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Producing high quality biodiesel from used cooking oil in Indonesia

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Introduction

In 2008, Indonesia started its mandatory biodiesel program with a 2.5% blending rate. That rate gradually increased to 20% in 2016 and 35% in 2023 (Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi [EBTKE], 2019; Kementerian Energi dan Sumber Daya Mineral [ESDM], 2023). From 2008–2016, the mandatory program for the transport sector only applied to the public service obligation (PSO). Under the program, the Government of Indonesia explored several kinds of biodiesel feedstock, including jatropha, crude palm oil (CPO), and used cooking oil (UCO) (EBTKE, 2019). In 2015, the government established the Badan Pengelola Dana Perkebunan Kelapa Sawit (BPDPKS), also known as the Palm Oil Estate Fund (POEF) to manage the CPO Supporting Fund (CSF). That helped the country more effectively implement its mandatory biodiesel program by incentivizing CPO biodiesel (BPDPKS, 2018).

Since then, Indonesia has focused more on developing its biodiesel program under a single feedstock, CPO. Besides biodiesel, CPO is used in various food products in Indonesia, including cooking oil. The recent domestic cooking oil crisis that brought drastic prices increases and supply shortages created strong pressure on the biodiesel program. Some stakeholders, including members of the business community, argue that the large volume of CPO used in the biodiesel program contributed to distribution problems that helped, among other factors, to cause the cooking oil crisis (CNBC Indonesia, 2022). For this reason, policymakers are considering other feedstocks to produce biodiesel.

Biodiesel, comprised of fatty acid methyl esters (FAME), can be produced from several oily feedstocks besides CPO, including UCO (Kristiana & Baldino, 2021). Yet UCO is underutilized as a biodiesel feedstock in Indonesia. For example, a recent ICCT study found that Indonesia has the potential to collect up to 715 kilotonnes of UCO annually (Kristiana et al., 2022). While 651 kilotonnes of UCO biodiesel could potentially be produced in Indonesia from this volume, only approximately 0.7 kilotonnes is currently produced annually (Kristiana & Baldino, 2021). Because UCO is not currently included in Indonesia's biodiesel program, most UCO collected in the country is exported to Europe or other parts of Asia (Kristiana et al., 2022).

B100 is pure biodiesel consisting of 100% FAME. The Indonesian National Standard for B100 is set out in SNI 7182:2015 (Badan Standardisasi Nasional, 2015). Along with that, Ministry of Energy and Mineral Resources (MEMR) regulations, which include standards for biodiesel blending, govern Indonesia's current biodiesel program. In

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the B30 program, for example, the EBTKE Directorate General Decree No. 189.K/10/DJE/2019 specifies the requirements for FAME to be blended into diesel. Producers who participate in the biodiesel program qualify for government incentives. Every year, MEMR issues a quota for biodiesel blending and an estimate of the total financial incentives necessary. The total for incentives is not a fixed number since it is based on the market prices of palm oil and diesel; at times, high per-liter incentives are needed while at other times, no incentives are needed (Waseso, 2022).

Currently, UCO biodiesel producers do not participate in the national biodiesel program. While UCO was included on a limited basis in the program from 2014–2018, its use ended because of limited feedstock supply and high UCO biodiesel production costs (EBTKE, 2021). However, apart from the central government's national biodiesel program, several cities created local efforts to use UCO in biodiesel. For example, Bogor city attempted to run a UCO biodiesel program from 2008–2015, but the program stopped for several reasons, including inconsistent feedstock supply, inconsistent blending, and the low quality of biodiesel (which appeared to damage city buses) (Kharina et al., 2018). In one instance, the biodiesel in Bogor's city's program did not meet the national SNI standard mostly because it was not pretreated (Kharina et al., 2018).

Despite past difficulties, industry analysis and several academic studies show that biodiesel produced from UCO in Indonesia can meet national standards (GenOil, personal communication, February 3, 2022; Wicaksono et al. 2019; Zalfiatri et al., 2019; Efendi et al., 2018). Moreover, several companies in Indonesia are producing high quality UCO biodiesel. For example, two UCO biodiesel companies in MEMR's registry, Alpha Global Cinergy and Bali Hijau Biodiesel, meet the national biodiesel standard (EBTKE, 2021). And several companies, including Artha Metro Oil, GenOil, Aqua Danone, Unilever, and Cargill, have produced UCO biodiesel on a limited basis for their own use or to sell domestically (Kristiana et al., 2022; TNP2K & Traction, 2020). A community-based company in Kalimantan also produces UCO biodiesel for its own use (EBTKE, 2021).

The purpose of this study is to describe the processes that could be used in Indonesia to produce high-quality biodiesel particularly from UCO. We provide detailed information on production options that could be effectively used in Indonesia, including pretreatment, transesterification, and post-production purification options. We also discuss the use of antioxidants to maintain biodiesel quality during storage. Finally, we compare the costs of producing biodiesel from UCO and CPO. This study concludes that high quality, cost-competitive UCO biodiesel is technically feasible to produce in Indonesia if it undergoes proper pre- and post-treatment, particularly if the Government of Indonesia supports and incentivizes production through appropriate regulations.

UCO biodiesel production

Figure 1 illustrates the general process to produce biodiesel. However, it is important to understand UCO's properties within the context of that general process. UCO is contaminated by food products and contains water and impurities such as free fatty acid (FFA) molecules which escape from glycerol (Skelton, 2009; Susilowati et al., 2019). The amounts of FFA and water in UCO determines which pretreatment, transesterification, and post-treatment purification processes are needed to produce high quality biodiesel. Several studies (Aeni, 2020; Efendi et al., 2018; Wicaksono et al., 2019; Yuarini et al., 2018) have evaluated UCO samples from different sources across Indonesia (e.g., restaurants, hotels, street food and snack vendors, etc.). They found that UCO in Indonesia has less than 1% water content and between 1–2% FFA content.

These levels are considered high and indicate that additional pre- and post-treatment steps are needed.

