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AIR QUALITY IMPACTS OF PALM BIODIESEL IN INDONESIA

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EXECUTIVE SUMMARY

Since 2008, the production and consumption of palm biodiesel has significantly expanded across Indonesia, and it is now widely used in the transportation, industrial, and power sectors. This was facilitated by rising domestic biofuel blend mandates and high demand from overseas markets. In 2019, Indonesia blended palm biodiesel into conventional (fossil) diesel fuel at a 20% rate (B20) and blend rates are expected to continue increasing. Indonesia's Ministry of Energy and Mineral Resources (MEMR) announced the implementation of B30 this year, and there is interest in increasing targets up to B100, or pure biodiesel, in the future.

Meanwhile, poor air quality is a large concern in Indonesian cities, including Jakarta. To combat this, the government has implemented vehicle emission standards for pollutants known to be detrimental to human health including nitrogen oxides (NO_x), particulate matter (PM), unburned hydrocarbons (HC), and carbon monoxide (CO); these standards set maximum limits for pollutants in vehicle exhaust. The government plans to update the current Euro 2/II standards for diesel vehicles to Euro 4/IV to be fully implemented in 2022. In this paper, we investigate how the government's goal of increasing biodiesel blending will impact vehicle emissions.

We conduct a meta-analysis based on a literature review of 132 vehicle emission studies that tested tailpipe pollutant concentrations for NO_x, PM, HC, and CO. We compare the vehicle exhaust emissions from combusting biodiesel blends with the emissions from running identical tests on diesel fuel to calculate the emissions effect, or percent change in emissions from biodiesel relative to baseline diesel fuel. Where there are sufficient data, we present results from a subset of 28 studies conducted on biodiesel produced from palm oil, the predominant feedstock in Indonesia.

We run numerous linear regressions to test the effect of biodiesel blend level on vehicle exhaust emissions for different types of feedstocks, vehicle test cycles, exhaust aftertreatment systems, diesel sulfur levels, and fuel injection systems. When considering all 132 studies, we find that combusting pure palm biodiesel (B100) in vehicles increases NO_x by 8% compared to conventional diesel, on average. This NO_x increase is proportional to the biodiesel blend level; for example, we find that B50 increases NO_x by 4%.

However, a portion of the results in the dataset are from studies conducted decades ago on outdated engines using low-quality fuel. Indonesia has already begun the transition to more modern common rail diesel engines and has anounced targets for implementation of stricter limits on sulfur in fuel. Filtering our data to assess only studies reflecting these two modern developments, we find that palm biodiesel can be expected to increase NO_x to a much greater extent than when analyzing the whole of the literature. Figure ES1 shows a compilation of test results for the NO_x increase in palm biodiesel blends compared to diesel specifically for lower sulfur fuels (≤50 parts per million sulfur content) and modern engines. The trend line shows the statistically significant increase in the biodiesel NO_x effect relative to biodiesel blend level based on a regression analysis, and the shaded cone shows standard error. Based on this, we expect NO_x emissions from modern diesel engines, including vehicles adherent to Euro 4/IV emission standards, to increase 12%, 17%, and 41% for B30, B40, and B100, respectively, in Indonesia. Still, given the large variation in the dataset, there is uncertainty as to the precise magnitude of the biodiesel NO_x effect.

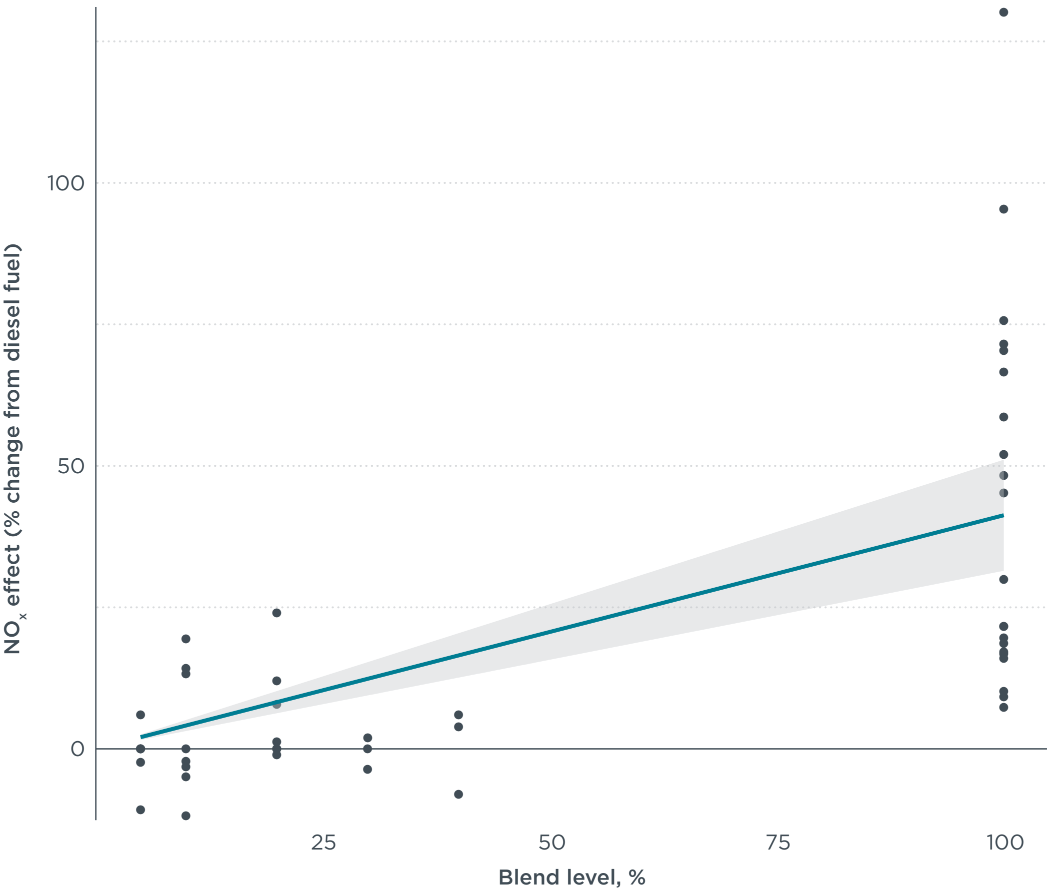

Figure ES1. Predicted palm biodiesel NO_x effect for modern Indonesian diesel engines.

The findings suggest that palm biodiesel is expected to increase NO_x emissions compared to conventional diesel in both old and new engines, and the effect is more pronounced in newer vehicles and with lower-sufur fuels. Moreover, although palm biodiesel may improve HC, CO, and PM emissions compared to conventional diesel, these benefits are reduced in more modern vehicles.

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INTRODUCTION

Indonesia is the fourth most populous country in the world and has a growing vehicle fleet (Shao, Miller, & Jin, 2020). Biodiesel makes up roughly 20% of the country's fuel market, and because of large domestic palm oil reserves, crude palm oil (CPO) is the primary feedstock used. Although diesel fuel consumption in the transportation sector declined between 2010 and 2015, this trend has since reversed (McDonald & Rahmanulloh, 2019). Biodiesel consumption has also scaled up quickly. Its use is bolstered by the national CPO fund, which subsidizes palm biodiesel using funds from a levy collected on exports of palm oil and palm products (Rifin, 2010). Blend mandates were first incorporated under Ministry of Energy and Mineral Resources (MEMR) Regulation 32, and they rose to 30% in 2020 under MEMR Regulation 12/2015.

More than half of Indonesians live in urban centers (Organisation for Economic Co-operation and Development & International Energy Agency, 2017) and air quality is of particular concern in densely packed regions with high mobility. Indonesia has one of the highest rates of deaths attributed to outdoor air pollution globally; one study found the country accounted for one-third of all deaths related to outdoor air pollution in Southeast Asia in 2017 (Health Effects Institute, 2019). Greenstone and Fan (2019) estimated that fine particulate matter (PM) reduces life expectancy by at least 1.2 years on average across the country. That study also found that vehicle emissions accounted for more than 30% of fine PM emissions and 70% of larger or coarse PM emissions in Jakarta in 2008 and 2009.

There is strong evidence that nitrogen oxides (NO_x), PM, carbon monoxide (CO), and unburned hydrocarbons (HC) have adverse health effects. NO_x contributes to smog and ozone formation that are detrimental to visibility and respiratory health (U.S. Environmental Protection Agency [EPA], 2015). Long-term ozone exposure increases the risk of death from respiratory causes (Jerrett et al., 2009) and short-term exposure can result in hospitalization from asthma and other respiratory illnesses (Burnett et al., 2001). One report on vehicle emissions and mortality estimated that NO_x emissions, a precursor for secondary PM and ozone production, were responsible for more than 100,000 premature deaths worldwide in 2015 (Anenberg et al., 2017). PM, also a byproduct of combustion, is additionally linked to premature mortality as well as respiratory and cardiovascular disease. Unburned HC compounds such as formaldehyde are classified as "probable human carcinogens" while exposure to CO, an intermediate compound formed during incomplete combustion, impacts cardiovascular health by limiting the blood's ability to carry oxygen. The groups most vulnerable to air pollutant exposure are children, the elderly, and those with preexisting conditions (U.S. Environmental Protection Agency [EPA], 2015).

To address air pollution concerns, Indonesia's Ministry of Environment and Forestry adopted Euro 2/II emission standards for heavy-duty and light-duty vehicles in 2010 and 2011, respectively, as part of MoEF Regulation No. 04/2009. Euro 4/IV equivalent standards were adopted for gasoline vehicles in 2018 under regulation number P. 20/MENLHK/SETJEN/KUM. 1/3/2017 and will apply to diesel vehicles beginning in 2022, after a one-year delay. To comply with Euro 4/IV emission standards, changes to the diesel market are expected to be twofold: greater use of advanced emission control technologies and the phase out of high-sulfur diesel. Although today 96.5% of the diesel fuel sold has a rated sulfur content of 2,500 parts per million (ppm), under Euro 4/IV, fuel sulfur content is limited to 50 ppm (Shao et al., 2020). Moving forward, the Directorate General of Oil and Gas has set a 50 ppm fuel target for 2025, reduced from a 500 ppm target beginning in 2021 (Directorate General of Oil and Gas Decision No. 3674K/24/DJM/2006 and 3675K/24/DJM/2006). Because the 2025 sulfur target is three years later then the planned implementation of Euro 4/IV vehicle standards, proper labeling of fuels at the pump and compliance and enforcement will be important during the early years of Euro 4/IV.

