coastal area of Leungah Village, Aceh Besar on Sumatra Island, enables nyamplung to produce a very high oil yield of around 40–74%, which is dominated by unsaturated fatty acids, such as oleic and linoleic acids and is rich in bioactive compounds like flavonoids and phenolics (Fitriyana & Sunartaty, 2025).

In the production of Green Diesel, Nyamplung oil is not the only feedstock used; Used Cooking Oil (UCO) also plays a significant role. In Indonesia, UCO has the potential to reach 1.2 million kiloliters per year, sourced from used oil generated by frying activities in households and micro-business units (MSMEs). The household sector contributes 40% of the total UCO, while MSMEs account for 30% of the total UCO in Indonesia (Traction Energy Asia, 2023). It is the most affordable feedstock for the production of Hydrogenation Derived Renewable Diesel (HDRD). However, despite its high potential as a raw material for green diesel, the use of UCO is currently limited to FAME production.

Meanwhile, Nyamplung oil has not yet been integrated into the national energy system, despite its significant potential. Therefore, innovations such as GreenFusion, which combines two raw materials, Nyamplung oil and UCO, using the hydrodeoxygenation method, is crucial for making the energy transition more inclusive, affordable, and sustainable. The development of GreenFusion aligns closely with the vision of Pertamina New & Renewable Energy (PNRE) to become a world-class green energy company and its mission to accelerate Indonesia's transition to Net Zero Emission (NZE) by 2060.

METHODOLOGY

Time and Place of Research

This research will be carried out from July to September 2025 at the Research Laboratory of the Advanced Laboratory and Research Laboratory of the Department of Biochemistry, Faculty of Mathematics and Natural Sciences, IPB.

Tools and Materials

The tools used in this research are stainless steel reactors, GC-MS, Viskometer, and AMETEK MiniFlash. The materials used in this research are crude Nyamplung oil from the Cilacap Region, natural zeolite is obtained from CV. Minatama Lampung, all precursors are derived from Merck, and UCO, NaOH, $NH_4CH_3CO_2$, aquades, and H_2. (Modification of (Febriyanti *et al.,* 2020) and (Heriyanto *et al*., 2018)).

Research Producers

Response Surface Methodology (RSM) was used to efficiently determine the optimal ratio between Nyamplung oil and UCO to maximize green diesel yield with temperature as a variable (Priscilla *et al.,* 2024). Nyamplung oil and used cooking oil were processed by hydrogenation to remove oxygen atoms from the vegetable oil structure. This process is superior to transesterification in biodiesel (Febriyanti *et al.,* 2020). A brief and comprehensive flowchart can be seen in Figure 2.

Synthesis Catalyst

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Catalyst synthesis was carried out in accordance with the research of Fauzi *et al.* (2019), and Aziz *et al.* (2022). The natural zeolite was first ground and then rinsed with distilled water until the rinse water became clear. A NiAg/ZH catalyst was synthesized by first activating natural zeolite with 0.5 N NaOH at 75°C, followed by treatment with 1 M ammonium acetate at 90°C and calcination at 450°C for 3 hours to create hierarchical zeolite (ZH). The ZH was then impregnated with nickel and silver nitrates at a 10% w/w total metal loading and a Ni/Ag ratio of 4. The mixture was subsequently calcined again at 450°C for 5 hours and finally activated via reduction under hydrogen gas at 500°C for 4 hours to yield the final catalyst.

Hydrodeoxygenation of Oil into Green Diesel

Through modification of the combination of research Febriyanti *et al.,* (2020) and Heriyanto *et al*., (2018). Hydrodeoxygenation was conducted in a reactor using a mixture ratio of Nyamplung oil consisting of 25%-75% with a total of 10 mL, and 0.5 g of natural zeolite catalyst. The effect of temperature was studied at three levels: 325 °C until 375 °C, while maintaining a constant reaction time of 2 hours. After the reaction, the liquid product was cooled, extracted, and filtered to separate the catalyst. The product was then analyzed using a GC-MS.