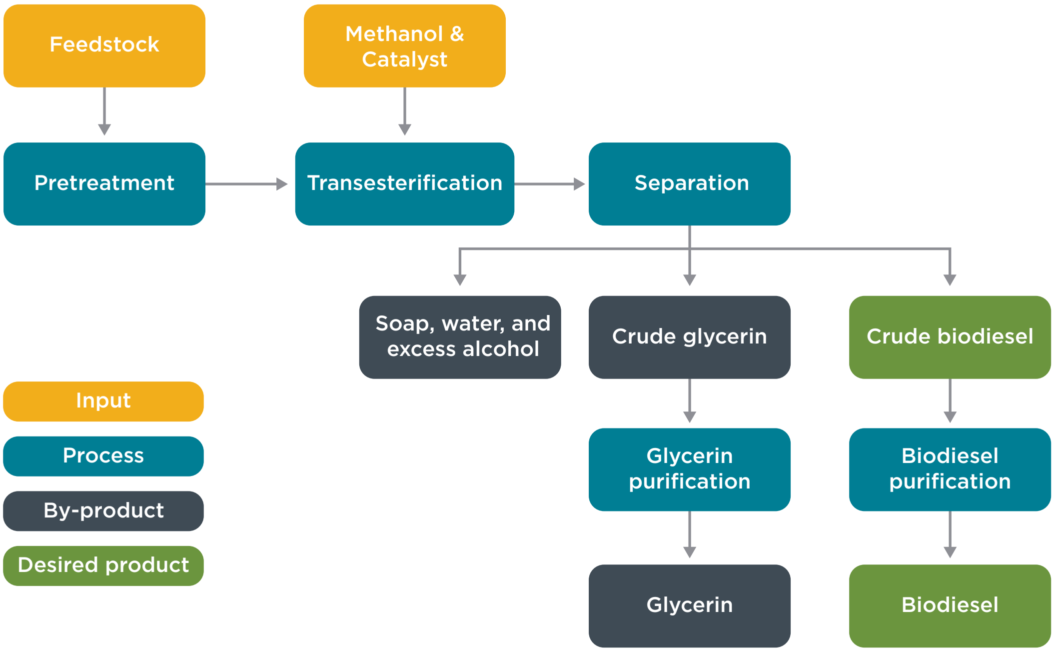

Figure 1. Simplified overview of biodiesel production (Kristiana & Baldino, 2021)

While UCO biodiesel is not widely produced in Indonesia, Europe has a mature UCO biodiesel industry. Figure 2 illustrates the typical European process for producing high-quality UCO biodiesel. It involves three steps: pretreatment, transesterification, and distillation. During pretreatment, heating, filtration, and settlement remove solids and moisture from UCO. Then crude biodiesel is produced through transesterification – mixing UCO with a catalyst to remove free fatty acids (FFA). After transesterification, distillation treats impurities to create high quality UCO biodiesel.

Figure 2. The typical European process for producing UCO biodiesel

The next sections describe the steps in the typical European process in more detail and describe several other options that are available in the biodiesel industry. Choosing the options among this list that best fit specific circumstances could help Indonesian biodiesel producers utilize UCO to effectively meet national biodiesel standards for road transport usage.

Pretreatment

Pretreatment produces higher quality biodiesel from UCO by removing solids, water, and FFA content. Here, we describe various options within five pretreatment categories: solid removal, FFA pretreatment, laboratory-scale FFA pretreatment, laboratory-scale moisture/water pretreatment, and degumming.

1. Solid removal

There are two options to pretreat UCO to remove particulate matter and suspended solids, like food residues: filtration/settlement and centrifugation.

Filtration/settlement: UCO is heated and passed through sieves. As it settles in a tank, dirt and water collect at the bottom (O'Connell, 2004). The heat treatment also helps to reduce moisture content and maintain the initial quality of oil by reducing impurities (i.e., acid and peroxide) (Gürdil et al., 2020; O'Connell, 2004). This is included in the typical European process.

Centrifugation: This process treats solid impurities and reduces water content (Cardenas et al., 2021). It is commonly used in large-scale facilities most often in Europe and North America for biodiesel derived from vegetable oils (Neuman, 2014). This process involves comparatively higher capital and operating costs.

2. FFA pretreatment

High FFA content can lead to the formation of soap and water during the biodiesel production process and can harm vehicle engines (Biofuels International, 2021; Gnanaprakasam et al., 2013). There are five commercially-available FFA pretreatment practices: esterification; adsorption; neutralization; distillation/deodorization; and glycerolysis.

Esterification: In this process, UCO is mixed with enzymes (such as lipases) or, more commonly, an acid catalyst (Cardenas et al., 2021). FFA and other acid compounds are converted into esters. Monohydroxylic alcohols are often used because they are more easily removed and recovered from the UCO. It is possible to obtain different esters depending on the alcohol used in the esterification process. For example, by using methanol, this reaction produces UCO FAME (UCOME) (i.e., biodiesel ester). There are a few drawbacks to this method, such as low catalyst recovery, the catalyst corroding equipment, and comparatively high processing costs. This is included in the typical European process.

Adsorption: This pretreatment method has economic advantages due to its low cost and flexibility of operation. It removes FFA, moisture, and other polar compounds like peroxides (another impurity) (Foo et al., 2022). In this process, UCO is put in contact with an active material that selectively retains some components of the liquid mixture including polar compounds (Cardenas et al., 2021; Ju et al., 2019). The most common adsorbent materials are activated carbon, ion exchange resin, clays, silicates, and aluminum silicates. Zeolite, magnesol, silica gel, magnesium oxide, and aluminum hydroxide are also used though less commonly (Schneider et al., 2017; Shahdan & Hirzin, 2021). Commonly used adsorbents are costly, and researchers are searching for alternatives, such as agricultural residues like rice husk, coconut husk, and sugarcane bagasse. Schneider et al. (2017) found that rice husk removed acidity in UCO as effectively as activated carbon. Besides removing FFA, applying adsorption to UCO by using activated carbon also can reduce the value of other acids and address the polymer content, another impurity in UCO (Phillips, 2019). However, adsorption leaves a significant fraction of the oil embedded in the solid material, which results in UCO loss. While adsorption is well-developed on the industrial scale to refine edible oils, current industrial processes are ill-suited for UCO.

Neutralization: This method blends UCO with alkaline solutions (e.g., potassium hydroxide or sodium hydroxide), which turns FFA into a solid soap (Cardenas et al., 2021; Foo et al., 2022). The soaps, insoluble in the oil, are removed by first washing the mixture with a water spray and then with decantation or centrifugation. Neutralization is commonly used in the edible oil industry, where it is known as chemical refining (Cardenas et al., 2021). This treatment is not recommended for UCO, especially for UCO with an FFA content greater than 5% by weight, due to the amount of alkaline solution that would be required. Moreover, this method generates a large amount of waste.

