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NO_X Emissions and Performance of a Compact Diesel Tractor Fueled with Emulsified and Non-Emulsified Biodiesel

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Abstract

A John Deere 3203 compact utility tractor (23.9 kW rated engine power) was fueled with No. 2 petroleum diesel (D2), neat biodiesel (B100), and a 10% water-in-biodiesel emulsion (Em-B100) to determine the effects on exhaust gas temperature, oxides of nitrogen (NO_X) emissions, power, specific fuel consumption, and thermal efficiency under two load conditions (rated engine speed and peak torque). At rated engine speed, fueling with D2 resulted in statistically significantly ($p < .05$) higher exhaust gas temperatures than B100 and Em-B100; however, there were no significant differences in power take-off (PTO) specific NO_X emissions. Specific fuel consumption was statistically significantly lower for D2 when compared to B100 and Em-B100, but there were no significant differences in thermal efficiency among fuels. For peak torque tests, exhaust gas temperatures were statistically significantly lower with Em-B100 than with D2 or B100. PTO specific NO_X emissions with Em-B100 were equal to D2 and statistically significantly lower than B100. There was no significant difference between B100 and Em-B100 in specific fuel consumption, but specific fuel consumption for both fuels was statistically significantly higher than D2. However, fueling with B100 and Em-B100 resulted in statistically significantly higher thermal efficiencies as compared to D2. At both rated engine speed and peak torque, there were statistically significant decreases in PTO power as fuel was switched from D2 to B100 to Em-B100. These results indicate that Em-B100 has the potential to decrease NO_X emissions and increase engine thermal efficiency under heavy load conditions; however, NO_X reduction with Em-B100 will be at the expense of decreased power at both rated engine speed and peak torque.

Keywords**:** biodiesel, engine performance, emulsified biodiesel, fuel efficiency, oxides of nitrogen, power

Introduction

When fully implemented in 2015, EPA Tier IV emissions standards mandate a 90% reduction in regulated diesel engine exhaust emissions as compared to pre-Tier standards (ASABE, 2010). In order to meet theses mandates, manufacturers have made a number of engine modifications including increased injection pressures, optimized combustion chamber design, and multiple injection strategies (Kumar, Bellettre, & Tazerout, 2009), as well as various methods of exhaust gas recirculation and after-treatment (ASABE, 2010). While these engineering modifications will reduce emissions from new engines, the EPA (2004) estimated there were over 7 million non-road diesel engines in use in 1995 and these will not be fully retired until 2030. Thus, there is considerable interest in effective, low-cost methods of reducing emissions from existing non-road diesel engines (Kumar et al., 2009).

The increasing world-wide demand for energy, coupled with concerns about emissions, have resulted in increased interest in renewable, clean-burning alternative fuels for transportation, industry, and agriculture. The U. S. Energy Independence and Security Act of 2007 mandated 36 billion gallons of renewable fuel will be produced annually by 2022. Approximately two-thirds of this fuel will consist of advanced biofuels, including biodiesel (Sadaka & Boateng, 2009).

Biodiesel is a renewable fuel produced primarily from vegetable oils, cooking greases and oils, or animal fats (DOE, 2009). Researchers (Canacki & Van Gerpen, 2003; Neel, Johnson, & Wardlow, 2008; Proc, Barnitt, Hayes, Ratcliff, & McCormick, 2006; Schumacher, Clark, Lyons, & Marshall, 2001) have found little difference in power or specific fuel consumption between engines fueled with petroleum diesel (D2) or a 20% biodiesel blend (B20) and decreased power and increased specific fuel consumption with 100% biodiesel (B100), because it contains approximately 12% less energy than D2 on a mass basis (DOE, 2009).

