# CASTOR BIODIESEL-DIESEL BLEND TO POWER A DIESEL ENGINE: EVALUATION OF THE BUS EFFICIENCY AND EMISSIONS UNDER DRIVING CONDITIONS

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*SUMMARY*

*Biodiesel produced from castor oil has attractive properties as this fuel can be produced from renewable energy sources without compromising food supply. A B20 castor biodiesel-diesel blend was used on a diesel engine without any other modification. A field study was conducted on a diesel school bus in the state of Morelos, Mexico, to evaluate fuel efficiency and fuel emissions from diesel and from the B20 castor biodiesel-diesel blend under bus driving conditions on the highway and in the urban area. Refined castor oil was used to produce biodiesel at pilot scale (300 liters) in compliance with the B100 ASTM D6751 standard. The results show the benefits of using castor biodiesel since, when compared to diesel fuel, similar fuel efficiencies and reductions in exhaust emissions were accomplished with the B20 castor biodiesel-diesel blend. This blend represents an environmental-friendly alternative to reduce diesel consumption without threatening the food supply, because castor biodiesel is produced from wild plant oil.*

## Introduction

Air pollution, climate change and reduced availability of fossil fuels have shifted the manner in which this traditional energy source is exploited and used. Renewable energy sources lessen the impact of environmental contamination. A feasible environmental alternative are the biofuels, known as 'green energy' sources. Green energy is essential to achieve the ultimate goal of sustainability since it may minimize environmental affectation and economic and social impact (Salvi and Panwar, 2012). Green energy is, consequently, a major factor in future sustainable development and world stability (Midilli *et al*., 2007). Biodiesel is biodegradable and renewable, less toxic for the environment compared to conventional diesel and it does not contribute to global warming, due to its closed carbon cycle (Van Gerpen, 2005). Biodiesel can be produced from various

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**MEZCLA DE BIODIESEL DE RICINO-DIESEL PARA PONER EN FUNCIONAMIENTO UN MOTOR DIESEL: EVALUACIÓN DE LA EFICIENCIA Y EMISIONES DE UN AUTOBÚS CONDUCIDO EN CONDICIONES REALES**
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*RESUMEN*

*El biodiesel producido a partir de aceite de ricino tiene propiedades atractivas debido a que este combustible puede ser producido de fuentes de energía renovable sin comprometer el suministro de alimentos. La mezcla B20 de biodiesel de ricino-diesel fue utilizada sin otra modificación para alimentar un motor diesel de un autobús escolar. Las eficiencias y emisiones de los combustibles diesel y mezcla B20 fueron evaluadas bajo condiciones reales de conducción del autobús, tanto en la autopista como en la zona urbana en el estado de Morelos, México. El biodiesel fue producido conforme a la norma B100 ASTM D 6751 a escala piloto (300 litros) a partir de aceite de ricino refinado. Este estudio demostró los beneficios de usar biodiesel de ricino debido a que el combustible B20 mostró que la eficiencia y las reducciones en las emisiones en el escape fueron similares a las obtenidas con el combustible diesel. La mezcla B20 de biodiesel de ricino-diesel representa una alternativa ambiental para reducir el consumo de diesel sin poner en peligro el suministro de alimentos, ya que el biodiesel es producido a partir del aceite de ricino proveniente de plantas silvestres.*

**MISTURA DE BIODIESEL DE RICINO-DIESEL PARA POR EM FUNCIONAMENTO UM MOTOR DIESEL: AVALUAÇÃO DA EFICIÊNCIA E EMISSÕES DE UM ÔNIBUS CONDUZIDO EM CONDIÇÕES REAIS**
Fabián Jesús Rendón Hernández, José Luis Gutiérrez Diaz, Susana Silva Martínez, J. A. Hernández e Alberto Álvarez Gallegos