Distillation/deodorization: In the vegetable oils industry, vacuum and stripping distillation is commonly used to remove FFA (typically when it makes up less than 10% of the oil). In industrial practice, distillation is combined with adsorption to remove polar compounds (Foo et al., 2022). Cardenas et al. (2021) argue that compared to neutralization and esterification, the distillation method generates a lower amount of waste, minor oil losses, and FFA that is high enough quality to be used to produce other products. This method also could help remove other impurities (Foo et al., 2022). However, compared to other pretreatment options, distillation carries high capital and operating costs since it requires vacuum equipment, large energy consumption, and high temperatures. While not included in the typical European process, most UCO in Indonesia could be pretreated with this process (since it is used in Indonesia's vegetable oil industry).

Glycerolysis: In this process, glycerol, a by-product of biodiesel production, is added to UCO with a high amount of FFA (usually higher than 5%). Under high temperatures, the glycerol recombines with FFA to form glycerides (Kombe et al., 2013; Mamtani et al., 2021). A study by Kombe et al. (2013) noted that this process could be done by adding metallic catalysts, such as zinc chloride and zinc dust, or without a catalyst. Advantages of this process include that glycerol is readily available, no alcohol is needed (unlike esterification), and water from the reaction is vaporized immediately (Kombe et al., 2013; Mamtani et al., 2021). This method has been demonstrated at an industrial scale; JatroDiesel, a company based in the United States, sells units for glycerolysis of feedstock with different levels of FFA (Voegele, 2012; Tafesh & Basheer, 2013). However, this method is it requires a high temperature with a slow reaction rate.

3. Laboratory-scale FFA pretreatment

UCO is increasingly used as a biodiesel feedstock. Accordingly, new pretreatment processes are under development. There are four laboratory-scale pretreatment options of note: solvent extraction; membrane technology; column chromatography; and biotreatment.

Solvent extraction: In this process, a solvent (i.e., a separation agent) removes impurities from UCO (Cardenas et al., 2021). The selection of the solvent determines the operating conditions for this process, such as boiling temperature, separation effectiveness, and techno-economic feasibility. While this method is promising for the removal of FFA in edible oil refining, its application for UCO remains limited. Further testing and study continues. For example, Rincon et al. (2021) tested this process on UCO using methanol, ethanol, and isopropanol as solvents. Moreover, a study by Foo et al. (2022) noted that this process combined with water or aqueous acid solutions can remove moisture content and impurities from UCO.

Membrane technology: In this process, a permeable membrane separates impurities under a pressure gradient (Cardenas et al., 2021). This method has several advantages, including comparatively higher UCO yields and low energy consumption. It could be applied to any quality of oil and does not require additional chemical substances (Cardenas et al., 2021; Foo et al., 2022). However, the price of membranes means this process costs more than other pretreatment options. This process also has short reuse cycles which means it generates a large amount of solid waste. This process is currently limited to the laboratory and pilot scale.

Column chromatography: Lee et al. (2002) conducted a laboratory test to treat restaurant UCO with 10–15% FFA content. The process they used – column chromatography – mixed UCO with hexane, filtered it, and passed it through a column. After the hexane evaporates, the FFA-free UCO can be recovered. Next, the

UCO enters the base-catalyzed process called alcoholysis, using an alcohol such as methanol. This method has advantages, such as comparatively higher feedstock yields and the ability to eliminate moisture content.

Biotreatment: Preliminary laboratory test results show that microorganisms can consume some (but not all) types of FFA (Cardenas et al., 2021). Short-chain fatty acids inhibit the microorganisms, for example. Biotreatment is mainly used to obtain value-added products like lipids. The development of this method to remove FFA in UCO faces several challenges, such as high costs and the need to remove the microorganisms used.

4. Laboratory-scale moisture/water pretreatment

Moisture/water pretreatment can be used when producers want to reduce water content to below 0.5% to obtain a 90% biodiesel yield (Gnanaprakasam et al., 2013). Water content in UCO could accelerate the hydrolysis of glycerides into FFA, which is undesirable, and simultaneously inhibit ester formation due to the catalyst's sensitivity to water (Foo et al., 2022). In general, the pretreatment options described earlier remove water (along with other impurities). Three additional moisture pretreatment methods (the use of microwaves, chemicals/desiccants, and pretreatment modules) are described here.

Microwave: If heating during solid removal, which is part of the typical European process, is considered energy-intensive, an alternative is to use a microwave to evaporate water (Cardenas et al., 2021). The heating temperature of microwaves is lower compared to temperatures during solid removal and achieves high separation efficiency. However, this method carries the risk of overheating which can destroy organic molecules.

Chemical and desiccants: Moisture can be removed using chemicals and desiccants such as silica gel, magnesium sulfate, or sodium sulfate (Cardenas et al., 2021; Palanisamy et al., 2013). However, this method increases production costs due to the regeneration limit of the chemicals used, is energy-intensive, and generates waste (Cardenas et al., 2021; Palanisamy et al., 2013).

Pretreatment module: The moisture content in UCO can also be removed with a "pretreatment module" as described in a laboratory trial conducted by Palanisamy et al. (2013). The module is equipped with a vacuum pump and condenser system to reduce moisture vapor temperature. The module reduces UCO's moisture content and operates at 100 degrees Celsius. This method consumes half the energy of the conventional heating method.

5. Degumming

Besides FFA, moisture, and solid impurities in UCO, other impurities such as polymers and phospholipids should be removed during biodiesel processing. The presence of phospholipids in feedstocks can complicate the separation of products and create problems for storage by forming deposits or gums (Tafesh & Basheer, 2013). Furthermore, phospholipids could block catalysts during the FAME production process (Kanakraj and Dixit, 2026). Several degumming methods to remove phospholipids are used in the vegetable oil refining industry: membranes, enzymes, water degumming, and total degumming. Water degumming, for example, works typically by hydrating feedstock with water to remove phospholipids (Rincon et al., 2021).

Transesterification

After pretreatment, UCO undergoes transesterification, where it reacts with methanol or another alcohol and a catalyst to produce FAME and by-products. The use of a catalyst speeds the process. Non-catalytic transesterification requires higher temperatures and pressure. Methanol is used more often than other alcohol types due to its quick reaction with triglycerides and ability to dissolve with a catalyst.