As Indonesia simultaneously moves toward more advanced vehicle emission standards, lower sulfur limits, and palm biodiesel expansion, it is important to understand the impact increasing palm biodiesel blending will have on vehicle emissions. This study builds on a 2018 ICCT paper that analyzed the effects of biodiesel blending on air pollutant emissions in Indonesia (Searle & Bitnere, 2018). In this update, we incorporate 84 new biodiesel performance and exhaust emission studies, 28 conducted on palm oil and nine conducted in Indonesia or Malaysia, and compile results into a meta-analysis. This study also focuses on vehicle driving conditions, emission control technologies, and physicochemical fuel properties.

BACKGROUND

Research on biodiesel exhaust emissions over the past 20 years is extensive. The U.S. EPA (2002) published a seminal study that found a 2.2% increase in NO_x emissions for 20% biodiesel blends (B20) relative to pure, conventional diesel fuel, and a reduction in HC, CO, and PM emissions across biodiesel blend levels. A decade later, EPA's findings were supported by an analysis conducted by Hoekman and Robbins (2012). Their meta-analysis followed methodology similar to that used by the EPA but restricted data to medium- and heavy-duty four-stroke engines from model year 1987 onward.

Although the literature is largely in agreement that biodiesel increases NO_x emissions, the cause for this trend is attributed to numerous theoretical mechanisms (Hoekman & Robbins, 2012). The most well understood mechanism by which biodiesel might increase NO_x emissions relates to the timing of fuel injection. Biodiesel has higher density and bulk modulus than conventional diesel and thus is compressed to a lesser extent when injected into a diesel engine.[1] This leads to faster injection and a longer period of time between when the fuel enters the combustion chamber and when ignition occurs; this is known as the ignition delay. An extended ignition delay means there is more time for biodiesel blends to mix with air prior to combustion. The greater air-fuel mixing leads to more rapid and complete combustion, which is followed by increased in-cylinder pressure and temperature (Heywood, 1988). Although NO_x formation increases exponentially with combustion temperature, the ignition delay alone does not explain the increase in NO_x with biodiesel blends. Studies have found that when the ignition delay is tightly controlled, either by mechanical changes that delay injection timing or chemical changes such as increasing the cetane number (CN) of the fuel, biodiesel blends still produce higher NO_x (Monyem & Gerpen, 2001). Additionally, the effects of biodiesel on the efficacy of emission control technologies and engine injection systems is not as well understood.

An analysis conducted by Searle and Bitnere (2018) on biodiesel emissions effects in Indonesia established the foundation for this study. Drawing upon results from 52 studies, the authors found that palm biodiesel blending increases NO_x and PM formation while it decreases HC and CO. They also suggested that the harmful air pollution impacts associated with biodiesel can be expected to be exacerbated as Indonesia moves toward cleaner vehicles and engine technology. Our study presents a more comprehensive meta-analysis based on a larger number of vehicle studies and analyzes trends among vehicle and fuel characteristics in greater depth. Our results are then applied to the Indonesian context considering its primary biodiesel feedstocks, driving conditions, and vehicle emission standards. Most studies on biodiesel emission effects focus on European and North American markets, but in comparison with those regions, the Indonesian vehicle market tends to be equipped with older vehicle technology, run on higher sulfur fuel, and use palm rather than soy or rapeseed feedstocks; the country also is situated in a warmer climate (Searle & Bitnere, 2018).

Our analysis also accounts for recent trends, including the implementation of advanced emission control technologies, common rail fuel injection systems, and low-sulfur diesel fuel (LSD). In addition to NO_x, our study analyzes the effects of biodiesel on HC, CO, and PM emissions.

1 Bulk modulus or elasticity measures a fuel's resistance to compression.

METHODOLOGY

This analysis includes datapoints from 132 biodiesel performance and exhaust emissions studies conducted between 1983 and 2018. Herein, biodiesel refers to fatty acid methyl esters (FAME) and not to any other alternative diesel substitutes such as hydrotreated vegetable oil (HVO). A detailed list of all performance studies is provided in Appendix B. Twenty-eight studies included tests on palm biodiesel; we analyzed those studies as a data subset. Where palm-specific data were insufficient or statistically insignificant, we included results from other feedstocks such as soy, rapeseed, and used cooking oil (UCO) and analyzed the complete dataset. A larger dataset provides greater statistical power to detect significant effects.

The emission studies analyzed were conducted on both light-duty and heavy-duty vehicles, as well as laboratory single-cylinder engines. Although the EPA omitted studies on single-cylinder engines in its 2002 meta-analysis, we found that results were consistent with those of on-road vehicle engines. Laboratory studies are conducted on a chassis dynamometer under a variety of transient and steady-state test cycles. Most studies include some information about the vehicle/engine emission control technologies such as exhaust gas recirculation and selective catalytic reduction (SCR).

From each study, we recorded exhaust emissions data for pure diesel and biodiesel blends along with their corresponding fuel properties, vehicle specifications, and test cycle conditions. We calculated the biodiesel emissions effect as the percent change in the concentration of a pollutant relative to that of pure conventional diesel fuel. By calculating the percent rather than total change, data are normalized to control for any confounding variables. After compiling all calculated datapoints, we performed a series of linear regressions setting biodiesel blend level as the independent variable.

As in Searle and Bitnere (2018), we fixed the y-intercept at 0 and interpreted statistically significant relationships when $p < 0.05$. Trend lines are only presented in figures when they are statistically significant. Positive trend lines indicate that biodiesel blends produce higher emissions than conventional diesel, whereas negative values indicate emissions reductions with biodiesel compared to conventional diesel. None of the 132 studies were omitted from our results, although there were numerous outliers; this could be due to faulty instrumentation, unrepresentative test cycle conditions, or human error. In cases where linear regressions were not an appropriate explanatory model, multiple regression and analysis of statistical variance (ANOVA) tests were used to detect differences between treatments.

RESULTS AND DISCUSSION

Consistent with two other meta-analyses conducted in the last two decades, we find that, on average, palm biodiesel increases NO_x formation and decreases PM, CO, and HC. This is illustrated in Figure 1. Using a linear regression on the NO_x effect with biodiesel blend level applied to our full dataset, we find that the biodiesel NO_x effect is 8% for 100% biodiesel (B100). This result would predict a 0.8% increase in NO_x with a 10% biodiesel blend compared to conventional diesel.

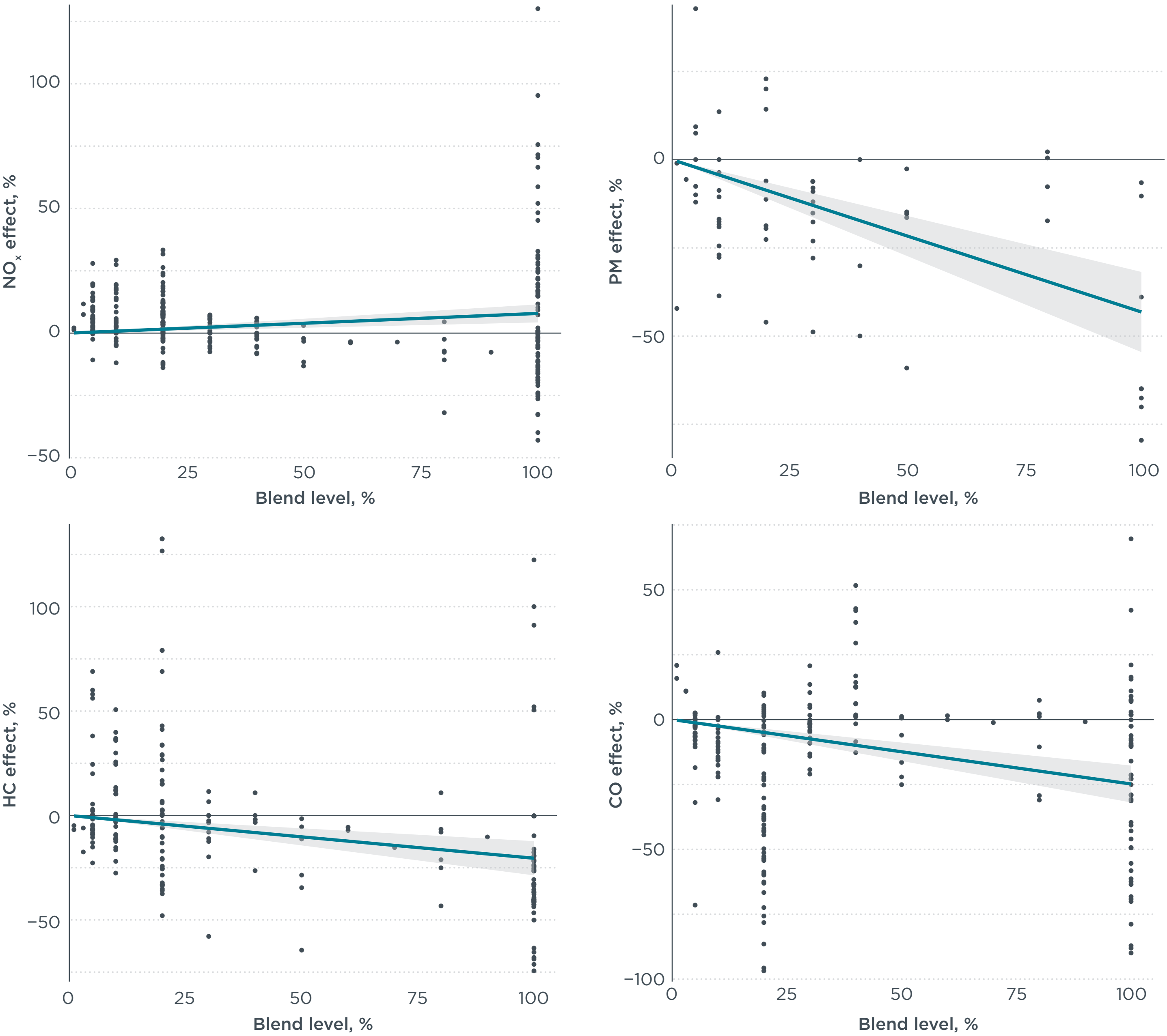

Figure 1. Emissions effects by palm biodiesel blend level.

For PM, we estimate a 43% reduction in emissions from B100 relative to conventional diesel fuel. Although the PM trend is significant, there is higher uncertainty in the magnitude of the biodiesel effect than for NO_x; this is indicated by the larger cone encasing the regression trend line, which shows the standard error of the regression. There also are significant reductions in HC and CO emissions with biodiesel blending; we estimate these reductions to be 20% and 25%, respectively, for B100 compared to conventional diesel.

Regarding the effects of other variables on the relationship between biodiesel blend level and air pollutant emissions, we organize our analysis into three sections: feedstock properties, vehicle test cycle conditions, and modern developments across the diesel industry. Considering that palm oil is the dominant biodiesel feedstock in Indonesia, we narrow our results to palm-only studies when sufficient data are available.

