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Use of Hydrotreated Vegetable Oil from Palm Oil Sludge by Catalytic Hydrogenation Method as a Solution to Reduce Greenhouse Gas Emission

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Abstract

This study aims to assess Hydrotreated Vegetable Oil (HVO) from Sludge Palm Oil (SPO), a waste of the palm oil industry, as a sustainable energy solution for the transportation sector in Indonesia. The method used was catalytic hydrogenation at 350°C and 30 MPa pressure to convert SPO into high-quality HVO. The results show that HVO from SPO can reduce Greenhouse Gas (GHG) emissions by up to 80% compared to fossil fuels. This process supports the principle of circular economy, utilizes previously unused SPO waste, and reduces pollution and improves resource efficiency. In addition, HVO production also contributes to the reduction of landfilled waste, improving the sustainability of the palm oil industry. Therefore, HVO from SPO has the potential to be a key solution in sustainable energy transition, improving national energy security, and supporting GHG emission reduction in Indonesia.

Keywords: *Hydrotreated Vegetable Oil (HVO); Sludge Palm Oil (SPO); Sustainable Energy; GHG emissions reduction; circular economy.*

1. Introduction

Indonesia, as the world's largest palm oil producer, produces about 59% of the total global production, or about 45.5 million tons per year. In 2022, Indonesia exported 25.01 million tons of Crude Palm Oil (CPO) and its derivative products. Sludge Palm Oil (SPO), a waste from the palm oil industry, has the potential to be a renewable energy source that not only helps reduce waste, but also supports a sustainable energy transition. One of the products that can be produced from SPO is Hydrotreated Vegetable Oil (HVO), a biofuel produced through a catalytic hydrogenation process.

The energy transition towards renewable energy has become a global agenda to reduce dependence on fossil fuels and face the challenges of climate change. . According to the International Renewable Energy Agency (IRENA), the energy transition involves shifting from fossil energy to renewable energy, driven by technologies and policies aimed at ensuring energy sustainability and affordability. In Indonesia, President Joko Widodo highlighted three key challenges in the energy transition: access to clean energy for all, unburdensome financing, and efficient technological innovation. These three aspects are crucial in ensuring an equitable energy transition.

However, in addition to the great benefits that the energy transition can provide, there are economic challenges, one of which is the phenomenon of greenflation, which is an increase in the cost of energy transition that can burden the economy, especially in the transportation sector that is highly dependent on fossil fuels. Therefore, an equitable energy transition that takes into account procedural, distributive and restorative justice is crucial. Procedural justice ensures the involvement of vulnerable groups in decision-making, while distributive justice regulates the sharing of risks and responsibilities, and restorative justice considers long-term social and environmental impacts.

Indonesia's transportation sector, a major contributor to Greenhouse Gas (GHG) emissions, requires sustainable renewable energy solutions. Amid efforts to achieve B30 biodiesel blending, reliance on palm oil alone may not be sufficient to meet higher targets. Therefore, there is a need for innovation in utilizing Palm Oil Sludge (SPO) as an alternative energy source. SPO, which is residue from palm oil mill

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effluent, is often overlooked. However, research shows that SPO can be processed into HVO, a purer and environmentally friendly fuel through a hydrogenation process.

HVO produced from SPO has various benefits, including up to 80% reduction in GHG emissions compared to fossil fuels, as well as reduced emissions of particulate matter, sulfur, and nitrogen oxides (NOx) that contribute to improved air quality. With approximately 2% of Indonesia's total palm oil production coming from SPO, and expected to reach 938 thousand tons by 2023, utilizing SPO as an energy source can support biodiesel blending, reduce dependence on imported fossil fuels, and create new jobs and improve the sustainability of the palm oil industry.

The novelty value in this research lies in the use of SPO as a feedstock for HVO, with a more efficient catalytic hydrogenation approach. This research aims to assess the potential of HVO from SPO as an innovative and strategic solution in supporting an equitable energy transition in Indonesia's transportation sector. This approach is expected to address energy transition challenges, such as greenflation, while providing sustainable benefits to Indonesia's economy and environment.

2. Materials and Methods

2.1. Research Design

This study used a literature review method to evaluate the potential production of Hydrotreated Vegetable Oil (HVO) from palm oil sludge. The literature review was conducted to collect data and information related to production technology, technical and economic challenges, and the environmental potential of using HVO as a renewable fuel in Indonesia's transportation sector. The literature reviewed included scientific publications, industry reports, and regulations and policies related to renewable energy in Indonesia.

2.2. Data Source

The data in this study consisted of two main sources, Primary data, collected from experimental studies related to the HVO production process from sludge oil. Secondary Data, available in scientific journals, palm oil industry reports, and publications on renewable energy policies in Indonesia and other countries. Some of the key publications referenced include studies on the use of HVO in the transportation sector, HVO production techniques through catalytic hydrogenation, and analysis of greenhouse gas emissions from the conversion of sludge oil to HVO.