An alkaline-catalyzed transesterification process is part of the typical European process and is combined with esterification pretreatment (see Figure 2). The combination of these two processes is common in the biodiesel industry particularly for UCO as feedstock; this is not applicable to refined vegetable oil which does not require esterification treatment. The process is an effective way to convert triglycerides into esters when the FFA level is less than 1%, which is possible for Indonesian UCO. As explained earlier, the esterification of FFA present in UCO is carried out using an acid catalyst to decrease the FFA level to less than 1%, which is important because the alkaline catalyst is sensitive to FFA (San, 2017; Banerjee & Chakraborty, 2009).

In general, the alkaline-based production process requires moderate temperature and low pressures to operate, and it achieves a high conversion efficiency in less time compared to other processes. The major drawback of this process is the formation of soap which can reduce the conversion rate. Alkali catalysts used in transesterification are sodium methoxide (CH_3ONa), sodium hydroxide (NaOH), potassium hydroxide (KOH), or potassium methoxide (CH_3KO). Among those, biodiesel producers commonly use KOH for producing biodiesel from UCO. Studies also find that KOH is the most effective catalyst for transesterification of UCO.

Purification and post-treatment

Crude biodiesel usually still contains impurities, such as methanol, FFA, catalyst, water, and glycerides (especially when producers use lower quality feedstock, like UCO). The impurities in biodiesel need to be removed to prevent negative impacts on the diesel with which it is blended and on engines (Berrios et al., 2011). This section explains in more detail five purification or post-treatment methods that could be used to produce high-quality UCO biodiesel: distillation; wet washing; dry washing; membrane reactor; and liquid-liquid extraction.

Distillation: To obtain a final UCO biodiesel product that meets specifications like the Indonesian biodiesel standard, distillation is recommended. There are several distillation techniques, such as conventional distillation (ordinary, vacuum, and steam distillation), azeotropic distillation, reactive distillation, and molecular distillation. Several studies show conventional and molecular distillation provide higher quality FAME (Torres et al., 2017; Xie et al., 2019; Wang et al., 2010). However, this process could impact the oxidative properties in biodiesel and needs high temperatures which raises operating costs compared to other purification techniques. This process is commercially available. It is included in the typical European process.

Wet washing: This process washes crude biodiesel with warm acidic water (Demirbas, 2008). It is adopted in conventional processes using alkaline catalysts, especially in large-scale production. This method efficiently removes a higher content of contaminants, but requires high equipment and energy costs since it involves multiple steps such as water treatment, methanol distillation, and glycerol drying (Dimian & Kiss, 2019).

Dry washing (ion exchange or use adsorbent): This process usually involves washing crude biodiesel with an ion exchange resin or magnesium silicate powder (Skelton in Waldron, 2009). When an ion exchange resin is used, the UCO biodiesel is fed through a resin column at room temperature. The biodiesel is then washed with methanol. The resin used in the process can be regenerated and reused (Berrios et al., 2011). This approach is popular among small producers, as it avoids wastewater treatment and is suitable to reduce glycerol from crude FAME (Dimian & Kiss, 2019). This method is used on the commercial scale in Indonesia; GenOil, a UCO biodiesel producers, uses it to purify FAME (GenOil, personal communication, February 3, 2022). One drawback of this method is the high cost of resin (GenOil, personal communication, February 3, 2022). The use of magnesium silicate powder, an adsorbent, is promoted on the industrial scale in the UK and the US (Skelton in Waldron, 2009). However, this generates solid waste.

Membrane reactor: Membrane reactors are commonly used in the vegetable oil biodiesel industry for purification utilizing the immiscibility of methanol and vegetable oils (Talebian-Kiakalaieh et al., 2013). There are two types of membranes, organic and inorganic. This process offers lower production costs due to the integrated reaction and separation step and relatively easy waste removal. However, this method requires methanol purification and the need to clean up the membrane.

Liquid-liquid extraction: At the laboratory-scale, liquid-liquid extractions wash biodiesel with distilled water, tap water, or glycerol at room temperature, then left to settle, and finally separated by centrifugation (Berrios et al., 2011). Testing shows this method could remove all impurities. Residual glycerol could also be a co-product of this method.

Summary of pre- and post-treatment options

UCO and CPO biodiesel production process differ most in the pre- and post-treatment steps. Table 1 summarizes the pre- and post-treatment options for UCO biodiesel. Processes included in the typical European process are highlighted.

Table 1. Pre- and post-treatment options for UCO biodiesel.

