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Compatibility of mid-level biodiesel blends in vehicles in Indonesia

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Executive summary

Indonesia strongly promotes palm biodiesel consumption with a current target of 20% biodiesel blending at present, increasing to 30% in 2020. If met, these targets would require the use of high biodiesel blends, raising concerns about compatibility with Indonesia's current vehicle fleet. In this study, we review evidence on the impact of biodiesel on emissions of harmful pollutants from vehicles and on vehicle material compatibility.

Previous reviews have reported that soy and rapeseed biodiesel increase nitrogen oxide (NO_x) emissions compared to fossil diesel, but that palm biodiesel reduces NO_x emissions due to its high level of saturated compounds. These reviews also report that all types of biodiesel reduce particulate matter (PM), carbon monoxide (CO), and unburned hydrocarbon (HC) emissions compared to diesel. On the contrary, we find that, on average, palm biodiesel increases NO_x and PM emissions compared to fossil diesel when conducting a meta-analysis that includes evidence from a number of recent studies. There is substantial variation in results, and these effects appear to differ with fuel sulfur content; palm biodiesel tends to increase emissions when blended in low-sulfur diesel (<50 ppm) but can decrease emissions in higher-sulfur diesel (>50 ppm). High-sulfur diesel use is widespread today in Indonesia. Fuel sulfur content could be an indicator of other fuel quality properties that could influence the effect of biodiesel blends on emissions. Indonesia is making a commendable step in moving toward cleaner fuels and vehicles with its expected adoption of Euro 4/IV standards starting in 2021, which will deliver substantial air quality benefits. However, our findings suggest that biodiesel consumption will detract from the air quality benefits of using cleaner diesel fuel. We also find that, when including recent evidence from studies using low-sulfur diesel, rapeseed biodiesel worsens CO and PM emissions compared to fossil diesel, and soybean biodiesel does not provide any benefit with regard to these pollutants.

Biodiesel also affects materials used in vehicle components differently than fossil diesel. Compared to diesel, biodiesel causes greater corrosion in several types of metals used in vehicle components. The negative impacts of corrosion are partially offset by improved lubricity with biodiesel blends, which can reduce wear in moving vehicle parts. Biodiesel also degrades some types of elastomers and leads to greater deposit formation and plugging of some vehicle components compared to fossil diesel. Overall, studies on whole fuel/engine and vehicle systems find that more frequent replacement of various components such as fuel filters, fuel injector nozzles, and seals, as well as potentially more costly components central to diesel engines, is required when operating vehicles on biodiesel blends. Based on the available evidence, it thus appears likely that meeting Indonesia's goals to blend 20%–30% palm biodiesel in its diesel supply will result in increased vehicle maintenance costs.

Introduction

The government of Indonesia has required the blending of biodiesel in diesel fuel since issuing its first set of blending targets in 2008 for the 2008–2025 time frame in its Ministry of Energy and Mineral Resources (MEMR)

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Regulation No. 32/2008. The targets have been revised several times, and Indonesia currently requires 20% biodiesel blending, increasing to 30% starting in 2020, per MEMR Regulation No.12/2015. Historically, these targets have been missed by half or more, and the actual biodiesel blend level in 2016 was around 11% (U.S. Department of Agriculture Foreign Agricultural Service, 2017). In October 2017, the Indonesian government indicated the move to 30% blending in 2020 may be delayed (Rachman, 2017).

The high biodiesel blending levels targeted by the government of Indonesia may raise concerns of compatibility in vehicles. Although biodiesel has some positive characteristics for use in diesel vehicles, it reduces fuel economy, can degrade some vehicle components and materials, and may affect vehicle emissions. Vehicle manufacturers recommend the use of biodiesel blends only up to 5% in the United States and 7% in Europe and Malaysia in regular diesel vehicles, and use of higher biodiesel blends may void customer warranties (National Biodiesel Board, 2005; Toyota, n.d.; "Car warranty," 2017). In addition, the Worldwide Fuel Charter only allows up to 5% biodiesel blending in fossil diesel (European Automobile Manufacturers' Association [ACEA] et al., 2013). The Indonesian Trucking Association Drs Gemilang Tarigan has stated that warranties extend to B20 for all trucks included in the association ("Greater push," 2017). However, the Association of Indonesian Automotive Manufacturers (Gaikindo) has stated that not all vehicles can accept B15 or higher biodiesel blends, and PT Pertamina, the largest fuel distributor in Indonesia, reports receiving complaints from automotive producers that engines are limited to biodiesel blends as low as 12.5% (Cahyafitri & Yulisman, 2015). Vehicles specially designed for higher blends, such as B20 or B100, are available, but typically at a higher price.

This study reviews the likely impacts of Indonesia's biofuel policy on vehicle consumers. Whereas previous studies have reviewed the impacts of biodiesel on vehicle emissions and the durability of components (Hoekman & Robbins, 2012; U.S. Environmental Protection Agency [EPA] et al., 2002; Lapuerta, Armas, & Rodriguez-Fernandez, 2008; Haseeb, Fazal, Jahirul, & Masjuki, 2011; Singh, Korstad, & Sharma, 2012), most empirical evidence included in these reviews is from vehicles and fuels in Europe and the United States, and none of these reviews have addressed vehicle impacts specifically in the Indonesian context. Indonesia's case is different from biodiesel impacts studied in Europe and the United States for several reasons:

- The vast majority of biodiesel consumed in Indonesia is produced from palm oil, rather than soy oil or rapeseed oils, which are the dominant biodiesel feedstocks in many other countries;
- Indonesia has a warm climate, which has different effects on the viscosity of biodiesel compared to countries in cooler climates;
- Indonesian vehicles tend to have older technology than in Europe and the United States; and
- Indonesia has lower fuel quality, in particular higher sulfur content, than fuel in Europe and the United States.

Here, we review the effects of biodiesel—specifically, fatty acid methyl esther—on vehicle component durability and conventional pollutant emissions. We do not address other renewable diesel substitutes such as hydrotreated vegetable oil (HVO). This study focuses on palm biodiesel where information is available, and examines the interaction of fuel quality and vehicle operation with biodiesel effects on emissions to understand what the likely impacts are of increasing biodiesel blending in Indonesia and how those effects may change in the future.

Effect of biodiesel on conventional pollutant emissions from vehicles

Biodiesel has several properties that influence its effect on vehicle emissions. In particular, it has a higher oxygen content, cetane number, density, and viscosity, and lower sulfur than diesel (Sivaramakrishnan & Ravikumar, 2012). Review studies generally agree that biodiesel usage leads to a decrease in emissions of CO, PM, and HC, and a modest increase in NO_x emissions (Hoekman & Robbins, 2012; EPA, 2002; Lapuerta et al., 2008).

EFFECT OF BIODIESEL ON NO_X EMISSIONS

Whereas most studies measure increases in NO_x in biodiesel blends compared to diesel, some studies report the opposite. Overall, a review by EPA (2002) found that a blend of 20% biodiesel in diesel (B20) increases NO_x emissions by 2%. This finding was supported by a later meta-analysis by Hoekman and Robbins (2012). The measured impacts of palm biodiesel on NO_x have been mixed. Some studies have reported that palm biodiesel in particular results in a decrease in NO_x, postulating that the high saturation level and cetane number of palm biodiesel may contribute to this beneficial effect (Wirawan et al., 2008; Ng et al., 2011; Kinoshita, Hamasaki, & Jaqin, 2003). On the other hand, others have reported that palm biodiesel increases NO_x compared to fossil diesel (Acevedo & Mantilla, 2011; Vedaraman, Puhan, Nagarajan, & Velappan, 2011; Fattah, Masjuki, Kalam, Mofijur, & Abedin, 2014; Karavalakis, Bakeas, Fontaras, & Stournas, 2011). In particular, Acevedo and Mantilla (2011) measured 30%–130% higher NO_x compared to fossil diesel when combusting 100% palm biodiesel in a heavy-duty diesel engine. We identified and reviewed eight studies that specifically tested exhaust emissions using palm biodiesel in light-duty vehicles or engines and one study that tested palm biodiesel in a heavy-duty engine (references listed in Appendix). We compared emissions of NO_x and other pollutants from combusting biodiesel blends to those of pure diesel in each study, and listed all combinations of blend level, engine or vehicle, and test cycle as separate observations. The difference in NO_x between biodiesel blends and fossil diesel is shown in Figure 1. Positive values indicate the biodiesel blend resulted in higher NO_x than fossil diesel, whereas negative values indicate biodiesel reduced NO_x compared to diesel. We perform a linear regression with the change in NO_x emissions using the biodiesel blend compared to diesel and the biodiesel blend level. For all similar regressions presented in this study, we fix the intercept at 0 and consider significant relationships to be indicated when $p<0.05$, and only present regression lines in our figures where such relationships are statistically significant. We find a statistically significant positive relationship between palm biodiesel blend level and NO_x emissions in these compiled results (Figure 1), although similar to other reviews, we find high variability in results. In contrast to conclusions drawn from some of the few individual experimental studies listed previously, when examining all of the available data, it appears that palm biodiesel increases NO_x emissions compared to fossil diesel. However, it should be noted that this regression is heavily influenced by the results in Acevedo and Mantilla (2011), and that if the data from that study were omitted, we would find no relationship between the biodiesel NO_x effect and palm biodiesel blend level.