The use of biodiesel and biodiesel blends significantly reduces total hydrocarbon, particulate matter, CO, and life-cycle CO_2 emissions (DOE, 2009; Xue, Grift, & Hansen, 2011). However, there are concerns about the potential for biodiesel, especially B100, to increase NO_X emissions (Xue et al., 2011). NO_X is an EPA-regulated pollutant associated with several adverse environmental and health effects including smog, emphysema, bronchitis, and heart disease (EPA, 1998).

Sun, Caton, and Jacobs (2010) stated the factors contributing to formation of engine NO_X emissions are complex and interrelated, but one primary mechanism appears to be thermal and is related to both the design of the engine and the physical and chemical properties of the biodiesel. These interactions between engine design and fuel characteristics influence injection timing, ignition delay, adiabatic flame temperature, and radiant heat transfer from the combustion chamber. When the net effect of these changes is an increase in post-flame combustion temperatures, NO_X emissions tend to increase (Sun et al., 2010).

NO_X emissions tend to increase at higher engine torque loads and at lower engine speeds. This inverse relationship between engine speed and NO_X emissions has been attributed to increased oxygen availability in a lean air-fuel mixture (i.e., equivalence ratio is less than 1) and an increased in-cylinder mixture residency time at decreased engine speeds (De Risi, Manieri, & Laforgia, 1999; Xue et al., 2011).

One potential method of reducing NO_X emissions from current non-road diesel engines is using water-in-biodiesel emulsions (Davis, Johnson, Edgar, Wardlow, & Sadaka, 2012; Kass et al., 2009; Koc & Abdullah, in press; Kumar et al., 2009). Emulsified biofuels are believed to reduce

NO_X emissions by lowering the combustion flame temperature and by increasing hydroxyl (OH) radicals. Reducing combustion temperature has been shown to reduce thermal NO_X production (Sun et al., 2011) while OH radicals do not combine effectively with molecular nitrogen to form NO, also reducing NO_X emissions (Alahmer, Yamin, Sakhrieh, & Hamdan, 2010; Kass et al., 2009). Several studies have found that emulsified biodiesel has the potential to reduce NO_X emissions from emulsified B100 to levels equal to or less than that of D2 (Awang & May, 2007; Davis et al., 2012; Kass et al., 2009; Koc & Abdullah, in press).

The effects of emulsified fuels on engine performance have been mixed, with some researchers reporting increased power (Abu-Zaid, 2004; Davis et al., 2011) while others (Kass et al., 2009) have found decreased power. Emulsified fuels affect engine power through several mechanisms (Alamar et al., 2010; Chadwell & Dingle, 2008; Kass et al., 2009; Kumar et al., 2009). As water changes from liquid to vapor it absorbs energy in the combustion chamber reducing the force acting on the piston, decreasing power. Conversely, as water expands during the phase change from liquid to gas the resulting high-pressure steam increases the force acting on the piston, increasing power. Finally, the increased injection velocity and micro-explosion of water droplets during combustion results in better fuel atomization and more complete combustion, increasing power. Thus, the relative power from use of emulsified fuels varies depending on which of these three mechanisms predominate (Chadwell & Dingle, 2008).

Purpose

Emulsified biodiesel has the potential to decrease NO_X emissions from current non-road diesel engines and may affect engine performance. The purpose of this study was to fuel a compact diesel tractor with D2, B100, and a 10% (water by volume) emulsified B100 (Em-B100) to determine if there were significant differences in exhaust gas temperature, specific NO_X emissions, PTO power, specific fuel consumption, or thermal efficiency at rated engine speed and at peak torque.

Materials and Methods

Fuels and Fuel Preparation

FutureFuel Corporation (Batesville, Ark.), a BQ9000 certified biodiesel producer, donated 208 L each of D2 and B100 for use in this study. The B100 was 83% beef tallow methyl ester and 17% crude corn oil methyl ester. Em-B100 was prepared by the researchers following the procedures described by Kass et al. (2009). B100 (86.5% by volume) was placed in a beaker and mixed with Croda International's (Edison, N.J.) Hypermer A-70 emulsifier (3.5% by volume) using a Corning (Corning, N.Y.) PC-520 hotplate and magnetic stirring rod. The biodiesel and surfactant were heated to approximately 40.5° C and stirred for 20 min. Distilled water (10% by volume) was then added and stirred, without additional heat, for another 20 min. The resulting Em-B100 was a uniform, milky-white color.

