

# Evaluation of PM Emissions of a Diesel Engine Fueled with Waste Cooking Oil Biodiesel: A Systematic Review

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**Abstract:** The Navigation Guide developed by Johnson et al was used to conduct a robust systematic review of six experimental intervention studies comparing particulate matter (PM) emissions from heavy-duty diesel engines using waste cooking oil biodiesel versus conventional petroleum diesel fuel. Waste cooking oil biodiesel is thought to be a more sustainably sourced alternative to its fossil fuel counterpart and can aid in reducing cooking oil waste streams. The Navigation Guide systematic review methodology tool was applied to analyse the hypothesized question: Does the replacement of petroleum diesel with waste cooking oil biodiesel reduce hazardous PM emissions in heavy duty vehicles? The study question was specified, evidence was selected and the quality and strength of the overall evidence was assessed for both individual studies and across the body of studies. Precise criteria and protocols were developed and followed throughout the review process to ensure that a thorough evaluation of all data was completed. All six studies that met the review inclusion criteria utilized six-cylinder direct injection engines. Although the PM emissions were measured differently across the exposure continuum, there was an overall PM emission reduction of 28% across the studies when petroleum diesel was substituted with waste cooking oil biodiesel. The overall risk of bias across the studies was determined to be 'low'. Based on the application of the Navigation guide methodology, it was found that the strength of the evidence provided was 'sufficient' to suggest an association between waste cooking oil biodiesel and PM emission reductions.

**Keywords:** Waste cooking oil, Biodiesel, Particulate matter, Sustainability

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## Introduction

For decades, the vast increase in the human population coupled with the combustion and use of non-renewable energy sources has led to an ongoing discussion on the relationship between outdoor air pollutants and its associated environmental and health effects. Air pollution, defined as the presence of air pollutants in large enough quantities that may prove harmful to human, animal or plant life, has been researched extensively.

In particular, there are growing global concerns regarding the depletion of natural crude oil and the increased greenhouse gas emissions associated with high petroleum usage. Petroleum oil accounts for approximately 40% of the total energy usage in the United States (U.S. EIA 2016). Of that, the transportation sector utilizes motor gasoline at increasing levels, with 8964 thousand barrels used per day in 2016 (U.S. EIA 2017). Diesel is a substituent formed from petroleum crude oil, and has become a popular transportation fuel alternative to gasoline, constituting 21% of petroleum consumed in the U.S. transportation sector (U.S. EIA 2017). It's typically used in trucks, trains and heavy-duty off-road automotive vehicles due to its lighter weight and greater energy density per unit of volume.

Despite its energy benefits, diesel is still a major contributor of carbon dioxide, the most prevalent greenhouse gas. Approximately 22 pounds of CO<sub>2</sub> is produced for every gallon of diesel fuel that is burned, compared to about 19 pounds of CO<sub>2</sub> per gallon of gasoline. (U.S. EIA 2017). Advances in technology have allowed for the development of more sustainably-sourced diesel fuel-blend (biodiesel) alternatives. Research has shown that combustion of B20, a common biodiesel fuel composed of 20% soybean oil and 80% petroleum diesel, has

shown promising results in emissions of 17 pounds of CO<sub>2</sub> per gallon (U.S. EIA 2017). Using waste cooking oil (WCO) as a petroleum diesel blend has become an attractive sustainable solution. It can be locally sourced more easily and contribute to a large reduction in waste production. Hotels and restaurants in the U.S. alone are estimated to generate up to 3 billion gallons of WCO each year (U.S. EIA 2016), demonstrating a large potential for WCO collection from other sectors.

Although benefits in carbon dioxide reduction have already been established, there are still some uncertainties as to whether there are similar trends shown for particulate matter (PM) emissions. A subcategory of particulate matters, PM<sub>2.5</sub>, is a prevalent air pollutant made up of a variety of particulates with a size of 2.5µm or smaller. These particulates raise public health concerns because of their ability to penetrate deeply into the respiratory tract, and have been studied extensively to determine potential adverse health impacts. Identified health issues that have been linked to PM<sub>2.5</sub> exposure include coughing, shortness and tightness of breath, reduced lung function and aggravation of existing lung and/or heart conditions (U.S. EPA 2012).

PM emissions from petroleum diesel engines vary based on the type of engine used, but are approximately six to ten times higher than standard gasoline engines (Reşitoğlu et.al 2014), and have shown to contribute 10-36% of total PM emissions in some densely populated urban areas (U.S. EPA 2002). This paper is a detailed systematic review that assesses the overall quality of evidence from relevant studies that comprehensively looked at PM emissions in heavy-duty compression ignition engines tested with petroleum diesel versus a 20% WCO-biodiesel blend. Conclusions will be drawn by evaluating whether a WCO- biodiesel alternative is associated with reduced PM emissions and how this could aid to combat adverse environmental, health and waste impacts seen today.