Separation Process

During the deoxygenation process, agitation within the reactor may lead to partial breakage of the catalyst particles. As a result, the catalyst present in the water-PCO mixture needs to be filtered in stages. The final filtration step is carried out using a vacuum filtration system to ensure the removal of any remaining impurities (Prasetyo *et al.,* 2018).

Data Analysis

This study utilized several analytical methods: the viscosity of PCO samples was measured with a viscometer; gas-phase components such as H_2, CO, CO_2, and CH_4 were analyzed using a GC-TCD ; the composition of the upgraded PCO was analyzed using a GC-FID; and the flash point was determined with an MiniFlash instrument according to the ASTM D6450 standard (Aziz *et al.* 2022).

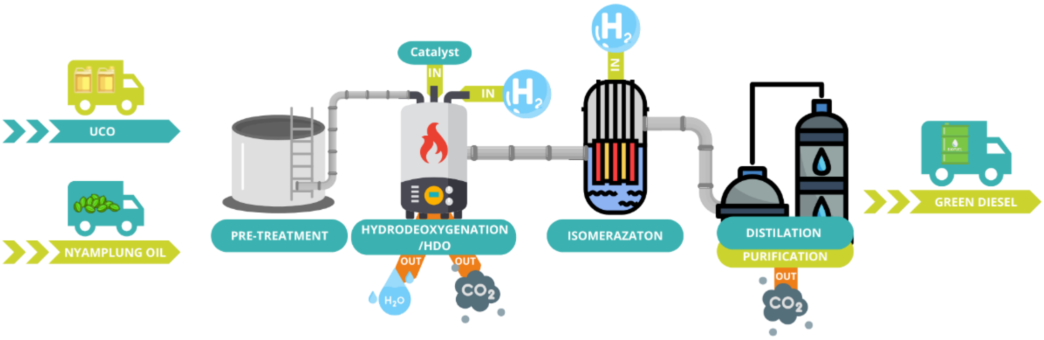

Figure 2. FlowChart of The Green Diesel Production Process

Literature Review

Characteristics of Zeolite Catalyst

The natural zeolite from CV. Minatama Lampung used as a support material for the nickel-silver bimetallic catalyst (NiAg/ZH) is focused on its physico-chemical modification to form a hierarchical zeolite (ZH) structure (Aziz et al., 2022). Physically and chemically, the modification of this raw zeolite is carried out through desilication and activation processes using an alkaline solution (0.5 N NaOH at 75 °C) and ammonium acetate (1 M at 90 °C), followed by calcination at 450 °C for 3 hours to form the hierarchical zeolite (ZH) structure before being impregnated with nickel and silver metals at a total loading of 10% w/w (Aziz et al., 2022). Based on various related studies using zeolite from the same supplier (CV. Minatama Lampung), this natural zeolite is dominated by a clinoptilolite mineral phase with a monoclinic structure,

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along with an initial chemical composition dominated by silica (Si) at 60.7% as well as accompanying metal elements such as K, Ca, Al, and Fe (Cahyono et al., 2018).

The activation process and the formation of pore hierarchy in the Lampung-derived NiAg/ZH catalyst support have been proven to produce a material with a specific surface area of 46.70 m²/g, a pore volume of 0.0813 cc/g, and an average pore diameter of 6.96 nm, which falls within the mesoporous range, possessing an acidity level of 1.6882 mmol/g (Aziz et al., 2022). There are highly significant differences when utilizing natural zeolite from other regions outside of CV. Minatama Lampung, because the fundamental physical and chemical characteristics of natural zeolite are highly dependent on its geological genesis and mining location. Differences in regional origin result in variations in the crystalline mineral phase composition, inherent pore size, and impurity cations, all of which strongly influence the zeolite's response to activation engineering (Cahyono et al., 2018). As a comparison with zeolite from another region, such as Bayah Zeolite from Banten, the Banten-derived zeolite possesses an orthorhombic crystal system heavily dominated by the mordenite mineral group. Chemically, this Banten-derived zeolite has a higher sodium (Na) content compared to the Lampung zeolite, but it is poorer in Fe, Ca, and K elements (Razzak et al., n.d.). Meanwhile, the Klaten Zeolite from Central Java, a natural zeolite originating from Klaten, exists as an almost balanced phase mixture of 56.21% mordenite and 43.79% clinoptilolite. Physically, this material from Klaten is classified as a pure microporous type with a pore size of <2 nm, specifically 1.95 nm, and a much smaller initial surface area of only 26 m²/g (Prihadiyono et al., 2022).