2.3. Research Stages

This research was carried out through several main stages, as follows, identification of literature sources The literature review began by identifying and collecting relevant references related to HVO production from sludge oil and its application in the transportation sector. The reference selection criteria include publications that discuss hydrotreating technology, environmental impacts of HVO, and renewable energy policies in Indonesia. Literature Selection and Classification, after the references were collected, the literature was selected based on its relevance and credibility. Scientific journal articles, industry reports, and policy publications that met high quality standards (SINTA 1 or equivalent) were prioritized. The selected literature was then classified into several categories, HVO Production Technology, Environmental Impacts and Emissions Reduction, Economic Challenges and Opportunities. Data Analysis, after the literature classification, the data were analyzed descriptively to describe HVO production technologies, technical challenges, and environmental benefits of HVO use. Quantitative analysis was also conducted on studies that provided empirical data on greenhouse gas emission reductions due to HVO use in the transportation sector. These data were compared with emissions from fossil fuels and conventional biodiesel. Emission Reduction Simulation, based on the data obtained, a simulation was conducted to assess the greenhouse gas emission reduction potential of HVO use in Indonesia's transportation sector. The simulation considers factors such as carbon emission intensity of the production process, energy conversion efficiency, and potential substitution of fossil fuels with HVO.

2.4. Tools and Instruments

In the referenced experimental study, the production of HVO from sludge oil involved the following main tools and instruments, like centrifuge used to separate the solid and liquid components of sludge oil, resulting in a purer feedstock. Hydrotreating Reactor used to hydrogenate sludge oil at high temperature and pressure to convert it into hydrocarbons suitable for fuel. Gas Chromatography used to analyze the chemical composition of HVO products, including measuring the content of long-chain hydrocarbons. Spectrophotometer used to analyze the quality of HVO fuel, especially in terms of oxidation stability and fuel purity. Viscometer used to measure the viscosity of HVO, which is an important indicator in determining the performance of the fuel in the engine.

2.5. Production Procedures and Quality Test

In the study used as the main reference, the HVO production process goes through several stages, including, Extraction and Purification, sludge oil obtained from palm oil mills is processed through a centrifuge to separate solid contaminants and water. This purification process is important to ensure optimal feedstock quality for the hydrogenation stage. Catalytic

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Hydrogenation: After purification, sludge oil is reacted with hydrogen in a hydrotreating reactor at 300-400°C and high pressure (40-80 bar). This process removes oxygen from the oil molecules, producing long-chain hydrocarbons that resemble fossil diesel. HVO Quality Testing, the resulting HVO product is tested using gas chromatography to determine the chemical composition and stability of the fuel. In addition, the viscosity of the fuel is measured to ensure compatibility with diesel engines.

2.6. Production Procedures and Quality Test

Data from the production and testing of HVO from palm oil sludge were analyzed descriptively and comparatively. HVO quality test results were compared with conventional biodiesel and fossil diesel standards, especially in terms of oxidation stability, viscosity, and carbon emissions. Greenhouse gas emission simulations were conducted to evaluate the emission reduction potential of HVO compared to conventional fuels.

3. Results and Discussion

3.1. Potential Utilization of Palm Oil Sludge

Compliant manuscripts Palm oil sludge (POME - Palm Oil Mill Effluent) is a waste produced during the palm oil extraction process. In the context of waste management, this sludge contains components such as free fatty acids, water, and other solids that can be utilized. Qualitatively, POME has great potential as a feedstock in the production of biofuels, including Hydrotreated Vegetable Oil (HVO), due to its high content of organic compounds.

Quantitatively, POME generated by the palm oil industry can reach 60-70% of the total water used in the oil extraction process. In some studies, one ton of crude palm oil (CPO) can produce about 2.5 to 3.5 tons of POME. The use of these sludges in HVO production can provide significant environmental benefits, including the reduction of water and soil pollution that typically results from conventional waste disposal. In addition, the utilization of POME in the form of HVO can reduce the waste load generated by the palm oil industry, thereby reducing environmental pollution in the surrounding area.

In addition, palm oil sludge (POM sludge) is a waste produced from the palm oil processing process that also contains a large amount of organic and inorganic material. The quality of this sludge varies depending on the processing method and processing conditions. In general, this sludge contains, Oils and Fats 15-25%, Water 40-60%, Solid Material 20-30%, Organic matter 10-15%. The potential utilization of POM sludge in HVO production can be calculated based on the main components contained in it. **Table 1** shows the composition and potential conversion of palm oil sludge into HVO.

The utilization of POM sludge for HVO production also offers some key environmental benefits, such as pollution reduction, reduce water and soil pollution by diverting waste that would normally go to landfills. Reduction of Methane Emissions is reduce methane emissions resulting from the decomposition of sludge in landfills. Waste Reduction, reducing the amount of waste generated from the palm oil production process.