## **Methods**

### ***Systematic Review Methodology***

This systematic review was conducted in conjunction with an environmental health sciences review methodology tool called the Navigation Guide (Johnson et.al 2014). The use of this guide required that each of the selected studies were assessed and rated based on the investigations of the association between PM emissions and the use of petroleum diesel versus WCO-biodiesel. The risk of bias, strength of evidence and overall study quality were evaluated and are presented in the results section.

### ***Study Question***

The objective of this systematic review is based on the hypothesis that PM tailpipe emissions are affected by switching from petroleum diesel to a WCO-biodiesel alternative. Each element of the study question is outlined and developed from the PICO statement below.

*Population* – Heavy-duty automotive diesel engines

*Intervention* – Waste Cooking Oil Biodiesel: Experimental intervention studies were selected that used a WCO-biodiesel blend in replacement of standard petroleum diesel in heavy-duty compression ignition engines under similar experimental conditions.

*Comparator* – Petroleum Diesel

*Outcome* – PM emission levels: A quantitative analysis including the percentage of PM emitted was recorded in each study.

### ***Data Sources***

A thorough and extensive search strategy was conducted by using the PICO statement as a guide to coin a series of search terms and synonyms which addressed the specified intervention and outcome of interest. Minute changes were then made in the search terms to aid in widening the range of results found. The search primarily utilized the electronic databases ScienceDirect, and Scopus, between the 20th September and 3rd October 2017. Additional terms were coined and searched between the 10th and 13th of October 2017. Other sources used included academic literature, such as the George Washington University Library, and internet databases. The citations and bibliographies of titles and abstracts that were screened for further review were checked for additional potential studies. The search was limited to studies written in English and that were published after 2010.

### ***Study Selection***

Studies were selected in which a primary experimental intervention was conducted to test and compare the PM emissions from heavy-duty compression ignition automotive engines using standard petroleum diesel versus a 20% WCO-biodiesel blend. A general screening of titles was conducted and then once studies were selected, a further screening of abstracts was completed to determine if the subject matter of the article was appropriate for further intensive review. The online citation tool, RefWorks, was used to remove duplicates and organize the chosen studies throughout the screening process. Only studies that were published from 2010 onwards were reviewed, due to the development and improvement of technology used to produce these biodiesels. The list below outlines the eligibility criteria used to screen studies.

Studies were excluded if:

- They did not contain their own original data or observations.
- They failed to mention the blend ratio of the waste cooking oil biodiesel (20%) and the observance of PM in the title/abstract.
- The biodiesel and petroleum diesel comparisons were not carried out on heavy-duty compression ignition automotive engines.
- They were not experimental intervention studies (i.e. engines were not tested under the same circumstances)
- They were conducted prior to 2010.
- They were not written in English.

### ***Assessing the Risk of Bias for Each Included Study***

Each of the final individual papers selected for the systematic review were evaluated to determine if and what risk of bias may have occurred during the completion of the study. As outlined in the Navigation Guide, the different bias domains considered included: recruitment strategy, blinding, confounding, exposure assessment, selective outcome reporting and possible conflicts of interest (Johnson et.al 2014). Each bias domain has their own specific assessment criteria and was appointed a rating on a scale of “low risk”, “probably low risk”, “probably high risk”, “high risk” and “not applicable” (Johnson et.al, 2014), with accompanying support as to why these judgements were made. Once the individual study assessments were made, the risks were then evaluated based on the entire body of studies using the same criteria, to aid in ensuring consistent interpretation.

The recruitment strategy was assessed to determine whether the procedures used in the experimental testing of the studies were applied consistently amongst the entire study population. Whether blinding was used showed

that the PM emission outcome was fairly presented without any prior knowledge of the type of fuel used by the investigator.

The exposure assessment was evaluated to discern if appropriate measures were taken to avoid exposure misclassification and if the testing procedures and methods containing WCO-biodiesel and petroleum diesel had been done in the same fashion across the study. Identification of any alterations to the engines were also evaluated within this risk domain.

Potential confounding variables should have been acknowledged and controlled for appropriately throughout the course of the experiments. The final investigative studies chosen for this review were conducted under the most similar circumstances to aid in controlling for these factors. All the outcomes measured should have been presented, regardless if they met the hypothesized result or not, to reduce the risk of selective outcome reporting and increase the robustness of the obtained results. Finally, the acknowledgement sections were assessed to determine if any conflict of interests occurred. This may have been in the form of any outstanding financial support from private organizations or other entities that would obscure the overall results of the study.