*RESUMO*

*O biodiesel produzido a partir de óleo de ricino tem propriedades atrativas devido a que este combustível pode ser produzido de fontes de energia renovável sem comprometer o subministro de alimentos. A mistura B20 de biodiesel de ricino-diesel foi utilizada sem outra modificação para alimentar um motor diesel de um ônibus escolar. As eficiencias e emissões dos combustíveis diesel e mistura B20 foram avaliadas sob condições reais de condução do ônibus, tanto em autopista como na zona urbana no estado de Morelos, México. O biodiesel foi produzido conforme à norma B100 ASTM D 6751 a escala piloto (300 litros) a partir de óleo de ricino refinado. Este estudo demonstrou os benefícios de usar biodiesel de ricino devido a que o combustível B20 mostrou que a eficiencia e as reduções nas emissões no escape foram similares às obtidas com o combustível diesel. A misturaa B20 de biodiesel de ricino-diesel representa uma alternativa ambiental para reducir o consumo de diesel sem por em perigo o subministro de alimentos, já que o biodiesel é produzido a partir do óleo de ricino proveniente de plantas silvestres.*

edible biolipds (rapeseed, soybean, sunflower and palm virgin oils, from waste vegetable oil, as well as from animal fats) and non-edible ones (jatropha, neem oil, castor oil, tall oil). Biodiesel is most commonly produced by the base catalyst transesterification of vegetable oils, since this process is carried out at relatively low temperature and atmospheric pressure, resulting in lower capital and operating costs for the biodiesel plant (Demirbas *et al*., 2009). The composition of fatty acid methyl esters produced by transesterification of vegetable oil determines the physical and chemical properties of the biodiesel, which in turn influence the efficiency of a diesel engine and its emissions (Klopfenstein, 1985; Peterson and Reece, 1996; Munoz *et al*., 2004; Chhina *et al*., 2005; Szybist *et al*., 2007; Tat *et al*., 2007; Lapuerta *et al*., 2008; Ozcanli *et al*., 2011; Panwar *et al*., 2010; Siva *et al*., 2011; Chauhan *et al*., 2012; Pattamaproma *et al*., 2012; Salvi and Panwar, 2012).

Biodiesel represents a renewable and environmentally friendly alternative for the transport sector. For use as diesel fuels, vegetable and animal fats and oils undergo a transesterification process to improve the fuel combustion characteristics of biolipids by reducing their viscosity. Salvi and Panwar (2012) reviewed biodiesel resources and the production technologies for large scale and sustainable production of biodiesel. These authors concluded, from many case studies, that engine efficiency with B20 biodiesel blends and mineral diesel were comparable (the most common blends of biodiesel contain 20% biodiesel and 80% conventional diesel). Also, based on the increasing interest in the use of biodiesel as an alternative to conventional diesel, the U.S. Envi-ronmental Protection Agency (EPA, 2002) conducted a comprehensive analysis of the emission impacts of biodiesel using available data from heavy-duty diesel-powered highway engines. It was reported that biodiesel impact on emissions varied depending on the type of biodiesel (biolipids source) and on the type of conventional diesel used to be blended with the biodiesel. The report also highlighted that the use of biodiesel increases nitrogen oxides (NOx) emissions; although the increase is small in comparison to the reductions in other regulated pollutants. Therefore, additional research was suggested so as to find ways to mitigate the NOx increase (EPA, 2002). Pillay *et al*. (2013) employed a high-performance instrument to study the levels of $CO_2$, NOx, and toxic gas (such as CO, NO, $SO_2$) emissions in blended mixtures of neem biodiesel with commercial diesel, and compared the overall combustion efficiency with that of diesel. These authors found that the 95/5% (diesel/neem biodiesel) blend compared reasonably well with pure petroleum diesel, in terms of combustion efficiency, while the main drawback was the elevated production of NO and NOx as in the diesel.

The aim of the present study was to produce B100 castor biodiesel in a pilot plant in compliance with the ASTM D6751 standard and to study the emissions and engine efficiency of a diesel school bus fuelled with diesel and B20 castor biodiesel-diesel blend, travelling on the highway and the urban area.

## Materials and Methods

### *Chemicals*

Edible refined castor oil (purchased from a Mexican store, Aceites y Maquilas S.A.) and ultra-low sulphur diesel (purchased from service stations) were used as received, without further purification. The industrial grade chemical reagents involved in the transesterification process were sulphuric acid, sodium hydroxide, and 99% methanol. Tap water was used to prepare all solutions.