Samples of each fuel were sent to the FutureFuel laboratory for analysis (Table 1). Analyses revealed that B100 and Em-B100 contained 12.9% and 25.3% less heat energy, respectively, than D2. As expected, Em-B100 had a higher specific gravity and viscosity and a lower iodine number than B100. The FutureFuel lab did not test Em-B100 for cetane number and cloud or pour points.

Table 1. Physical and chemical properties of test fuels.

Property	D2	B100	Em-B100
Heat of combustion (MJ/kg)	45.57	39.70	34.03
Viscosity (cSt @ 40° C)	2.39	4.27	7.26
Specific gravity (@ 15° C)	0.8351	0.8804	0.8986
Cetane No.	42	56	--
Cloud point	-10.0	7.4	--
Pour point (º C)	-18.3	6.0	--
Total glycerin (% mass)	*na*	0.106	0.104
Iodine No.	*na*	86.5	70.3

Note. Analysis provided by FutureFuel Corporation (Batesville, Ark.).

Tractor and Instrumentation

A 2006 model John Deere 3203 compact utility tractor (Deere & Co., Moline, Ill.) with a three-cylinder, four-stroke, naturally-aspirated, compression-ignition engine was used for all fuel tests (Table 2). The EPA Tier II compliant engine has a mechanical inline fuel injection pump with direct cylinder injection. This type of tractor is typically used for small farm and suburban applications.

Table 2. Test tractor specifications.

Model	John Deere 3203
Engine manufacturer	Yanmar
Bore x Stroke	84 mm x 90 mm
Engine displacement	1.5 L
Gross engine power (rated)	23.9 kW @ 2800 rpm ($\pm$ 50 rpm)
Compression ratio	19:1

Engine load was manually applied using an AW NEB-400 (North Pontiac, Ill.) PTO dynamometer with a maximum braking capacity of 149 kW at 540 PTO rpm. An auxiliary fuel tank was mounted on an Arlyn (East Rockaway, N.Y.) digital bench scale (22.68 kg capacity with an accuracy of 0.005 kg) to measure mass fuel consumption. NO_X emissions were measured in the exhaust pipe using a Horiba (Kyoto, Japan) MEXA-720 NO_X analyzer (0 to 5000 ppm @ 1-ppm resolution and 0.6% full-scale accuracy). Engine temperatures were measured using a Raytec (Santa Cruz, Cal.) AutoPro ST25 non-contact infrared temperature gun (-32° C to 535° C at 1% accuracy). Ambient conditions (temperature, barometric pressure, and relative humidity) were measured using an Accu-Rite (Miramar, Fla.) model 00973 weather station. All instruments were calibrated prior to fuel testing and were checked (and recalibrated if necessary), between tests. The test set-up is shown in Figure 1.

Experimental Procedures

The objective of this experiment was to determine engine performance, fuel efficiency, and NO_X emissions with three fuels (D2, B100, and Em-B100) under two standard load conditions (rated engine speed and peak torque). Thus, ISO emissions certification protocols, such as ISO 1878-4 (ISO, 1996) were not used at this initial stage of testing, since comparison, not certification, was the objective (Davis et al., 2012; Kass et al., 2009).

Figure 1. Experimental set-up for fuel testing.

Torque maps were produced for the tractor using each test fuel to determine engine speeds for peak torque output and maximum power output (to verify governor's maximum, i.e. rated engine speed). Peak torque output for D2, B100, and Em-B100 occurred at approximately 1530 engine rpm, 1505 engine rpm, and 1560 engine rpm, respectively and these speeds were used in subsequent peak torque testing for each fuel. Maximum power output occurred at approximately 2760 engine rpm with each fuel [which was consistent with the manufacturer's rated engine speed specification of 2800 ($\pm$50) rpm]; this engine speed was used for testing at rated engine speed.