### ***Rating the Quality and Strength of the Evidence across Studies***

A rating scale ranging from 'high' to 'moderate' to 'low' was developed to methodically assess the overall quality of the body of evidence presented across the studies. Due to the nature of these experimental investigative studies and the lack of human participants, the 'Grading and Recommendations Assessment Development and Evaluation' System (GRADE) (Balslem et.al 2011) typically used in conjunction with the Navigation Guide, could not be directly utilized. Therefore, all the studies were assigned an initial 'high' rating, and downgraded based on whether any of the evaluated risk of bias domains were categorized as 'probably high risk' or 'high risk'.

Rating the strength of the body of evidence aided in determining if there was enough indication to decide whether the hypothesized intervention can lead to decided action. In conjunction with the quality of evidence rating mentioned above, the direction of the effect estimate and identification of other compelling attributes of the data that might influence uncertainty (Johnson et.al 2014) contributed towards the rating for the overall strength of evidence. The rating scale assignments are 'sufficient evidence of reduced PM emissions', 'limited evidence of reduced PM emissions', 'inadequate evidence of reduced PM emissions' or 'evidence of no reduction in PM emissions'.

## **Results**

### ***Included Studies***

Out of 2295 uniquely screened studies, a total of six were selected for final comparative analysis. Figure 1 is a flowchart that demonstrates the literature search and the breakdown of the number of studies selected during each screening process. In addition to the exclusion criteria outlined in the methods, additional reasons for excluding studies during the title/abstract and final study screenings included:

- They were not an experimental intervention study design
- The use of bioethanol instead of petroleum biodiesel as a comparator
- The use of diesel generator engines instead of heavy-duty automotive engines
- Studies that only conducted life cycle assessments of biodiesel
- Studies using a different blend ratio of biodiesel other than 20%

- The conducted emissions tests did not include particulate matter (PM) in the final analysis

The characteristics of each study are outlined in Table 1 below. All were experimental interventions studies that were conducted between 2010 and 2017, allowing for the implementation of newer technologies for biodiesel development.

### ***Risk of Bias Assessment for Individual Studies***

The Hadavi et al study (Hadavi et.al 2015) was one of three studies (including Kawana et.al and Martin et.al) to test the use of WCO-biodiesel under real world conditions. PM emissions were tested using a refined straight used cooking oil (named C2G Ultra Biofuel) on 10 heavy-duty commercial trucks provided by United Biscuits Ltd, a large multinational food manufacturing company. Selecting vehicles from the same fleet increased the likelihood of comparative results (i.e. low risk for recruitment bias), however, the involvement of this large

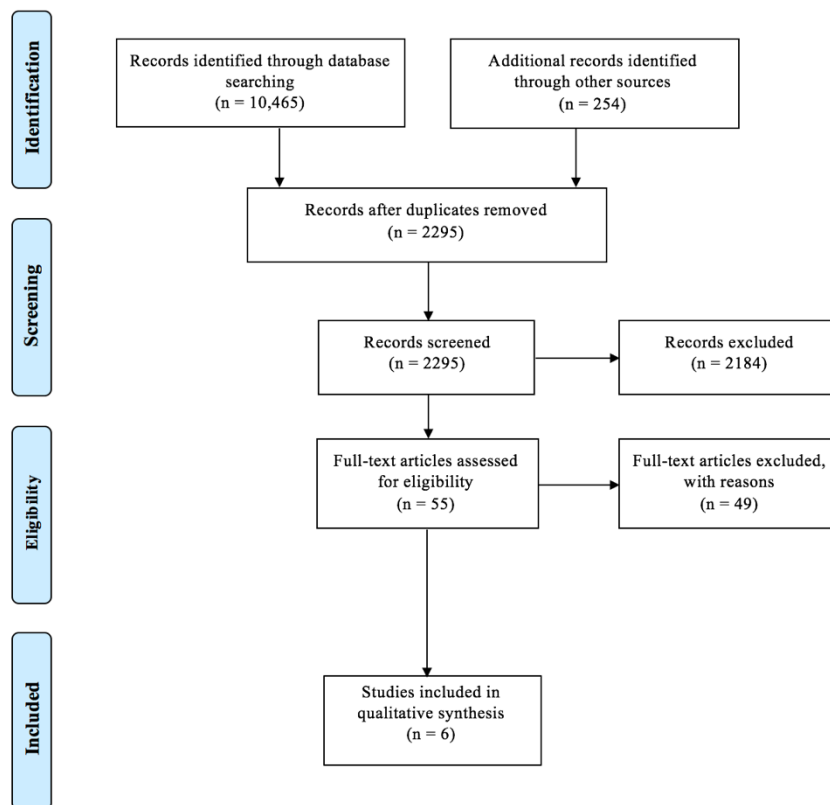


Figure 1. Flowchart demonstrating breakdown of literature search and screening process.