### *Pilot plant biodiesel production*

The transesterification reaction took place in a 300 liters commercial complete-biodiesel-processor Fuel Meister II™ (Home BioDiesel). Biodiesel production was carried out following the step-by-step procedure described in the equipment manual. Briefly, the main steps were: methoxide formation, transesterification reaction, glycerin separation, biodiesel water washing and drying, biodiesel filtration, biodiesel and glycerin storage, and alcohol recuperation. To produce the methoxide, a methanol:oil molar ratio of 2.9:1 was used and 0.233mol·mol$^{-1}$ at 1%wt of NaOH catalyst was mixed with methanol. The amount of catalyst (Singh *et al*., 2006) was obtained according to the molecular weight of castor oil (932.0g·mol$^{-1}$; Loaiza, 2003). Mixing of methanol (9.72 liters) with the catalyst took place inside a reactor under reflux for ~30min or until the catalyst was completely diluted in the alcohol, forming methoxide. This was followed by addition of hot vegetable oil (80 liters) to be mixed with the methoxide under reflux for ~3h. The refined castor oil was previously heated to 50-55ºC by means of electrical resistances. After the reaction time, the methyl esters were separated from the glycerin by settling for 24h, followed by water washing and drying. The water (200ml of tap water were used per liter of biodiesel) was introduced from the top of the reactor by mixing at the time of entering in contact with the biodiesel. At this stage the biodiesel becomes cloudy, and is then allowed to rest for 24h in order to separate biodiesel impurities (glycerol) that are then drained. This washing procedure was repeated three times and the biodiesel became less cloudy after each wash. The drying procedure was carried out by heating the biodiesel to 100ºC for 15min after the last wash, so as to evaporate the excess water and recover the golden color of the oil. Higher temperatures were avoided to prevent the biodiesel from being burnt. Once the biodiesel was cold, it was filtered using a funnel and filter for biodiesel and placed in a storage container. At this stage, the B20 castor biodiesel-diesel blend was prepared by mixing 20 parts of castor biodiesel with 80 parts of diesel. Finally, the alcohol was recovered through distillation and the glycerin was used as an additive to manufacture soap by saponification. The biodiesel produced from refined castor oil was analysed for kinematic viscosity, flash point, cloud point, sulphur and carbon residue (Conradson), water and sediment content, free glycerine and sulphate ash. Standard methods and standard procedures were used in the biodiesel characterization (ASTM D 6751).

### *Bus wear and driving conditions*

The diesel school bus (urban bus Mercedes Benz, year 2000, capacity 34 seats, motor 4 CIL 190 HP transmission of 5 Vel. with Dual) used for the emissions and efficiency test showed an initial wear in its mechanical components, since it had been used for about 100000km with diesel prior to being used in this study. The bus was always driven by the same driver and the driving speeds were similar during all the tests of the diesel and B20 castor biodiesel-diesel blend. The B20 castor biodiesel-diesel blend was prepared and immediately loaded in the fuel tank as soon as the B100 castor biodiesel was produced. Average speeds were 80km·h$^{-1}$ on the highway and 40km·h$^{-1}$ in the urban area. Bus exhaust emissions were measured using the Unigas 3000 MKIII equipment (Cole-Palmer). At the start of each bus test the fuel tank was totally drained out; then, a known amount of fuel was fed into it. At the end of the bus test, the tank was totally drained again and the remaining fuel was measured with a graduated 20 liter container. The difference in volume was the fuel consumed during the bus test.

## Results and Discussion

### *Biodiesel production at pilot plant scale*

The castor biodiesel production and its characterization in compliance with the B100 ASTM D6751 standard requires special facilities and such characterization is expensive to be carried out routinely. The B100 castor biodiesel obtained from refined castor oil was almost fully characterized, as shown in Table I. As can be seen, all the main parameters were within the limits established by B100 ASTM D6751, except for the kinematic viscosity, which is higher than the standard value. However, this parameter falls within the standard limits, as a B20 biodiesel-diesel blend is used in the diesel engine of the school bus.