3.1.1. Greenhouse Gas Emissions Reduction

HVO (Hydrotreated Vegetable Oil) is an alternative fuel that has great potential to reduce greenhouse gas emissions compared to conventional The use of HVO produced from palm oil waste, such as POME, also has great potential in reducing greenhouse gas emissions compared to conventional fossil fuels and biodiesel. Based on qualitative analysis, HVO has a

Table 1. Composition and Conversion Potential of Palm Oil Sludge to HVO

Component	Percentage	Conversion to HVO
Oils and fats	20%	80% conversion to HVO
Water	50%	Not used for HVO
Solid materials	25%	40% conversion to HVO
Organic matter	10%	70% conversion to HVO

Table 2. Composition Parameters and Conversion Potential of Palm Oil Sludge into HVO

Parameters	Average Value
Oil content	6-10%
Water content	85-90%
Organic solid matter	4-6%
pH	4.5-5.5

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more stable chemical structure, with less oxygen content leading to lower harmful gas emissions upon combustion. From a quantitative perspective, HVO can reduce CO_2 emissions by up to 90% compared to fossil fuels. In operational studies in the transportation sector, HVO has been shown to reduce greenhouse gas emissions by about 50-85% compared to conventional biodiesel based on Fatty Acid Methyl Esters (FAME).

Other studies have shown that the use of HVO under ideal operating conditions results in a 60-70% reduction in CO_2 emissions compared to conventional diesel. This is due to the purity and properties of HVO fuels that are close to fossil diesel, but with a much lower carbon footprint. This quantitative data strengthens the argument that HVOs, especially those based on waste such as POME, make a significant contribution to the global target of reducing greenhouse gas emissions.

3.1.2. Sustainable Waste Management

The utilization of palm oil sludge as a raw material in the production of HVO also has the potential to be an environmentally friendly waste management solution. POME waste usually has a very high Biochemical Oxygen Demand (BOD) level, which if disposed of without proper treatment, can pollute water and soil. Treating POME for HVO production not only helps to reduce the impact of pollution, but can also reduce methane gas (CH_4) emissions resulting from conventional waste disposal. Anaerobic decomposition of palm oil waste in open dumps typically produces methane, a greenhouse gas that is 25 times more potent than CO_2 in terms of global warming potential.

Palm oil sludge can be used as a feedstock source for HVO production, which offers an environmentally friendly waste management solution. This process can reduce water pollution by reducing the amount of sludge discharged into the environment, soil pollution reduce soil contamination from industrial waste, methane emissions reduce methane emissions resulting from conventional waste disposal.

By utilizing POME as a biofuel feedstock, the palm oil industry can significantly reduce methane emissions. In addition, this process can improve the overall efficiency of industrial waste management. The use of palm oil waste as feedstock for HVO is also in line with the circular economy principle, where waste is converted into valuable products, while minimizing negative impacts on the environment.

3.1.3. Comparison with Other Biofuels

HVO has advantages over other biofuels, such as FAME-based biodiesel, there are several important aspects that make HVO superior. First, in terms of oxidation stability, HVO shows superior performance because it does not contain oxygen double bonds like FAME, which makes it more stable over long periods of storage. In addition, the combustion quality of HVO is also better, as its molecules are more similar to fossil diesel, resulting in cleaner combustion with less deposit formation in the engine.

Empirical studies show that the use of HVO in transportation applications provides significant advantages over FAME, especially in terms of nitrogen oxide (NO_x) and solid particle emissions. Tests on various types of modern diesel engines reveal that HVO produces up to 30% lower NO_x emissions compared to FAME biodiesel. In addition, since HVO is purer and does not contain polar compounds, its compatibility with conventional diesel engines is excellent, without requiring significant engine modifications.

3.2. Technical Challenges of HVO Production from Palm Oil Sludge

3.2.1. Hydrotreating Process

The production of Hydrotreated Vegetable Oil (HVO) from palm oil sludge via the hydrotreating process faces significant technical challenges. Hydrotreating is a process in which oils or fats are

Table 3. Comparison of Emissions by Fuel Type

Fuel Type	CO_2 emission (g/km)	Emission No_x (g/km)	Particulate Emissions (mg/km)
Fossil diesel	250	0.7	50
Conventional biodiesel	200	0.8	40
HVO	25	0.6	30

Table 4. Comparison of Emission and Pollution Reduction Before and After HVO Use

Aspects	Before HVO Use	After HVO Usage
Methane emissions	High	Low
Water pollution	High	Low
Soil pollution	High	Low

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converted into hydrocarbons by removing oxygen through a hydrogenation reaction. In this process, catalysts play a key role in optimizing the reaction, especially to improve the efficiency of deoxygenation and hydrodesulfurization. Nickel-molybdenum (NiMo) and cobalt-molybdenum (CoMo) based catalysts are commonly used. NiMo has a good ability in removing sulfur and nitrogen, making it suitable for oils with high sulfur content, while CoMo is more effective for oils with higher nitrogen content (Millo et al., 2025).

