EFFECT OF THE USE OF WASTE VEGETABLE OIL BASED BIODIESEL ON THE LANDSCAPE IN DIESEL ENGINES

by

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Petroleum-based fuels are now widely known as environmentally unfriendly because of non-renewable supplies and its contribution to environmental pollution. The challenge, therefore is to ensure appropriate energy supplies at minimum cost. There is an increasing energy demand in the world and nowadays it can be fulfilled only on the basis of fossil fuels. Therefore, it is necessary to evolve a renewable energy source with lower environmental impact. One alternative solution can be oils of plant origin, like vegetable oils and non-edible oils. With waste vegetable oil methyl ester, biofuel dependency can be decreased. Therefore, the aim of this research paper is to analyze the economic and environmental effect of waste vegetable oil methyl ester compared to fossil fuels. In some cases only the age of vehicles could raise burdens to biofuel utilization in road vehicles. Transport and energy policy – on a large scale – can play an important role in fuel consumption. Author is aware that waste vegetable oil methyl ester can play only a limited role in biofuel substitution.

Key words: *analysis, waste vegetable oil, compression ignition engines, biodiesel, emissions*

Introduction

Economic growth and transport performance are closely linked. The high energy demand and pollution problems caused by fossil fuels based transport make it necessary to use renewable energy sources [1]. Therefore, an alternative fuel solution shall be technically feasible, economically competitive, and environmentally acceptable. One possible alternative could be the use of oils of plants, like vegetable oils and non-edible oils. These biofuels are biodegradable and non-toxic and have low emission profiles compared to petroleum diesel [2]. Chemically oils/fats consist of triglyceride molecules [3]. Thus, biodiesel refers to lower alkyl esters of long chain fatty acids, which are synthesized either by transesterification with lower alcohols or by esterification of fatty acids [4-6]. Edible oils are used in frying pans or fryers worldwide and afterwards they are discarded. Physical properties of used cooking oils are different from refined or crude vegetable oils. Cooking increases the content of free fatty acids (FFA) in the oil [7] which needs to subtracted because FFA and water content have negative effects on the transesterification reaction [8]. They also interfere with the separation of fatty acid esters and glycerol. Especially, the viscosity of the oil increases considerably because of the formation of dimer and polymeric acids and glycerides in used cooking oils. Mo-

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lecular mass and iodine values decrease while saponification value and density increase [7-9]. At present, there is no standardized method of processing used oils from households and most of the used oil is discarded through drains leading to water pollution. Moreover, more than 80% of the oil is consumed at home and the control of this disposal behavior becomes a huge problem. Despite the advances of biodiesel production, the cost of biodiesel is still higher than that of diesel and this has been a major barrier to its commercialization. The use of waste vegetable oil methyl ester (WVOME) could be one way reduce the cost of biodiesel [10]. The use of waste cooking oil instead of virgin (neat) oil to produce biodiesel has been found to be an effective way to reduce the raw material cost, and it is a better alternative than food crop based fuels [11]. The methods of production of biodiesel from used cooking oil do not differ from the conventional transesterification process. Depending on the undesirable compounds (especially FFA and water), each catalyst has its advantages and disadvantages [12, 13]. A typical flow chart of the production of biodiesel from used cooking oil is shown in fig. 1. Firstly, filtration, separation and neutralization are necessary. Then, the second step is transesterification. Thirdly, methyl or ethyl ester needs to be purified [14].