These results demonstrate that high quality biodiesel can be produced with the procedure described in the pilot plant manual. The kinematic viscosity (Table II) of B100 castor biodiesel is very high compared to B100 ASTM D6751 standard value. This high value is attributed to hydrogen bonding of hydroxyl groups in ricinoleic acid (Ogunniyi, 2006). Also, a high correlation was found (Kim *et al*., 2010) between oil viscosity and fatty acid composition, where the flow behavior of castor oil was positively governed by its major components (oleic acid 18:1, and linoleic acid 18:2 fatty acids). Nevertheless, the B20 castor biodiesel-diesel blend, used as biofuel in the school bus in the present study was within the limits established by the biodiesel standard, as shown in Table II. The castor biodiesel displayed a clear, bright and golden color without impurities during the visual inspection. The HPLC analyses revealed that castor biodiesel was mainly composed of a mixture of five fatty acid methyl esters.

The fatty acid methyl esters found in the produced biodiesel (Table III) are palmitic (hexadecanoic) acid, linoleic acid, oleic acid, and stearic (octadecanoic) acid, which correspond with biodiesel feedstock such as corn and rapeseed oils (Knothe, 2008), whereas the methyl ricinoleate in the castor biodiesel corresponds to the ricinoleic acid in the castor oil (Knothe, 2008). These fatty acid methyl esters found in the biodiesel may give an estimation of the cetane number in the biofuel produced in the pilot plant. The cetane number is related to the ignition quality of a fuel in a diesel engine and its determination biodiesel is expensive (Gopinath *et al*., 2009; Knothe *et al*., 2003). It has been reported (Gopinath *et al*., 2009) that the cetane number of biofuels is considerably influenced by their fatty acid methyl ester composition, and a model proposed to predict this ignition quality parameter of biodiesels based on such composition. It is desirable that fuels exhibit high cetane number (Van Gerpen *et al*., 2006). The cetane number of diesel is 40, whereas 47 is the cetane number for biodiesel to comply with ASTM D 6751. Thus, according to Tables III and IV, the biofuel produced in the pilot plant may exhibit the minimum required value.

TABLE I
ANALYSIS OF B100 CASTOR BIODIESEL PRODUCED FROM REFINED CASTOR OIL AT PILOT PLANT SCALE FOR QUALITY CONTROL

| Parameter / Units | B100 Castor oil | Biodiesel B100 ASTM specification (Pillay *et al.*, 2013) |
|---|---|---|
| Visual inspection | Clear and bright, without impurities | |
| Kinematic viscosity ($mm^2$ $s^{-1}$, at 40ºC) | 26.2 | 1.9-6.0 |
| Flash point (ºC) | 202 | >130 |
| Cloud point (ºC) | -18 | It has to be reported |
| Sulfur (wt.%) | 0.02 | <0.05 |
| Carbon residue (wt.%) | 0.04 | <0.05 |
| Water and sediments (wt.%) | Traces | <0.02 |
| Free glycerine (wt.%) | Traces | <0.02 |
| Sulfate ash (wt.%) | 0.03 | <0.02 |

TABLE II
PARAMETERS ANALYZED ON B100 CASTOR BIODIESEL PRODUCED FROM REFINED CASTOR OIL IN THE PILOT PLANT AND B20 CASTOR BIODIESEL-DIESEL BLEND

| Parameter | Diesel ASTM D975-05 | Castor biodiesel | | Biodiesel ASTM D6751 |
|---|---|---|---|---|
| | (Van Gerpen *et al.*, 2006) | B100 | B20 | (Van Gerpen *et al.*, 2006) |
| Visual inspection | | Clear and bright without impurities | | |
| Kinematic viscosity ($mm^2$ $s^{-1}$, 40ºC) | 1.3-5.5 | 26.2 | 5.69 | 1.9-6.0 |
| Free glycerin | | Traces | Traces | <0.02 |

TABLE III
REPORTED VALUES OF THE CETANE NUMBER FROM THE MAIN FATTY ACID METHYL ESTERS PRESENT IN THE BIODIESEL PRODUCED IN THE PILOT PLANT

| Fatty acids / Methyl-ester | Molecular formula | Molecular weight | Cetane number of pure fatty acid methyl esters | |
|---|---|---|---|---|
| | | | Experimental value (Knothe, 2008) | Average theoretical value (Gopinath *et al.*, 2009) |
| Methyl palmitate | $C_{17}H_{34}O_2$ | 270.5 | 85.9 | 76.6 |
| Methyl linolate | $C_{19}H_{34}O_2$ | 294.5 | 38.2 | 39.2 |
| Methyl oleate | $C_{19}H_{36}O_2$ | 296.5 | 56.55 | 56.9 |
| Methyl stearate | $C_{19}H_{38}O_2$ | 298.5 | 101 | 85.9 |
| Methyl ricinoleate | $C_{19}H_{36}O_3$ | 312.5 | 37.38 | 42 |