The main challenge in catalyst selection is its efficiency and durability, especially when dealing with contaminants in the sludge such as heavy metals that can accelerate catalyst deactivation. This results in a decrease in process efficiency and requires more intensive maintenance. In addition, extreme operating conditions are required, with temperatures between 300-400°C and pressures ranging from 30-100 bar. High temperatures accelerate the hydrogenation reaction and improve product quality, but if they are too high, they can lead to catalyst degradation and unwanted by-products. High pressure is required to keep enough hydrogen in gaseous form, vital in the hydrogenation process (Hunicz et al., 2022).

The need for large amounts of hydrogen is one of the factors determining the cost and sustainability of the process. Hydrogen is not only used in hydrogenation reactions, but also to remove impurities such as sulfur and nitrogen from oil. Conventional hydrogen production requires expensive resources, especially if renewable energy sources are not used, adding to the challenge of maintaining the sustainability of this process (Lee et al., 2015). Therefore, efficient management of hydrogen usage is essential to reduce operational costs and environmental impacts.

To overcome these challenges, innovations in reactor design and processing techniques are required. Modifications such as increased hydrogen circulation and the use of more efficient heating systems can improve overall process efficiency. Research is ongoing to develop more efficient and energy-efficient catalysts, which are expected to reduce the cost and environmental impact of HVO production (Gilani et al., 2019). By optimizing factors such as catalyst selection, temperature, pressure, as well as hydrogen management, HVO production from palm oil sludge can be done more efficiently and sustainably.

3.2.2. Raw Material Quality

The quality of palm oil sludge feedstock is one of the important factors that can significantly affect the efficiency of the hydrogenation process as well as the life and performance of the catalyst in the production of Hydrotreated Vegetable Oil (HVO). Palm oil sludge often contains various contaminants, such as heavy metals (iron, copper, lead, nickel, vanadium, cobalt) as well as water and impurities, which can negatively impact the production process (Han et al., 2019). These heavy metals can adhere to the catalyst surface, disrupting catalytic activity, as well as causing deposit formation that clogs the catalyst pores. As a result, the flow of reactants and products is disrupted, reducing the efficiency of the hydrogenation process.

The presence of heavy metals not only reduces catalyst activity but also accelerates catalyst degradation, requiring more frequent catalyst replacement and increasing operational costs. This poses a major challenge in the HVO hydrogenation process, as catalyst life largely determines the overall efficiency and stability of the process. In addition to heavy metals, the high water content in palm oil sludge is also a significant problem. Water and impurities can cause unwanted vapor formation in the reactor, which interferes with the chemical reaction and reduces hydrogenation efficiency. Furthermore, water can react with hydrogen to form hydrogen oxide, which breaks the reaction balance and decreases the conversion of oil to HVO (Afiqah-Idrus et al., 2024). It can also cause direct damage to the catalyst, such as swelling or dissolution, which affects the performance of the catalyst and shortens its lifespan.

To overcome these challenges, more complex pre-purification steps are required to remove contaminants, which ultimately adds to the cost and process time. Techniques such as water separation from palm oil sludge through physical separation processes or the use of filtration membranes can reduce the water content entering the hydrogenation process. Additionally, heavy metal removal can be done using adsorption techniques with specialized sorbents or filtration to reduce contamination before the oil sludge is used in the hydrogenation process (Li & Williams, 2024).

These efforts not only improve feedstock quality, but also extend catalyst life and improve overall process efficiency. The development of catalysts that are more resistant to contaminants and the optimization of operational conditions are important steps to ensure that the production of HVO from palm oil sludge can be carried out more efficiently and sustainably, reducing operational costs and producing high-quality products.

3.2.3. Integration with Existing Infrastructure

The integration of Hydrotreated Vegetable Oil (HVO) into the existing fuel distribution infrastructure faces a number of significant challenges. Fuel storage tanks and distribution pipelines need to be adapted to accommodate the different physical and chemical properties of HVO compared to conventional biodiesel or fossil fuels. One of the main differences is HVO's higher oxidation stability and lower freezing point. These properties necessitate adjustments to the storage

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tank, as without modifications, the quality of HVO can degrade over long storage times. HVO also has oxidative properties that can cause corrosion in tank materials not specifically designed to handle it (Kourkoumpas et al., 2024). Therefore, storage tanks may require corrosion-resistant material coatings or the use of alternative construction materials to prevent damage.

The different viscosities and densities of HVO require adjustments to the pumping system and distribution pipelines to ensure efficient flow (Hunicz et al., 2022). Distribution pipelines used for fossil fuels may not be fully suitable for HVO without modification. Without proper customization, HVO can cause deposit buildup or even damage to the pipe walls. This could require more frequent pipe cleaning to prevent contamination and maintain smooth fuel flow. In addition, fuel terminals also require customization, including filling and monitoring systems, in order to handle the special characteristics of HVO and ensure safe and efficient operation (Millo et al., 2025).