Unlike the Lampung zeolite, whose pores widen to a 6.96 nm mesopore upon modification (Aziz et al., 2022), the metal impregnation process on the Klaten zeolite actually tends to decrease its surface area to 16 m²/g due to its extremely small pores being blocked by metal particles. These fundamental differences in mineralogy and basic pore cavities will directly alter the distribution efficiency of active site metals, the catalyst's interaction area with the feedstock, and the acidity parameters, which ultimately heavily impact the catalyst's performance rate in the deoxygenation reaction for green diesel production (Prihadiyono et al., 2022).

Characterization of *Calophyllum inophyllum* L. (Nyamplung).

Calophyllum inophyllum L., commonly known as Poon, is a medium to large-sized tree belonging to the Clusiaceae family. Nyamplung grows optimally in sandy soils with excellent drainage and can adapt to a pH range of 4.0 to 7.5. It also demonstrates high tolerance to salt content, making it highly suitable for Indonesia, which has a coastline of 99,093 kilometers (Kannan, 2010). Green diesel can be produced from vegetable oil extracted from the seeds of the Nyamplung. One of its main advantages is its relatively high oil content compared to other biodiesel feedstocks, such as jatropha (40–60%) and palm oil (46–54%), with Nyamplung yielding between 40–73% (Qadariyah *et al.,* 2018). The characteristics of crude Nyamplung oil are shown in Table 1.

Table 1. Characteristics of Nyamplung L. Oil (Prasetyo *et al.,* 2018)

Characterization	**Annotation**
Color	Dark green
Viscosity	High viscosity
Iodine number (mg iod/g oil)	100 – 115
Density at 20 °C(g/cm^3)	0,920 - 0,940
Refraction Index	1,4750 - 1,4820
PeroxideNumber(meq/kg)	<20,0
Lipid fraction	98 – 99,5 %
Fatty Acid (%)	
• Palmitic Acid (C16 : 0)	15 – 17 %
• Palmitoleic Acid (C16 : 1)	0,5 – 1 %
• Stearic Acid (C18 : 0)	8 – 16 %
• Oleic Acid (C18 : 1)	30 – 50 %

• LinoleicAcid(C18 : 2)	25 – 40 %
• ArachidAcid(C20 : 0)	0,5 – 1 %
• GadoleicAcid(C20 : 1)	0,5 – 1 %

Characterization of UCO

Used Cooking Oil (UCO) waste refers to vegetable oils or animal fats that have been used for cooking or frying and are no longer suitable for food preparation. It is typically collected from households, restaurants, food stalls, and food processing industries. The characteristics of UCO are shown in Table 2.

Table 2. Characteristics of UCO (Singh *et al.* 2018)

Characterization	**Annotation**
Acid value (mg of KOH/gm)	4.48
FFA (in terms of oleic acid)	2.24
Iodine value (gm of I_2/100 gm)	154.81
Density (kg/cm^3)	907.45
Kinematic viscosity (cSt)	37.17
Flash point (°C)	185
Calorific value (MJ/kg)	37,9
Fatty Acid (%)	
• Palmitic Acid	12.13
• Stearic Acid	4.66
• Oleic Acid	24.25
• Linoleic Acid	52.17
• Linolenic Acid	5.58
• Arachid Acid	0.35
• Behenic Acid	0.20