Prior to each test, the tractor was operated under moderate dynamometer load until the engine reached operating temperature as indicated by measurement of the engine coolant and oil temperatures. To begin the test, the dynamometer load was then removed and the engine governor control was set to high-idle speed (approximately 3100 engine rpm). Next, the dynamometer load was gradually re-applied until engine speed slowed and stabilized at the specific target speed (either peak torque speed or rated engine speed). Four, 15 min repeated tests were conducted with each of the three fuels at both load conditions (24 total tests). Dynamometer (PTO power, rpm, and torque) and NO_X data were automatically logged once per second (1-Hz) during all tests. Engine temperatures (fuel, oil, coolant, and intake air) were measured and manually recorded at the beginning of each fuel test and at 5-min intervals throughout each test. The weight of the fuel tank was read and manually recorded at the beginning and end of each timed 15 min test.

After all tests with one fuel were completed, the axillary fuel tank and fuel system were drained and flushed with the next fuel to be tested and the engine oil and filter and the fuel filters were changed. Tests were conducted only when ambient environmental conditions complied with EPA (2011) requirements for testing non-road compression-ignition engines. As specified, values for *f* (eq. 1) were calculated and tests were conducted only when the resulting values were within approved parameters (0.98 < *f* < 1.02).

$$f = [(99 / p_s)\ (T / 298)]^{0.7} \qquad (1)$$

where
p_s = dry atmospheric pressure (kPa)
T = absolute temperature (°K)

Results

Test Conditions

Engine speeds and temperatures were fairly consistent within replications of each fuel and test condition and between fuel tests within each test condition (Table 3). Within each test condition there were no significant ($p < .05$) differences in intake air or engine operating temperatures by fuel type. The largest coefficient of variation (0.88%) for engine speed occurred with Em-B100 during peak torque testing. Although this value is small, the researchers did note a slight difficulty in maintaining a constant engine speed with Em-B100 under peak torque conditions.

Table 3. Engine speeds and temperatures by fuel and test.

	Rated engine speed		Peak torque	
Fuel and Variable	*M*	*SD*	*M*	*SD*
D2				
Engine speed (rpm)	2761.38	1.98	1530.13	2.16
Intake air temp (°C)	32.40	4.64	33.09	2.39
Fuel temp (°C)	39.20	7.71	40.78	0.85
Coolant temp (°C)	44.15	4.82	41.96	1.84
Oil temp (°C)	88.99	3.61	82.88	1.28
B100				
Engine speed (rpm)	2760.58	1.40	1505.21	3.89
Intake air temp (°C)	30.07	5.09	31.28	2.99
Fuel temp (°C)	34.86	3.37	41.30	0.89
Coolant temp (°C)	39.11	6.04	41.49	5.72
Oil temp (°C)	84.84	2.92	80.09	6.28
Em-B100				
Engine speed (rpm)	2759.97	1.30	1562.00	13.88
Intake air temp (°C)	32.64	0.79	32.95	1.41
Fuel temp (°C)	38.89	4.74	40.43	2.82
Coolant temp (°C)	38.04	1.30	40.19	0.32
Oil temp (°C)	89.11	2.88	83.02	0.97

Exhaust Gas Temperature

At rated engine speed, fueling with B100 and Em-B100 resulted in statistically significantly lower exhaust gas temperatures than D2 (Table 4). At peak torque, Em-B100 resulted in a statistically significant decrease in exhaust gas temperature compared to both D2 and B100. The obtained R^2 values of 0.80 and 0.83, respectively, for rated engine speed and peak torque, indicated that 80% or more of the variance in exhaust gas temperature could be explained by fuel type.