private organization resulted in the ‘probably high risk’ rating for the conflict of interest domain. Upon further review, it was determined that this private funding was not shown to affect the quality of the study’s results. The engines were converted to be able to burn both the C2G Ultra Biofuel and standard petroleum diesel before testing began. PM exhaust samples were taken using Anderson impactors in the tailpipe. Although alterations were made, they were consistent amongst all the engines, ensuing the ‘probably low risk’ determination for the exposure assessment. Additionally, all vehicles were tested when loaded versus empty, were driven by the same driver, and were driven along the same route, to ensure consistency among testing procedures. Confounding variables were not acknowledged, but using the same drivers and routes decreased their likelihood. Also, selective outcome reporting was not shown in this study. Overall, PM emissions decreased by 69.5% when

looking at the average concentration between petroleum diesel ( $1.77\text{mg}/\text{m}^3$ ) and C2G Ultra Biofuel ( $0.53\text{mg}/\text{m}^3$ ). The overall risk of bias for this study was concluded to be ‘probably low risk’.

The aim of the Kawano et al study was to determine if the use of WCO-biodiesel would comply with national short-term and long-term regulations for exhaust emissions, potentially strengthening the argument for the biodiesel’s implementation and feasibility (Kawano et.al 2010). An older heavy-duty diesel bus was used to test compliance with short-term regulations, and two newer heavy-duty diesel busses tested compliance with long-term regulations. Blinding was not utilized in this study; however, it may have been effective as these researchers are already accustomed to the use of WCO-biodiesel and may be expecting positive results. These buses were already equipped to work with WCO-biodiesel, making the recruitment strategy low risk. In Kyoto, Japan (where the study was conducted), there is already a WCO collection scheme and large biodiesel production plant in place. The tests were conducted according to Japanese regulation by using a chassis dynamometer for transient emission characteristics. No measurement alterations were made to the engines, and PM was collected on a Teflon filter downstream of the exhaust pipes. No selective outcome reporting was observed. There was an average PM reduction of approximately 19% with the use of biodiesel when averaged between the older and newer vehicles. The overall risk of bias was found to be ‘low risk’ for this study.

The entirety of this Lin et al study (Lin et.al 2010) was conducted in close resemblance to the Liu et al study described below, excluding the use of a catalyzer. The test engine provided is one that is commonly used to conduct emissions tests for national pollutant emission regulations. Testing conditions were made to resemble urban and freeway driving conditions, although it was not necessarily conducted in a real-world setting. The use of blinding was not acknowledged, although it does not appear to have affected study outcomes. A monitoring system were used to facilitate continuous measurements of PM emissions, but no alterations were made to the engine itself, demonstrating low risk of bias for exposure assessment. Selective outcome reporting was not shown in this study. The conflict of interest domain was found to be ‘probably low risk’, as most of the financial support was provided from a grant by the National Science Council of Taiwan, but the engine was provided by CPC Corporation, a publicly owned petroleum, natural gas and gasoline company. There was a PM reduction of approximately 7.4% when fueled with WCO-biodiesel ( $0.212\text{ g BHP}^{-1}\text{ h}^{-1}$ ) compared to petroleum diesel ( $0.229\text{ g BHP}^{-1}\text{ h}^{-1}$ ). The overall risk of bias was ‘low risk’ for this study.

The Liu et al study utilized a heavy-duty diesel engine equipped with a catalyzer under conditions to mimic typical urban and freeway driving conditions. There was no mention of how the engine was obtained, or chosen for this particular study. Therefore, recruitment strategy was deemed ‘probably low risk’. The use of blinding was not acknowledged, although it does not appear to have affected study outcomes. A similar dilution and monitoring system were utilized to collect PM emissions, with no alterations made. PM emissions were collected using glass-fiber filters. Confounding variables were not acknowledged, but are assumed to not have affected results shown. Also, selective outcome reporting was not shown in this study. No financial conflicts of interest were identified with this study, as the only support provided was through a grant from the National Science Council of Taiwan. PM emissions were shown to decrease by 15.5% when fueled with WCO-biodiesel ( $0.087\text{ g BHP}^{-1}\text{ h}^{-1}$ ) compared to petroleum diesel ( $0.103\text{ g BHP}^{-1}\text{ h}^{-1}$ ). The overall risk of bias was ‘low risk’ for this study.