Limitation of Biodiesel

Biodiesel is a type of diesel fuel derived from vegetable oils, primarily composed of long-chain alkyl esters. Currently, biodiesel is approximately 1.5 times more expensive than petroleum-based diesel. Its production requires significant energy input, not only for the conversion process but also for agricultural activities such as sowing, fertilizing, and harvesting crops like soybeans. Additionally, biodiesel can degrade rubber components in certain engine types, causing maintenance issues. As biodiesel has a cleaning effect on engine systems, it may dislodge accumulated dirt, which can clog fuel filters and require more frequent replacements. Furthermore, the existing distribution infrastructure for biodiesel remains underdeveloped, presenting another major limitation to its widespread adoption (Firoz, 2017).

Green Diesel or Renewable Diesel

Green diesel is a next-generation biofuel, commonly referred to as renewable diesel. It is a straight-chain hydrocarbon fraction similar to diesel fuel and is produced through the hydrogenation reaction of triglycerides. This type of diesel offers higher quality compared to conventional diesel fuel in engine combustion applications. Unlike previous biofuels, which can be used in conventional vehicles in 100% purity but may cause engine damage, green diesel

provides a viable alternative due to its low emissions (Yudhistira & Wibowo, 2022). The raw material for green diesel primarily comes from vegetable oils, which are suitable substrates for producing hydrocarbon biofuels similar to petroleum (Taromi & Kaliaguine, 2018).

Hydroprocess of Triglycerida

The reactions that occur during hydroprocessing can be categorized into two main types: hydrotreating and hydrocracking. Hydrotreating, also known as hydrofining, aims to improve the quality of the feedstock

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without altering the boiling point. Hydroprocessing involves the hydrogenation of double bonds in fatty acid chains and the removal of oxygen from triglyceride molecules, converting them into saturated hydrocarbons. The process of oxygen removal from triglycerides, includes three reactions: decarbonylation, decarboxylation, and hydrodeoxygenation (Figure 3). The chemical formulas for these three reactions are provided below (Yudhistira & Wibowo, 2022).

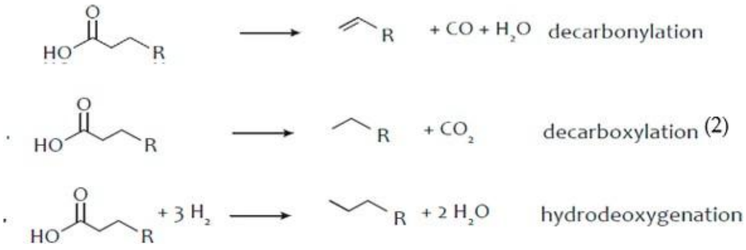

Figure 3. Deoxygenation Reactions (Yudhistira & Wibowo 2022)

Identified Gaps and Research Justification

Although interest in renewable diesel is growing, there is still a lack of research exploring the combined use of used cooking oil (UCO) and locally sourced ny oil. Most existing research focuses on single feedstock systems or relies on expensive industrial catalysts. Furthermore, little attention has been given to the practical implications of this technology in the Indonesian context. This study aims to address this gap by proposing an inclusive, affordable, and sustainable approach to green diesel production, in line with national low-carbon energy goals, building upon the work of Febriyanti *et al.,* (2020) and Heriyanto *et al.,* (2018).

RESULTS AND DISCUSSION

Result

The hydrotreating process produces green diesel by addressing various molecules, such as Free Fatty Acids (FFA). The reaction takes place under high temperature and pressure, with the assistance of hydrogen. FFA are converted into paraffin hydrocarbons and water through hydrodeoxygenation (HDO). This process effectively removes acid groups without causing issues such as soap formation (saponification). The HDO process can reduce FFA content by up to 100% (Bezergianni & Kalogianni, 2009).