NO_X Emissions

At rated engine speed, there were no statistically significant differences between fuels in PTO specific NO_X emissions (Table 5). This is consistent with previous research indicating no difference between fuels at higher engine speeds and lower torque loads (Neel et al., 2008; De Risi et al., 1999; Xue et al., 2011). At peak torque, fueling with B100 resulted in statistically significantly higher specific NO_X emissions than both D2 and Em-B100. Compared to B100, NO_X emissions for D2 and Em-B100 were 15.5% and 14.5% lower, respectively. There was no significant difference in NO_X emissions between D2 and Em-B100, indicating that a 10% (by volume) water-in-biodiesel emulsion was effective in reducing NO_X emissions to levels typical of D2. Fuel type explained virtually all (R^2 = 0.99) of the variance in PTO specific NO_X emissions at peak torque.

Table 4. ANOVA summary and descriptive statistics for exhaust gas temperatures (°C) by fuel and test.

Fuel	Exhaust gas temperature @ rated engine speed		Exhaust gas temperature @ peak torque	
	M[a]	*SD*	*M*[a]	*SD*
D2	331.01[a]	20.75	249.51[a]	14.64
B100	285.47[b]	2.94	232.43[a]	6.85
Em-B100	266.77[b]	1.59	204.51[b]	5.32
$F(2, 9)$[b]	17.92 ($p = 0.0007$)		21.24 ($p = 0.0004$)	

[a] Means in the same column that do not share a letter are significantly different
($p < .05$) by the Tukey post-hoc test.
[b] ANOVA *F*-value with 2 and 9 degrees of freedom.

Table 5. ANOVA summary and descriptive statistics for PTO specific NO_X emissions (ppm/kW) by fuel and test.

Fuel	PTO specific NO_X emissions @ rated engine speed		PTO specific NO_X emissions @ peak torque	
	M[a]	SD	M[a]	SD
D2	21.32[a]	0.92	31.06[b]	0.11
B100	21.65[a]	1.12	36.75[a]	0.17
Em-B100	20.23[a]	0.37	31.41[b]	0.34
$F(2, 9)$[b]	2.98 ($p = 0.1014$)		789.20 ($p < 0.0001$)	

[a] Means in the same column that do not share a letter are significantly different ($p < .05$) by the Tukey post-hoc test.
[b] ANOVA F-value with 2 and 9 degrees of freedom.

Power

There were statistically significant differences between fuels in PTO power output at both rated engine speed and at peak torque (Table 6). Under both test conditions, power output decreased significantly as fuel was switched from D2 to B100 and then to Em-B100. Fuel type accounted for nearly all of the variance in PTO power at both rated engine speed ($R^2 = 0.96$) and at peak torque ($R^2 = 0.97$).

Table 6. ANOVA summary and descriptive statistics for PTO power (kW) by fuel and test.

Fuel	PTO power @ rated engine speed		PTO power @ peak torque	
	M[a]	SD	M[a]	SD
D2	16.97[a]	0.16	12.46[a]	0.03
B100	16.22[b]	0.13	12.12[b]	0.16
Em-B100	14.00[c]	0.36	11.20[c]	0.14
$F(2, 9)$[b]	166.23 ($p < 0.0001$)		112.59 ($p < 0.0001$)	

[a] Means in the same column that do not share a letter are significantly different
($p < .05$) by the Tukey post-hoc test.
[b] ANOVA F-value with 2 and 9 degrees of freedom.

Compared to D2, fueling with B100 resulted in power reductions of 4.4% and 2.7% at rated engine speed and peak torque, respectively. Fueling with Em-B100 resulted in 17.5% and 8.9% reductions in power (compared to D2) at rated engine speed and at peak torque, respectively. The power losses for Em-B100 compared to B100 at rated engine speed and at peak torque were 13.7% and 7.6%, respectively. In each case the reduction in power was less than the percentage difference in the relative energy content of the three fuels, indicating increased fuel consumption or engine thermal efficiency, or both, with B100 and Em-B100.