Table III shows the molecular formulas for the methyl esters present in the castor biodiesel produced in the pilot plant, as well as the theoretical (Gopinath *et al.*, 2009) and experimental (Knothe, 2008) cetane number of pure fatty acid methyl esters found in the biodiesel produced. Table IV also shows experimental values for cetane number of diesel and B100 biodiesels reported in the literature (Pillay *et al*, 2013; Gopinath *et al.*, 2009; Bello and Makanju, 2011). It is expected that the castor biofuel produced here have the minimum standard value since the procedure used in the pilot plant produces a high quality biodiesel.

TABLE IV
EXPERIMENTAL VALUES REPORTED FOR CETANE NUMBER OF DIESEL AND B100 CASTOR BIODIESEL-DIESEL BLEND PRODUCED IN THE PILOT PLANT

| Fuel | Average value* | Standard value** |
|---|---|---|
| Diesel | 47.4 | 40 (ASTM D975) |
| Castor biodiesel | 53.0 | 47 (ASTM D6751) |

* Bello and Makanju (2011).
** Gopinath *et al.* (2009).

*Bus efficiency and gas emissions*

Several studies have reported the benefits of using biodiesel and biodiesel-diesel blends as an alternative to diesel since biodiesel has a positive impact in the environment with fewer atmospheric emissions (Kalligeros *et al.*, 2003; Demirbas, 2007; Hess *et al.*, 2007; Lechon *et al.*, 2009; Gokalp *et al.*, 2011). The main emissions from biodiesel are CO, $CO_2$, NOx, $SO_2$ and smoke (Basha *et al.*, 2009). B20 biodiesel blends are more commonly used in diesel engines. It is evident that biodiesel impacts on emissions vary depending on the type of biodiesel (soybean, palm, castor, rapeseed, animal fats, etc) and on the type of conventional diesel to which the biodiesel is added (EPA, 2002). In this study, the B20 castor biodiesel-diesel blend was used to evaluate bus engine efficiency in fuel consumption and exhaust emissions. Table V shows the travelling bus conditions, such like distance travelled, bus load (with or without passengers), travel on the highway or in the urban area, average speed and bus engine efficiency on fuel consumption. The consumption of fuel on the highway and in the urban area with no passengers on the bus was similar for both fuels. Conversely, on the highway, with a loaded bus to its maximal capacity, with 34 passengers, the bus engine efficiency using diesel was 13% higher than with B20 castor biodiesel. Diesel fuel showed higher fuel efficiency than B20 castor biodiesel-diesel blend regardless of the test driving conditions. This was attributed to the higher calorific value that diesel fuel has compared to biodiesel (Basheer *et al.*, 2012).

Table VI reports emissions of $O_2$, CO, NO, $NO_x$ and $SO_2$ for B20 castor biodiesel-diesel blend and diesel for a bus travelling on the highway and in the urban area. $O_2$ emissions were slightly higher with respect to diesel for B20 castor biodiesel-diesel blend. The higher $O_2$ content in the biofuel is part of the oxygenated nature of biodiesels, which contributes to more complete combustion and lower emissions (Murillo *et al.*, 2007), as shown in the results reported on Table VI. CO emissions were similar for both fuels on the urban area and on the highway. Lower bus emissions were detected for B20 castor biodiesel-diesel blend in the