The deoxygenation of Nyamplung oil was performed in a batch reactor, with variations in reaction temperature and duration. At an optimal temperature of 350 °C, the resulting selectivity for gasoline (9.4%) and green diesel (71.78%) remained high, with kerosene at 6.5% (Figure 4). The increase in temperature enhanced the reactants' kinetic energy, thereby promoting better interaction with the catalyst (Febriyanti *et al.,* 2020). Under an initial pressure of 30 bar and a reaction time of 2 hours for UCO, the highest yield of green diesel, reaching 94.34% within the C_{13}–C_{22} range, was achieved at an operating temperature of 360 °C. This optimal result is attributed to the enhanced cracking efficiency at higher temperatures, where increased thermal energy accelerates the reaction and promotes more effective conversion (Heriyanto *et al*., 2018).

The combination of UCO and Nyamplung oil as feedstocks for green diesel production offers a promising solution for sustainable and low-carbon energy. UCO has demonstrated high conversion efficiency, with green diesel yields reaching up to 98.93% under optimal hydrodeoxygenation conditions. Meanwhile, Nyamplug oil has shown green diesel selectivity of up to 71.78% when processed with bio-based catalysts. Based on the results of the RSM, it shows that the maximum ratio between Nyamplung oil and UCO is 75%

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or (15:1) at a temperature of 350 °C and an estimate that green diesel yields could reach approximately 91,2% (The properties of the blend of Nyamplung oil and UCO are presented in Table 3.

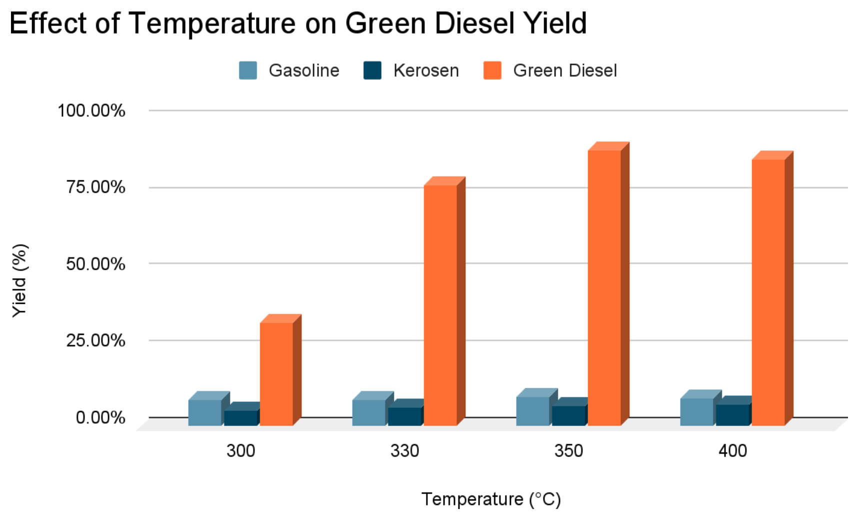

Figure 4. Effect Temperature of Result Catalytic Deoxygenation Products (Modification (Febriyanti *et al.,* 2020) (Heriyanto *et al.* 2018)

Table 3. Properties of Nyamplung Oil with UCO (Modification (Pamatatya & Susanto 2015) and (Engman *et al.,* 2018)

Properties	**Green Diesel of blending UCO and Nyamplung**	**ASTM Standard D975 – 3**	**ASTM Test Method (ASTM International, 2023)**
Density, g/cm3	0.829	0.81–0.87	D 0975
Viscosity, mm^2/s	2.8	2.0–4.5	D 445
Cetane Index	75	>40	D 976
Cold Flow Properties	Poor	Poor	D 4539
Cloud Point (°C)	-20, +20	≤ 15	D 2500
Sulfur (ppm)	<1	≤ 15	D 2622