Specific Fuel Consumption

In this study, specific fuel consumption values for Em-B100 were calculated on the actual mass of fuel consumed, excluding water, as recommended by Abu-Zaid (2004) and Kass et al. (2009). The specific fuel consumption for diesel was significantly lower than B100 and Em-B100 for both the rated engine speed and the peak torque tests (Table 7). At rated engine speed, specific fuel consumption for B100 and Em-B100 were 13.6% and 20.0% higher, respectively, than D2; at peak torque, specific fuel consumption for B100 and Em-B100 were 8.6% and 11.6% higher, respectively, than D2. There were no significant differences in specific fuel consumption between B100 and Em-B100 for either test condition. The R^2 values for fuel type at rated engine speed and at peak torque were 0.75 and 0.86, respectively.

Table 7. ANOVA summary and descriptive statistics for PTO specific fuel consumption (kg/kWh) by fuel and test.

	PTO specific fuel consumption @ rated engine speed		PTO specific fuel consumption @ peak torque	
Fuel	M[a]	SD	M[a]	SD
D2	0.316[b]	0.027	0.268[b]	0.002
B100	0.359[a]	0.011	0.291[a]	0.010
Em-B100	0.379[a]	0.007	0.299[a]	0.003
$F(2, 9)$[b]	13.58 ($p = 0.0019$)		27.60 ($p < 0.0001$)	

[a] Means in the same column that do not share a letter are significantly different (p < .05) by the Tukey post-hoc test.
[b] ANOVA F-value with 2 and 9 degrees of freedom.

Thermal Efficiency

There were no significant differences in PTO thermal efficiency between the three fuels at rated engine speed; each fuel resulted in a thermal efficiency of approximately 25% (Table 8). However, at peak torque, thermal efficiencies were higher for both B100 (5.8% higher) and Em-B100 (8.1% higher) than for D2. There was no statistically significant difference in thermal efficiency between B100 and Em-B100. Fuel type explained 75% ($R^2 = 0.75$) of the variance in thermal efficiency at peak torque. The increased thermal efficiency for B100 and Em-B100 is consistent with previous research (Abu-Zaid, 2004; Davis et al., 2012; Lin et al., 2006) and is likely due to the increased oxygen content (both B100 and Em-B100) and the effects of high-pressure steam, increased injection velocity, and micro-explosions (Em-B100 only) described by Chadwell and Dingle (2008).

Table 8. ANOVA summary and descriptive statistics for PTO thermal efficiency by fuel and test.

	PTO thermal efficiency @ rated engine speed		PTO thermal efficiency @ peak torque	
Fuel	*M*[a]	*SD*	*M*[a]	*SD*
D2	0.253[a]	0.024	0.295[b]	0.002
B100	0.252[a]	0.008	0.312[a]	0.011
Em-B100	0.251[a]	0.005	0.319[a]	0.003
$F(2, 9)$[b]	0.01 ($p = 0.9897$)		13.65 ($p = 0.0019$)	

[a] Means in the same column that do not share a letter are significantly different ($p < .05$) by the Tukey post-hoc test.
[b] ANOVA *F*-value with 2 and 9 degrees of freedom.

Conclusions and Recommendations

Results indicate that use of a 10% (by volume) water-in-B100 emulsion effectively reduced combustion temperatures (as indicated by lower exhaust gas temperatures), thus decreasing specific NO_X emissions to a level equivalent to petroleum diesel (D2) under peak torque conditions. This finding is important, given the fact that increased NO_X emissions with B100 are most commonly associated with lower engine speeds and heavier torque loads (De Risi et al., 1999; Xue et al., 2011). The reduction in NO_X emissions with Em-B100 is consistent with previous research (Abu-Zaid, 2004; Davis et al., 2012; Kass et al., 2009) and indicate that emulsification of B100 provides a low-cost, effective means of reducing NO_X emissions from pre-Tier and early-Tier non-road diesel engines. This finding also supports Sun's (2010) contention that engine NO_X production is primarily a thermal phenomenon and reducing combustion temperatures is an effective NO_X mitigation strategy.