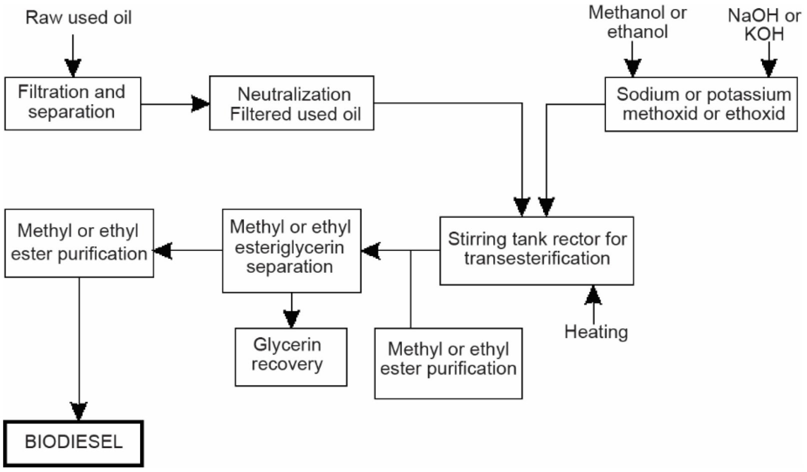

Figure 1. Schematic flow chart of biodiesel production from used cooking oil [14]

No scientific paper was found where the total chain from used cooking oil to engine fuel was investigated. The author has made a literature overview on the treatment of cooking oils and made measurements on engine bench tests to determine engine performance and emission of biofuels.

Methodology

Taking into account that fertile fields are needed for biofuel production, which is not the case for used cooking oil, the economic effect on food security is obvious. First and second generation biofuels have a negative effect on food security and agriculture. In a macro economic sense, grains used for food or biofuel purposes need to be distinguished [15]. The author would like to emphasize the advantages of employing used cooking oils in internal combustion engines although the author is aware that the supplies do not fully cover the demand. Therefore, a supply and demand curve analysis is required in order to understand the change in equilibrium price and quantity caused by the market penetration of WVOME.

The author has considered that the total cultivation area is constant over the whole period of time in this model. Mathematically, the demand function can be simply described as linear:

$$x_t = ap_t + \alpha \qquad \text{as demand function} \tag{1}$$

The increase in demand would lead to increase in profit with constant supply. This would lead to technological invention. In other words, producers are willing to seek alternative products in order to increase their profits and this would result in a shift in the supply curve. This increase in supply would decrease the equilibrium price. The equilibrium quantity increases as quantity demand increases at the new lower price. Mathematically, the supply function can be also simplified:

$$y_t = \beta + bp_{t-1} \qquad \text{the supply function} \tag{2}$$

It is well known that market equilibrium occurs when demand x_t and supply y_t are equal at the same time. For every time period, *t*, there is an equilibrium that can be described with:

$$\begin{cases} ap_t + \alpha = bp_{t-1} + \beta \\ ap_t = b\ p_{t-1} + (\beta - \alpha) \end{cases} \tag{3}$$

where $x_t = ap_t + \alpha$ is the demand function, $y_t = \beta + bp_{t-1}$ – the supply function, and p_t – the price in time *t*.

Market equilibrium is reached when $p_t = p_{t-1}$:

$$\hat{p} = \frac{\beta - \alpha}{a - b} \tag{4}$$

and the actual price differs from the market equilibrium price with:

$$\tilde{p} = p_t - \hat{p} = p_t - \frac{\beta - \alpha}{a - b} \tag{5}$$

The market equilibrium here can be described as eq. (6) and can be modelled as fig. 2:

$$\begin{cases} ap_t + \alpha = bp_{t-1} \\ \tilde{p}_t = \dfrac{b}{a}\tilde{p}_{t-1} \end{cases} \tag{6}$$

The market equilibrium was modelled as the equilibrium of supply and demand. The demand and supply of fossil fuel is affected by the demand and supply of biofuels. In this model biofuels and fossils fuels are competing on the same market.