Overcoming these barriers requires additional investment in infrastructure, including costs for storage tank modifications, distribution pipeline adjustments and equipment updates at fuel terminals. Technology to monitor the quality of HVO during storage and distribution is also critical to ensure the quality of the fuel is maintained all the way to the end user. In some cases, building new infrastructure specifically designed for HVO may be a more economical option than modifying existing infrastructure. By making the right adjustments, it is possible to integrate HVO into existing fuel distribution systems more efficiently and effectively, ensuring that fuel quality is maintained throughout the distribution process to the end user.

3.3. Economic Challenges of HVO Production from Palm Oil Sludge

3.3.1. Production Cost

The production of Hydrotreated Vegetable Oil (HVO) from palm oil sludge involves a number of significant cost factors, which collectively affect the total cost of production and its economic efficiency. One of the major factors is the cost of feedstock. Palm oil sludge, as a feedstock, has a price that varies between $400 and $600 per ton (Afiqah-Idrus et al., 2024). This price is relatively lower than that of vegetable oils for conventional biodiesel, such as soybean oil, which ranges from $700 to $1,000 per ton (Mata et al., 2023). Although palm oil sludge can be a more economical feedstock source, quality variability and potential contamination may affect further processing costs.

Energy cost is another important factor in HVO production, as the hydrogenation process requires substantial energy to produce hydrogen and maintain reactor temperature and pressure. The energy cost for this process can reach $0.5 to $1.0 per liter of HVO produced (Han et al., 2019). This is much higher than the energy cost for conventional biodiesel production through transesterification, which typically ranges from $0.2 to $0.4 per liter (Muanruksa et al., 2019). This difference is due to the higher energy requirements to maintain optimal hydrogenation operating conditions and overcome the reactive nature of the more complex bio-oils compared to the vegetable oils used in conventional biodiesel.

Catalysts are also a significant cost component in HVO production. The catalysts used, such as nickel-molybdenum (Ni-Mo) or cobalt-molybdenum (Co-Mo), can add $0.1 to $0.2 per liter of HVO production cost (Mohd Yusof et al., 2023). These catalysts are expensive and require periodic maintenance and replacement, which adds to the total cost. In contrast, conventional biodiesel production uses cheaper and simpler catalysts, reducing catalyst-related costs.

Operating costs, which include facility maintenance, labor, and management, also affect the cost of HVO production. These costs can range from $0.3 to $0.5 per liter of HVO, depending on the scale of the facility and operational efficiency (Kourkoumpas et al., 2024). The complex hydrogenation process and the need for more rigorous maintenance and supervision can add to these costs. In comparison, operating costs for conventional biodiesel production are typically lower, between $0.2 and $0.3 per liter, due to the simpler process and less need for advanced technology.

In comparison to fossil diesel, whose production costs range from $0.6 to $1.0 per liter (Pongraktham & Somnuk, 2023), HVO still faces economic challenges despite offering significant environmental benefits. Fossil diesel remains cheaper due to established infrastructure and more cost-efficient production processes. Thus, while HVO is a more sustainable option and has the potential to reduce emissions, its higher production cost compared to conventional biodiesel and fossil diesel is a major challenge that needs to be overcome. Efforts to improve production efficiency, reduce feedstock costs, and develop more energy- and cost-efficient technologies can help bridge this cost gap and support wider adoption of HVOs in the future.

3.3.2. Economies of scale

Economies of scale play an important role in lowering the production cost of Hydrotreated Vegetable Oil (HVO), with efficiencies gained from increased production volumes significantly reducing the average cost per unit. One of the key factors in achieving economies of scale is the location of the plant. A plant located close to the source of raw materials, such as palm oil sludge, can reduce transportation and logistics costs. For example, a plant located near an oil palm

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producing region in Southeast Asia will face lower transportation costs compared to a plant that has to import feedstock from a more distant location (Wu et al., 2024). In addition, large production capacity allows mills to utilize more efficient equipment and reduce fixed costs per unit. High-capacity plants can purchase raw materials in large volumes at discounted prices, as well as use advanced technology and automation that reduce labor costs and increase output per unit cost (Fathurrahman et al., 2024). Good access to raw materials is also important, as consistent and cheap procurement of raw materials helps control price fluctuations and reduces transportation and storage costs (Millo et al., 2025). Supporting infrastructure, such as distribution systems and storage facilities, also contribute to achieving economies of scale. Efficient infrastructure supports the smooth flow of goods, reduces the risk of production downtime, and allows plants to focus more on process efficiency (Hegedűs et al., 2024). By utilizing economies of scale, HVO producers can significantly lower production costs, improve the competitiveness of their products, and support the wider adoption of HVO in the energy industry.