Discussion

Comparison of Nyamplung Biofuel Yield Across Different Indonesia Islands

The comparison of biofuel yields from *C. inophyllum* (Nyamplung) originating from different regions in Indonesia demonstrates notable variation, influenced by geographical and environmental factors. Data show that Nyamplung oil from Cilacap, Central Java, when processed into green diesel, achieved a yield of 71.78% (Febriyanti *et al.,* 2020). In contrast, biodiesel production from Nyamplung in Tanah Merah, East Kalimantan, yielded the highest output at 88.27% (Sarwono *et al.,* 2018), suggesting favorable oil composition or process optimization in this region. Meanwhile, biodiesel derived from Nyamplung sourced in Kendari City, South East Sulawesi, produced a yield of 74.06% (Musta *et al.,* 2017). The data comparison is shown in Table 4. These differences in yield may be attributed to variations in seed oil content, fatty acid profile, and processing conditions, highlighting the importance of regional feedstock characterization to optimize biofuel production efficiency.

Table 4. Comparison of Nyamplung Biofuel Yield Across Different Indonesia Islands

Originally	**Kind of Biofuel**	**Yield (%)**	**Sources**
Cilacap, Central Java	Green Diesel	71.78	(Febriyanti *et al.,*2020)
Tanah Merah, East Kalimantan	Biodiesel	88.27	(Sarwono *et al.*, 2018)

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Kendari City, South East Sulawesi	Biodiesel	74.06	(Musta *et al.,* 2017)

Compare with Other Vegetable Oils

One major challenge in using vegetable oils for biofuel production is the reliance on edible oils, which creates competition with the food sector. To address this issue, research is shifting toward non-edible sources such as Nyamplung oil, UCO, and microalgae (Song *et al.*, 2013). Microalgae offer high growth rates and triglyceride yields (20–50% of biomass), can grow in wastewater, and do not require arable land. Similarly, Nyamplung is non-edible, drought-resistant, and produces seeds with up to 70% oil, making it suitable for cultivation on marginal lands (Febriyanti *et al.*, 2020). Waste oils, such as UCO, are also an attractive option due to their low cost about three times cheaper than edible oils and their environmental benefits, as recycling them helps reduce pollution (Morais *et al.*, 2010).

Table 5 compares various vegetable oil feedstocks for green diesel production via hydrodeoxygenation (HDO), highlighting Nyamplung oil combined with UCO as the most efficient, yielding 90% green diesel (n-C15–C18) at 350°C and 92 bar H_2 (Febriyanti *et al.,* 2020; Heriyanto *et al.,* 2018). In comparison, soybean oil produced a 64.5% yield at a higher temperature (400°C), while rapeseed and sunflower oils yielded 51.8% and 69.5%, respectively, under varied conditions. Microalgae oil provided a moderate yield of 72% at a lower temperature (260°C), producing similar hydrocarbon chains (n-C15–C18). These results suggest that the combination of Nyamplung oil and UCO is a highly promising and sustainable feedstock for green diesel production (Peng *et al.*, 2012).

Table 5. Comparison of Different Vegetables Oil

Feedstocks	Best Reaction Condition	Green Diesel Yield (%)	Sources
Nyamplung Oil + UCO	350 °C, 92 bar H_2	90, *n*-C15–C18	(Febriyanti *et al.,* 2020) (Heriyanto *et al.,*2018)
Soybean Oil	400 °C, 92 bar H_2	64.5, *n*-C15–C18	(Veriansyah *et al.,* 2012)
Rapeseed Oil	360 °C, 70 bar H_2	51.8, *n*-C17	(Šimáček *et al.,* 2010)
Sunflower Oil	380 °C, 20–80 bar H2	69,5, n-C11	(Krár et al., 2011)
Microalgae Oil	260 °C, 40 bar H2	72%, n-C15–C18	(Peng et al., 2012)