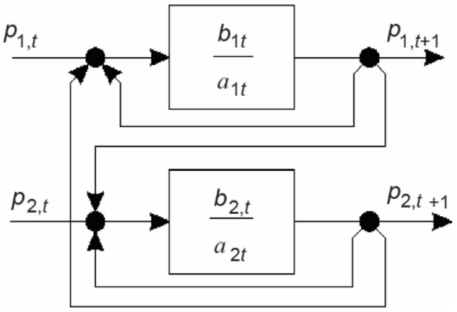

Figure 2. Cybernetic model of market equilibrium with two concurring products [15, 16]

The production of first generation biofuels (*first-generation* or conventional biofuels are biofuels made from sugar, starch, and vegetable oil) created a shift in land use; for instance, lands used only for the production of food were now used for the production of food and biofuel as well. This problem was still not solved by the introduction of second generation biofuels (*second generation* biofuels are produced from sustainable feedstock). With the force of agricultural or food based biodiesel production a new competitor has been introduced in the agricultural sector that was different from the core competences. This new fuel producing competence will lead to market distortion. However, fueling internal combustion engines with used cooking oil (WVOME), avoids the conflict associated with the use of land: not only the production of biofuels from agricultural products but food security as well.

The application of used cooking oil (which is not influenced by land use) in internal combustion engines offers an alternative or partial solution to the problem of the use of land for food security or for fuel supply. It could be only a partial solution due to its limited availability and collection need [17]. In consequence, biodiesel produced from cooking oil can be used in place of diesel fuel (D2) [18]. Furthermore, the author has investigated the behavior of WVOME in internal combustion engines in order to extend the results found in the literature. The results showed that in case of an engine operating on pure biodiesel and on a fuel blend, the brake effective power was decreased and the brake specific fuel consumption (BSFC) was increased, while the brake thermal efficiency (BTE) was decreased by the sources [19, 20].

Equipment set-up

There were four different fuels investigated by the modified European stationary cycle (ESC) test cycle [21]. The four fuels were D2 as a reference fuel, 100% WVOME (methyl esther of blend of different waste vegetable oils), 100% pure waste palm oil methyl ester (WPOME) and 10 V/V % WVOME, and 90 V/V% rapeseed methyl ester (RME) to compare the RME and WVOME (tab. 1).

The waste oil was procured from the market, WVOME fuel has been produced in Inter-tram Ltd. at Mátészalka. 3 m^3 used cooking oil was used to produce WVOME with traditional KOH/methanol technology. The problem was the high acid number (2.6 mg KOH/g) and water content (5900 ppm) of the raw material. During the process the acid number was established to 0.44 mg KOH/g. The iodine value of the experimental test biodiesel was between 104 and 106. This very low value could be caused by the high palm oil content of the used cooking oil, which has very low iodine value (45-50) [22]. The waste palm oil was procured from a restaurant supply chain, WPOME fuel has been produced by the CORDI R&D Inc. with traditional KOH/methanol technology with the use of Cu catalyst. The RME was procured from a filling station in Austria.

Table 1. Main parameters of the investigated fuels

Test	Viscosity$^{(1)}$ [mm^2s^{-1}]	LHV [$MJkg^{-1}$]	CN [–]	Density$^{(2)}$ [$kgdm^{-3}$]	CFPP [°C]
Test method	ASTM D-445	ASTM D 240	ASTM D 613	ISO 3675	ASTM D6371
VWOME	3.97	37.2	56.4	0.882	–5,5
D2 [23]	2.30	42.9	54.6	0.838	≤ –20
WPOME [24]	4.40	38.7	60.4	0.863	+10
RME [25]	5.05	36.3	51.4	0.875	–12

$^{(1)}$ at 40 °C, $^{(2)}$ at 15 °C.

The investigated turbocharged, direct injection with distributor-type injector and Bowl-in-piston type combustion chamber engine type 1Z (Audi, 1.9 l, TDI, tab. 2) was coupled with an eddy-current type dynamometer (BORGHI & SAVERI FE350S) in order to provide the brake load, while the engine throttling and dynamometer settings were controlled by a data acquisition system, fig. 3.