FAME FEEDSTOCK PROPERTIES

Several studies have suggested that the biodiesel NO_x effect is less for palm oil compared with other feedstocks (Kinoshita, Hamasaki, & Jaqin, 2003; Mormino, Verhelst, Sierens, Stevens, & De Meulenaer, 2009). This is presumably due to palm's physical characteristics, which differ from other common vegetable oils such as soy, rapeseed, and UCO. Our results also show these trends, and Table 1 indicates that palm has the lowest NO_x effect across blend levels among the full set of feedstocks. The primary value reported in Table 1 represents the mean biodiesel NO_x effect whereas results in parentheses represent the standard error of the regression. Data for B30 reflects near-term policy in Indonesia, B40 demonstrates the NO_x effect if Indonesia were to increase its blend mandate, and B100 shows the full magnitude of the biodiesel effect.

Of the dataset, rapeseed biodiesel has the highest NO_x effect, measured to be 13.4% at 100% blend rates. We also investigate the effects of feedstock properties on HC, CO, and PM.

Table 1. Predicted NO_x effect by biodiesel feedstock and blend rate with standard error in parentheses

NO_x effect (%)	Palm	Rapeseed	Soybean	UCO
B30	2.4 *(1.8, 2.9)*	4.0 *(3.6, 4.4)*	2.5 *(2.1, 3.0)*	2.5 *(2.0, 3.1)*
B40	3.2 *(2.4, 3.9)*	5.3 *(4.8, 5.9)*	3.4 *(2.8, 4.0)*	3.4 *(2.8, 3.9)*
B100	7.9 *(6.1, 9.7)*	13.4 *(12.0, 14.7)*	8.5 *(7.0, 10.0)*	8.4 *(7.1, 9.7)*

The difference in NO_x emissions among the various biodiesel feedstocks may be due to differences in physical properties such as density, viscosity, and CN, as detailed in Table 2. A feedstock's degree of unsaturation and fatty acid chain length is also likely to influence NO_x formation. Data for the latter two variables are drawn from Hoekman et al. (2012). The remaining parameters are sourced from property tables in the literature review and averaged by feedstock type.

Table 2. FAME feedstock properties

Feedstock	Cetane number*	Density (kg/m³)*	Viscosity (mm²/s)*	Unsaturation†	Chain length†
Diesel	50.37	0.836	3.08	N/A	N/A
Soybean	51.29	0.857	3.54	1.50	17.90
Rapeseed	56.45	0.859	4.42	1.31	17.90
UCO	54.64	0.860	4.64	1.06	18.50
Animal fat	56.65	0.876	3.83	0.59	17.30
Palm	57.81	0.851	5.01	0.62	17.20
Coconut	58.68	0.875	4.39	0.12	13.40

* Data sourced from the literature averaged by feedstock type
† Data adapted from Hoekman et al. (2012)

For all feedstocks reviewed here, biodiesel has a higher CN than conventional diesel fuel. CN is a nonphysical property representing a fuel's ignitability (Graboski, McCormick, Alleman, & Herring, 2003; Hoekman et al., 2012). CN is inversely related to the amount of time between fuel injection into the combustion chamber and ignition. Thus, fuel with a higher CN ignites faster. Biodiesel also has high oxygen content, estimated between 10% and12% by weight, whereas conventional diesel fuel contains none (Demirbas, 2009). Although highly oxygenated fuel has lower energy content, oxygenated fuels burn more efficiently, reducing the formation of CO, an intermediate combustion compound, and unburned HCs in the exhaust stream. Oxidation also suppresses formation of PM, or "soot," in tailpipe exhaust (Wang, Li, Wang, & Reitz, 2016).

Fatty acid chain length and degree of unsaturation play a role in CN and viscosity. Average degree of unsaturation is a function of each fuel's fatty acid profile, and it is calculated by multiplying the mass percentage of fatty acid in FAME by its number of carbon double bonds (Hoekman et al., 2012). Average chain length of each biodiesel is similarly calculated by multiplying fatty acid mass percentage by the number of carbon atoms in one fatty acid chain summed across the entire profile. Saturation and chain length are also correlated with other physical properties. Mishra, Anand, and Mehta (2016) found that an increase in both fatty acid chain length and degree of saturation increases the viscosity and CN of a fuel. Higher saturated fuels also correspond with lower fuel density (Dharma, Ong, Masjuki, Sebayang, & Silitonga, 2016). An experimental study found that unsaturated feedstocks also correspond with higher soot formation because of the presence of carbon double bonds (Wang, Li, et al., 2016).

Saturated fatty acids include palm and coconut oils, and soybean and rapeseed are the least saturated FAME feedstocks in this dataset. One reason palm biodiesel has among the highest CNs of the feedstocks presented here is because of its high saturation. A high CN means that palm biodiesel ignites faster than other fuels once it arrives in the combustion chamber, and this likely counteracts, to some extent, the longer ignition delay observed in biodiesel compared to conventional diesel. Because the longer ignition delay of biodiesel is thought to be one of the main contributors to the biodiesel NO_x effect, palm biodiesel's high saturation—and thus higher CN—likely explains why it is generally found to have a lower NO_x effect than biodiesels produced from other feedstocks.

Biodiesel is also denser and more viscous than conventional diesel. Both properties have implications for combustion efficiency and the degree to which the fuel disperses into finer droplets (i.e., spray atomization). The effects of more viscous fuels on combustion are three-fold: poor spray atomization, which reduces combustion efficiency (Agarwal et al., 2015); increased heat of combustion (Mirhashemi & Sadrnia, 2020); and rapid pressure increases within the fuel pump (Lapuerta, Agudelo, Prorok, & Boehman, 2012). High pressure lowers the compressibility of fuels and leads to advanced injection timing. Given that biodiesel increases NO_x emissions overall and that saturated fuels have particularly high viscosity but a reduced NO_x effect, the impact of fuel viscosity on spray atomization does not appear to be a dominant effect on NO_x formation.

Fuel density is also correlated with combustion properties, although the mechanisms are not as well understood throughout the literature. High densities are correlated with high aromatics and low CN, properties both associated with high NO_x formation (Lee, Pedley, & Hobbs, 1998). Lee et al. (1998) also found that although low density has large benefits for PM and NO_x reduction, it may also lead to increases in CO and HC. Changes in density also affect volumetric efficiency, which is especially relevant for older technology engines that cannot compensate for volumetric changes when injecting fuel into the combustion chamber (Bacha et al., 2007). Thus, the relationship between density and emissions may be less relevant for modern engines, which have the ability to dynamically respond to changes in injection timing and mass flow rate.

Our results show a positive correlation between density and the biodiesel NO_x effect (see Figure 2). For palm biodiesel, which has the lowest density of FAME feedstocks in the dataset, the NO_x effect is diminished, but still remains greater than that of conventional diesel fuel. In contrast with the findings in Lee et al. (1998), we find an inverse relationship between both HC, PM, and density, and no significant relationship between density and CO across our entire dataset.

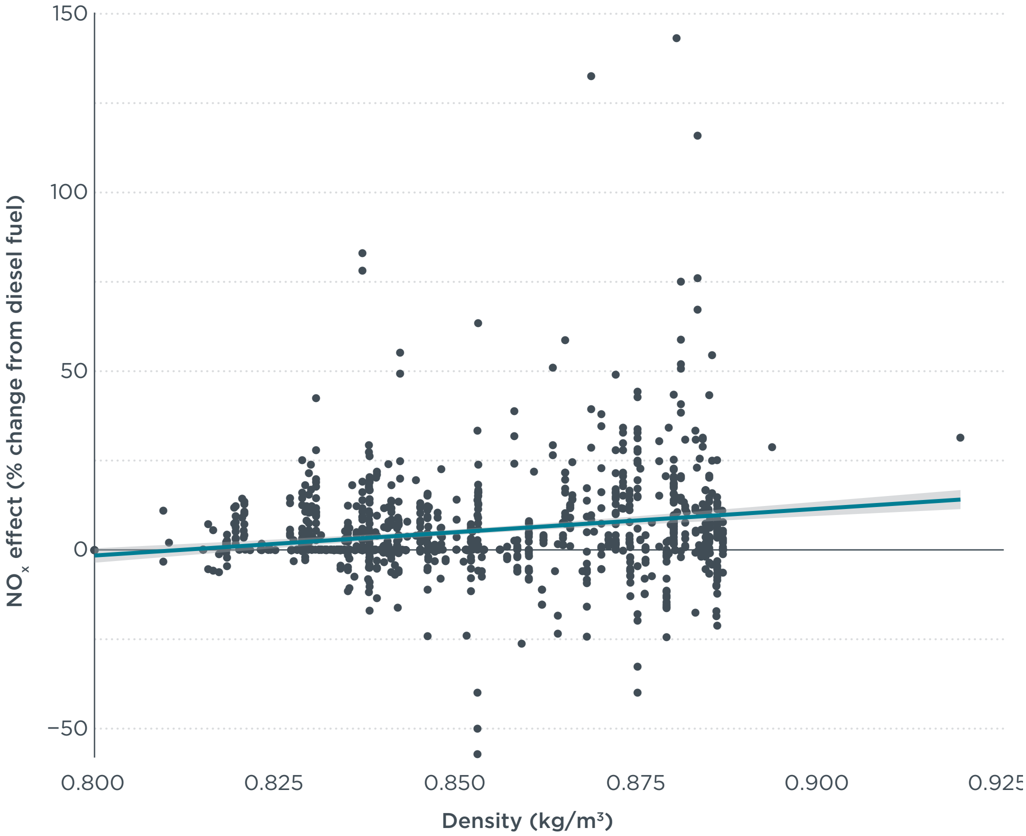

Figure 2. Biodiesel NO_x effect by fuel density (all data).

In addition to the chemical makeup of a feedstock, external conditions such as storage and handling practices can alter its physical properties. Khalid et al. (2013) found that longer storage times increase the viscosity, density, and insoluble fuel impurities of feedstocks, while decreasing their iodine value, or degree of saturation. For palm oil, extended storage periods are expected to increase NO_x emissions due to the higher viscosity and decreased saturation of the resulting fuel. Khalid et al. (2013) also observed that high temperature storage environments can counteract the effects of extended storage periods by mitigating increases in feedstock viscosity. However, it is unknown whether the high temperature storage environments that would typically be experienced in Indonesia could fully offset the feedstock degradation that occurs with storage.

As detailed above, feedstock properties often have competing effects on the mechanisms for conventional air pollutant formation. Physical properties are not the only parameters that affect exhaust emissions formation; therefore, we investigate the effects of additional parameters such as emission test cycles and diesel quality in the following sections.