The aim of the Martin et al study was to “perform an exposure assessment on an active worksite to better approximate PM inhalation levels” (Martin et al 2016). One heavy-duty 6-cylinder non-road vehicle was first fueled with petroleum diesel and then a 20% waste grease (WG) biodiesel blend. Smoking was identified and eliminated as a confounding factor due to the testing taking place in a smoke-free worksite. The recruitment strategy was considered to be low risk for this study, as the day-to-day operations were not interfered with, therefore not effecting the PM emissions shown. The use of blinding was not mentioned by researchers, and was classified as probably low risk. PM emissions were collected using pumped cascade impactors on the vehicles and in the areas of the site that were estimated to have the most worker activity. No alterations were made to the

test vehicles' engines before the use of petroleum diesel and WG-biodiesel, therefore the exposure assessment was also found to be low risk. Selective outcome reporting was not present and was deemed as low risk.

Additionally, no conflict of bias appeared to be present, although no official statements were declared. This resulted in a rating of 'probably low risk'. The PM emitted when the engine used WG-biodiesel was  $53 \mu\text{g}/\text{m}^3$ , an 8.6% reduction from the  $58 \mu\text{g}/\text{m}^3$  seen from use of petroleum diesel. Overall, this study was determined to have an overall low risk of bias.

Finally, the Nabi et al study evaluated engine performance and emission patterns with WCO-biodiesel on a 6-cylinder heavy-duty common rail diesel engine. The reason for the researchers using this engine was not identified, resulting in the 'probably low risk' rating for recruitment strategy. The test procedure was conducted multiple times while the engine was set at different speeds and different loads, making for a robust exposure assessment. A dilution tunnel and aerosol monitor were used to gather PM emission measurements, but no alterations were made to the engine itself. There were no conflicting interests identified, as the study was funded under the Australian Research Council. On average, there was an approximately 47% reduction in PM emissions across all loads and speeds when compared to the petroleum diesel results. The overall risk of bias for this study was deemed to be 'low'.

Figures 2a and 2b provide a visualization of the risk of bias ratings for each of the studies and across the body of studies. All the studies carried out their tests on heavy-duty 6-cylinder direct injection diesel engines, and minimal, if any, adjustments were made to the engines themselves. The conflict of interest domain had the highest risk across the studies, due to the involvement of some private organizations, however no major concerns were raised that would obscure the accuracy of results shown.

*Table 1 Summary of study characteristics evaluating PM emissions from use of WCO-biodiesel in heavy-duty diesel engines*

Source	Location of Study	Type of Engine	Type of Biodiesel	Outcome Measured	Test Procedure	Major Results
Hadavi et al, 2015	Ashby, United Kingdom	Heavy-duty direct injection compression ignition turbocharged 6-cylinder diesel engine	C2G ultra biofuel made with refined used cooking oils, 20% blend	PM emissions collected with Anderson Impactor and preconditioned glass fiber filter papers	Tests completed on tractors with empty and loaded trailers in real-world setting	<b>69.5%</b> reduction in PM emissions from petroleum diesel ( $1.77\text{mg}/\text{m}^3$ ) to C2G ultra biofuel ( $0.53\text{mg}/\text{m}^3$ )
Kawano et al, 2010	Kyoto, Japan	Heavy-duty 6-cylinder 7.79L direct injection turbo diesel engine	Waste cooking oil biodiesel, 20% blend-collected from households, hotels and restaurants and converted to biodiesel	PM collected on a Teflon filter while at constant air flow	Transient mode test cycle conducted on chassis dynamometer for investigation of transient emission characteristics	<b>19.2%</b> average reduction in PM emissions from petroleum diesel ( $0.026\text{g}/\text{kWh}$ ) to WCO-biodiesel ( $0.021\text{g}/\text{kWh}$ )
Lin et al. 2010	Kaohsiung, Taiwan	Heavy-duty Cummins BD.9-160 turbocharged direct injection 6-cylinder diesel engine	Waste cooking oil biodiesel, 20% blend	Dilution tunnel and monitoring system installed downstream of exhaust to facilitate continuous measurement of suspended PM particles	Schenck GS-350 dynamometer used to mimic typical driving conditions	<b>7.4%</b> reduction in PM emissions from petroleum diesel ( $0.229\text{g BHP}^{-1}\text{h}^{-1}$ ) to WCO-biodiesel ( $0.212\text{g BHP}^{-1}\text{h}^{-1}$ )
Liu et al, 2012	Kaohsiung, Taiwan	Heavy-duty Cummins BD.9-160 turbocharged direct injection 6-cylinder diesel engine	Waste cooking oil biodiesel, 20% blend	Dilution tunnel and monitoring system installed downstream of exhaust to facilitate continuous measurement of suspended PM particles	Mild engine loaded conditions to represent typical urban and freeway driving	<b>15.5%</b> reduction in PM emissions from petroleum diesel ( $0.103\text{g BHP}^{-1}\text{h}^{-1}$ ) to WCO-diesel ( $0.087\text{g BHP}^{-1}\text{h}^{-1}$ )
Martin et al, 2016	Keene, New Hampshire USA	Heavy-duty large front loader 6-cylinder diesel engine	Waste grease biodiesel., 20% blend	PM emissions collected using a Sioutas cascade impactor	Non-road equipment run on diesel and biodiesel for 16 days and impactors placed at different locations to collect varying PM exposure	<b>8.6%</b> reduction in PM emissions from petroleum diesel ( $58\mu\text{g}/\text{m}^3$ ) to WG-biodiesel ( $53\mu\text{g}/\text{m}^3$ )
Nabi et al, 2017	Perth, Australia	Heavy-duty 6-cylinder common rail diesel engine	Waste cooking oil biodiesel, 20% blend	PM was collected using a DustTrak II Aerosol Monitor 8530	Engine operated in 14-mode European Stationary Cycle to observe emissions with different biodiesel blends	<b>47%</b> average PM reduction from petroleum diesel to WCO-biodiesel across different speeds and loads