Green Diesel Yield (%) Comparison of Green Diesel with Biodiesel

Biodiesel and green diesel are both renewable alternatives to petroleum diesel; however, they differ significantly in their chemical composition and performance characteristics. Biodiesel contains approximately 11% oxygen, which aids in cleaner combustion but reduces its energy content to 38 MJ/kg, lower than the 44 MJ/kg of green diesel. In contrast, green diesel is fully deoxygenated, resulting in a higher heating value and better fuel efficiency. From a stability perspective, green diesel is more robust and resistant to degradation, whereas biodiesel is prone to oxidation and has limited storage stability. The cetane number, which indicates ignition quality, is much higher in green diesel (70–90) compared to biodiesel (50–65), making green diesel more efficient in combustion engines (Table 6). Although both fuels have poor cold flow properties, green diesel has the potential to achieve better performance through processing techniques such as isomerization, which can significantly lower its cloud point. Additionally, green diesel has a lower density (0.78 g/cm³) compared to biodiesel (0.88 g/cm³), which can affect engine calibration and fuel consumption (Vonortas & Papayannakos, 2014).

Table 6. Comparison physical properties of Biodiesel with Green Diesel (Vonortas & Papayannakos, 2014)

Properties	Biodiesel	Green Diesel
Sulfur (ppm)	<1	<1
Oxidative Stability	Marginal	Good
Cold Flow Properties	Poor	Poor
Energy Density (Mj/kg)	38	44
Cloud Point (°C)	-5, +15	-20,+20
Cetane Number	50-65	70-90

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Density (g/mL)	0.88	0,78

Competitor Analysis

The comparative analysis of Nyamplung oil and UCO-based green diesel with existing Pertamina fuel products highlights its promising potential as a sustainable alternative. The Nyamplung + UCO green diesel, classified as HVO, exhibits a cetane index of 75 and an energy density of approximately 44 MJ/kg (Pamatatya & Susanto, 2015; Engman *et al.,* 2018), which is comparable to Pertamina RD D100 (HVO from CPO) and higher than Pertamina Biodiesel B30 (FAME), which has an energy density of around 38 MJ/kg (Setiyawan, 2023). Both Nyamplung + UCO and RD D100 demonstrate good performance, efficiency, and low emissions, whereas B30 offers medium performance with very low emissions, and Pertamina Dex provides very good performance but with higher emissions. The primary advantage of Nyamplung + UCO green diesel lies in its high quality and drop-in capability, allowing for direct use in existing diesel engines without modification (Table 7).

Table 7. Analysis Competitor

Aspects	**Nyamplung + UCO**	**Pertamina RD D100**	**Pertamina Biodiesel B30**	**Pertamina Dex**
Fuel Type	Green Diesel (HVO)	Green Diesel (HVO)	Biodiesel Blend (FAME)	High Diesel Quality
Feedstocks	Nyamplung Oil + UCO	CPO	70% Diesel and 30% Biodiesel	Crude Oil
Cetane Index	75	70–90	>51	>53
Energy Density (MJ/kg)	~44	~44	~38	~43
Performance	Good	Good	Medium	Very IGood
Efficiency	Good	Good	Medium	Very Good
Emissions	Low	Low	Very Low	High
Main of Advantages	Sustainable, High Quality, drop in	High Quality and drop in	Low emissions	High Performance
Main of Disadvantages	No experiments yet	the issue of forest deforestation and competitions with food	Low Performance and poor stability	Non-renewable and high emissions
Sources	(Modification (Pamatatya and Susanto 2015) and (Engman *et al.* 2018)	(Pertamina, 2020) (Vonortas and Papayannako, 2014)	(Setiyawan, 2023)	(Pertamina, 2020) (Setiyawan, 2023)

Business Feasibility

The Green Diesel business is operationally viable but is a capital-intensive long-term investment. With a Cost of Goods Sold (COGS) of Rp 12,034 per liter, this project is capable of generating healthy profits, as evidenced by an R/C Ratio of 1.13 and a Net Value Margin of 11.6%. However, the high initial investment cost of Rp 7.9 billion results in a moderate Return on Investment (ROI) of 7.62% with a payback period of approximately 13 years. The success of this business heavily depends on the ability to maintain the stability of non-food raw material prices and sustain premium product selling prices, and would be significantly aided by government incentives for renewable energy. The business feasibility calculations can be seen in Table 8.