The primary negative aspect of Em-B100 use was the statistically significant decrease in power output when compared to both B100 and, especially, D2. Fueling with Em-B100 resulted in 17.5% less power at rated engine speed and 8.9% less power at peak torque as compared to D2. Power reductions such as these have potential to adversely affect tractor performance and productivity. Thus, those considering Em-B100 to reduce NO_X emissions must be aware of the significant power reduction resulting from its use.

Use of Em-B100 also resulted in increased specific fuel consumption, even with the volume of water excluded, at both rated engine speed (20.0% higher) and at peak torque (11.6% higher) compared to D2. However, the specific fuel consumption for Em-B100 was not statistically significantly different than for B100. This indicates the primary cause of increased fuel consumption with Em-B100 is the lower energy content of the B100 and not the result of any negative effects of the emulsification process. Relatedly, engine thermal efficiency with B100 and Em-B100 were both statistically significantly higher than with D2, partially off-setting the reduced energy content of the two biofuels.

While these results are promising, further research is needed to determine the long-term effects of Em-B100 on engine operation, maintenance, and durability. Research should include evaluation of potential fuel line deterioration and cold weather usability of Em-B100 as well as engine oil analysis and engine tear-down and inspection to evaluate potential engine damage caused by emulsified biodiesel. Research should also be conducted to determine the stability of Em-B100 under typical storage and use conditions. Emulsified biodiesel should be tested in a variety of engine types and applications to determine if, as Sun (2010) suggested, NO_X emissions results vary based on engine design and operating conditions. The effects of Em-B100 on particulate matter emissions should be studied. Finally, since this and other research (Davis et al., 2012; Kaas et al., 2009; Koc & Abdullah, in press) have demonstrated a decrease in NO_X emissions with emulsified biodiesel, further tests using ISO standard protocols should be conducted.

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References

Abu-Zaid, M. (2004). Performance of single cylinder, direct injection Diesel engine using water fuel emulsions. *Energy Conversion and Management, 45*, 697-705.

Alahmer, A., Yamin, J., Sakhrieh, A. & Hamdan, M. A. (2010). Engine performance using emulsified diesel fuel. *Energy Conversion and Management, 51*, 1708-1713.

Awang, R., & May, C. Y. (2007). Effect of hydroxylated compounds on properties and emission of palm biodiesel. *American Journal of Applied Sciences, 4*, 99-101.

ASABE. 2010. The EPA non-road diesel Tier IV final rule. *Resource, 17*(5), 10-13.

Canacki, M., and Van Gerpen, J. H. (2003). Comparison of engine performance and emissions for petroleum diesel fuel, yellow grease biodiesel, and soybean oil biodiesel. *Transactions of the ASAE, 46*, 937-944.

Chadwell, C. J., & Dingle, P. J. (2008). Effect of diesel and water co-injection with real-time control on diesel engine performance and emissions. SAE Paper No. 2008-01-1190. Warrendale, PA: SAE International.

Davis, J. A., Johnson, D. M., Edgar, D. W., Wardlow, G. W., & Sadaka, S. (2012). NO_X emissions and performance of a single-cylinder diesel engine with emulsified and non-emulsified fuels. *Applied Engineering in Agriculture, 28*, 179-186.

De Risi, A., Manieri, D. F., & Laforgia, D. (1999). A theoretical investigation on the effects of combustion chamber geometry and engine speed on soot and NO_X emissions. *Proc. 1999 ASME Intl. Congress and Exposition.* New York, N.Y.: American Soc. Mech. Eng. Available at: http://www.arturo.derisi.unisalento.it/Dowloads/Pubblicazioni/ASME_ICE99_camere.pdf Accessed 7 August 2012.