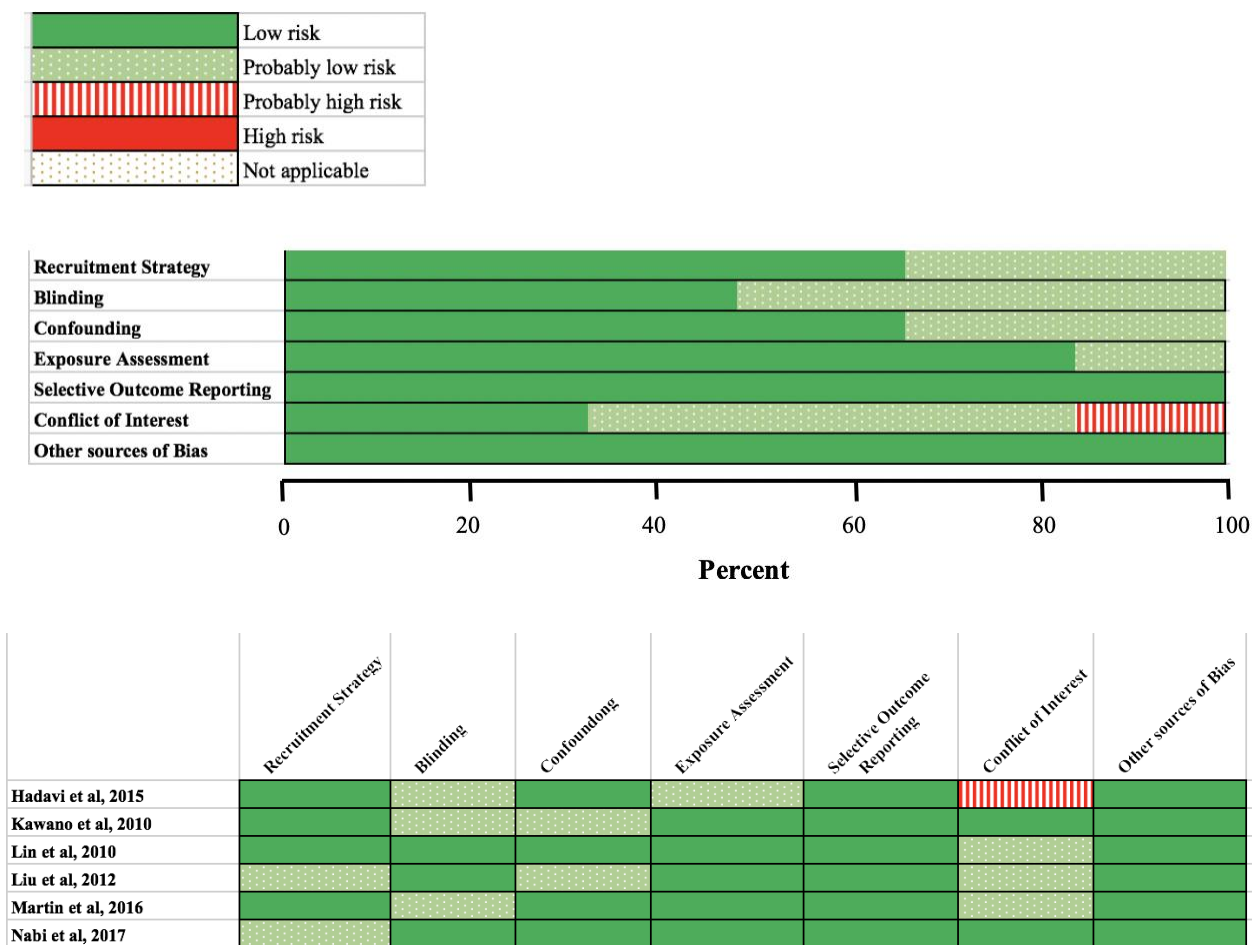


Figure 2b. Risk of bias designations given as percentages across all included studies

### Quality and Strength of the Body of Evidence

After thorough evaluation of the risk of bias within and between the studies chosen, the overall quality of evidence presented was deemed to be of high quality. The only bias domain classified as ‘probably high’ was the potential conflict of interest for the Hadavi et al study (Hadavi et al, as the trucks used in the investigation were provided by a large private multinational food manufacturer. However, it was not warranted as enough to consider the downgrading of the overall study quality.