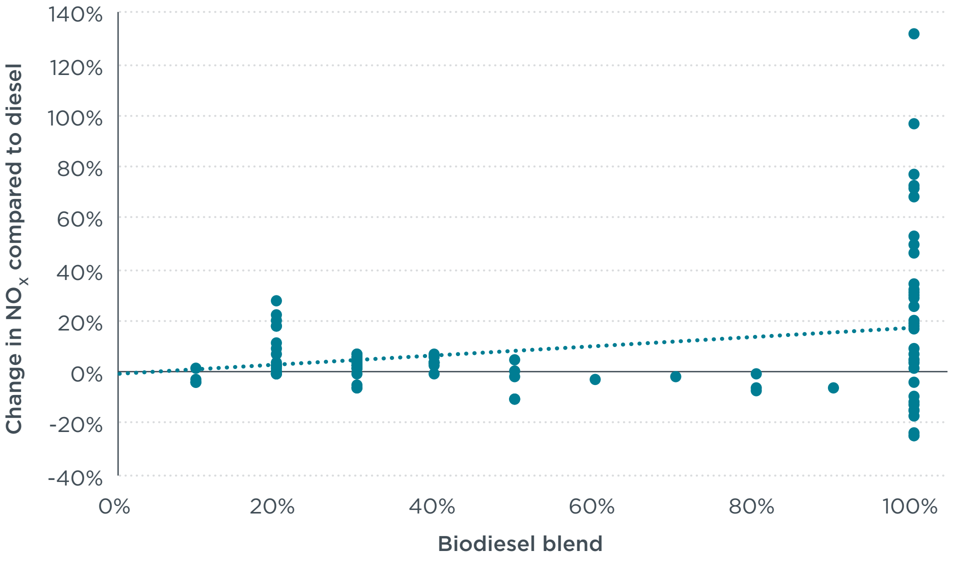

Figure 1. Effect of palm biodiesel on NO_x emissions at varying blend levels compared to fossil diesel in light-duty vehicles and engines.

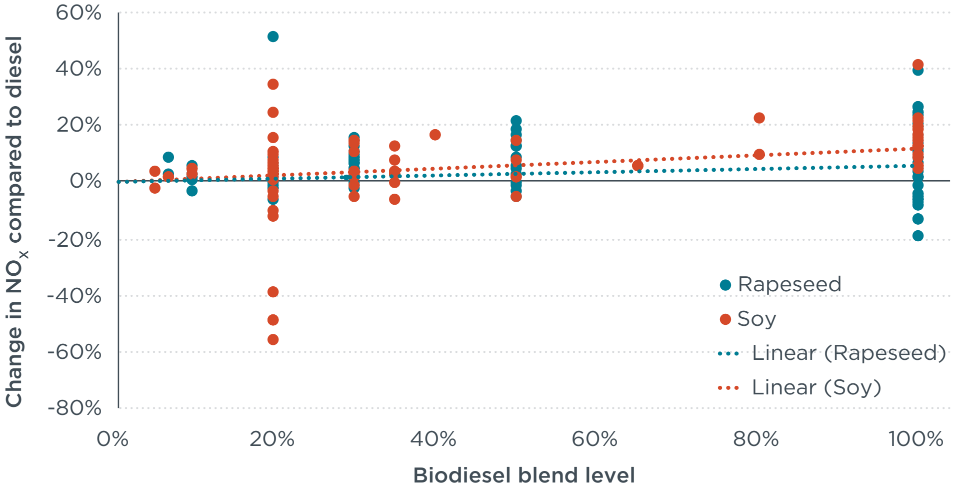

Figure 2. Effect of soy and rapeseed biodiesel on NO_x emissions at varying blend levels compared to fossil diesel in light-duty and heavy-duty vehicles and engines.

Similar to the effects of palm biodiesel blends, we find that biodiesel blends produced from rapeseed oil and from soy oil and soy oil blends (e.g., sunflower oil) significantly increase NO_x compared to fossil diesel when examining data from both light-duty and heavy-duty vehicles and engines (Figure 2). The effect of soy biodiesel on NO_x emissions appears to be stronger than the effect for rapeseed oil, in agreement with previous research reviewed in Hoekman and Robbins (2012). Although we have included many studies on the effects of soy and rapeseed biodiesel on exhaust emissions, we do not consider our review to be exhaustive for these feedstocks. There is some evidence concerning emissions for biodiesel produced from other feedstocks, such as used cooking oil and animal fats, but there are not sufficient data to justify a meta-analysis for these feedstocks.

POTENTIAL MECHANISMS OF NO_x EFFECTS

It is not well understood why biodiesel blending affects NO_x. The increase in NO_x with biodiesel content that is observed in most studies is likely due to a combination of effects that are reviewed in Lapuerta et al. (2008) and Hoekman and Robbins (2012):

- **Advanced fuel injection.** Biodiesel has lower compressibility and higher speed of sound than diesel. As a result of these factors, in mechanically operated fuel injection systems (the most popular among pre-Euro 4/IV systems) pressure increases more quickly with biodiesel, forcing the delivery valve to respond more quickly and ejecting the fuel into the cylinder earlier than with regular diesel. Because of a slightly earlier injection, biodiesel has a longer residence time in the cylinder before compression begins and the fuel ignites. This additional residence time allows the fuel and air to mix more thoroughly, leading to more intense combustion, and thus heat release, once ignition begins. This period of intense heat release leads to higher peak temperatures in the cylinder, although the duration of heat release and high temperatures is likely shorter compared to later injection. NO_x formation increases exponentially with temperature, and thus a short period of very high temperatures leads to overall higher NO_x formation compared to the more drawn out combustion and softer temperature peaks that would be expected with delayed injection. Supporting this theory, Monyem and Van Gerpen (2001, as cited in Lapuerta et al., 2008) found a correlation between the start of injection and NO_x emissions, independent of the fuel used. In fact, delayed injection has been used as a strategy for reducing NO_x emissions in diesel vehicles (Minami, Takeuchi, & Shimazaki, 1995; Tanabe, Kohketsu, & Nakayama, 2005). However, Lapuerta et al. (2008) report that other experiments maintaining constant injection timing still find higher NO_x for biodiesel, suggesting that injection timing cannot be the only mechanism for higher NO_x.
- **Reduced radiative heat loss through lower soot formation.** As further described below, biodiesel produces less particulate matter, or soot, than fossil diesel. Soot formation absorbs heat and thus to some extent reduces cylinder temperature during and after combustion. As reviewed in Hoekman and Robbins (2012), there is some experimental evidence to support this theory. However, Schonborn (2008, 2009, as cited in Hoekman and Robbins, 2012) found simultaneous increases in both PM and NO_x with the combustion of some biodiesel species, suggesting that reduced soot formation cannot be the sole mechanism of increased NO_x emissions. Furthermore, across the studies analyzed here, we do not observe any relationship between PM and NO_x. A negative correlation would be expected if reduced PM were a strong driver of increasing NO_x.
- **Higher adiabatic flame temperature.** Unsaturated compounds have been shown to exhibit higher adiabatic flame temperature than saturated compounds, but there is little evidence showing that this is a significant effect in NO_x emissions with biodiesel.
- **"Prompt NO_x" formation.** "Prompt NO_x" is caused by the reaction of HC fragments with nitrogen (N_2), typically under fuel-rich conditions. There is theoretical reason to expect unsaturated compounds to produce more HC radicals, and thus for biodiesel—especially that which has been produced from feedstocks with a high proportion of unsaturated fats, such as soy oil—to produce more NO_x from HC radicals. However, there is little experimental evidence to support this theory. Moreover, as discussed in more detail below, total HC emissions for biodiesel are less than those of fossil diesel fuel.
- **Higher oxygen availability during combustion.** Biodiesel contains more oxygen than diesel fuel, which may increase the reaction of oxygen with N_2 to produce NO_x. There is some evidence, reviewed in Lapuerta et al. (2008), that enriching intake air with oxygen increases NO_x. However, this relationship is weaker, or nonexistent, for increased oxygen contained within fuel molecules compared to enriched oxygen content of air.

Understanding these mechanisms may help elucidate why there is so much variability in NO_x emissions from palm biodiesel. Although the available data indicate that palm biodiesel increases NO_x emissions overall, compared to fossil diesel, some studies report a NO_x reduction with palm biodiesel.