Treatment		Technology Level	Advantages	Disadvantages
Solid removal	Filtration and settlement	Mature	Potential to reduce solid waste disposal and enable oil recovery in a grease trap	Requires high temperature (i.e., is energy-intensive); needs follow-up pretreatment to remove other impurities, such as free fatty acids
	Centrifugation	Mature	Potential to reduce solid waste disposal and enable oil recovery in a grease trap	High capital and operating costs; usually combined with another pretreatment method
Free fatty acid (FFA) pretreatment	Esterification	Mature	Applicable to any quality of oil; high efficiency; can be combined with transesterification; produces valuable by-product esters to use in the production of other chemicals	High processing costs; generates wastewater; acid catalysts cause corrosion in equipment; low catalyst recovery
	Adsorption	Mature	Low energy consumption; applicable to any quality of oil; low generation of wastewater; simultaneous removal of other impurities	Generate solid waste; consume a high amount of adsorbent; low retention percentage
	Neutralization	Mature	Applicable to any quality of oil with FFA below 5%;	High loss of oil; generate soaps and wastewater as by-products; consume large volume of water for washing process
	Distillation	Mature	Simple and common in Indonesia; low water consumption; recovered FFA are high enough quality to use in other products; minor oil losses	High capital and operating costs; high energy consumption; vacuum system can generate high wastewater
	Glycerolysis	Mature	Designed to treat high FFA content (above 5%); catalyst optional; utilizing glycerol, a by-product of biodiesel, which lowers the biodiesel production cost; no alcohol needed in the process; capability of converting FFA back to the glyceride molecule	Require high temperature; slow reaction rate
	Solvent extraction	Lab-scale	Remove FFA together with other impurities	Need to be careful when selecting solvent
	Membrane technology	Lab/pilot scale	Applicable to any quality of oil; low energy consumption; high efficiency; no additional chemical substances needed; relatively high yield of UCO	Generate large amount of solid waste; high costs of membrane
	Column chromatography	Lab-scale	Able to treat UCO with high FFA content (10–15%); increase feedstock conversion rate; simultaneous removal of moisture	Long and slow process
	Biotreatment	Lab-scale	Produce value-added products	High production costs; inefficient separation; inhibition sometimes occurs
Moisture pretreatment	Microwave	Lab-scale	Low energy consumption for heating; quick process; high separation efficiency	Risk of overheating which can destroy some organic molecules
	Chemicals/ desiccants	Lab-scale	Desiccant recovery	Increase production cost due to limited chemical regeneration; energy-intensive; generates waste
	Pretreatment module	Lab-scale	Intermediate temperature requirement and energy consumption is lower compared to conventional heating method	
Degumming	Membranes, enzymes, water degumming, total degumming	Mature	Removes several impurities; prevent the formation of gum deposits	Requires high temperature and high water loading to get better extraction
Purification & post-treatment	Distillation	Mature	Produces high quality FAME; has plenty of options for distillation	Impacts oxidative properties in biodiesel; high cost technology; requires high temperatures
	Wet washing	Mature	Efficient treatment for a high content of impurities; suitable as continuity of alkaline transesterification process; lower cost compared to other methods	Generates large volumes of wastewater; glycerol reduction is not as effective as dry washing
	Dry washing	Mature	Resin can remove efficiently soap, glycerol and catalyst; resin can be regenerated and reused; little wastewater generated	High cost of resin; generate solid waste; cannot remove methanol
	Membrane reactor	Mature	Relatively low cost due to integrated process; no waste is generated; soap and glycerol are easily removed	Membrane must be cleaned; methanol must be purified to reuse it
	Liquid-liquid extraction	Lab-scale	Process is carried out under room temperature; able to remove all impurities	

Biodiesel storage

The next common practice in the biodiesel industry is storage. During storage, biodiesel must remain stable to avoid the formation of gums and sediment which could clog filters and form deposits on fueling components, such as in fuel pumps and injectors. Furthermore, oxidative degradation occurs during long-term storage, which also affects biodiesel quality (Dunn, 2008). Dunn (2008) noted that antioxidants are a promising low-cost method for increasing biodiesel resistance to oxidation.

Biodiesel has varying levels of oxidative stability due to differences in natural antioxidants, which impacts the kinds of antioxidants that should be added (Tang et al., 2008). There are two different sources of antioxidants, natural and synthetic. Natural antioxidants include tocopherol (a compound in vegetable oils) and vitamin E. Several studies have found that synthetic antioxidants (which include pyrogallol, gallic acid, and propyl gallate) are more effective than natural antioxidants (Dunn, 2008; Jain & Sharma, 2010; Sarin et al., 2010). Synthetics are generally preferred by producers due to their effectiveness in treating distilled and undistilled biodiesel.

Comparison of UCO and CPO as biodiesel feedstock

This study described several pre- and post-treatment options for producing UCO biodiesel. The impurities in UCO require extensive treatment; some treatment options are costlier than others. In this section, we offer examples of UCO biodiesel production costs using different treatment options.

A study by Sutanto et al. (2021) modeled a new UCO biodiesel plant with two pretreatment steps, esterification and neutralization. With an annual plant capacity of around 50,000 tons and those two pretreatment steps, the net UCO biodiesel cost would be IDR 10,152/liter.

Separately from that study, a UCO biodiesel producer in Indonesia, GenOil, uses adsorption as a pretreatment method and ion-exchange resin for post-treatment (GenOil, personal communication, February 3, 2022). As mentioned earlier, resin costs are high and raise production costs. GenOil has shared that their total production cost is IDR 8,675/liter (GenOil, personal communication, February 3, 2022).

A slightly cheaper UCO biodiesel production cost is taken from a study by Ula and Kurniadi (2017) which used a pre-heating method to decrease moisture content before transesterification. With only one pretreatment method, production costs decrease to IDR 7,214/liter.

However, regardless of pre- and post-production options, the cost of feedstock most influences production costs. For example, GenOil's feedstock cost is IDR 6,000, which is 69% of its total production cost (GenOil, personal communication, February 3, 2022). In the study by Ula and Kurniadi (2017), the feedstock cost is IDR 3,000/liter or 42% of total production costs.

CPO is the feedstock for the biodiesel program in Indonesia. While CPO is considered higher quality than UCO, but it is important to note that palm oil fresh fruit bunch (FFB) undergoes five extraction processes before becoming CPO (Jilan, 2021):

1. FFB loading to ramp station
2. FFB sterilization
3. Threshing
4. Digesting and pressing
5. Clarification

CPO and other vegetable oils have FFA and water content, just like UCO. Studies found that CPO produced in Indonesia has FFA content above 3% and water content below 1% (Ihsan & Fajri, 2019; Yuniva, 2010). Since CPO carries impurities, it needs pretreatment such as degumming, bleaching, neutralization, or deodorizing before transesterification.

Jilan (2021) provides the cost of the different processes in CPO production for a state-owned enterprise, PTPN III. We use these cost components to calculate the base production cost (without profit margin) to derive a CPO production cost of IDR 9,349/kg. The price of CPO represents most of this cost. However, Jilan (2021) used palm oil prices from October 2020, which falls at the higher range of the past five years of CPO prices (Palm Oil Analytics, 2023).

CPO production costs, which we consider as feedstock costs, make up a large share of biodiesel production costs. In Indonesia's biodiesel program, the government sets a fixed CPO biodiesel production cost, excluding feedstock costs, at USD 85 per metric ton (1,058 IDR/liter using the 2021 USD to IDR average exchange rate). Biodiesel producers must pay any production costs higher than USD 85, as the government only gives incentives for the final price gap between biodiesel and diesel. Even with this fixed price, the average CPO biodiesel total production cost in 2022 was 12,495 IDR/liter, which is higher than UCO biodiesel costs from the sources examined for this study (GenOil, 2022; Sutanto et al., 2021; Ula & Kurniadi, 2017).