Table 8. Business analysis

Indicator	**Total**
COGS/Liter	Rp12.034
Profit/year	Rp603.500.000
R/C Ratio	1.13
Net Value Margin (NVM)	11,6%
Playback Period (PP)	13,1 Tahun
Return of Investment (ROI)	7,62%

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Environmental Analysis

Assuming a pilot plant scale that processes 1,000 liters of raw materials per day, the "GreenFusion" project significantly contributes to environmental protection by reducing used cooking oil (UCO) waste by 99,000 liters per year. This waste diversion prevents anaerobic decomposition at landfills, thereby reducing methane gas (CH_4) emissions by approximately 18.9 tons annually. Furthermore, the project has a significant impact on the carbon footprint, with a total reduction in carbon dioxide (CO_2) emissions of 1,281.2 tons per year, which is the combined result of carbon absorption by approximately 7,000 Nyamplung trees required as raw material (763.8 tons) and the reduction in methane emissions (1,507.2 tons) emissions by 1,281.2 tons per year, which is the combined result of carbon absorption by approximately 7,000 Nyamplung trees required as raw material (763.8 tons) and emission reductions from replacing fossil diesel with cleaner green diesel (517.4 tons). The results of the environmental analysis above are based on Government Regulation No. 22 of 2021 (Kementerian Lingkungan Hidup dan Kehutanan, 2021).

Sustainability Implementation

The implementation of the GreenFusion project executed through a long-term strategic roadmap. The initiation and acceleration phase (2026-2030), rooted in innovation from the academic domain for technology validation, requires capital investment and managerial expertise from the business sector to scale up production, penetrate markets, and achieve international certification.

This operational sustainability is based on a synergistic pentahelix collaboration paradigm which supported by active community participation as a pillar of the raw material supply chain (UCO and Nyamplung), which also serves as a socio-economic beneficiary, while the government creates a conducive ecosystem through regulatory frameworks, decarbonization policies, and incentive schemes. This synergy is amplified by the media, which plays a role in disseminating knowledge and exercising social control for public acceptance. This strategic projection maps GreenFusion's evolution into a pillar of the green economy by 2045 through the diversification of high-value-added products such as Bio-SAF, and reaches its culmination by 2060 as a zero-carbon footprint industrial entity that significantly contributes to achieving the national Net-Zero Emission target.

CONCLUSIONS

The "GreenFusion" approach is an innovative and superior solution to address the challenges of energy transition in Indonesia, in line with the expectations outlined in the introduction. The synthesis of Green Diesel through the hydrodeoxygenation method using dual non-food feedstocks and waste materials, namely Nyamplung oil and Used Cooking Oil (UCO), with natural zeolite catalyst has been technically proven to produce high-quality fuel (cetane number 75) with an estimated yield of up to 90%. This finding not only offers a superior alternative to conventional biodiesel in terms of stability and energy density but also addresses the deforestation issues associated with palm oil use. Holistically, this project presents a sustainable ecosystem model where technical viability, positive environmental impact (reducing CO_2 emissions by 1,281.2 tons/year at the pilot scale) and long-term business viability (R/C Ratio 1.13) have been confirmed. Therefore, GreenFusion has significant development prospects as one of the main pillars in the roadmap toward achieving energy sovereignty and Indonesia's 2060 Net-Zero Emission target.

Suggestion or the government, it is recommended to design a specific fiscal incentive scheme for producers of green diesel based on non-food raw materials to stimulate investment, given the high initial capital costs. For industries such as PNRE, it is recommended to adopt the GreenFusion model in their decarbonization portfolios by initiating large-scale pilot projects for commercial validation, and for future research this study has limitations at the laboratory scale and in the assumptions of the pilot model. Therefore, future research should focus on: 1) Catalyst stability and regeneration for long-term use to reduce operational costs; 2) Process optimization using continuous-flow reactor systems to enhance industrial-scale efficiency.

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