- **Higher cetane number (CN) offsetting advanced injection.** The high CN of palm biodiesel may partially or completely mitigate advanced fuel injection. CN is defined as the inverse of the time delay between the start of fuel injection and the start of combustion; higher CN thus indicates a shorter delay from injection to combustion (ignition delay). It should be understood, however, that CN is not necessarily completely correlated with actual ignition delay. CN is determined by the chemical composition of fuel, and the actual ignition delay may vary for any given CN fuel if injection timing is changed. For example, rapeseed, which is also known as canola, or soy biodiesel with a CN similar to diesel, per Sivaramakrishnan and Ravikumar (2012), would be expected to result in a longer ignition delay than fossil diesel because of advanced injection. Palm biodiesel has a higher CN than fossil diesel, and so ignition would be expected to occur sooner than for diesel for any given injection timing. The higher CN of palm biodiesel may thus partially or fully offset the earlier timing of injection, resulting in a shorter residence time, and thus lower temperature peaks and NO_x formation, compared to biodiesel produced from other feedstocks. For fossil diesel fuel, higher CN has been linked with lower NO_x formation (Lapuerta et al., 2008). Independent of other factors, higher CN for diesel fuel should have an effect similar to delayed injection in reducing precombustion residence time and thus fuel-air mixing, producing more spread out heat release, softer temperature gradients, and lower NO_x formation.

- **High saturation level.** Some other theoretical mechanisms for increased NO_x formation with biodiesel, including higher adiabatic flame temperature and prompt NO_x formation, are thought to be a result of the high level of unsaturated fatty acids in some feedstocks (e.g., soy). These effects potentially could be mitigated or erased with the relatively high saturation level of palm oil when used as a feedstock for biodiesel.

Regardless of the specific mechanism involved, saturation level of biodiesel feedstocks appears to be tied to NO_x. Several studies find higher NO_x with lower saturation level and shorter fatty acid chain length when testing multiple biodiesel feedstocks (Graboski, McCormick, Alleman, & Herring, 2003; McCormick, Graboski, Alleman, & Herring, 2001; Lapuerta et al., 2008; Pala-En, Sattler, Dennis, Chen, & Muncrief, 2013). Saturation level may be directly related to some potential mechanisms of NO_x effects previously discussed, such as adiabatic flame temperature and prompt NO_x, and also is correlated with CN. Iodine value can serve as an indicator for saturation, and several studies have found a relationship between iodine number and NO_x (Hoekman & Robbins, 2012). Palm oil is more saturated than soy and rapeseed oils; however, we find a greater increase in NO_x emissions with palm biodiesel compared to diesel than with soy biodiesel or rapeseed biodiesel compared to diesel, so other factors must be determining the relationship between feedstock and NO_x effect.

Other factors such as the quality of the base diesel fuel may affect the relationship between biodiesel and NO_x. In its 2002 review, EPA found greater NO_x increases when biodiesel was blended into "clean" diesel fuels with lower aromatics, higher cetane number, lower density, and lower distillation temperatures compared to "average" fuels. In our analysis, we find a particularly strong influence of the base fuel sulfur content on the biodiesel NO_x effect: biodiesel results in the greatest increase in NO_x when blended in low-sulfur fuels (<50 ppm S), with a reduced NO_x increase for biodiesel blended in moderately high-sulfur fuels (50–500 ppm S) and a NO_x reduction when biodiesel is blended in very high-sulfur fuels (>500 ppm S) (Figure 3). This figure shows data only from studies on heavy-duty vehicles or

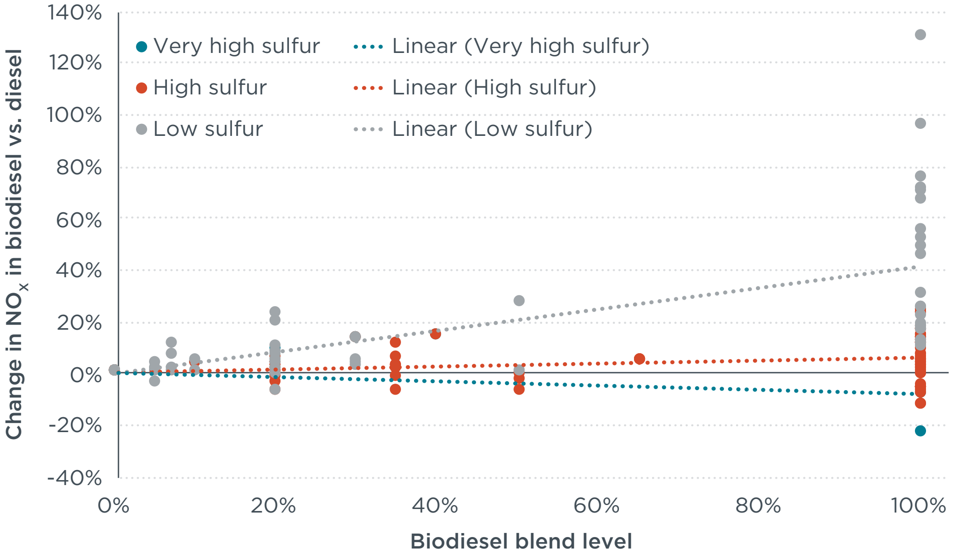

Figure 3. Effect of base fuel sulfur content on the biodiesel NO_x effect in heavy-duty vehicles and engines.

engines, in contrast to the data shown in Figure 1 and Figure 2, which was for light-duty vehicles and engines only, because almost all studies included in our light-duty dataset blended biodiesel in very low-sulfur diesel. We similarly find that with palm biodiesel specifically, biodiesel is associated with greater NO_x emissions when compared to low-sulfur diesel, but there is no relationship between biodiesel blend level and NO_x emissions when compared to high-sulfur diesel (Figure 4). Although studies using lower sulfur diesel also tend to use emission control technologies—selective catalytic reduction (SCR), for example—compared to studies using higher-sulfur diesel, this did not appear to be a factor in our dataset; in five studies that specifically tested the effect of emission control devices on the biodiesel NO_x effect, there was no significant or consistent change in the biodiesel NO_x relationship (Sharp, 1996; Sharp, Howell, & Jobe, 2000; Czerwinski, 2013; Mizushima & Takada, 2014; Peterson, Taberski, Thompson, & Chase, 2000). Diesel sulfur content could be correlated with the other factors EPA used to identify "clean" fuel, listed above, and could be indicative of other fuel quality characteristics that affect NO_x and other pollutants. In any case, it is not mechanistically clear why base fuel sulfur content should affect the relationship between biodiesel and NO_x.

There may be reason to believe that vehicle operation can change the biodiesel NO_x effect, although few studies have specifically investigated the effect of vehicle load or test cycle on the biodiesel NO_x effect. In general, NO_x increases with both load and engine speed. Here, we discuss whether these relationships change with biodiesel blends compared to fossil diesel. Both Fattah et al. (2014) and Acevedo and Mantilla (2011) found that the change in NO_x with biodiesel versus diesel depends on engine speed. Fattah et al. (2014) tested 20% and 100% palm biodiesel and measured increased NO_x emissions compared to diesel with both blend levels. The difference in NO_x emissions between biodiesel and diesel increased with engine speeds ranging from 1000 to 4000 rpm (Figure 5). Like other studies, Fattah et al. (2014) measured a decrease in CO and HC with biodiesel compared to diesel. Acevedo and Mantilla (2011) also measured the greatest biodiesel NO_x effect at the highest engine speed (Figure 6). Kinoshita et al. (2003) tested both palm and rapeseed biodiesel and found that palm biodiesel had lower NO_x than gas oil, which is similar to diesel. Rapeseed biodiesel had lower or higher NO_x compared to gas oil depending on the type of engine tested. In Kinoshita et al. (2003), the NO_x benefit of palm biodiesel declined with increasing load; palm biodiesel performed worse in terms of NO_x emissions at high loads compared to low loads. However, Vedaraman et al. (2011) also tested palm biodiesel at varying loads and

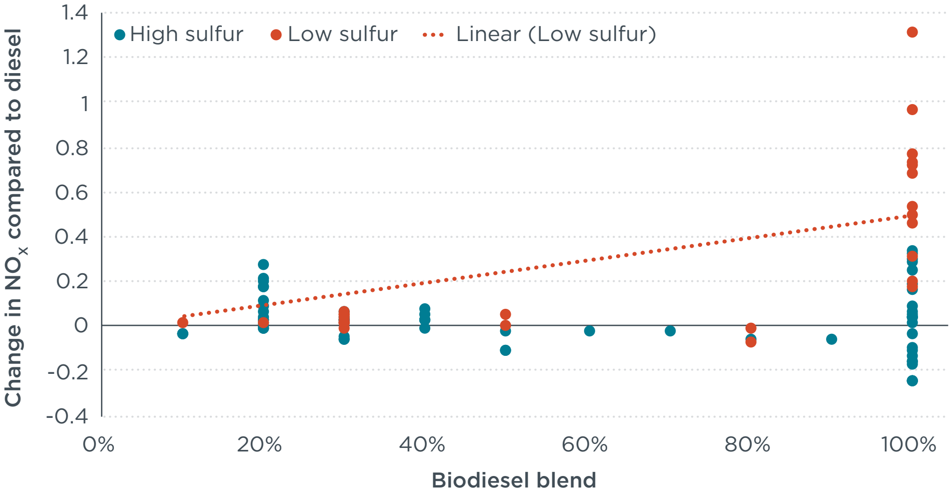

Figure 4. Effect of base fuel sulfur content on the biodiesel NO_x effect in light- and heavy-duty vehicles and engines with palm biodiesel.