Again, in biodiesel production, feedstock costs comprise a large percentage of total production costs. Based on the above comparison, in Indonesia, the production cost of UCO biodiesel is cheaper than CPO biodiesel. However, since the pre- and post-treatment options used to derive UCO biodiesel production costs differ from the typical European process, production cost will change if Indonesian producers were to adopt processes typically used in Europe to produce higher-quality UCO biodiesel. The adoption of such processes would require investment in pre- and post-treatment equipment. Securing UCO at lower prices would help producers to offset higher capital expenditures or upfront investments and mitigate higher production costs.

Indonesia has abundant UCO available to be collected and processed into biodiesel. The country has an opportunity to produce high-quality UCO biodiesel at a competitive price. In Europe, UCO is in high demand; the feedstock price is high. This means producing UCO biodiesel there is more expensive than producing vegetable oil-based biodiesel. Currently, UCO collected in Indonesia is mostly exported to Europe and other Asian countries. Indonesia could use UCO as feedstock for its domestic biodiesel program, which would help defuse the food versus fuel debate and avoid a cooking oil crisis. First, the Indonesian government could consider incorporating UCO into the biodiesel program. By listing UCO as alternative feedstock in the biodiesel program, UCO biodiesel quality would be regulated to meet the national standard, UCO biodiesel would get incentives, and investors and biodiesel producers could invest more confidently in UCO biodiesel production.

Conclusions

The current biodiesel program in Indonesia uses a single feedstock, CPO, despite the abundant availability and low price of UCO in Indonesia. Our last study found that Indonesia could collect up to 715 kilotonnes of UCO which could be used to produce 651 kilotonnes of biodiesel (Kristiana & Baldino, 2021). However, UCO is mostly exported to countries in Europe and Asia instead of being used domestically. UCO could be an alternative feedstock in Indonesia's biodiesel program.

Both UCO and CPO need pretreatment before transesterification. With the right pre- and post-treatment methods, UCO biodiesel could be as high quality as biodiesel from vegetable oils. Several pre- and post-treatment methods use technologies similar to those used to produce vegetable oil biodiesel. Previous attempts to use UCO as feedstock for biodiesel failed due to inadequate pre- or post-treatment. However, given the many pre- and post-treatment options available, UCO biodiesel producers can avoid past failures to successfully develop their industry.

In Europe, producers typically combine esterification and transesterification with post-production distillation. Indonesian producers could consider adopting that approach to produce high-quality UCO biodiesel to meet the Indonesian standard. Meanwhile, in Indonesia, companies such as GenOil and Bali Hijau have used other pretreatment and purification methods to produce biodiesel from UCO.

The literature suggests that currently, it costs less to produce UCO biodiesel in Indonesia than CPO biodiesel. Even with costlier pre- and post-treatment equipment, depending on the cost of the UCO, Indonesian producers could still produce cost-competitive UCO biodiesel.

The Government of Indonesia (specifically MEMR) should consider listing UCO as an alternative feedstock in the current biodiesel program. UCO biodiesel could then be regulated to meet the national biodiesel standard and it could qualify for the biodiesel incentive from the Ministry of Finance under the POEF. By issuing a new regulation or policy to incorporate UCO into the biodiesel program, UCO biodiesel quality can be ensured under SNI and MEMR regulations and further fiscal or non-fiscal incentives could be given to support UCO biodiesel development and ensure UCO is cost-competitive with CPO biodiesel.

References

Aeni, Q. (2020). Analisis timbulan minyak jelantah dari rumah makan di kawasan kuliner alun-alun Kecamatan Kendal. Tugas Akhir Universitas Islam Indonesia. https://dspace.uii.ac.id/handle/123456789/31012

Banerjee, A., & Cakraborty, R. (2009). Parametric sensitivity in transesterification of waste cooking oil for biodiesel production – A review. *Resources, Conservation and Recycling*, *53*(9), 490–497. http://doi.org/10.1016/j.resconrec.2009.04.003

Berrios, M., Martin, M. A., Chica, A. F., & Martin, A. (2011). Purification of biodiesel from used cooking oils. *Applied Energy*, *88*(11), 3625–3631. https://doi.org/10.1016/j.apenergy.2011.04.060

Biofuels International. (2021, April 13). The conversion of used cooking oils into biodiesel. https://biofuels-news.com/news/the-conversion-of-used-cooking-oils-into-biodiesel/

Badan Pengelola Dana Perkebunan Kelapa Sawit (BPDPKS). (2018, August 20). Pembentukan badan pengelola dana perkebunan kelapa sawit (BPDPKS) untuk mendukung sawit Indonesia yang berkelanjutan. http://www.bpdp.or.id/wp-content/uploads/2018/08/Sesi-1-1-Musdhalifah-Machmud-Bahan-Ibu-Deputi-200818.rev2_.pdf

Badan Standardisasi Nasional. (2015). Standar Nasional Indonesia: Biodiesel. Retrieved from https://fluidteknologi.com/demo/wp-content/uploads/2019/11/sni_7182_2015.pdf

Cardenas, J., Orjuela, A., Sanchez, D. L., Narvaez, P. C., Katryniok, B., & Clark, J. (2021). Pre-treatment of used cooking oils for the production of green chemicals: A review. *Journal of Cleaner Production*, *289*, 125129. https://doi.org/10.1016/j.jclepro.2020.125129

CNBC Indonesia. (2022, February 25). Benarkah program B30 biang kerok migor melejit?. https://www.cnbcindonesia.com/news/20220225171616-4-318534/benarkah-program-b30-biang-kerok-migor-melejit

Demirbas, A. (2008). *Biodiesel: A realistic fuel alternative for diesel engines*. Springer.