3.3.3. Market Demand and Consumer Acceptance

Creating strong market demand for Hydrotreated Vegetable Oil (HVO) in Indonesia faces several key challenges that need to be overcome to ensure widespread and sustainable adoption. One of the key challenges is consumer perception of quality. To increase market acceptance, HVO must prove its superiority in terms of efficiency and vehicle performance compared to traditional fossil fuels. Clear and transparent information on the environmental and performance benefits of HVO is crucial in changing consumer perceptions and increasing trust in this product (Pongraktham & Somnuk, 2024). In addition, the price of HVO is also a critical factor. Currently, the production cost of HVO is higher than that of conventional biodiesel and fossil diesel, which is due to the complex production process and high feedstock costs. To increase the attractiveness of HVO, the selling price should be competitive or government subsidy support may be needed to lower the market price. Reduction of production costs through technological innovation and economies of scale efficiency can help lower the price of HVO. Availability of HVO is also a challenge, as the development of adequate distribution infrastructure is critical to ensure easy access for consumers across Indonesia. Without adequate storage facilities and filling stations, HVO adoption will be hampered (Debler et al., 2008). Government policy support is also crucial in creating market demand. Policies that support the use of alternative fuels through incentives, subsidies, or regulations that promote clean fuels can accelerate the adoption of HVOs. Overall, to advance the HVO market in Indonesia, it is important to improve quality perception, lower prices, ensure availability, and gain strong policy support.

3.4. Policy Implications for HVO Development from Palm Oil Sludge

3.4.1. Renewable Energy Policy

The production of *Hydrotreated Vegetable Oil* (HVO) from palm oil sludge can have a significant positive economic impact, especially in oil palm producing regions. One of the main benefits is job creation. The HVO production process requires an increased demand for palm oil, which can create jobs in the oil palm plantation sector, including harvesting and processing of oil palm fruits. In addition, the construction and operation of HVO processing facilities require skilled labor such as technicians and machine operators, as well as jobs in plant construction. The distribution sector will also require labor for logistics and transportation. According to Millo (2025), each job in the biofuel sector can create an additional 2 to 3 jobs in related sectors, so projections of new employment can be very positive (Millo et al., 2025).

Local economic impacts may also include increased income for oil palm farmers and entrepreneurs due to increased demand for palm oil. This could potentially improve local economic welfare in rural areas that depend on oil palm plantations. In addition, investment in HVO facilities may increase tax revenue for local governments, which can be used for infrastructure development and public services. However, there are challenges related to environmental impacts and price fluctuations that need to be considered. The use of palm oil sludge must be well managed to avoid environmental damage, which could have a negative impact on the local economy. In addition, fluctuations in palm oil prices can affect the stability of the local economy, although product and market diversification can help mitigate this risk (Atabani et al., 2012).

3.4.2. Subsidies or Fiscal Incentives

Subsidies and fiscal incentives play an important role in accelerating the adoption of new technologies, including HVO. In Indonesia, existing biofuel subsidies are mostly focused on Fatty Acid Methyl Ester (FAME)-based biodiesel. Meanwhile, to encourage the development of HVO, additional subsidies or fiscal incentives are needed that can reduce production costs and provide competitiveness against fossil fuels.

In comparison, the European Union has implemented significant subsidies for biofuel producers through its Common Agricultural Policy (CAP) program that provides subsidies for the development of renewable energy from agricultural waste and vegetable

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oils. In Brazil, the government provides tax incentives for companies producing biofuels, including HVO, through the RenovaBio policy that aims to increase sustainable biofuel production. This subsidy, in addition to reducing production costs, also provides market security for HVO producers.

The implementation of effective subsidies or fiscal incentives in Indonesia would help lower the cost of producing HVO from palm oil sludge and accelerate its adoption in the transportation sector. Such incentives could also encourage private investment in the development of catalytic hydrogenation technology and other supporting infrastructure.

3.4.3. Regulations and Quality Standards

The development of HVO in Indonesia also requires clear regulations regarding fuel quality standards and compatibility with vehicle engines. Currently, there are no national standards that specifically regulate the quality of HVO, whether in terms of carbon emissions, viscosity, or oxidation stability. This could be a barrier to the widespread adoption of HVOs as the industry needs assurance that HVOs meet the technical standards required for use in conventional diesel engines.

Countries such as the European Union and the United States have set strict standards for biofuels, including HVO. In the European Union, the EN 15940 standard regulates the quality of synthetic and paraffinic fuels, including HVO, so that they can be widely used in diesel vehicles. The standard covers requirements for emissions, physicochemical properties, and oxidation stability. In the United States, the Environmental Protection Agency (EPA) sets emission and quality standards for all types of biofuels through the Renewable Fuel Standard. The implementation of regulations and quality standards in Indonesia will provide certainty for producers and consumers that HVO is a reliable and environmentally friendly fuel. This regulation may also increase the automotive industry's interest in developing engines that are more compatible with HVO, thus accelerating the energy transition in the transportation sector.

3.5. Social and Economic Impacts of HVO Use

3.5.1. Impact on Local Economy

The production of HVO from palm oil sludge can have a significant economic impact, especially in palm oil producing regions such as Sumatra and Kalimantan. The palm oil industry is one of the pillars of the local economy, and utilizing palm oil sludge waste for HVO production will create a new value chain in the biofuel sector. This will create employment opportunities at various stages of production, from raw material collection, processing, to HVO distribution.