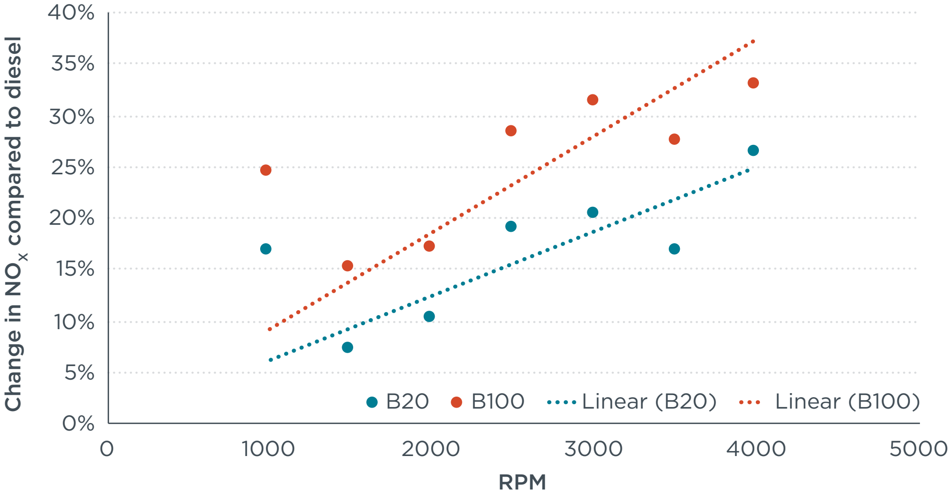

Figure 5. Effect of engine speed on the biodiesel NO_x effect in Fattah et al. (2014).

did not measure a change in the NO_x effect with load. Similarly, load did not have a clear effect on the biodiesel NO_x effect in Acevedo and Mantilla (2011). Thus, although the biodiesel NO_x effect appears to worsen with increasing engine speed, it does not appear to depend on load.

These findings may be relevant for two reasons. NO_x emissions in general increase with both load and engine speed, and this problem could be exacerbated if biodiesel NO_x emissions worsen in particular at high engine speed. Secondly, real-world drivers tend to experience higher engine speeds overall than in commonly used test cycles such as the New European Driving Cycle (NEDC). Karavalakis, Alvanou, Stournas, and Bakeas (2009) measured the effect of biodiesel produced from a blend of palm and coconut oils on NO_x emissions under two different driving cycles: the NEDC and the Athens Driving Cycle, which much more closely approximates real-world driving conditions (Tzirakis, Pitsas, Zannikos, & Stournas, 2006). In most cases in Karavalakis et al. (2009), NO_x emissions were higher with biodiesel blends compared to diesel, and this effect was greater when using the Athens Driving Cycle compared to the NEDC. This result suggests that biodiesel NO_x effects could be worse under real-world driving conditions compared to laboratory tests, but there is not enough evidence available on the effect of driving cycle to draw conclusions.

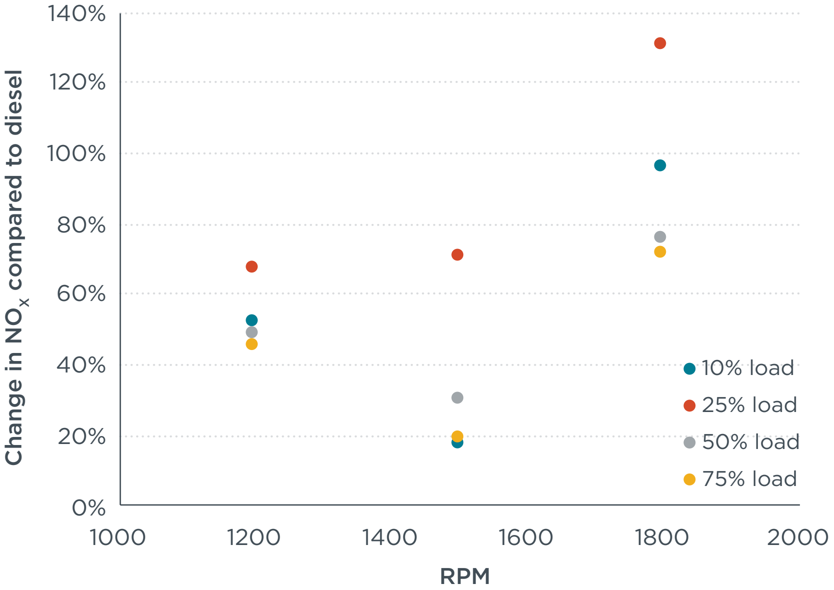

Figure 6. Effect of engine speed on the biodiesel NO_x effect in Acevedo and Mantilla (2011).

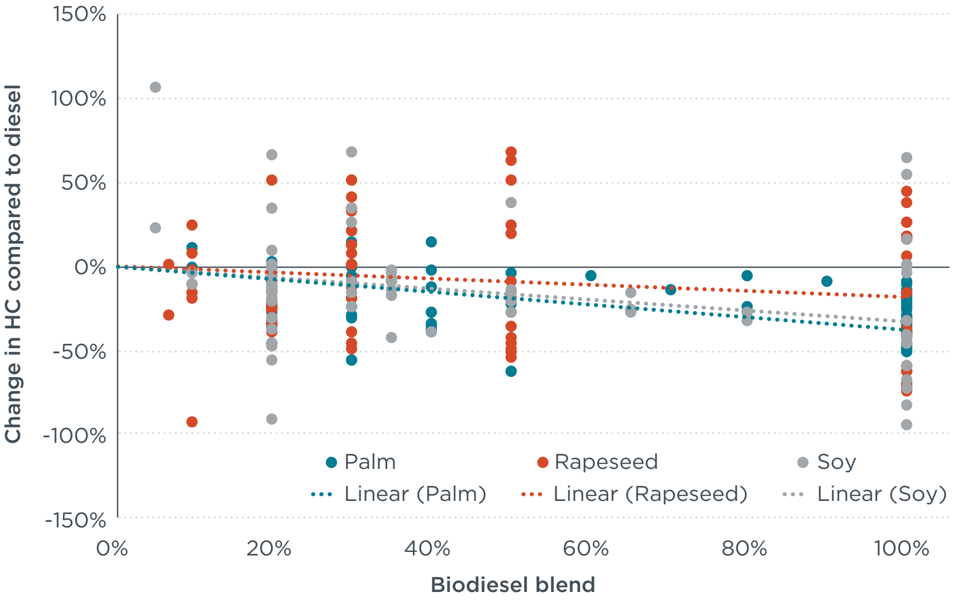

Figure 7. Effect of palm, soy, and rapeseed biodiesel on HC emissions at varying blend levels compared to diesel in light-duty and heavy-duty vehicles and engines.

PM, CO, AND HC

Biodiesel also has been known to affect other types of pollutant emissions (EPA, 2002; Lapuerta et al., 2008; Hoekman & Robbins, 2012). In its review, EPA (2002) found that 100% biodiesel (B100) reduces HC emissions by around 60%–70% compared to diesel. In our analysis, including data from both light- and heavy-duty vehicles, we find a more modest but still statistically significant reduction in HC of around 20%–40% for biodiesel produced from palm, soy, and rapeseed oils when outliers are excluded (Figure 7), although as for NO_x emissions, there is considerable variability among studies. A likely explanation for the reduction in HC emissions with biodiesel is that the higher oxygen content of biodiesel compared to diesel enables more complete combustion of the fuel (Lapuerta et al., 2008).

We also find that CO decreases with palm biodiesel compared to diesel

(Figure 8). However, contrary to previous findings, we find no statistically significant response of CO to soy biodiesel blends and detect a significant increase in CO with rapeseed biodiesel compared to diesel. In its 2002 review, EPA found that biodiesel reduces CO emissions by around 40%–50% compared to diesel. The dataset used in that study included results mainly from soy and rapeseed biodiesel. We note that almost all of the observations finding an increase in CO emissions with biodiesel compared to diesel in our dataset are included in papers published after EPA's review. Our analysis thus suggests that, taking recent data into account, it is not clear that soy and rapeseed biodiesel decrease CO, and in some cases may actually increase CO. Palm biodiesel, on the other hand, almost uniformly results in lower CO compared to diesel, although this overall effect is rather modest, on the order of a 20%–30% reduction.