EMISSION TEST CYCLES

Emission test cycles were developed in industry and laboratory settings to demonstrate compliance with vehicle emission standards. In addition, these test cycles are often used by researchers who are measuring air pollutant emissions from combusting biodiesel. Most test cycles simulate transient driving conditions on a chassis dynamometer by alternating engine speed and load changes dynamically. The most widely used cycle for regulatory compliance in passenger cars is the New European Driving Cycle (NEDC). For heavy-duty vehicle (HDV) engines, the European Engine Transient Cycle (ETC) and European Stationary Cycle (ESC) are used for vehicle compliance for the Euro III–V standards, and the EPA Federal Transient Procedure (FTP) cycle is used for emissions certification in the United States. Several Asian countries, including Indonesia, have adopted the NEDC. Japan, meanwhile, developed its own cycle comparable to the NEDC but, along with Europe, is moving toward the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) in coming years (Yang & Rutherford, 2019). An overview of emissions test cycles used in this dataset is provided in Appendix C.

Across biodiesel vehicle emission studies, researchers found that test cycles strongly affect the rate of exhaust emissions formation (Sze, Whinihan, Olson, Schenk, & Sobotowski, 2007; Kaya, Kutlar, & Taskiran, 2018). Test cycles are intended to reflect on-road driving conditions including idling, acceleration, deceleration, and cruise periods. However, emission measurements recorded in a laboratory setting are often lower than on-road results because controlled environments do not account for external variables such as route topography and traffic patterns, and because automakers sometimes design vehicles to minimize emissions during test cycles (Brown, Harris, & King, 2000).

We grouped test cycles into *urban*, *highway*, and *rural* on-road driving condition categories based on the Common Artemis Driving Cycles (Baldino, Tietge, Muncrief, Bernard, & Mock, 2017; Thompson, Carder, Besch, Thiruvengadam, & McCormick, 2014). Additionally, we made several assumptions with regard to load and speed parameters and aligned test cycle data accordingly. *Motorway* or highway driving is defined as lengthy cruise periods at high load and speed, with little to no idling, and infrequent acceleration and deceleration periods. Rural driving exhibits some of the same characteristics as highway driving such as extended cruise periods and high speeds, but these conditions are punctuated with periods of stops and starts to adhere to turns and road signals (Wang, Lyons, Clark, Gautam, & Norton, 2000). Urban driving exhibits the highest share of idling and acceleration/deceleration periods due to heavy traffic. Urban conditions are characterized by low speeds and medium-to-high loads, and are generally associated with low horsepower (Sze et al., 2007). Vehicles may exhibit high load and horsepower during urban driving due to heavy vehicle weight class and frequent periods of acceleration. Collecting data from chassis dynamometer tests, Sze et al. (2007) found that engines exert the highest horsepower during highway conditions and city-suburban driving conditions fall within the middle of the range.

Engine load, or torque, data are presented in Figure 3 as a percentage of different engine power ratings. *Low* engine load represents between 0%, or idling conditions, and 40% capacity; *medium* load represents 40% to 70% capacity; and *high* engine load represents 70% to full load conditions. We find a higher biodiesel NO_x effect at higher engine load and lower PM and CO effects at higher load running a regression analysis on the full dataset. We observe no significant relationship between engine load and the biodiesel HC effect. Thus, we can infer that, for biodiesel, low-load driving conditions correspond with the lowest NO_x increases and highest levels of PM and CO relative to conventional diesel fuel. Trend lines even show a positive emissions effect for PM and CO at low load.

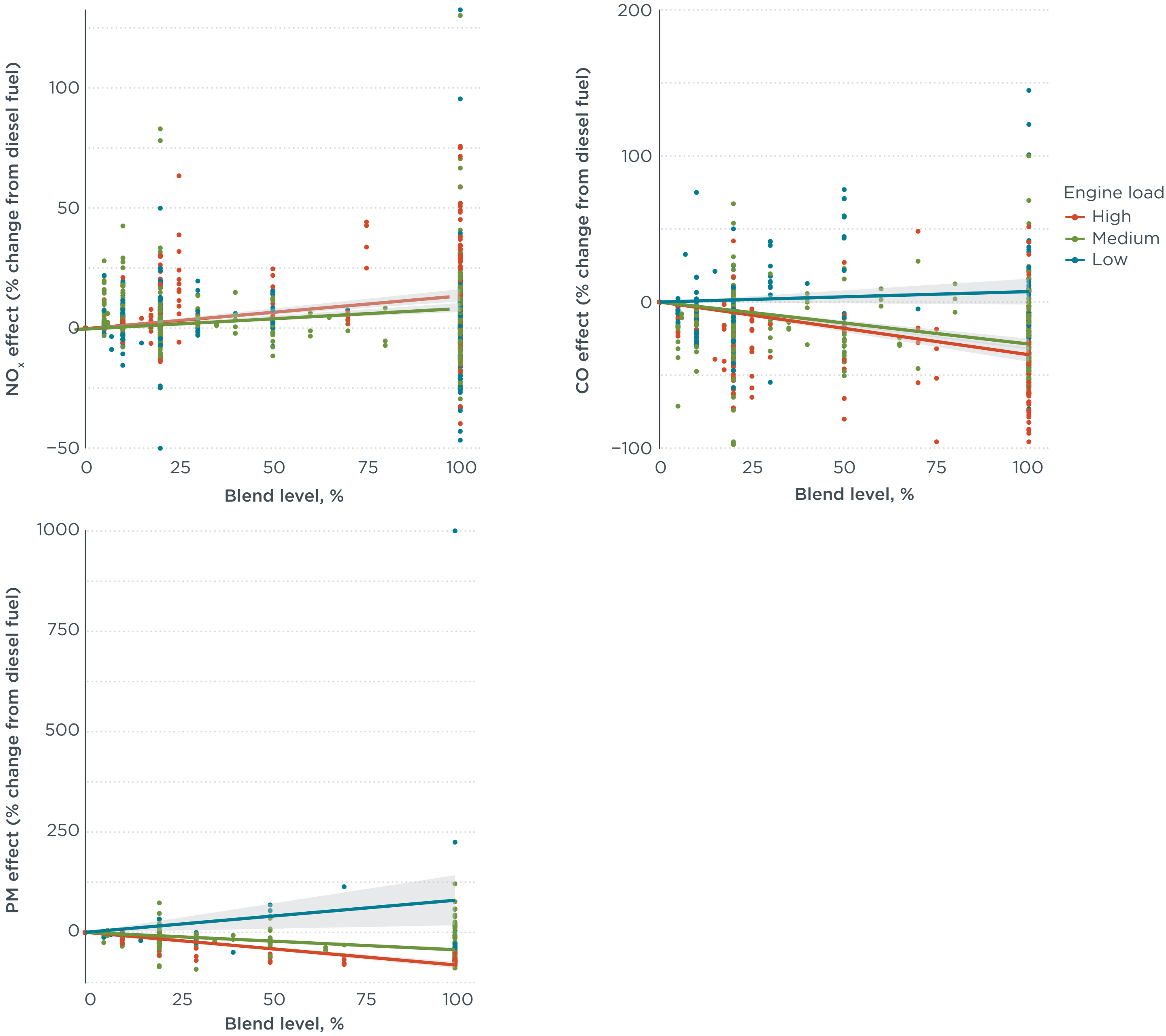

Figure 3. Emissions effects by engine load (all data).

NEW DEVELOPMENTS

In addition to FAME feedstock properties and emission test cycles, several modern advancements across the diesel industry may contribute to disparities in the emissions effect among biodiesel performance studies. These include the phase-in of low-sulfur diesel, adoption of emission control technologies, and an industry shift toward common rail direct fuel injection systems.

Diesel sulfur content

As the Indonesian diesel market moves to adopt Euro 4/IV emission standards, low-sulfur fuel (≤50 ppm) is also slated to be phased in to enable the use of emission control devices. These devices require fuel with a lower sulfur content than current market levels in Indonesia (2,500 ppm) to perform effectively. For example, exhaust gas recirculation (EGR) requires use of fuel with 500 ppm sulfur content or less to avoid pipe corrosion (Posada, Chambliss, & Blumberg, 2016). Diesel oxidation catalysts (DOCs) also require fuel with 500 ppm or less whereas diesel particulate filters (DPFs), introduced under Euro VI, perform most effectively using fuel with maximum 10 ppm sulfur content (Xie, Posada, & Minjares, 2020).

Low-sulfur fuels have also been found to exacerbate the NO_x effect when blended with biodiesel. Although there is not yet a consensus on the mechanism for this phenomenon, the relationship between sulfur content and the biodiesel NO_x effect is widely observed. The two variables are inversely related such that comparing biodiesel to LSD produces the highest biodiesel NO_x effect while this effect is less pronounced when compared to high-sulfur diesel. Previous regressions include datapoints from a variety of diesel fuel sulfur levels, minimizing the conflation of sulfur quality with other independent variables. Below, we define high-sulfur diesel as >50 ppm whereas low-sulfur diesel is defined as ≤50 ppm sulfur content. We observe a six-fold increase in the biodiesel NO_x effect at 100% palm biodiesel between high-sulfur diesel and LSD (Figure 4).

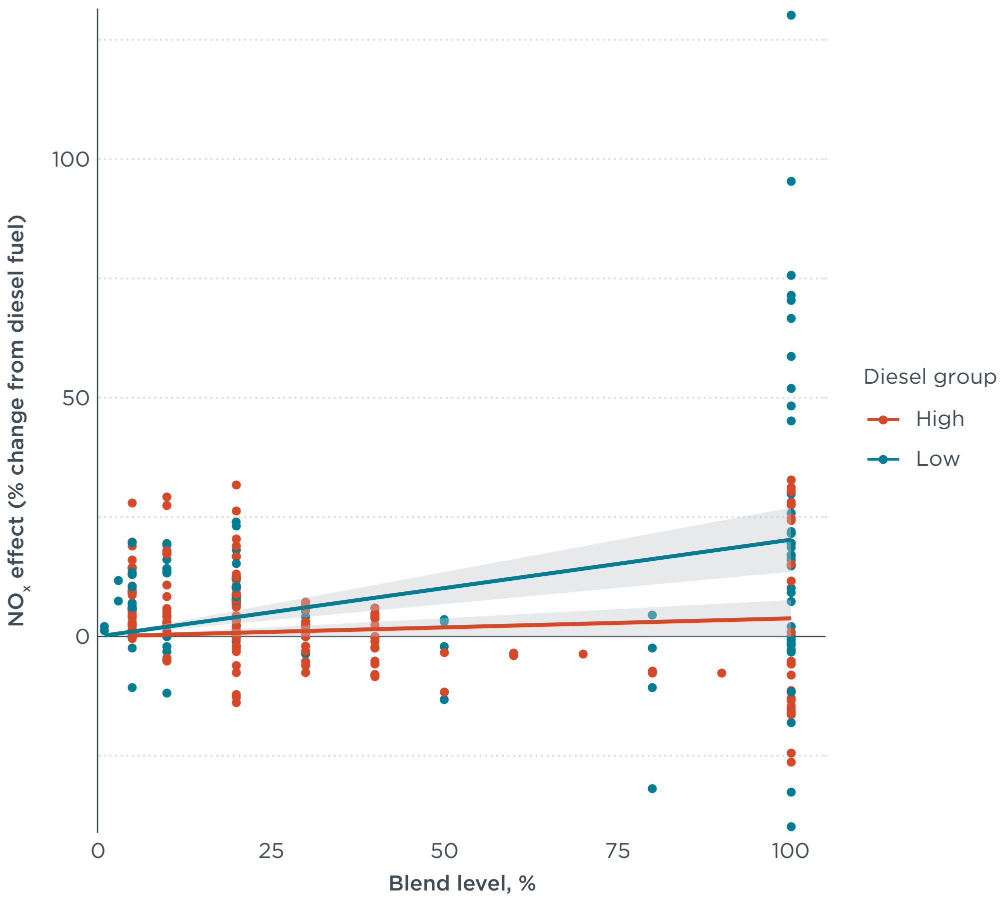

Figure 4. Biodiesel NO_x effect grouped by diesel quality (palm).