DOE. (2009). *Biodiesel Handling and Use Guidelines.* 4th ed. DOE/GO-102004-1999. Oak Ridge, Tenn.: U.S. Department of Energy, Office of Scientific and Technical Information. Available at: http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/43672.pdf

Energy Independence and Security Act of 2007, 42 USC 17001. Available at: http://www.gpo.gov/fdsys/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf

EPA. (2004). Final regulatory impact analysis: Control of emissions from nonroad diesel engines. Available at: http://www.epa.gov/otaq/documents/nonroad-diesel/420r04007.pdf Accessed 7 August 2012.

EPA. (1998). NO_X: How nitrogen oxides affect the way we live and breathe. EPA-456/F-98-005. Research Triangle Park, N.C.: U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards.

EPA. (2011). 40 CFR 89: Control of emissions from new and in-use nonroad compression-ignition engines; Subpart D: Emission test equipment provisions; 89.331: Test conditions. Washington, D.C.: U.S. Environmental Protection Agency.

ISO. (1996). ISO 8178-4: Reciprocating internal combustion engines, exhaust emission measurement: Part 4. Test cycles for different engine applications. Geneva, Switzerland: International Organization of Standardization.

Kass, M. D., Lewis, S. A. Sr., Swartz, M. M., Huff, S. P., Lee D.-W., Wagner, R. M., & Storey J. M. E. (2009). Utilizing water emulsification to reduce NO_X and particulate emissions associated with biodiesel. *Transactions of the ASABE, 52*, 5-13.

Koc, A. B., & Abdullah, M. In press, corrected proof. Performance and NO_X emissions of a diesel engine fueled with biodiesel-diesel-water nanoemulsions. *Fuel Processing Technology*. Retrieved from: http://www.sciencedirect.com/science/article/pii/S0378382012003657

Kumar, M. S., Bellettre, J. & Tazerout, M. (2009). The use of biofuel emulsions as fuel for diesel engines: A review. *Journal of Power and Energy, 223*, 729-742.

Lin, C.-Y., & Lin, H.-A. (2006). Diesel engine performance and emission characteristics of biodiesel produced by the peroxidation process. *Fuel*, *85*, 298-305.

Neel, C. M., Johnson, D. M., & Wardlow, G. W. (2008). Performance, efficiency, and NO_X emissions of a compact diesel tractor fueled with D2, B20, and B100 under steady-state loads. *Applied Engineering in Agriculture*, *24*, 717-721.

Proc, K., Barnitt, R., Hayes, R. R., Ratcliff, M. & McCormick, R. L. (2006). 100,000-mile evaluation of transit busses operated on biodiesel blends (B20). SAE Paper No. 2006-01-3253. Warrendale, Pa.: Soc. of Auto. Eng. Available at: http://www.nrel.gov/vehiclesandfuels/npbf/pdfs/40128.pdf. Accessed 8 July 2010.

Sadaka, S., & Boateng, A. A. (2009). Pyrolysis and bio-oil. Little Rock, Ark.: University of Arkansas, Division of Agriculture, Cooperative Extension Service.

Schumacher, L. G., Clark, N. N., Lyons, D. W., & Marshall, W. (2001). Diesel engine exhaust emissions evaluation of biodiesel blends using a Cummings L10E engine. *Transactions of the ASAE, 44*, 1461-1464.

Sun, J., Caton, J. A., & Jacobs, T. J. (2010). Oxides of nitrogen emissions from biodiesel-fuelled diesel engines. *Progress in Energy and Combustion Science, 36*, 677-695.

Xue, J., Grift, T. E., & Hansen, A. C. (2011). Effect of biodiesel on engine performances and emissions. *Renewable and Sustainable Energy Reviews, 15*, 1098-1116.