PM has also been reported to decrease with biodiesel blends in previous reviews. In a meta-analysis of results from several studies using mostly soy and rapeseed biodiesel, EPA (2002) had also reported a 40%–50% decrease in PM emissions with biodiesel compared to diesel. Biodiesel has been thought to reduce PM in part due to its low sulfur content and also because its higher oxygen content enables more complete combustion of the fuel (Lapuerta et al., 2008). However, we find a statistically significant increase in PM emissions with palm biodiesel and, to a lesser extent, rapeseed biodiesel. We find no relationship between biodiesel blend and PM with soy biodiesel (Figure 9). Again, almost all of the positive responses we saw of PM to biodiesel were reported in studies more recent than EPA's 2002 review. Most of these results are also more recent than the Lapuerta et al. 2008 review, which supported EPA's conclusion that biodiesel reduces PM. Although there is very high variability in results on PM emissions, the increase in PM with rapeseed and palm biodiesel appears to be rather high, with B100 associated with around a 50% increase in PM and with around a 500% increase with palm biodiesel. These results for palm biodiesel are heavily influenced by the data presented in Acevedo and Mantilla (2011), who report far higher PM emissions with palm biodiesel compared to diesel. The authors believe that this is because of incomplete combustion

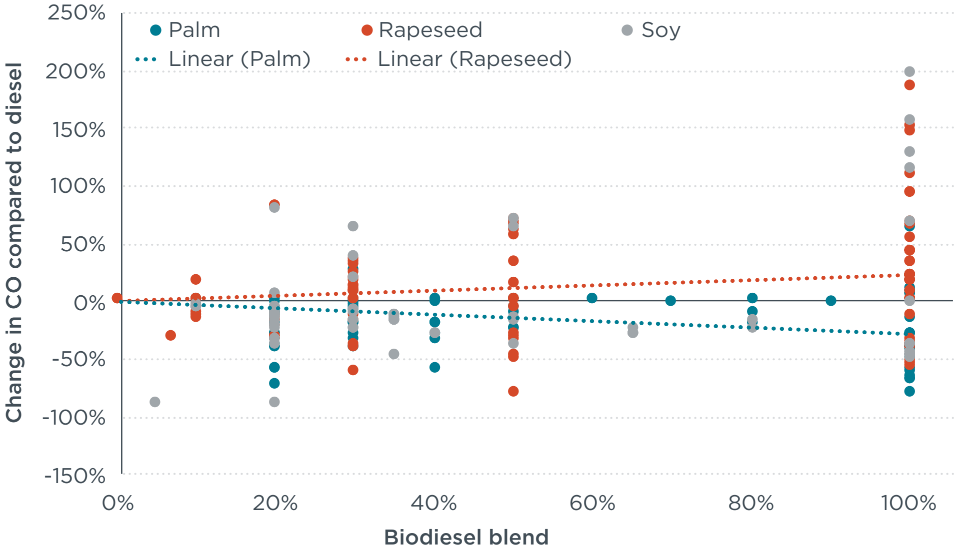

Figure 8. Effect of palm, soy, and rapeseed biodiesel on CO emissions at varying blend levels compared to diesel in light-duty and heavy-duty vehicles and engines

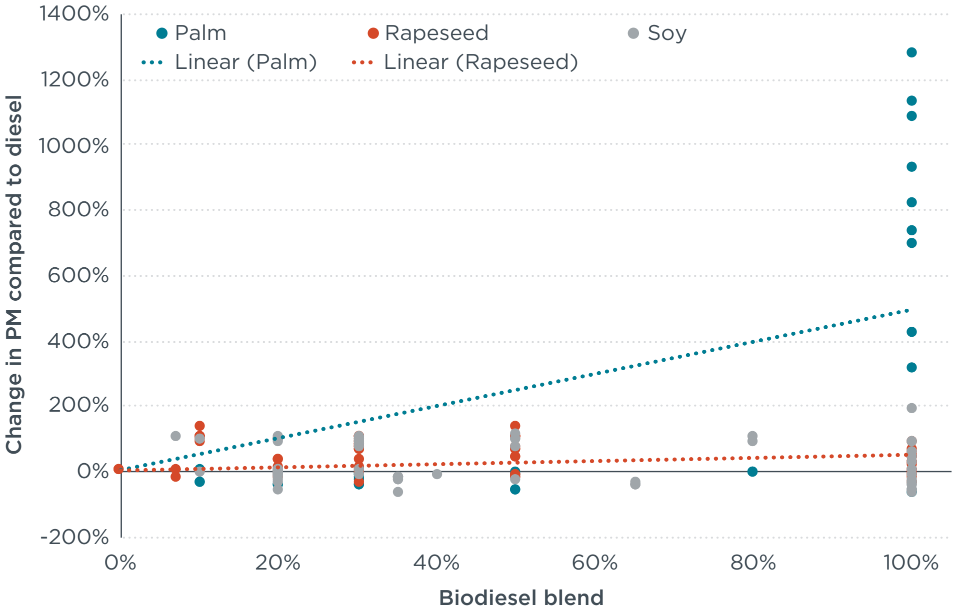

Figure 9. Effect of palm, soy, and rapeseed biodiesel on PM emissions at varying blend levels compared to diesel in light-duty and heavy-duty vehicles and engines.

with palm biodiesel, and speculate that other studies may have found PM reductions with palm biodiesel because they may have used filters that only capture larger particles (>2.5 or 10 µm). Palm biodiesel has been found to produce high amounts of particles in a diesel generator in the range 0.056–0.31 µm, but produced lower PM than diesel if only particles larger than 0.18 µm are considered (Lin, Lee, Wu, & Wang, 2006). If early studies used filters that only captured larger particles, this could explain why EPA (2002) and Lapuerta et al. (2008) found that biodiesel reduces PM overall.

In fact, when we narrow our analysis for rapeseed and soy biodiesel to include only studies published after EPA's 2002 review, we observe very different trends from those reported in EPA (2002). For both rapeseed and soy biodiesel, we find no significant change in HC with biodiesel compared to diesel, and significant positive responses of CO and PM, as well as NO_x, with biodiesel compared to diesel. The increases in CO and PM observed across these more recent studies is non-negligible, with emissions on the order of 50% greater for B100 compared to diesel.

We hypothesize that the change in results for soy and rapeseed biodiesel from earlier studies to later studies stems from improvements in fuel quality and vehicle technology over time. For example, biodiesel provides a PM benefit compared to low-quality diesel with high sulfur content, because fuel sulfur content is strongly linked to PM generation. Because biodiesel has a very low sulfur content, biodiesel would be expected to produce less PM than diesel, especially high-sulfur diesel. In fact, pooling data across all feedstocks, we find a statistically significant negative relationship between biodiesel blend and PM compared to diesel when biodiesel is compared to high-sulfur fuels (>50ppm), and a statistically significant positive relationship when biodiesel is compared to low-sulfur fuels (<50ppm) (Figure 10). This finding supports the idea that the PM reduction benefit of biodiesel disappears and may even be reversed with lower sulfur, cleaner fuel.

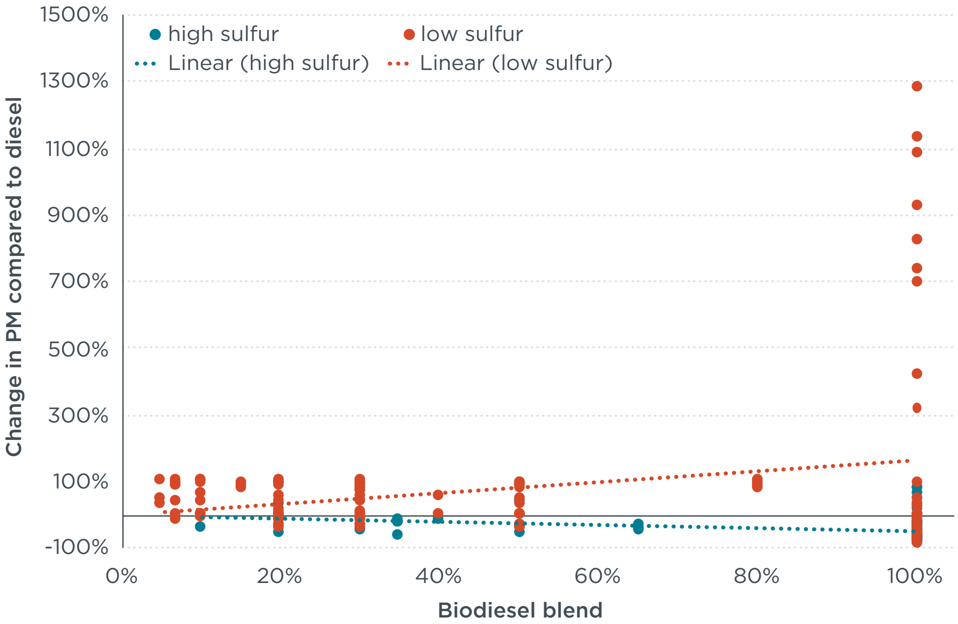

Figure 10. Effect of biodiesel on PM emissions at varying blend levels when compared to high- or low-sulfur diesel in light- and heavy-duty vehicles and engines.