Although the relationship between sulfur content and emissions formation is often centered around PM in the literature, we identified several studies that investigated the relationship between NO_x and LSD. Alam, Song, Acharya, Boehman, and Miller (2004) found that LSD has lower density and higher CN than high-sulfur fuels. As described in Section I, these properties correspond with reduced NO_x. Because biodiesel has a higher density than petroleum diesel, when blended with low-sulfur fuel, the relative change in density is greater than with higher sulfur fuels. The biodiesel NO_x effect is thus larger when blended into low-sulfur diesel fuel due to its lower-NO_x baseline.

Zhu, Zhang, Liu, and Huang (2010) found that LSD has a much lower aromatic content than higher sulfur diesel. Low aromatic content corresponds with higher CN, which reduces NO_x but may increase PM formation; this relationship is known as the soot-NO_x tradeoff (Reijnders, Boot, & de Goey, 2016). The longer ignition delay for low CN fuels leads to greater air-fuel mixing and improves combustion of aromatics, which are soot precursors. The extent to which the greater CN of biodiesel compared to diesel reduces the ignition delay and partially offsets the NO_x increase with biodiesel may be reduced when biodiesel is compared to LSD because LSD also has higher CN relative to high-sulfur diesel. However, due to the competing effects of other fuel and engine properties, it is difficult to determine causality for each of these effects.

We also observed a strong relationship between fuel sulfur content and the biodiesel PM emissions effect (see Figure 5). This effect is well understood due to increased production of sulfate aerosols during combustion for high-sulfur fuel relative to LSD (Heywood, 1988). As a result, the PM benefits of biodiesel, which contains little to no sulfur content, are expected to diminish in LSD blends. Although data are scattered, when looking at results for all feedstocks, the biodiesel PM benefits are significantly reduced for LSD compared to high-sulfur diesel. For Indonesia, the implications for public health will be significant as the country phases in LSD to comply with Euro 4/IV emission standards.

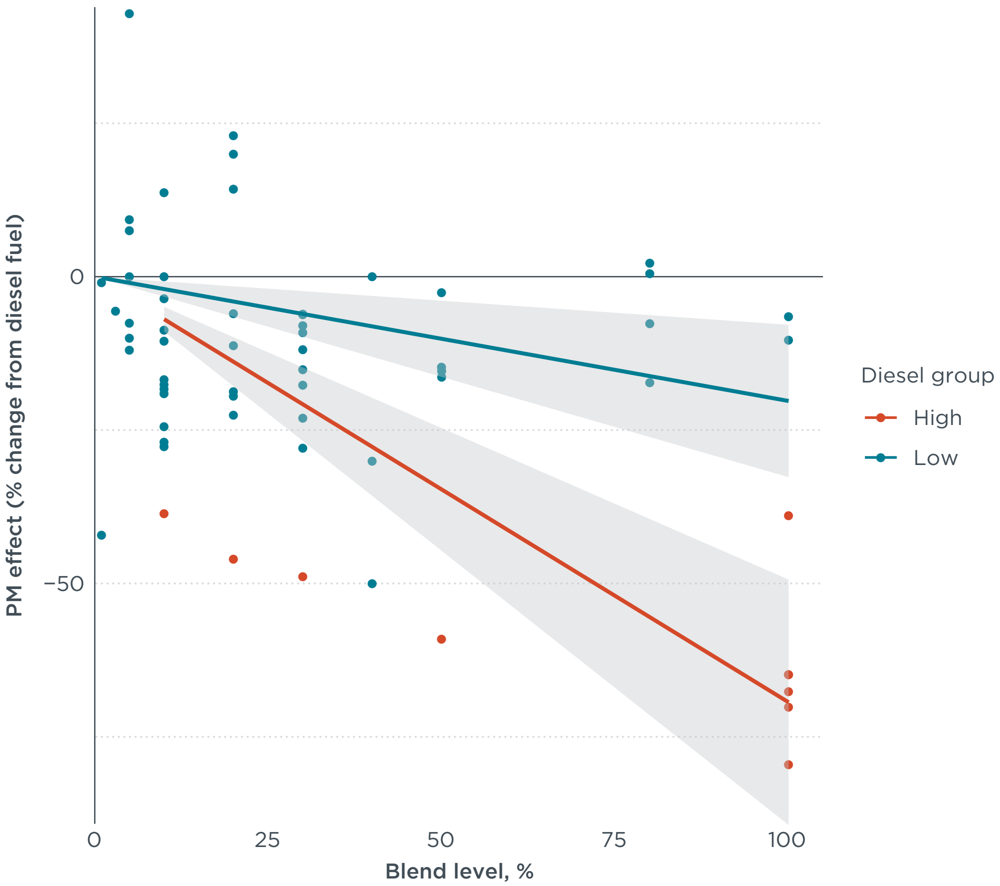

Figure 5. Biodiesel PM effect by diesel sulfur quality (palm).

Emission control technologies

Vehicle manufacturers have developed several NO_x mitigation technologies to comply with increasingly stringent vehicle emission standards. EGR, one of the earliest control technologies implemented in diesel engines, reduces NO_x by recycling a fraction of exhaust gas back to the engine cylinders to lower combustion temperatures. In so doing, EGR also restricts oxygen and NO_x formation (López, Jiménez, Aparicio, & Flores, 2009). EGR is an effective way to reduce emissions with relative ease, but it is not by itself effective enough to comply with newer emission standards such as Euro 6/VI.

Other control technologies have been developed to reduce emissions of other conventional pollutants. For example, meeting the Euro 4/IV standard requires incorporating technologies such as DOCs to reduce HC and CO formation (López et al., 2009). Along with DPFs, DOCs can also control PM levels in the exhaust stream. DOCs can further be used in combination with other systems such as SCR to reduce PM emissions via in-cylinder strategies (Posada et al., 2016). Although vehicle emission standards are technology-neutral rather than prescriptive, a common set of technologies used in combination is generally applied. Thus, we consider emission standards as a proxy for an ensemble of control technologies.

Consistent with the literature, we found few significant relationships between emission control technologies and the biodiesel emissions effect. We did not observe emissions effects for HC and CO and observed a small positive increase in NO_x emissions for Euro 4/IV which is reversed at 100% biodiesel blend levels (see Figure 6). However, we did identify a greater reduction in PM emissions for B20, B30, and B100 versus diesel in vehicles compliant with the Euro 4/IV standard compared to those compliance with the Euro 2/II standard (see Figure 6). Czerwinski et al. (2013) found that biodiesel assists the regeneration behavior of DPFs by altering the composition of PM and the nanostructure of primary soot particles thus “reduc[ing] the temperature required to initiate regeneration” (p. 2). Although we do not have enough data on the latest Euro 6/VI standards, we expect those and later standards will exhibit a similar trend.

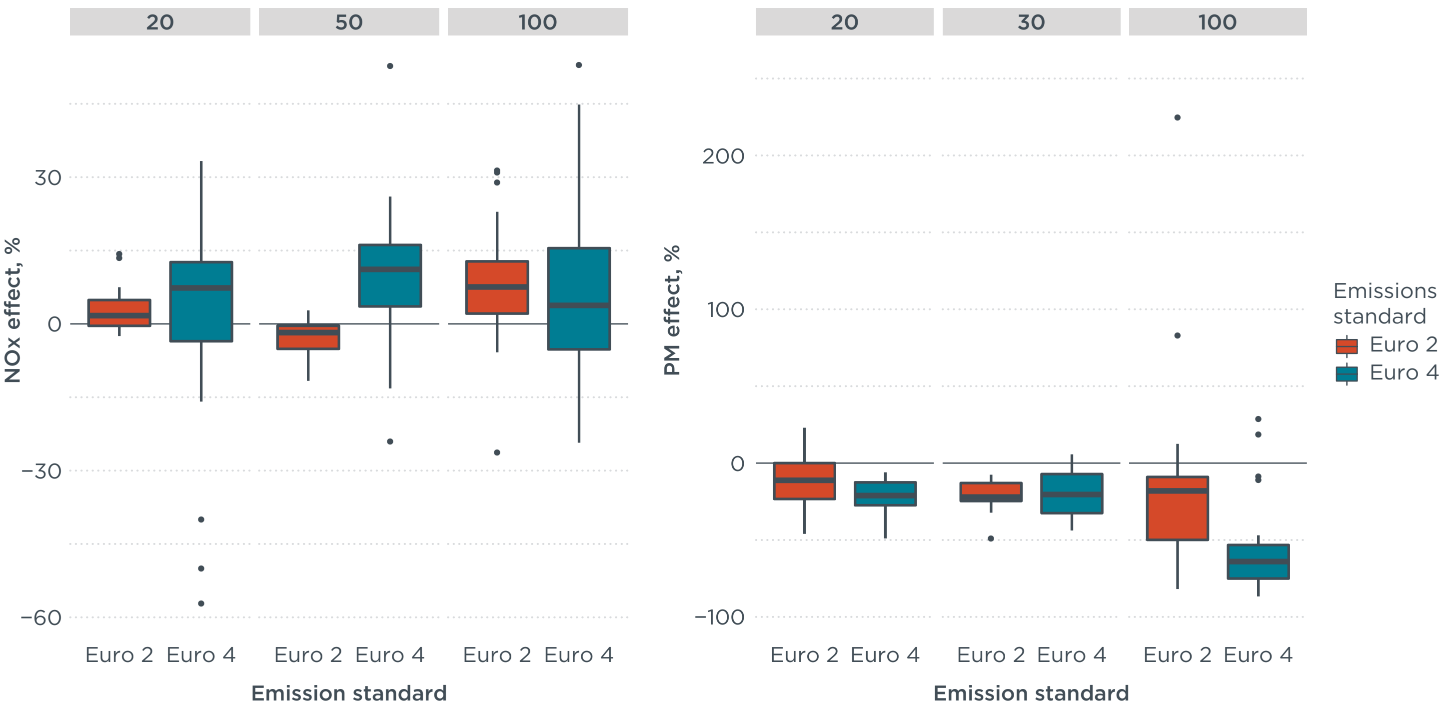

Figure 6. Left: Biodiesel NO_x effect by biodiesel blend level and emission standard (all data). Right: Biodiesel PM effect by biodiesel blend level and emission standard (all data).