- The overall strength of evidence was determined based on three considerations.
- The quality of the body of evidence was high
- Direction of the effect estimate: in general, the use of WCO-biodiesel decreased the emissions of PM
- There were no other compelling attributes of the data that influenced uncertainty of the study, and no evidence of publication bias.

Based on these factors shown, the overall strength of evidence was determined as 'sufficient'. It is believed with reasonable confidence, that the available evidence demonstrates studies that have been well conducted, and results that have been outline concisely.

## **Discussion**

After concise application of the Navigation Guide tool, it was determined that the major conclusion from the data collected supports the initial hypothesis and demonstrates that the use of waste cooking oil as a biodiesel is a beneficial substitution to standard petroleum diesel when aiming to reduce PM emission concentrations. All six studies chosen for review conducted an experimental intervention by using a 20% waste cooking oil biodiesel blend on a 6-cylinder heavy-duty engine. The calculated average percentage reduction of particulate matter emissions among the six studies when switching from petroleum diesel to a WCO-biodiesel was 27.9%. This data presented was deemed to be sufficient, with 'high' strength and quality of the evidence presented, as well as a low risk of bias amongst the studies.

Diesel engines are one of the largest sources of particulate emissions, contributing to adverse effects seen in the environment and to human health (Agarwal et al 2015). Diesel particulate matter exposure is thought to be associated with an array of chronic and acute cardiopulmonary health risks, including lung and cardiovascular inflammation, exacerbation of asthma, and development of lung cancer (Martin et al 2016). A study by Pope et al, even suggests that there may be no safe exposure threshold between PM exposure and the development of negative health impacts (Pope et al 2009). These are just some of the public health implications involved with mass utilization of petroleum diesel. A study by the World Bank found that from 1990 to 2013, annual premature deaths attributed to PM emission exposure increased by approximately 30% from 2.2 to 2.9 million. (World Bank Group 2016).

In addition to reduced PM and other gaseous compound emissions (particularly carbon dioxide and carbon monoxide), the concept of using WCO biodiesel as an alternative fuel source is an attractive one for several reasons. Heavy-duty diesel engines were chosen as the experimental population for this review, as the majority of diesel-powered vehicles in the United States are classified as large trucks, buses, commercial and off-road. The potential scope of influence for switching to a cleaner burning fuel source is a major consideration for implementation of this biodiesel. Additionally, improvements in waste control in conjunction with the increased longevity of the world's rapidly depleting petroleum sources cannot be ignored.

A limitation of this review is that the Navigation Guide utilized for completion, is not really suited to studies that do not have a human population. This made it quite difficult to adjust the risk of bias domains, and strength of evidence categories to adequately assess these papers. Additionally, only two of the six studies evaluated for PM emissions specifically. The rest of the studies encompassed PM into a single particulate matter category, failing to mention the diameter range in which they were specifically measuring for. Although PM would be included in these concentrations, it does not allow from completely synchronous comparisons. Issues for systematic comparisons also arose when looking at different studies, due to the different units used for analyzing and reporting PM emissions between studies. Percentage change in emissions were calculated for each study, to aid in strengthening overall conclusions of the review.

Ample studies have been conducted that demonstrate the improvements in particulate matter and other gaseous pollutant emissions with the use of a WCO biodiesel blend. Feasibility and life-cycle assessments should be further conducted to cover gaps in knowledge and to aid in determining whether mass production, distribution and collection of this form of biodiesel can be transitioned to over the discernable future. Based on the results from this review, it is suggested that enough evidence is present in the literature to warrant the benefits of using waste cooking oil biodiesel blend.

## **Conclusion**

Based on the entire evaluation of this evidence using the Navigation Guide, the conclusion of this systematic review is that there is ‘sufficient’ evidence to suggest an association between reduced PM emissions and the use of WCO-biodiesel in replacement of standard petroleum diesel. As the benefits of reduced PM emissions have been recognized, it is believed that decided action should be taken to determine next steps in regard to mass production and distribution of such a fuel. Waste cooking oil biodiesel is a promising next step towards a more sustainable environment, reduced waste and improved public health.