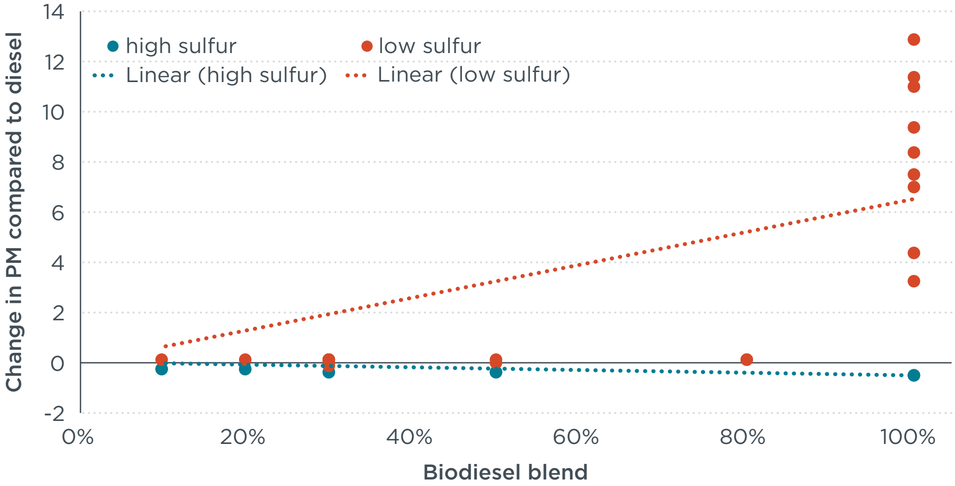

Figure 11. Effect of palm biodiesel on PM emissions at varying blend levels when compared to high- or low-sulfur diesel in light-duty vehicles and engines.

We observe a similar effect when examining only results using palm biodiesel. A PM reduction is observed when palm biodiesel is compared to high-sulfur diesel, but a PM increase occurs when comparing palm biodiesel to low-sulfur diesel (Figure 11). Some studies using palm biodiesel did not specify the base diesel sulfur content, so for Figure 11 we assumed that the diesel used in studies conducted in Malaysia and India had sulfur content >50ppm, because at the time the research was likely done, the fuel standards in these countries specified a maximum of 350 or 500 ppm sulfur in diesel (Platts, 2017; India: Fuels: Diesel and gasoline, n.d.).

IMPLICATIONS OF EMISSION TESTING RESULTS FOR INDONESIA

When considering all available evidence, palm biodiesel has mixed effects on harmful pollutant emissions from vehicles, increasing NO_x and PM but decreasing CO and HC emissions compared to diesel. At present, palm biodiesel may offer pollution benefits in Indonesia specifically due to the high sulfur content of diesel fuel in that country. However, there are several reasons to believe that the harmful effect of palm biodiesel on emissions may be understated in the studies we analyzed and may worsen compared to fossil diesel as Indonesia moves toward cleaner fuels and vehicles.

There is some reason to believe that the emissions benefits conferred by palm biodiesel may be lower under real-world conditions compared to the studies reviewed here, which for the most part conducted measurements in the laboratory. The biodiesel NO_x effect in particular appears to be worse when vehicles are operating at high engine speeds or in test cycles that better represent the real world. Not enough evidence is available at present to draw conclusions on this hypothesis, but it raises an important question. If the biodiesel NO_x effect is indeed systematically worse in the real world compared to laboratory tests, then consuming palm biodiesel may exacerbate NO_x emissions in Indonesia even when compared to high-sulfur diesel. Furthermore, there is reason to expect the effect of palm biodiesel on exhaust emissions to worsen in the future as Indonesia moves toward cleaner fuel and vehicles. Indonesia has established a schedule to reduce fuel sulfur over time, with a goal to limit sulfur in diesel to 50 ppm starting in 2025. (Indonesia: Fuels: Diesel and gasoline, n.d.) Our analysis finds that the effect of palm biodiesel and biodiesel more generally on NO_x and PM emissions worsens considerably with lower sulfur fuel, and we would expect emissions of these pollutants to worsen with palm biodiesel blends compared to fossil diesel as Indonesia moves toward cleaner fuel. The NO_x increase with biodiesel blends is likely to be more pronounced in vehicles with older technology compared to vehicles with newer technology, because emission control systems may help mitigate higher NO_x emissions with biodiesel; this may thus remain a significant problem for a number of years as Indonesia's fleet gradually turns over to Euro 4/IV-compliant vehicles.

However, there is also reason to believe that the relative emissions performance of biodiesel compared to fossil diesel also may worsen as Indonesia's fleet transitions to more modern vehicle technology. Indonesia is scheduled to move to Euro 4 standards for both light-duty and heavy-duty diesel vehicles starting in 2021. (Indonesia: Light-Duty: Emissions, n.d.) Some studies find that higher saturation of biodiesel feedstocks is associated with a reduction in NO_x, so the relatively high saturation level of palm biodiesel may blunt its effect on NO_x emissions. McCormick et al. (2001) found that the benefit of feedstock saturation on NO_x emissions was less significant when using common rail fuel injectors—which would be necessary to comply with the Euro 4 vehicle emission standard—than with older vehicle technology. As Indonesia moves toward more advanced vehicle technology, the effect of palm biodiesel on NO_x compared to fossil diesel may worsen.

It is important to note that conventional pollutant emissions in general will substantially decline as Indonesia moves to the Euro 4 standard and lower sulfur fuel. It is very likely that Indonesia will benefit from a reduction in transportation pollution regardless of biodiesel. Increased use of palm biodiesel, though, could potentially reduce those air quality gains.

Compatibility of biodiesel with vehicle components

In addition to affecting vehicle fuel consumption and exhaust emissions, biodiesel can directly affect components of the vehicle that come in contact with the fuel. These components include: the fuel tank, fuel feed pump, fuel lines, fuel filter, fuel pump, fuel injector, piston, and exhaust system. Many of these components are made of metal and elastomers. In this section, we review how biodiesel can affect vehicle components through corrosion, changes in mechanical wear, elastomer degradation, and deposits. It is important to note that in all the studies reviewed here, the biodiesel tested met commonly used fuel quality specifications, such as ASTM D6751 and EN 14214, and that impacts on materials could be worse if poor-quality biodiesel is used.

FUEL PROPERTIES AND STABILITY

Biodiesel differs from fossil diesel in several ways that affect its impact on vehicle components: It is more able to absorb water from the air; has higher viscosity, electrical conductivity, polarity and solvency; has lower stability; and is more sensitive to light, temperature, and metal ions compared to fossil diesel (Haseeb, Fazal, et al., 2011; Fazal, Haseeb, & Masjuki, 2011, 2014; Jakeria, Fasal, & Haseeb, 2014).

Biodiesel tends to degrade through oxidation over a period of days to months. When biodiesel is exposed to oxygen, oxygen attaches to biodiesel molecules at sites adjacent to double bonds, leading to oxidation products including peroxides, aldehydes, alcohols, carboxylic acids, and sediments (Jakeria et al., 2014). These oxidation products can lead to corrosion and deposit formation. Because unsaturated vegetable oils have more double bonds compared to saturated vegetable oils, biodiesel produced from feedstocks such as soy, rapeseed, and sunflower oils are thought to be less stable, whereas palm biodiesel is thought to be relatively more stable because it is produced from a more saturated oil. However, in laboratory tests palm biodiesel has been found to degrade at a similar rate as biodiesel produced from other feedstocks, and a one-month storage time limit has been suggested for palm biodiesel (Jakeria et al., 2014).

CORROSION

Metals always have a tendency to pass into solution, but this effect can be exacerbated by fuel type. Corrosion is typically tested by immersing materials in fuel for a period of time and measuring weight change, the degree of tarnish, or by visual inspection. Biodiesel is almost universally found to be more corrosive than fossil diesel. A significantly greater degree of corrosion has been tested and found in copper, copper alloys (brass and bronze), lead, tin, zinc, aluminum, and cast iron when soaked in biodiesel compared to fossil diesel. Copper and its alloys have generally been found to be the least resistant to corrosion; cast iron is the most resistant of these metals in biodiesel. Stainless steel and carbon steel have been found to experience little to no corrosion in biodiesel (Haseeb, Fazal, et al., 2011; Fazal, Haseeb, & Masjuki, 2011, 2014; Singh et al., 2012). Although many studies test the effects of 20% or 100% biodiesel, increased corrosion has been detected with as low a biodiesel concentration as 2%, compared to diesel (Tsuchiya, Shiotani, Goto, Sugiyama, & Maeda, 2006).