According to an economic model developed by the World Bank, the development of a waste-based biofuel industry could increase local income by 5-10%, with the creation of up to 20,000 new jobs per year. The industry can also attract private investment in the development of biofuel processing infrastructure, which will have a long-term impact on local economic growth.

3.5.2. Local Community Empowerment

Renewable energy projects often have positive social impacts by empowering local communities. Renewable energy projects can improve the skills and knowledge of local communities, create new economic opportunities, and encourage participation in decision-making regarding energy projects.

In the context of HVO development, community-based programs can be integrated to ensure that local communities are actively involved in the production and distribution process. For example, technical skills training programs in processing palm oil waste into HVO can be provided to local farmers and workers. In addition, this community-based approach can encourage collaboration between government, industry and communities to create an inclusive and sustainable biofuel business model.

3.5.3. Improved National Energy Security

Diversification of energy sources through the use of HVO can significantly improve national energy security. Indonesia's dependence on fossil fuel imports, especially diesel, has created vulnerability to global energy price fluctuations. By producing HVO from palm oil sludge, Indonesia can reduce this dependency and create a more stable and sustainable energy supply.

Studies by the International Energy Agency (IEA) show that diversification of energy sources through biofuels can reduce energy price volatility and improve supply stability. In Indonesia, the development of HVO can also support the government's efforts to achieve *Net Zero Emission* by 2060, as HVO has a lower carbon footprint compared to fossil fuels. In addition, the increased use of HVO in the transportation sector can reduce Indonesia's dependence on fuel imports, which will ultimately improve economic stability and national energy security.

Policy Strategy for Development of a National Roadmap for Biofuels: The Indonesian government needs to develop a national roadmap specifically for the development of HVO from palm oil waste sludge. This roadmap should include short, medium and long-term targets for the production and use of HVO in the transportation and industrial sectors. Clear and measurable targets will provide direction for industry stakeholders and increase investment certainty for companies wishing to participate in the development of this technology. The roadmap can also set goals for the integration of HVO into the national energy mix, including scaling up production to industrial scale. For example, countries such as Finland have developed

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biofuel *roadmaps* with an emphasis on renewable energy, which include specific targets for second-generation biofuels such as HVO. Indonesia could adopt a similar model by integrating plans to increase the use of HVO as part of its overall renewable energy program.

Integration of Environmental and Energy Policies: The development of HVO from palm oil sludge has the potential to reduce greenhouse gas emissions and industrial waste. Therefore, environmental and energy policies must be integrated to support this development. The government needs to strengthen regulations that require palm oil producers to manage their waste more sustainably, as well as provide incentives to convert such waste into renewable fuels such as HVO. For example, regulations on waste management and greenhouse gas emissions could be combined with renewable energy policies to create additional impetus for HVO development.

Public-Private Partnerships: HVO development requires large investments in research, technology development and infrastructure. To overcome this challenge, public-private partnerships (PPPs) can be an effective strategy. Governments can work with energy companies, palm oil producers, and research institutions to fund HVO development projects. PPPs can leverage private sector resources to overcome shortfalls in public funding and accelerate the commercialization of HVO technologies. In Europe, PPP in biofuel development has been a successful model by involving private industry in research and development, as well as infrastructure procurement. Indonesia could adopt a similar approach, with the government providing tax incentives and regulatory support to the private sector involved in HVO development.

Technology Development and Innovation for Research and Development of a More Efficient Hydrogenation Technology: One of the major challenges in the production of HVO from palm oil sludge is the hydrogenation process which requires high pressure and temperature and large energy consumption. Therefore, there needs to be a focus on research and development (R&D) of more efficient and energy-efficient hydrogenation technologies. Innovations in hydrogenation technologies may include the use of new, more efficient reactors, energy recovery systems, or catalytic hydrogenation technologies that reduce energy requirements. Countries such as Japan have developed more efficient hydrogenation reactors through the use of new catalyst technologies. Indonesia could work with academic institutions and research institutes to develop similar technologies tailored to the specific needs of palm oil sludge.

Development of New Catalysts and Effective Pretreatment Methods: In addition to hydrogenation technology, the development of new catalysts that are more durable and efficient is essential to reduce HVO production costs. Nickel-molybdenum or cobalt-molybdenum based catalysts are common choices, but further research is needed to find more optimized catalysts for sludge oil. Research should also focus on more effective palm oil sludge pretreatment methods to minimize heavy metal and water contamination that can damage the catalyst and reduce process efficiency. This innovative catalyst development can be done through collaboration with countries that are already advanced in biofuel research, such as the Netherlands or Germany, where catalyst research is a priority for the development of second-generation biofuels.