TABLE V
DIESEL SCHOOL BUS DRIVEN USING DIESEL AND CASTOR BIODIESEL-DIESEL BLEND PRODUCED IN A PILOT PLANT (AVERAGE SPEED: 80 km·h$^{-1}$ ON THE HIGHWAY AND 40 km·h$^{-1}$ IN THE URBAN AREA)

| Fuel | Distance travelled on highway (km) | Bus condition | Bus engine efficiency (km·l$^{-1}$) | Distance travelled in urban area (km) | Bus condition | Bus engine efficiency (km·l$^{-1}$) |
|---|---|---|---|---|---|---|
| Diesel | 80 | No passengers | 4.7 | 11 | No passengers | 3.7 |
| | 94 | 34 passengers | 3.8 | 82 | 34 passengers | 3.6 |
| B20 Castor biodiesel diesel blend | 81 | No passengers | 4.7 | 13 | No passengers | 3.6 |
| | 81 | 34 passengers | 3.3 | 13 | 34 passengers | 3.2 |

TABLE VI
EMISSIONS FROM A SCHOOL BUS DRIVEN IN THE URBAN AREA AND ON THE HIGHWAY

| | Urban area | | Highway | |
|---|---|---|---|---|
| Gas | Diesel | B20 castor biodiesel | Diesel | B20 castor biodiesel |
| $O_2$ (%) | 18.5 | 19.1 | 18.6 | 19.1 |
| $CO_2$ (%) | 1.8 | 1.4 | 1.8 | 1.4 |
| CO (ppm) | 254 | 231 | 179 | 161 |
| NO (ppm) | 155 | 154 | 133 | 131 |
| $NO_x$ (ppm) | 160 | 163 | 137 | 135 |

dl: detection limit.

urban area except for NO and NOx which were similar to diesel fuel. In all cases. $SO_2$ was always below the detection limit. The use of B20 castor biodiesel-diesel blend yielded an important reduction of greenhouse gases such as $CO_2$ and CO in the urban area. However, regarding the amount of $CO_2$ gas emitted to the atmosphere, it should be considered that it was already available in the atmosphere to be used by the castor plant in its vital process of photosynthesis to produce its oil seeds. Therefore, the released $CO_2$ during the combustion process of B20 castor biodiesel-diesel blend has no additional negative effects to the environment, as $CO_2$ is recycled through the photosynthesis process by plants and trees; even by the next castor crops.

A review of the influence of fuel properties and fuel omposition on NOx emissions from biodiesel powered diesel engines was written by Varatharajan and Cheralathan (2012). In that revie, it was highlighted that most of the studies have shown that $NO_x$ emissions from biodiesel increased, as compared with diesel. Also, the authors concluded that the exact cause of this increase is still unclear and, according to the revised studies, the fuel properties have been shown to effect the NOx emissions. In our study, NO and NOx emissions were similar for both diesel and B20 castor biodiesel-diesel blend. . It was reported that biodiesel with high cetane numbers had NOx emissions comparable to those of diesel (Varatharajan and Cheralathan, 2012). Also, the value of the iodine number influences the NOx emissions since iodine number is a measure of unsaturation degree of the fatty acid; thus, a high iodine number indicates a high degree of unsaturation (McCormick *et al*., 2001). The latter authors reported a relationship between $NO_x$ emissions and iodine value of biodiesel, and found that NOx increases with the iodine value of the biofuel. Tat *et al*. (2007) reported that NOx emissions were significantly reduced from an engine fueled with unsaturated biodiesel from high-oleic soybeans.

## Conclusions

The pilot scale process for the production of B20 castor biodiesel-diesel blend complied with the ASTM D6751 standard. B20 castor biodiesel-diesel blend showed similar efficiency to that of diesel in fuel consumption. CO emissions were similar for both fuels on the urban area and on the highway. B20 castor biodiesel-diesel blend produced less exhaust emissions in the urban area as compared to diesel except for NO and NOx, which were similar. The results obtained in this study demonstrate that B20 castor biodiesel-diesel blend shows good performance and can gradually be introduced as biofuel for the diesel engines of the school buses and shuttle buses that travel in the campus of the Autonomous University of Morelos State without putting at risk the diesel engines and food supply, since this biodiesel is B100 ASTM compliant and was made out of an oil that is unsuitable for human consumption. Additionally, the methodology developed in this work can be spread out in different regions of the Morelos State in order to contribute to a cleaner air and a better environment. However, the availability of castor oil represents a very important challenge since this oil is not produced in Mexico; thus, a feasibility study for castor seed crops and castor oil extraction in a large scale is needed to introduce the biodiesel as environmental biofuels in the State in the near future.


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