Palm biodiesel has been found to lead to corrosion in copper and aluminum at roughly double the rate of fossil diesel, while also increasing corrosion in brass and cast iron, but not stainless steel, compared to fossil diesel (Fazal et al., 2010, 2012).

Biodiesel is thought to be more corrosive than fossil diesel because of several of its properties: It is more prone to absorb water, has higher polarity and solvency, and contains more impurities than fossil diesel. Water itself is corrosive, but it also can allow the growth of micro-organisms, which can further contribute to corrosion (Haseeb, Fazal, et al., 2011; Fazal et al., 2014; Jakeria et al., 2014). The higher solvency of biodiesel allows it to dissolve paints and coatings on vehicle components, which can bring the metal underneath into direct contact with the fuel, accelerating corrosion (Fazal et al., 2011). Some of the impurities common in biodiesel also can react with metals, including unreacted methanol, catalytic sodium or potassium, and free glycerol (Haseeb, Fazal, et al., 2011). Furthermore, the presence of water can hydrolyze biodiesel, resulting in the presence of free fatty acids, which cause corrosion (Singh et al., 2012).

Corrosion also accelerates fuel degradation, creating a positive feedback loop. For example, copper has been found to enhance oxidation of biodiesel, leading to copper ions in the fuel and an increase in the total acid number, whereas these effects were not observed with fossil diesel. The presence of metal also can accelerate water contamination, as water condenses on metal components and thus enters the fuel (Fazal et al., 2010).

The possibility of adding corrosion inhibitors to biodiesel has been explored, although further research is needed in this area (Haseeb, Fazal, et al., 2011; Fazal et al., 2011; Singh et al., 2012). It does not appear that any particular corrosion inhibitor has been widely recommended for use.

WEAR

Wear is the removal of metal from surfaces due to mechanical rubbing. Although wear is typically thought of as distinct from corrosion, which is caused by chemical reactions, in reality wear and corrosion often occur simultaneously. Wear typically is measured using laboratory tests that simulate mechanical rubbing (e.g., the four-ball wear test) and by testing metal concentrations in lube oil, which is thought to indicate the degree of metal removal through wear.

Biodiesel tends to provide better lubricity than fossil diesel, which in turn should reduce wear. The lubricity benefit of biodiesel is thought to occur because the fatty acids in biodiesel form a soap film against metal surfaces (Masjuki & Maleque, 1996). Several studies have found that wear decreases with increasing biodiesel blend when using laboratory tests such as the four-ball wear test (Haseeb, Fazal, et al., 2011; Fazal et al., 2011, 2014). Wear has been found to be greater when biodiesel is oxidized (Haseeb, Fazal, et al., 2011; Fazal et al., 2011). This finding highlights the interaction that can occur between wear and corrosion, as oxidation can cause corrosion, which accelerates metal loss; in addition, corrosion can increase oxidation of biodiesel. Results for metal concentrations in lube oil, which likely reflects to some extent the combined effects of wear and corrosion, are mixed, with various studies finding lower or higher metal concentrations in biodiesel and biodiesel blends compared to fossil diesel. In agreement with the results reviewed on corrosion, concentrations of copper and copper alloys in particular tend to be higher in biodiesel compared to fossil diesel. In contrast, iron concentrations are generally lower in biodiesel compared to fossil diesel (Haseeb, Fazal, et al., 2011). These results suggest that the combined effects of wear and corrosion are complex, and that the lubricity benefits of biodiesel may offset to some extent the increased corrosion potential of biodiesel.

The degree of saturation in biodiesel has been negatively correlated with lubricity (Geller & Goodrum, 2004), so in theory the lubricity benefits of palm biodiesel may be lower than for rapeseed or soy biodiesel, although this effect has not been clearly demonstrated for palm biodiesel specifically. To the best of our knowledge, wear has not been directly compared in palm biodiesel versus biodiesel produced from other feedstocks in the same study. Masjuki and Maleque (1996) measured reduced wear with 5% palm biodiesel compared to fossil diesel in a mechanical sliding test on cast iron, but higher wear in 7%–10% palm biodiesel compared to fossil diesel. The authors hypothesized that higher oxidation in the higher palm biodiesel blends may have increased corrosion, which in turn increased wear. Similarly, Terry (2005) measured significantly higher wear using B20 produced from soy and rapeseed compared to fossil diesel, but no effect comparing B5 to fossil diesel. Palm biodiesel does not appear to affect metal concentrations in lube oil differently than biodiesel produced from other feedstocks (Haseeb, Fazal, et al., 2011).

In a review, Fazal et al., (2011) found that studies reporting lubricity benefits of biodiesel are generally very short term, such as one hour, but that lubricity benefits appear to disappear in long-term field trials, which are discussed below. One potential explanation is that biodiesel leads to more deposits than fossil diesel, which would reduce lubricity over time (Fazal et al., 2014).

ELASTOMER DEGRADATION

Elastomers are polymers with viscosity and elasticity that often are used to manufacture seals and hoses found in vehicles. Common elastomers used in vehicle components include nitrile rubber, natural rubber, neoprene, Viton®, silicone, and other materials. Biodiesel can affect elastomers by dissolving them; some elastomers also swell as a result of absorbing liquid (Singh et al., 2012). The compatibility of elastomers with biodiesel usually is tested by soaking these materials in biodiesel for a period of time and measuring weight change, tensile strength, elongation, and hardness.

Studies have found various elastomers to decrease, increase, or maintain weight when exposed to biodiesel. In addition, dimensional changes and a reduction in tensile strength have been observed in some types of elastomers. One study measured significantly lower tensile strength, elongation, and hardness for nitrile rubber and polychloroprene when soaked in palm biodiesel compared to fossil diesel, but did not find an effect of biodiesel on fluoro-viton (Haseeb, Masjuki, Ann, & Fazal, 2010). In another study using palm biodiesel, Haseeb, Jun, Fazal, and Masjuki (2011) found swelling in nitrile rubber and polychloroprene, weight loss in polytetrafluoroethylene, and no change in ethylene propylene diene monomer and silicone rubber. As with corrosion, oxidation of biodiesel appears to worsen elastomer degradation: Greater dimensional changes have been observed with oxidized biodiesel compared to biodiesel that meets specifications (Terry, 2005). It has generally been concluded that nitrile, natural rubber, chloroprene, neoprene, polypropylene, polyethylene, and some other materials are not compatible with biodiesel, although fluorinated elastomers, Viton, and Teflon are not significantly affected by biodiesel (Haseeb, Fazal, et al., 2011; Singh et al., 2012; Mofijur et al., 2013). It is thought that biodiesel leads to elastomer degradation because of its increased polarity and solvency compared to fossil diesel (Fazal et al., 2011).

Elastomer swelling has been shown to be slowed by the addition of peroxide (van Duin et al., 2010). However, peroxide contributes to corrosion of metals, as previously discussed.

DEPOSIT FORMATION

Biodiesel has been found to result in higher rates of deposit formation on vehicle components compared to fossil diesel. Several studies have reported fuel filter plugging with biodiesel. In addition, trucking associations and state transportation agencies in the United States have reported problems with fuel filter plugging when using biodiesel or biodiesel blends (often 20%) in surveys. Other problems associated with deposit formation include fuel injector plugging, piston ring sticking, and injector cocking (Fazal et al., 2011; Mofijur et al., 2013). Potential mechanisms for increased deposit formation with biodiesel include the higher viscosity of biodiesel (Knothe,

2005) and dissolved elastomers in the fuel (Fazal et al., 2011).

ENGINE DURABILITY AND FIELD TESTS

A number of studies have tested the effects of biodiesel on entire engine systems (rig tests) or vehicles (road tests), sometimes over several years. The National Biodiesel Board commissioned two 1,000-hour laboratory studies on the effects of B20 on heavy-duty engines. In one 1995 study by Ortech Corporation, cited in Fazal et al. (2011), the fuel lines, fuel filters, and fuel transfer pump had to be replaced after 700 hours due to deposits. At the end of the experiment, the researchers found substantial deposits on many components, deteriorated seals, broken rings, and severe degradation of the fuel injector. In the other study from 1995 by Fosseen, again as cited in Fazal et al. (2011), the test was terminated after 650 hours due to failure of the engine pump caused by a buildup of residue in the pump. The fuel filter also was plugged in this test.

Long-term field trials have had varied results. Chase et al. (2000) found no significant changes except higher NO_x and PM emissions when performing a 322,000 km long-haul test using B50 produced from used cooking oil in a heavy-duty truck. On the other hand, in a long-term 4-year study, Fraer et al. (2005) found a higher frequency of fuel filter plugging and injector nozzle replacement in vans and tractors operating on B20 compared to fossil diesel. In a 2-year study, Proc, Barnitt, Hayes, Ratcliff, and McCormick (2006) experienced overall greater maintenance costs with buses operating on B20 ($0.07/mile) compared to fossil diesel ($0.05/mile) due to required replacement of components including fuel injectors and cylinder heads in the biodiesel-run vehicles toward the end of the experiment.