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**Appendix**

**Risk of Bias Judgements for Individual Studies**

*Table 1a: Emissions from a HGV using Used Cooking Oil as a Fuel under Real World Driving Conditions. Hadavi et al. 2015*

Bias	Rating	Support For Judgement
Recruitment Strategy	Low Risk	All vehicles selected used the same type of engine as they were from the same fleet
Blinding	Probably Low Risk	Was not mentioned although did not seem to affect study results
Exposure Assessment	Probably Low Risk	Consistent alterations were made across all test vehicles to be able to burn the C2G Ultra Biofuel
Confounding	Low Risk	Not necessarily mentioned, but used the same drivers and routes for testing
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Probably High Risk	Although the study was supported in part by the UK Department of Transport, the trucks were provided by the United Biscuits Ltd, a large private multinational food manufacturing company
Other bias	Low Risk	No other biases identified

*Table 1b: Exhaust Emission Characteristics of Commercial Vehicles Fuelled with Biodiesel. Kawano et al, 2010*

Bias	Rating	Support For Judgement
Recruitment Strategy	Low Risk	All vehicles used already equipped for WCO-biodiesel use
Blinding	Probably Low Risk	Not acknowledged but may have been effective as researchers already accustomed to WCO-biodiesel use
Exposure Assessment	Low Risk	No alterations made to the engine itself that would affect PM emissions. Tests completed according to national regulations.
Confounding	Probably Low Risk	Did not mention whether same driving conditions were utilized, although no evidence to assume otherwise.
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Low Risk	Study was completed as part of a project for the Ministry of the Environment of Japan
Other bias	Low Risk	No other biases identified

*Table 1c: Experimental Investigation of the Performance and Emissions of a Heavy-duty Diesel Engine Fueled with Waste Cooking Oil Biodiesel/Ultra-low Sulfur Diesel Blends. Lin et al. 2010*

Bias	Rating	Support For Judgement
Recruitment Strategy	Low Risk	Testing conducted on engine commonly used for Federal regulation testing
Blinding	Low Risk	Was not mentioned although did not seem to affect study results
Exposure Assessment	Low Risk	No alterations made to the engine itself that would affect PM emissions.
Confounding	Low Risk	Not mentioned, but no evidence to assume results were affected
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Probably Low Risk	Although study was funded in part by a grant from the National Science Council of Taiwan, it was also supported by CPC Corporation, a petroleum, natural gas and gasoline company
Other bias	Low Risk	No other biases identified

*Table 1d: Emissions of Regulated Pollutants and PAHs from Waste-Cooking-Oil Biodiesel fuelled Heavy-duty Diesel Engine with Catalyzer. Liu et al. 2012*

Bias	Rating	Support For Judgement
Recruitment Strategy	Probably Low Risk	Reasons for acquirement of engine were not mentioned
Blinding	Low Risk	Was not mentioned although did not seem to affect study results
Exposure Assessment	Low Risk	No alterations made to the engine itself that would affect PM emissions.
Confounding	Probably Low Risk	Not mentioned, but no evidence to assume results were affected. Use of catalyzer may have skewed results.
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Probably Low Risk	Although study was funded in part by a grant from the National Science Council of Taiwan, it was also supported by CPC Corporation, a petroleum, natural gas and gasoline company
Other bias	Low Risk	No other biases identified

Table 1e: Effect of Biodiesel Fuel on “Real-World”, Nonroad Heavy Duty Diesel Engine Particulate Matter Emissions, Composition and Cytotoxicity. Martin et al, 2016

Bias	Rating	Support For Judgement
Recruitment Strategy	Low Risk	The study did not interfere with the day to day operations of workers on site.
Blinding	Probably Low Risk	Was not mentioned although did not seem to affect study results
Exposure Assessment	Low Risk	No alterations made to the engine itself that would affect PM emissions.
Confounding	Low Risk	Smoking removed as a confounding variable for PM inhalation
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Probably Low Risk	No statement claiming conflicts of interest were present, although no evidence to suggest otherwise.
Other bias	Low Risk	No other biases identified

Table 1f: Reductions in Diesel Emissions including PM and PN Emissions with Diesel-Biodiesel Blends. Nabi et al, 2017

Bias	Rating	Support For Judgement
Recruitment Strategy	Probably Low Risk	Reasons for acquirement of the engine were not mentioned.
Blinding	Low Risk	Was not acknowledged but not assumed to affect study results.
Exposure Assessment	Low Risk	No alterations made to the engine itself during testing. Tests completed multiple times under emission testing regulations.
Confounding	Low risk	Not mentioned, but no evidence to assume results were affected.
Selective Outcome Reporting	Low Risk	All outcomes identified were reported appropriately
Conflict of Interest	Low Risk	Study was funded by the Australian Research Council.
Other bias	Low Risk	No other biases identified