Dimian, A. C., & Kiss, A. A. (2019). Eco-efficient processes for biodiesel production from waste lipids. *Journal of Cleaner Production*, *239*. https://10.1016/j.jclepro.2019.118073

Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi (EBTKE). (2019, December 18). Pahami istilah B20, B30, B100, BBN dalam bioenenergi. https://ebtke.esdm.go.id/post/2019/12/18/2433/pahami.istilah.b20.b30.b100.bbn.dalam.bioenergi

Direktorat Jenderal Energi Baru, Terbarukan dan Konservasi Energi (EBTKE). (2021, March 17). Peluang dan tantangan pemanfaatan biodiesel berbasis minyak jelantah. Retrieved from https://ebtke.esdm.go.id/post/2021/03/09/2824/peluang.dan.tantangan.pemanfaatan.biodiesel.berbasis.minyak.jelantah

Dunn, R. O. (2008). Antioxidants for improving storage stability of biodiesel. *Biofuels Bioproducts and Biorefining*, *2*(4), 304–318. https://doi.org/10.1002/bbb.83

Efendi, R., Faiz, H. A., & Furdaus, E. R. (2018). Pembuatan biodiesel minyak jelantah menggunakan metode esterifikasi-transesterifikasi berdasarkan jumlah pemakaian minyak jelantah. 9th Industrial Research Workshop and National Seminar, 9. https://doi.org/10.35313/irwns.v9i0.1129

Foo, W. H., Koay, S. S., Tang, D.Y., Chia, W.Y., Chew, K. W., & Show, P. L. (2022). Safety control of waste cooking oil: Transforming hazard into multifarious products with available pre-treatment processes. *Food Materials Research*, *2*(1). https://doi.org/10.48130/FMR-2022-0001

Gnanaprakasam, A., Sivakumar, V. M., Surendhar, A., Thirumarimurugan, M., & Kannadasan, T. (2013). Recent strategy of biodiesel production from waste cooking oil and process influencing parameters: A review. *Journal of Energy*, *2013*, 926392. http://dx.doi.org/10.1155/2013/926392

Gürdil, G. A. K., Kabutey, A., Selvi, K. Ç., Hrabě, P., Herák, D., & Fraňková, A. (2020). Investigation on heating and freezing pretreatments on mechanical, chemical and spectral properties of bulk sunflower seeds and oil. *Processes*, *8*, 411. https://doi.org/10.3390/pr8040411

Ihsan, F. N., & Fajri, R. (2019). Pengaruh kadar free fatty acid (FFA) dalam bulk storage tank (BST) terhadap kualitas crude palm oil (CPO) hasil produksi pengolahan kelapa sawith PMKS PT. Sisirau Aceh Tamiang. *Quimica: Jurnal Kimia Sains dan Terapan*, *1*(1), 22–24. https://www.ejurnalunsam.id/index.php/JQ/article/view/1685/1263

Jain, S., & Sharma, M. P. (2010). Stability of biodiesel and its blends: A review. *Renewable and Sustainable Energy Reviews*, *14*, 667–678. https://doi.org/10.1016/j.rser.2009.10.011

Jilan, R. (2021). *Analisis nilai tambah pengolahan kelapa sawit menjadi CPO (crude palm oil) di PT.* [Undergraduate thesis, Universitas Sumatera Utara]. https://repositori.usu.ac.id/bitstream/handle/123456789/32291/170304003.pdf?sequence=1&isAllowed=y

Ju, J., Zheng, Z., Xu, Y., Cao, P., Li, J., Li, Q., & Liu, Y. (2019). Influence of total polar compounds on lipid metabolism, oxidative stress and cytotoxicity in HepG2 cells. *Lipids in Health and Disease*, *18*(1). https://doi.org/10.1186/s12944-019-0980-0

Kanakraj, S., & Dixit, S. (2016). A comprehensive review on degummed biodiesel. *Biofuels*, *7*(5), 1–12. https://doi.org/10.1080/17597269.2016.1168021

Kementerian Energi dan Sumber Daya Mineral (ESDM). (2023, February 1). Era baru BBN, Indonesia siap implementasikan B35. https://www.esdm.go.id/id/media-center/arsip-berita/era-baru-bbn-indonesia-siap-implementasikan-b35

Kharina, A., Searle, S., Rachmadini, D., Kurniawan, A. A., & Prionggo, A. (2018). *The potential economic, health and greenhouse gas benefits of incorporating used cooking oil into Indonesia's biodiesel*. The International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/UCO_Biodiesel_Indonesia_20180919.pdf

Kombe, G. G., Temu, A. K., Rajabu, H.M., Mrema, G. D., Kansedo, J., & Lee, K. T. (2013). Pre-treatment of high free fatty acids oils by chemical re-esterification for biodiesel production – A review. *Advances in Chemical Engineering and Science*, *3*, 242–247. http://dx.doi.org/10.4236/aces.2013.34031

Kristiana, T., & Baldino, C. (2021). *Potential biofuel production pathways in Indonesia: Overview of processes, feedstocks, and types of fuel*. The International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/Potential-biofuel-pathways- indonesia-EN-apr2021.pdf

Kristiana, T., Baldino, C., & Searle, S. (2022). *An estimate of current collection and potential collection of used cooking oil from major Asian exporting countries*. The International Council on Clean Transportation, https://theicct.org/wp-content/uploads/2022/02/UCO-from-Asia_wp_final.pdf

Lee, K. T., Foglia, T. A., & Chang, K. S. (2002). Production of alkyl ester as biodiesel from fractionated lard and restaurant grease. *Journal of the American Oil Chemists' Society*, *79*, 191–195. https://doi.org/10.1007/s11746-002-0457-y

Mamtani, K., Shahbaz, K., & Farid, M. M. (2021). Glycerolysis of free fatty acids: A review. *Renewable and Sustainable Energy Review*, *137*, 110501. https://doi.org/10.1016/j.rser.2020.110501

Neuman, T. (2014, March 6). Use of separators, decanters in biodiesel processing. *Biodiesel Magazine*. https://biodieselmagazine.com/articles/17995/use-of-separators-decanters-in-biodiesel-processing

O'Connell, A. (2005). Recycled vegetable oil as a fuel. [Master's thesis, University of Limerick].

Palanisamy, K., Idlan, M. K. & Saifudin, N. (2013). Preliminary evaluation of the effectiveness of moisture removal and energy usage in pretreatment module of waste cooking oil for biodiesel production. *IOP Conference Series: Earth and Environmental Science*, *16*, 012053. https://doi.org/10.1088/1755-1315/16/1/012053

Palm Oil Analytics. (2023). CPO- FOB Indonesia. https://palmoilanalytics.com/

Phillips, D. (2019). *Implications of imported used cooking oil (UCO) as a biodiesel feedstock.* NNFCC. https://www.nnfcc.co.uk/files/mydocs/UCO%20Report.pdf

Predojević, Z. J. (2008). The production of biodiesel from waste frying oils: A comparison of different purification steps. *Fuel*, *87*(17–18), 3522–3528. https://doi.org/10.1016/j.fuel.2008.07.003