Fuel injection systems

We identified a final variable that may alter biodiesel emission effects: fuel injection systems. Older engines use unit injectors, also called pump nozzle injectors, which assign an individual fuel pump to each cylinder (Bosch UK, 2009). Unit injectors offer a high degree of efficiency, low fuel consumption, and low-pressure injection at low speeds. However, these systems have been largely phased out in favor of common rail direct injection systems starting in 2000 (Yanowitz & McCormick, 2009).

Yanowitz and McCormick (2009) suggested that fuel injection timing may be related to the vehicle’s type of fuel injection equipment. In their study, the NO_x emissions effect for B20 blends was higher for common rail injection systems than for electronic unit injectors, which were the dominant unit injector model starting in the mid-1980s.

Although the average B20 NO_x effect for unit injectors hovered near zero, common rail systems exhibited a 4% increase in NO_x. We grouped data by fuel injection system and ran a regression on the whole dataset and palm biodiesel subset. For palm biodiesel, we find a 66% difference between the biodiesel NO_x effect for common rail and unit injector systems (see Figure 7, left). Sixteen studies that specified the type of fuel injection system used are included in the regression.

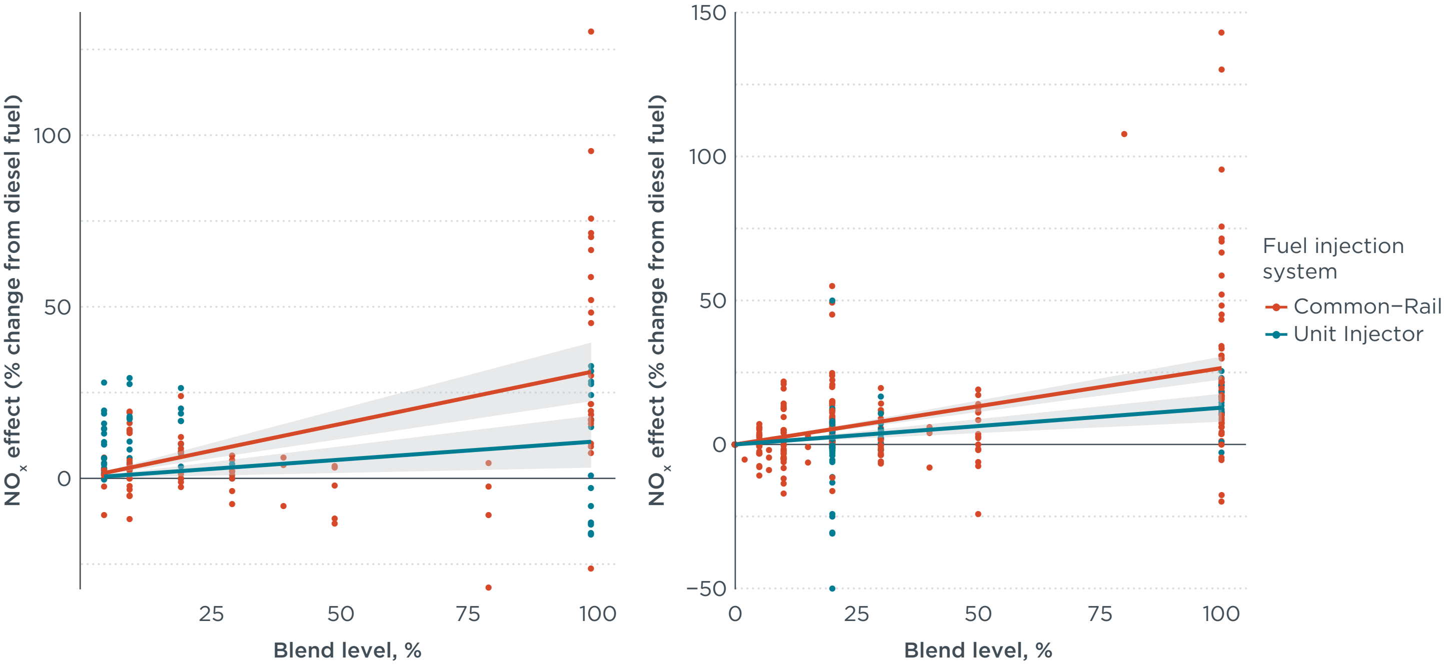

Figure 7. Left: Biodiesel NO_x effect by fuel injection system (palm). Right: Biodiesel NO_x effect by fuel injection system for low-sulfur diesel only (all data).

The effect of fuel injection system on the biodiesel NO_x effect could be confounded by the adoption of LSD (Yanowitz & McCormick, 2009); thus, we also ran another regression controlling for fuel sulfur level (see Figure 7, right). We performed this regression on the entire dataset because there were not enough palm-specific data when filtered by sulfur content and engine injection system parameters. Including results from only LSD blends, we still found that the biodiesel NO_x effect is nearly twice as large for common rail systems compared to unit injection.

A higher NO_x effect in common rail injection systems may be due to their use of high-pressure injection, which can exceed 200 megapascals (Xu et al., 2017). High pressures lead to advanced injection, and this allows more time for air-fuel mixing and thus more complete combustion; however, the increase in NO_x is a drawback. We can expect this effect to be exacerbated when using biodiesel, as it will further advance injection timing because of its low compressibility. During high-pressure injection, biodiesel will enter the injection chamber at a higher speed whereas with conventional diesel fuel, much of the force will be absorbed by compressing the fluid rather than advancing injection timing.

We anticipate that the common rail NO_x effect will continue to widen in coming years as Indonesia's vehicle fleet transitions to newer models equipped with the technology.

OVERALL BIODIESEL AIR POLLUTION IMPACTS ON INDONESIA

Our analysis found that blending palm biodiesel in diesel fuel increases NO_x emissions. These effects are especially pronounced with LSD and common rail injection systems. Figure 8 summarizes the increase in NO_x with palm biodiesel blending specifically from studies reflecting more modern conditions including LSD and common rail injection systems. This trend is statistically significant and shows an increase in NO_x emissions of 12%, 17%, and 41% for B30, B40, and B100 in future years in Indonesia. We also found that modern injection systems and fuels diminish the expected reductions of other pollutants from biodiesel, such as PM, CO, and HC compared to diesel fuel.

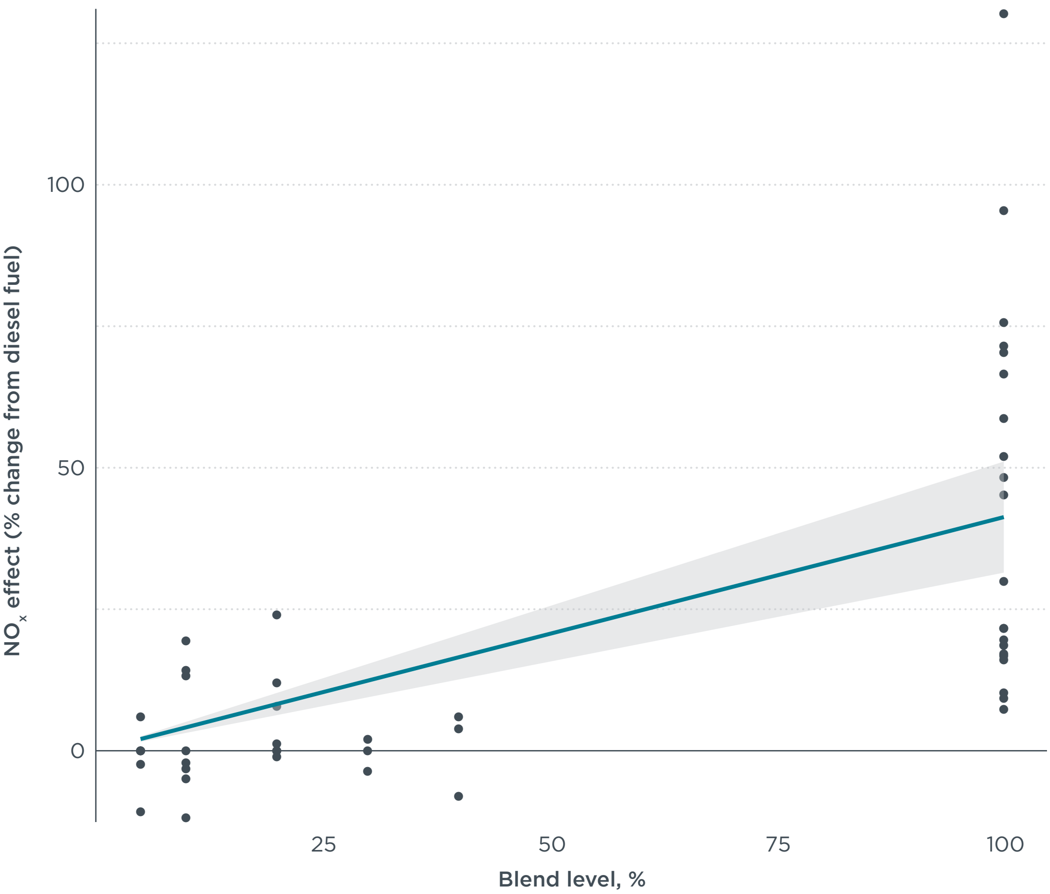

Figure 8. Palm biodiesel NO_x effect in modern engines.

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APPENDIX A – EMISSIONS FORMATION SUMMARY TABLE

Upward arrows represent an increase in the engine or fuel property variable.

Engine characteristics		
Variable	**Primary effect**	**Mechanism**
↑ Ignition delay	Increase in NO_x Decrease in HC, CO, PM	Ignition delay, or the period between fuel injection and fuel ignition, increases air-fuel mixing inside the combustion chamber. Extended delay improves combustion efficiency but leads to rapid pressure and temperature increases upon combustion.
↑ Injection pressure	Increase in NO_x Decrease in HC, CO	High pressure conditions improve combustion but advance injection timing and raise temperatures in the cylinder.
↑ Injection timing	Decrease in NO_x Increase in HC, CO, PM	Counter to ignition delay, retarded injection timing reduces air-fuel mixing and the associated high temperatures and pressures in the combustion chamber.