Increased Public Awareness and Education for Public Education Campaign on the Benefits of HVO important for the government and relevant organizations to raise public awareness on the benefits of HVO as an environmentally friendly renewable fuel. This could include educating consumers about the advantages of HVO over fossil fuels in terms of lower carbon emissions and energy security. The education program should also target policy makers at the regional and national levels to understand the potential of HVO in achieving Indonesia's renewable energy targets. For example, in the European Union, biofuel awareness campaigns are conducted massively through mass media and educational programs, involving civil society, government and the private sector. Indonesia could adopt a similar approach by emphasizing the benefits of HVO in the context of an equitable energy transition, especially in areas directly involved in palm oil production.

Civil Society Engagement in an Equitable Energy Transition: Civil society engagement is critical to ensure that HVO development supports an equitable energy transition. Civil society can be engaged through public dialog forums, where they can provide input on how HVO development should be managed. In addition, empowering local communities in oil palm producing areas through technical skills training in the biofuel industry can strengthen their participation in the HVO value chain. Renewable energy projects that actively involve civil society, such as those in Scandinavia, have proven to be more sustainable and have more positive long-term impacts. In Indonesia, this strategy can be applied through empowering communities in palm oil producing areas to participate in the HVO production and distribution process, as well as involvement in decision-making that affects their communities.

3.6. Recommendations for the Implementation of an Equitable Energy Strategy

3.6.1. Policy Strategy

To implement Hydrotreated Vegetable Oil (HVO) as part of an equitable energy strategy, policies that support this transition must be established and

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implemented. Indonesia is the 15th largest motor vehicle market in the world and is projected to become one of the 10 largest, with growing demand for transportation fuels. In 2023, biodiesel consumption reached 12.2 million metric tons (MMt), and Indonesia is targeting 12.5 MMt in 2024 as part of the B35 biodiesel blend program.

However, an important innovation that needs to be considered is the use of Palm Oil Sludge (SPO) as an HVO feedstock. Processing this palm oil waste offers a solution to reduce industrial waste while meeting biofuel demand. Policies that encourage the use of SPO should be further encouraged by introducing incentives for producers who adopt this processing technology. Indonesian Sustainable Palm Oil (ISPO) certification also needs to be strengthened to ensure the sustainability of biofuel production from SPO, while supporting the target of reducing GHG emissions by 29% by 2030.

3.6.2. Technology Development and Innovation

The development of technology to process Sludge Palm Oil (SPO) into HVO is a highly relevant innovation for Indonesia's energy future. In 2023, domestic consumption of biodiesel from palm oil reached 10.65 million tons, an increase of 17.68% from the previous year. The B35 program also plays a role in increasing local consumption, surpassing the use of palm oil for the food sector. The use of SPO as HVO feedstock not only utilizes palm oil industry waste, but can also reduce diesel imports by 65%, which in 2018 reached 6.5 billion liters.

In addition, SPO's HVO technology contributes to a significant reduction in greenhouse gas (GHG) emissions. HVO from palm oil waste can reduce CO_2e emissions by more than 70% compared to fossil-based diesel fuel, with a CO_2e reduction of approximately 12 million tons per year. This shows that HVO can be part of the circular economy strategy being developed by the Indonesian government.

3.6.3. Increased Public Awareness and Education

To ensure successful adoption of HVO technology from Sludge Palm Oil (SPO), increased public awareness and education is required. By 2023, domestic palm oil consumption for biofuel will reach more than 23 million tons, indicating increasing support for renewable energy solutions. However, further education is needed so that people understand the benefits of using palm waste-based HVO, especially in terms of sustainability and emission reduction. Training programs for the transportation industry, technicians, and fuel producers are also important to ensure that they are able to optimize the use of HVO from SPO. With this strategy, HVO from Palm Oil Sludge (SPO) is not only an environmentally friendly solution but also supports energy security and contributes to national GHG emission reduction targets.

4. Conclusion

This research shows that Hydrotreated Vegetable Oil (HVO) produced from Sludge Palm Oil (SPO) can serve as a key solution in an equitable energy strategy for Indonesia's transportation sector. HVO from SPO can reduce greenhouse gas (GHG) emissions by up to 80% compared to fossil fuels, contributing to improved air quality and reduced pollution. With a cetane number of 62 and better oxidation stability than regular biodiesel, this HVO also offers higher fuel quality, which improves efficiency and reduces negative impacts on vehicle engines. In addition, the production of HVO from SPO supports the circular economy, utilizing previously neglected waste and reducing Indonesia's dependence on fossil fuel imports. HVO from SPO can utilize approximately 2% of Indonesia's total palm oil production, which not only strengthens national energy security, but also helps create new jobs within the renewable energy sector. With this contribution, HVO from SPO has the potential to be an important part of an equitable energy strategy, where the transition to renewable energy not only reduces emissions and pollution, but also ensures that the energy is affordable for all, especially in areas that are hard to reach by conventional energy. This approach provides a more sustainable and inclusive solution, promotes more equitable energy policies that benefit society at large, and supports the achievement of Indonesia's equitable energy transition goals.

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