Rig tests and road tests have been performed in Indonesia, presumably all using palm biodiesel. Across these studies, some material compatibility issues were found. In a road test, fuel filter clogging occurred in an “older” vehicle fueled with B20 after 7,500 km. The only other problem detected in this 40,000 km road test was swelling of a rubber ring on the fuel filter (Gaikindo, 2015). However, in a rig test, no deposits were detected on the sliding injector, the sliding pump supply, or the inside of the common rail (Ministry of Energy and Mineral Resources of the Republic of Indonesia [KESDM], 2015). In another test, zinc from the fuel tank eluted with use of B20, leading to injector deposits and reduced jet volume (Komatsu, 2015). Komatsu noted zinc-coated fuels tanks may need to be replaced to be compatible with B20, and that there are more than 30,000 such tanks in Indonesian vehicles. Komatsu (2015) also observed degradation of several elastomers with use of B20, including nitrile rubber and chlorosulfonated polyethylene rubber.

IMPLICATIONS OF MATERIAL COMPATIBILITY RESULTS FOR INDONESIA

Biodiesel affects vehicle components differently than fossil diesel in several ways. Biodiesel leads to increased corrosion and deposit formation and degrades some types of elastomers compared to fossil diesel. Biodiesel generally has better lubricity than fossil diesel, but the beneficial effect this property has on wear in the short term appears to be offset by the effects of increased corrosion and deposit formation in the longer term. Studies on whole engine/fuel systems and vehicles have found overall negative effects of B20 on vehicle components. It is not clear that palm biodiesel will differentially affect vehicles compared to biodiesel produced from other feedstocks. Due to its relatively high level of saturation, there are theoretical reasons to expect palm biodiesel to affect corrosion and wear less than biodiesel produced from other feedstocks, when compared to fossil diesel. However, measurements of corrosion and wear with palm biodiesel have generally produced similar results as for other types of biodiesel. Studies using B20 in Indonesia specifically have observed several of the same problems reported from studies in other regions. There are not sufficient data available to draw firm conclusions on the maximum blend of biodiesel that can be tolerated by conventional vehicle components. Negative effects of biodiesel on corrosion have been observed with biodiesel blends as low as 2%. Some studies have found greater damage with biodiesel blends higher than 5% compared to B5.

Based on the available evidence, it thus appears likely that meeting Indonesia’s goals to blend 20%–30% palm biodiesel in its diesel supply will result in increased vehicle maintenance costs, with more frequent replacement needed of various components such as fuel filters, fuel injector nozzles, and seals, as well as potentially more costly components central to diesel engines.

Appendix

The studies used in this analysis are listed below, grouped by general vehicle classification.

STUDIES ON LIGHT-DUTY (PASSENGER) VEHICLES AND ENGINES

Study	FAME feedstock	Pollutants measured
Jansen et al. (2014)	Rapeseed	HC, CO, NO_x, PM
Serrano et al. (2015)	84% soybean and 16% palm oil	NO_x
Bielaczyc et al. (2009)	Rapeseed	HC, CO, NO_x, PM
Kinoshita et al. (2003)	Palm oil and rapeseed	HC, CO, NO_x
Karavalakis et al. (2009)	Palm oil and coconut oil blend	HC, CO, NO_x, PM
Karavalakis et al. (2011)	Palm oil, soybean, rapeseed	HC, CO, NO_x, PM
Bakeas, Karavalakis, & Stournas (2011)	Oxidized used cooking oil	HC, CO, NO_x, PM
Martini et al. (2007)	Rapeseed, a blend of soybean and sunflower (50/50), palm oil	HC, CO, NO_x, PM
Krahl et al. (2005)	Rapeseed/ soybean (75/25), rapeseed, rapeseed/ palm oil (45/55), rapeseed, soybean, palm oil (60/12.5/27.5)	HC, CO, NO_x, PM
Bakeas, Karavalakis, Fontaras, & Stournas (2011)	Palm oil, soybean and oxidized UCO	HC, CO, NO_x, PM
Macor, Avella, & Faedo (2011)	Rapeseed	HC, CO, NO_x, PM
Fontaras et al. (2009)	Soybean	HC, CO, NO_x, PM
Tatur, Nanjundaswamy, Tomazic, & Thornton (2008)	Soybean	NO_x
Prokopowicz, Zaciera, Sobczak, Bielaczyc, & Woodburn (2015)	Not indicated	HC, CO, NO_x, PM
Pala-En et al., 2013	Soybean, canola, waste cooking oil and animal fat	HC, CO, NO_x, PM
Wirawan et al. (2008)	Palm oil	HC, CO, NO_x, PM
Vedaraman et al. (2011)	Palm oil	HC, CO, NO_x
Fattah et al. (2014)	Palm oil	HC, CO, NO_x
Ng et al. (2011)	Palm oil	HC, CO, NO_x

STUDIES ON HEAVY-DUTY VEHICLES AND ENGINES

Study	FAME feedstock	Pollutants measured
Nikanjam, Rutherford, Byrne, Lyford-Pike, & Bartoli (2009)	Soybean	HC, CO, NO_x
Graboski et al. (2003)	Soybean, LFFAG (low free fatty acid grease), inedible tallow, methyl linolenate, methyl oleate, ethly oleate, methyl linoleate, methyl laurate, methyl soy (soyagold), oxidized methyl soy ester, ethyl linoleate ethyl linseed, 2:1 methyl stearate: methyl linseed, 1:2 methyl stearate: methyl linseed, ethyl stearate, methyl palmitate, ethyl soy ester	HC, CO, NO_x, PM
Olatunji et al. (2010)	Animal fat and soybean oil	HC, CO, NO_x, PM
Czerwinski et al. (2013)	Rapeseed	HC, NO_x, PM
McCormick et al. (2001)	Methyl-lard, methyl-soy, methyl-canola, methyl inedible-tallow, methyl edible-tallow, methyl-low free fatty acid grease, methyl-high free acid grease, methyl-laurate (C12:0), methyl-palmitate (C16:0), methyl-stearate (C18:0), methyl-oleate (C18:1), methyl-linoleate C18:2), methyl-linolenate (C18:3), methyl soy (soyagold), 1:2 M-terate: M-linseed, methyl-hydrogenated soy, ethyl-stearate (C18:0), ethyl-linoleate (C18:2), ethyl-linseed, ethyl-soy, ethyl-hydrogenated soy	NO_x, PM
Knothe, Sharp, & Ryan (2006)	Methyl soyate (commercial biodiesel), methyl oleate, methyl pamitate, methyl laurate (technical biodiesel)	HC, CO, NO_x, PM
Lopez, Jimenez, Aparicio, & Flores (2009)	Not indicated	HC, CO, NO_x, PM
Wang, Lyons, Clark, Gautam, & Norton (2000)	Soybean	HC, CO, NO_x, PM
Schumacher, Borgelt, Hires, Wetherell, & Nevils (1996)	Soybean oil	HC, CO, NO_x, PM
Marshall, Schumacher, & Howell (1995)	Transesterified soybean oil	HC, CO, NO_x, PM
Sharp et al. (2000)	Soybean oil	HC, CO, NO_x, PM
Starr (1997)	Soybean oil	HC, CO, NO_x, PM
Graboski, Ross, & McCormick (1996)	Soybean oil	HC, CO, NO_x, PM
Hansen & Jensen (1997)	Rapeseed oil	HC, CO, NO_x, PM
Clark, Atkinson, Thompson, & Nine (1999)	Soybean oil	HC, CO, NO_x, PM
Manicom, Green, & Goetz (1993)	Soybean oil	HC, CO, NO_x
Schumacher, Borgelt, & Hires (1995)	Soybean oil	HC, CO, NO_x, PM
Sharp (1996)	Rapeseed oil	HC, CO, NO_x, PM
Mizushima & Takada (2014)	Used cooking oil	NO_x, PM
Colorado Institute for Fuels and High Altitude Engine Research (1994)	Soybean oil	HC, CO, NO_x, PM
Ullman, Hare, & Baines (1983)	Once refined soybean oil heated 145 °C	HC, CO, NO_x, PM
Rantanen et al. (1993)	Rapeseed oil	HC, CO, NO_x, PM
Acevedo & Mantilla (2011)	Palm oil	HC, CO, NOx, PM
McCormick et al. (1997)	Soybean oil	HC, CO, NO_x, PM
Sharp (1994)	Not indicated	HC, CO, NO_x, PM
Peterson, Taberski, Thompson, & Chase (2000)	Rapeseed oil	HC, CO, NO_x, PM

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