Fuel properties		
Variable	**Primary effect**	**Mechanism**
↑ Cetane number	Decrease in NO_x	High cetane numbers correspond with faster ignitability and that, in turn, reduces premixed combustion. This limits rapid increases in pressure and temperature.
↑ Aromatics	Increase in NO_x	High aromatics are associated with high density and low CN. High aromatics content is also associated with high adiabatic flame temperatures.
↑ Degree of saturation	Decrease in NO_x, PM	More saturated (i.e., single bond) fuels like palm and coconut have higher CN so they ignite more easily. Saturated fuels are also correlated with high viscosity and low density.
↑ Density	Increase in NO_x, PM	High density fuels are associated with high aromatics and low CN. Dense fuels also have high volumetric efficiency, which raises in-cylinder temperatures.
↑ Viscosity	Increase in NO_x, HC, CO	High viscosity may lead to pressure build-up and advanced injection. High pressure conditions also improve air-fuel mixing. However, high viscosity fuels also produce large diameter droplets which hinder vaporization and complete combustion.
↑ Bulk Modulus	Increase in NO_x Decrease in HC, CO, PM	Bulk modulus is inverse to compressibility such that fuels with high bulk modulus have low compressibility and arrive in the combustion chamber earlier.
↑ Diesel sulfur content	Increase in PM	Combustion of high-sulfur fuel produces sulfate aerosols, a component of PM. High-sulfur fuels are also associated with high aromatics and reduced CN.

APPENDIX B – FULL STUDY LIST

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Acevedo & Mantilla (2011)	Colombia	HDV engine	Palm	Steady-state test	—	NO_x, PM (omitted), HC, CO
Adi et al. (2012)	United States	Engine	Cold-flow Soybean	Steady-state test	—	NO_x, PM
Alam et al. (2004)	United States	HDV	Soybean	AVL 8-Mode	Tier 2	NO_x, PM, HC, CO
Altun (2011)	Turkey	LDV engine	UCO, Animal fat	Steady-state test	—	NO_x, CO
Arapaki et al. (2007)	Greece	LDV	UCO	NEDC	Euro 3	NO_x, PM, HC, CO
Arbab et al. (2013)	Malaysia	Engine	Palm, Palm/ Jatropha/ Coconut blends	Steady-state test	—	NO_x, HC, CO
Armas et al. (2013)	Spain	LDV	Animal fat	EUDC, NEDC	Euro 4	NO_x, HC, CO
Bakeas et al. (June 2011)	Greece/Italy	LDV	Soybean, Palm, UCO	Artemis Urban, Road, Motorway, NEDC	Euro 4	NO_x, PM, HC, CO
Behçet (2011)	Turkey	Engine	Fish oil	Steady-state test	—	NO_x, HC, CO
Behçet et al. (2014)	Turkey	Engine	Fish oil, UCO	Steady-state test	—	NO_x, HC, CO
Bielaczyc et al. (2009)	Poland	LDV	Rapeseed	UDC, EUDC	Euro 4	NO_x, PM, HC, CO
Canakci & Van Gerpen (2003)	United States	HDV engine	UCO, Soybean	Steady-state test	—	NO_x, HC, CO
Chang et al. (1996)	United States	HDV engine	Soybean	Steady-state test	—	NO_x, PM, HC, CO
Chase et al. (2000)	United States	HDV	Rapeseed Ethyl Ester (REE), Vegetable oil	FTP Transient	Tier 1	NO_x, PM, HC, CO
Chin et al. (2012)	United States	HDV	Soybean	Steady-state test	Tier 2	NO_x, PM, CO
Clark et al. (1999)	United States	HDV	Soybean	FTP	Tier 1	NO_x, PM, HC, CO
Clark & Lyons (1999)	United States	HDV	Soybean	WVU 5 peak truck cycle	Tier 1	NO_x, PM, HC, CO
Concawe (2014)	Greece	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NO_x, HC, CO
Czerwinski et al. (2013)	Germany	HDV	Rapeseed	Steady-state test	—	NO_x, PM, HC, CO
Di et al. (2009)	China	HDV Engine	UCO	Steady-state test	—	NO_x, PM, HC
Durbin et al. (1999)	United States	HDV	FAME	FTP	Tier 1	NO_x, HC, CO
Durbin & Norbeck (2002)	United States	HDV	Soybean, UCO	FTP	Tier 1	NO_x, PM, HC, CO
Eckerle et al. (2008)	United States	HDV	Soybean	UDDS (6k), HWY55	Tier 2	NO_x
Farzaneh et al. (2006)	United States	HDV	Soybean, FAME	On-road driving cycles (Urban, Rural)	Tier 1	NO_x
Fontaras et al. (2009)	Greece	LDV	Soybean	Artemis Urban, Road; UDC	Euro 2	NO_x, PM, HC, CO
Fontaras et al. (2010)	Greece	LDV	Palm, Rapeseed, Sunflower oil, UCO, Soybean	Artemis Urban, Road, Motorway; UDC	Euro 3	NO_x, PM, HC

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Frank et al. (2004)	United States	HDV	FAME	FTP	Tier 2	NO_x, PM, HC, CO
Ge et al. (2017)	Korea	LDV	Rapeseed	Steady-state test	—	NO_x, PM, CO
Geng et al. (2019)	United States/ China	HDV Engine	UCO	Steady-state test	—	NO_x
Graboski et al. (1996)	United States	HDV	Soybean	FTP Transient (Composite)	Tier 1	NO_x, PM, HC, CO
Graboski et al. (2003)	United States	HDV	Methyl-lard, methyl-soy, methyl-canola, methyl inedibletallow, 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), methyllinolenate (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	FTP Transient	Tier 1	NO_x, PM, HC, CO
Gautam (2013)	India	Engine	Jatropha	Steady-state test	—	NO_x, HC, CO
Guido (2013)	Italy	LDV Engine	Rapeseed	Open/closed loop operating modes	Euro 5	NO_x, PM, HC, CO
Haas (2001)	United States	HDV	Soybean, Soapstock	FTP Transient	Tier 1	NO_x, PM, HC, CO
Han et al. (2008)	United States	LDV	Soybean, Coconut	Ad-hoc operating points/Misc.	—	NO_x, PM, HC, CO
Hansen & Jensen (1997)	Denmark	HDV	Rapeseed	5-mode test (subset of ECE R49)	Euro 2	NO_x, PM, HC, CO
Hearne (2005)	United States	HDV	FAME	Rowan University Composite School Bus Cycle (RUCSBC)	Tier 1	NO_x, PM, HC, CO
Holden et al. (2011)	United States	HDV	Soybean, UCO	FTP Transient, US06, AVL 8-Mode, In-Use Test	Tier 1, Tier 2	NOx, PM, HC, CO
Kalam & Masjuki (2008)	Malaysia	HDV	Palm	Steady-state test	—	NO_x, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Karavalakis et al. (2007)	Greece	LDV	Soybean	Athens Driving Cycle	Euro 2	NO_x, PM, HC, CO
Karavalakis et al. (2009a)	Greece	HDV	Palm	UDC, NEDC, ADC	Euro 3	NO_x, PM, HC, CO
Karavalakis et al. (2009b)	Greece	LDV	Soybean	UDC, NEDC, ADC	Euro 2	NO_x, PM, HC, CO
Karavalakis et al. (2009c)	Greece	LDV	Rapeseed, Palm	NEDC, UDC, ADC	Euro 2	NO_x, PM, HC, CO
Karavalakis et al. (2011)	Greece	LDV	Palm, Soybean, Rapeseed blended w/ sunflower oil and UCO	Artemis (full), NEDC	Euro 4	NO_x, PM, HC, CO
Karavalakis et al. (2016)	United States	LDV	UCO	UDDS, HHDDT Transient	Tier 2	NO_x, PM, HC, CO
Kawano et al. (2008)	Japan	LDV	Rapeseed	JE05 Mode Test	Euro 5	NO_x, PM, HC, CO
Kaya et al. (2018)	Turkey	LDV	FAME (unspecified)	NEDC, WLTC	Euro 5	NO_x, HC, CO
Kinoshita et al. (2003)	Japan	Engine	Palm, Rapeseed	Steady-state test	—	NO_x, HC, CO
Kinoshita et al. (2006)	Japan	Engine	Palm, Coconut, Rapeseed	Steady-state test	—	NO_x, HC, CO
Kinoshita et al. (2011)	Japan	Engine	Palm, Rapeseed	Steady-state test	—	NO_x
Knothe et al. (2006)	United States	HDV	Methyl soyate (commercial biodiesel), methyl oleate, methyl pamitate, methyl laurate (technical biodiesel)	FTP Transient	Tier 2	NO_x, PM, HC, CO
Koszalka et al. (2010)	Poland	HDV	FAME	13-mode ESC test	Tier 2	NO_x, HC, CO
Kousoulidou et al. (2009)	Greece	LDV	Palm, Rapeseed	NEDC; Artemis Urban, Road, Motorway	Euro 3	NO_x, PM, HC, CO
Krahl et al. (2005)	Germany	HDV	Rapeseed, Rapeseed/ Soybean/Palm oil blends	13-mode ESC test	Euro 3	NO_x, PM, HC, CO
Krahl et al. (2008)	Germany	HDV	Rapeseed	13-mode ESC test	Euro 4	NO_x, PM, HC, CO
Krahl et al. (2009)	Germany	HDV	Rapeseed	13-mode ESC test	Euro 3	NO_x, PM, CO
Lahane et al. (2015)	India	Engine	Karanja	Steady-state test	—	NO_x, HC, CO
Lance et al. (2009)	United States/ Japan	LDV	Jatropha, Coconut, Rapeseed	NEDC	Euro 4	NO_x, HC, CO
Lapuerta et al. (2008)	Spain	LDV	UCO, Sunflower oil	Various SS operating points	Euro 4	NO_x, PM
Leevijit & Prateepchaikul (2011)	Thailand	Engine	Palm	Steady-state test	—	NO_x, CO
Lesnik et al. (2013)	Slovenia	HDV Engine	Rapeseed	Steady-state test	—	NO_x, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Li et al. (2007)	Europe	HDV	Rapeseed	23 kW Hot-Start SS	Euro 2	NO_x, PM, HC, CO
Lim et al. (2014)	Korea	LDV	Soybean, UCO, Jatropha, Palm, Rapeseed	NEDC	Euro 4	NO_x, PM, HC, CO
Liotta & Montalvo (1993)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Lopez et al. (2009)	Spain	HDV	FAME (unspecified)	Transient Cycle	Euro 4	NO_x, PM, HC, CO
Lujan et al. (2009)	Spain	LDV	FAME (unspecified)	NEDC	Euro 4	NO_x, PM, HC, CO
Macor et al. (2011)	Italy	LDV	Rapeseed	UDC, Artemis Urban	Euro 4	NO_x, PM, HC, CO
Marshall et al. (1995)	United States	HDV	Soybean	FTP retarded timing	Tier 1	NO_x, PM, HC, CO
Martini et al. (2007)	Italy/EU Joint Research Centre	LDV	50/50 soybean and sunflower, Palm, Rapeseed	NEDC, EUDC	Euro 3	NO_x, PM, HC, CO
Mazzoleni et al. (2007)	United States	HDV	FAME	On-road Driving Cycle	Tier 1	NO_x, PM, HC, CO
McCormick et al. (1997)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
McCormick et al. (2003)	United States	HDV	UCO, Soybean	FTP Transient (Composite)	Tier 1	NO_x, PM, HC, CO
McCormick et al. (2005)	United States	HDV	Soybean, UCO, Rapeseed, Animal fat	FTP Transient	Tier 1	NO_x, PM
McCormick et al. (2006)	United States	HDV	Soybean	City-Suburban Heavy Vehicle Cycle (CSHVC), UDDS, RUCSBC, Freeway Cycle	Tier 1, Tier 2	NO_x, PM, HC, CO
McGill et al. (2003)	United States	LDV, HDV	Rapeseed	FTP 75, AVL 8-Mode	Tier 1, Euro 2	NO_x, PM
Mizushima & Takada (2014)	Japan	HDV	FAME	JE05 "ED12" transient test cycle	Euro 5	NO_x, PM
Mofijur et al. (2014)	Malaysia	LDV	Palm, M. oliefera oil	Steady-state test	Euro 2	NO_x, HC, CO
Mormino et al. (2009)	Belgium	LDV	Animal fat, Palm, Rapeseed	Steady-state test	—	NO_x, HC
Nabi et al.(2006)	Bangladesh	Engine	Neem oil	Steady-state test	—	NO_x, CO
Nathangopal et al. (2018)	India	Engine	Calophyllum inophyllum	Steady-state test	—	NO_x, HC, CO
Ng et al. (2011)	Malaysia	LDV	Palm	Steady-state (representative of on-road conditions)	—	NO_x, HC, CO
Ng et al. (2012)	Malaysia	Engine	Palm, Soybean, Coconut	7-mode ESC test	Euro 2	NO_x, HC, CO
Nikanjam et al. (2009)	United States	HDV	Soybean	UDDS	Tier 2	NO_x, HC, CO
Nuszkowki et al. (2008)	United States	HDV	Soybean, Animal fat, Cottonseed	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Olatunji et al. (2010)	United States	HDV	Soybean, Animal fat	Steady-state test	Tier 2	NO_x, PM, HC, CO
Ozsezen & Canakci (2010)	Turkey	HDV	Palm	Steady-state test	—	NO_x, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Ozsezen & Canakci (2011)	Turkey	Engine	Palm, Rapeseed	Steady-state test	—	NO_x, HC, CO
Pala-En et al. (2013)	United States	HDV	Rapeseed, UCO, Animal fat, Soybean	UDDS, On-road (highway, arterial, idling)	Tier 2	NO_x, PM, HC, CO
Payri et al. (2005)	Spain	HDV	UCO	Steady-state test	Euro 3	NO_x, PM, HC, CO
Peterson (2000)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Peterson & Reece (1996)	United States	HDV	Rapeseed Ethyl Ester (REE)	FTP Transient	Tier 1	NO_x, PM, HC, CO
Proc et al. (2006)	United States	HDV	FAME	City-Suburban Heavy Vehicle Cycle (CSHVC)	Tier 1	NO_x, PM, HC, CO
Prokopowicz et al. (2015)	Poland	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NO_x, PM, HC, CO
Purcell et al. (1996)	United States	LDV	Soybean	Heavy Duty Transient (U.S. Bureau of Mines)	Tier 1	NO_x, PM, HC, CO
Purcell et al. (1996)	United States	HDV	Soybean	Transient Cycle (U.S. Bureau of Mines)	Euro 1	NO_x, PM, HC, CO
Rahman et al. (2013)	Malaysia	Engine	Palm, Calophyllum inophyllum	Steady-state test	—	NO_x, HC, CO
Rakopoulos et al. (2008)	Greece	HDV	Sunflower oil, Cottonseed	Steady-state test	—	NO_x, HC, CO
Rantanen & Mikkonen (1993)	Finland	HDV	Rapeseed	13-mode ESC test	Tier 1	NO_x, PM, HC, CO
Rizwanal Fattah (2014)	Malaysia	Engine	Palm	Steady-state test	—	NO_x, HC, CO
Ropkins et al. (2007)	UK	LDV	Rapeseed	UDC, EUDC, FTP 75	Euro 1	NO_x
Rose et al. (2010)	Europe	LDV	Rapeseed	NEDC, UDC, EUDC	Euro 4	NO_x, HC, CO
Roy et al. (2013)	Canada	HDV Engine	Rapeseed	Steady-state test	—	NO_x, HC, CO
Schumacher et al. (1994)	United States	HDV	Soybean	FTP Transient	Euro 2	NO_x, PM, HC, CO
Schumacher et al. (1996)	United States	HDV	Soybean	FTP Transient	Tier 1	NO_x, PM, HC, CO
Sedari et al. (1999)	Greece	LDV, Engine	Sunflower oil	On-road idling, Steady-state	Euro 1	NO_x
Serrano et al. (2015)	Portugal	LDV	Soybean	NEDC, UDC, EUDC	Euro 5	NO_x
Sharp (1994)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Sharp (1996)	United States	HDV	Rapeseed	FTP Transient	Tier 1	NO_x, PM, HC, CO
Sharp et al. (2000)	United States	HDV	Soybean	FTP Transient	Tier 1	NO_x, PM, HC, CO
Sharp, Ryan, & Knothe (2005)	United States	HDV	Soybean	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Shen et al. (2018)	China	LDV	Rapeseed	PEMS (Non Highway/ Highway Driving)	Euro 3, Euro 4	NO_x, PM, HC, CO
Sinha and Kumar (2019)	India	Engine	Jatropha	Steady-state test	—	NO_x, HC, CO