Rincon, L. A., Ramirez, J. C., & Orjuela, A. (2021). Assessment of degumming and bleaching processes for used cooking oils upgrading into oleochemical feedstocks. *Journal of Environmental Chemical Engineering*, *9*(1), 104610. https://doi.org/10.1016/j.jece.2020.104610

San, D. (2017). *Biodiesel production from jatropha and waste cooking oils in Mozambique*. [Master's thesis, KTH School of Industrial Engineering and Management]. https://kth.diva-portal.org/smash/get/diva2:1152885/FULLTEXT01.pdf

Sarin, A., Singh, N. P., Sarin, R., & Malhotra, R. K. Natural and synthetic antioxidants: Influence on the oxidative stability of biodiesel synthesized from non-edible oil. *Energi*, *35*, 4645–4648. https://doi.org/10.1016/j.energy.2010.09.044

Schneider, L. T., Bonassa, G., Alves, H. J., Meier, T. R. W., Frigo, E. P., & Teleken, J. G. (2017). Use of rice husk in waste cooking oil pretreatment. *Environmental Technology*, *40*(5), 594–604. https://doi.org/10.1080/09593330.2017.1397772

Shahdan, S. N., & Hirzin, R. S. (2021). Pre-treatment of used cooking oil followed by transesterification reaction in the production of used cooking oil-based polyol. *Scientific Research Journal*, *18*(2), 129–146. https://doi.org/10.24191/srj.v18i2.13749

Skelton, R. L., Processing of used cooking oil for the production of biofuels. In K. Waldron (Ed.), *Handbook of Waste management and Co-Product Recovery in Food Processing* (pp. 441–454). Woodhead Publishing. https://doi.org/10.1533/9781845697051.4.441

Susilowati, E., Hasan, A., & Syarif, A. (2019). Free fatty acid reduction in a waste cooking oil as a raw material for biodiesel with activated coal ash adsorbent. *Journal of Physics: Conference Series*, *1167*, 012035. https://doi.org/10.1088/1742-6596/1167/1/012035

Sutanto, C. F., Wiryawan, F. P., & Kurniawansyah, F. (2021). Pra rancangan pabrik biodiesel dari minyak jelantah menggunakan metode transesterifikasi dengan kapasitas 50.000 ton/tahun. *Jurnal Teknik ITS*, *10*(2). https://doi.org/10.12962/j23373539.v10i2.70673

Tafesh, A., & Basheer, S., Pretreatment methods in biodiesel production processes. In Z. Fang (Ed.), *Pretreatment Techniques for Biofuels and Biorefineries* (pp. 417–434). Springer.

Talebian-Kiakalaieh, A., Amin, N. A. S., & Mazaheri, H. (2013). A review on novel processes of biodiesel production from waste cooking oil. *Applied Energy*, *104*, 683–710. http://dx.doi.org/10.1016/j.apenergy.2012.11.061

Tang, H., De Guzman, R. C., Salley, S. O., & Ng, S. K. Y. (2008). The oxidative stability of biodiesel: Effects of FAME composition and antioxidant. *Lipid Technology*, *20*(11), 249–252. https://doi.org/10.1002/lite.200800065

Tim Nasional Percepatan Penanggulangan Kemiskinan (TNP2K) & Traction Energy Asia. (2020). *Pemanfaatan minyak jelantah untuk produksi biodiesel dan pengentasan kemiskinan di Indonesia*. https://tractionenergy.asia/wp-content/uploads/2021/03/Paparan-Pemanfaatan-Minyak-Jelantah-Untuk-Produksi-Biodiesel-dan-Pengentasan-Kemiskinan-di-Indonesia.pdf

Torres, S., Acien, G., García-Cuadra, F., & Navia, R. (2017). Direct transesterification of microalgae biomass and biodiesel refining with vacuum distillation. *Algal Research*, *28*, 30–38. http://dx.doi.org/10.1016/j.algal.2017.10.001

Ula, S., & Kurniadi, W. (2017). Studi kelayakan produksi biodiesel dari minyak jelantah skala industry kecil. *Al Jazari Journal of Mechanical Engineering*, *2*(2), 1–7. https://www.journal.umtas.ac.id/index.php/aljazari/article/view/144/92

Voegele, E. (2012, January 18). A critical component. *Biodiesel Magazine*. https://biodieselmagazine.com/articles/8295/a-critical-component

Wang, Y., Nie, J., Zhao, M. Ma, S., Kuang, L., Han, X., &Tang, S. (2010). Production of biodiesel from waste cooking oil via a two-step catalyzed process and molecular distillation. *Energy Fuels*, *24*(3), 2104–2108. https://doi.org/10.1021/ef901347b

Waseso, R. (2022, September 11). Harga solar naik, BPDPKS tak bayar insentif program biodiesel hingga September 2022. *Kontan*. https://nasional.kontan.co.id/news/harga-solar-naik-bpdpks-tak-bayar-insentif-program-biodiesel-hingga-september-2022

Wicaksono, A., Widayat, & Saptadi, S. (2019). Waste cooking oil into biodiesel transformation and its economical potency through circular economic model in Semarang Barat Area Indonesia. *E3S Web of Conferences*, *125*, 14010. https://doi.org/10.1051/e3sconf/201912514010

Xie, Q., Cai, L., Xia, F., Liang, X., Wu, Z., Liu, X., Lu, M., Nie, Y., & Ji, J. (2019). High vacuum distillation for low-sulfur biodiesel production: From laboratory to large scale. *Journal of Cleaner Production*, *223*, 379–385. https://doi.org/10.1016/j.jclepro.2019.03.160

Yuarini, D. A., Putra, G. P., Wrasiati, L. P., & Wiranatha, A. A. (2018). Karakteristik minyak goreng bekas yang dihasilkan di Kota Denpasar. *Media Ilmiah Teknologi Pangan*, *5*(1), 49–55. http://erepo.unud.ac.id/id/eprint/22169/1/3ef55cc44066b557b1ec0466ddaf644f.pdf

Yuniva, N. (2010). *Analisa mutu crude palm oil (CPO) dengan parameter kadar asam lemak bebas (ALB), kadar air dan kadar zat pengotor di pabrik kelapa sawit PT. Perkebunan Nusantara-V Tandun Kabupaten Kampar.* [Undergraduate thesis, Universitas Islam Negeri Sultan Syarif Kasim Riau Pekanbaru]. https://repository.uin-suska.ac.id/10499/1/2010_2010390PK.pdf