Study	Location	Vehicle type	FAME feedstock(s)	Test cycle(s)	Emission standard	Pollutant(s) measured
Souligny et al. (2004)	Canada	HDV	Animal fat, UCO, Vegetable oil	FTP Transient	Tier 1	NO_x, PM, HC, CO
Spataru and Romig (1995)	United States	HDV	Rapeseed	FTP Transient (Hot Start)	Tier 1	NO_x, PM, HC, CO
Starr (1997)	United States	HDV	Soybean	FTP Transient	Tier 1	NO_x, PM, HC, CO
Sze et al. (2007)	United States	HDV	Soybean	HWY, FTP, WHTC, UDDC (6k, 28k)	Tier 2	NO_x, PM, HC, CO
Tadano et al. (2014)	Brazil	HDV	Soybean	13-Mode ESC test	Euro 5	NO_x
Tatur et al. (2009)	United States	LDV	Soybean	FTP 75, HWFET	Euro 4	NO_x, HC, CO
Tian et al. (2013)	China	LDV	Rapeseed	Various	—	NO_x, PM, HC
Tompkins et al. (2009)	United States	Engine	Palm	Steady-state test	—	NO_x
Tzirakis et al. (2007)	Greece	LDV	UCO	On-road (urban driving)	Euro 4	NO_x, CO
Ullman et al. (1983)	United States	HDV	Soybean	1979 13-mode Federal Test Procedure	Tier 1	NO_x, PM, HC, CO
Usta (2005)	Turkey	Engine	Tobacco seed oil	Steady-state test	—	NO_x, CO
van Niekerk et al. (2019)	UK	LDV	FAME (unspecified)	WLTC	Euro 4	NO_x, CO
Wallington et al. (2016)	United States	LDV	Butyl Nonanoate	FTP 75, HWFET, US06	Euro 4	NO_x, PM, HC, CO
Wang et al. (2000)	United States	HDV	Soybean	WVU 5 peak truck cycle	Tier 1	NO_x, PM, HC, CO
Wirawan et al. (2008)	Indonesia	LDV	Palm	UDC and EUDC	Euro 2	NO_x, PM, HC, CO
Wu et al. (2009)	China	HDV Engine	Coconut, Rapeseed, Soybean, Palm, UCO	Steady-state test	Euro 3	NO_x, PM, HC, CO
Yasin et al.(2015)	Malaysia/Iran	LDV	Palm	Steady-state test	—	NO_x, HC, CO
Yoshida et al. (2008)	Japan	LDV	Rapeseed	NEDC	Euro 5	NO_x, PM, HC, CO
Zhu, Cheung et al. (2010)	China	HDV Engine	UCO	Steady-state test	Euro 5	NO_x, PM, HC, CO
Zhu, Zhang et al. (2010)	China	HDV	Palm, Rapeseed, UCO	Steady-state test	—	NO_x

APPENDIX C – EMISSION TEST CYCLES SUMMARY

Test cycle	Description	Compliance location	Vehicle type	Avg speed (km/hr)	Comments
FTP	Heavy-duty engine certification cycle	United States	HDV	30	Adherent to Code of Federal Regulations 40 CFR 86
UDDS (6k, 28k)	Urban Dynamometer Driving Schedule	United States	HDV	30.4	—
AVL 8-Mode	Steady State (SS) test developed by AVL	United States	HDV	—	8 SS modes (comparable to FTP test)
WHTC	World Harmonized Transient Cycle	International	HDV	—	Developed by the UN ECE GRPE technical group
NEDC	New European Driving Cycle	Europe/ International	LDV	33.35	Previously called the MVEG-A cycle (4 runs of UDC, one run of EUDC)
ECE R-49	Test cycle introduced via Regulation ECE No. 49	Europe/ International	HDV	—	13-mode SS procedure (used for heavy engine certification through Euro II)
ESC	European Stationary Cycle	Europe/ International	HDV	—	13-mode SS procedure which replaced R-49 test (Euro III stage on)
UDC	Urban Driving Cycle	Europe	LDV	18.35	Also called the ECE-15
EUDC	Extra-Urban Driving Cycle	Europe	LDV	62.59	Representative of aggressive urban driving
Artemis Driving Cycle (Urban)	Assessment and Reliability of Transport Emission Models and Inventory Systems	Europe	LDV	17.7	Statistical analysis of real-world driving conditions in EU
Artemis Driving Cycle (Rural Road)	Assessment and Reliability of Transport Emission Models and Inventory Systems	Europe	LDV	57.5	Statistical analysis of real-world driving conditions in EU
Artemis Driving Cycle (Motorway)	Assessment and Reliability of Transport Emission Models and Inventory Systems	Europe	LDV	96.9	Statistical analysis of real-world driving conditions in EU
CSHVC	City-Suburban Heavy Vehicle Cycle	United States	HDV	22.77	Developed by Vehicle Emissions Testing Laboratory at West Virginia University (WVU)
WVU 5-Peak/5-Mile Cycles	Cycles developed by the Vehice Emissions Testing Laboratory at West Virginia University	United States	HDV	48.3	Developed at WVU; In 5-mile cycle, vehicle reaches peak speeds under high acceleration
JE-05	Transient cycle introduced via 2005 emissions standards	Japan	HDV	26.94	—