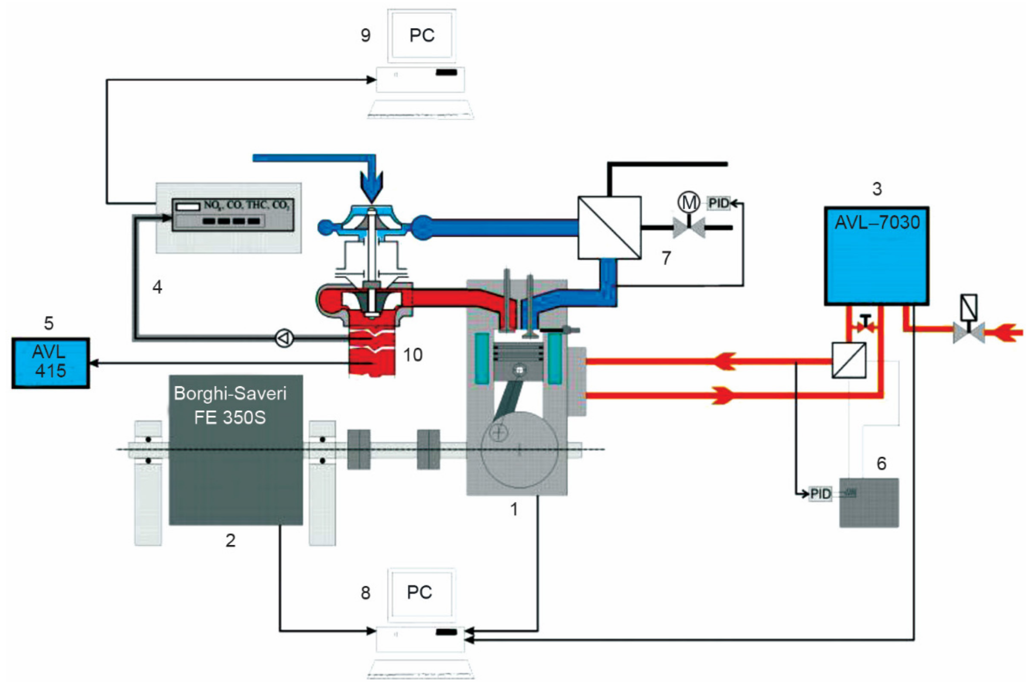

Figure 3. Measurement set-up based on [26]; *1 – engine, 2 – eddy current dynamometer, 3 – fuel consumption measuring system, 4 – exhaust gas analyser system, 5 – smoke meter, 6 – fuel temperature controller, 7 – intake air temperature controller, 8, 9 – computer, 10 – emission sampling*

Table 2. Engine details [23]

Engine model	VW 1Z, 1.9 TDI
Capacity	1896 cm^3
Bore	79.5 mm
Stroke	95.5 mm
Compression ratio	19.5:1
Emission standard	Euro 1
Maximum power	66 kW at 4000 rpm
Maximum torque	202 Nm at 1900 rpm

The 1Z engine was equipped with a VP37 distributor-type injector pump with electronic governor to control the effective stroke of the pump element. The electronic diesel controller had active injection timing control and exhaust gas re-circulation control based on the volumetric flow of the intake air, tab. 2.

The fuel was introduced from a fuel tank equipped with a mass flow measurement system (AVL 7030). During the fuel switching, the fuel tank was drained from the engine fuel filter, new fuel was introduced into the tank until the fuel filter was full, and the engine was then started and allowed to run to clear the fuel lines and to stabilize (tab. 3).

Emission was measured by the Horiba emission gas analyzer system (MEXA 8120) and a smoke meter (AVL 415) connected in front of the oxidative converter at the engine exhaust pipeline.

Results and discussion

Numerous papers have been published on RME performance, for instance, [27-29]. The author had not only investigated performance of RME blends compared to diesel oil, but extended the investigation with used cooking oil methyl ester or WVOME, its blend with

RME (10% V/V VWOME + 90 V/V% RME), and pure WPOME as an alternative environmental friendly limited source of fuel for internal combustion engines.

Table 3. Description of test equipment and equipment accuracy (source: own edition)

No.	Equipment	Description	Accuracy of measuring system
1	Engine	VW 1.9 TDI (1Z)	–
2	Eddy current dynamometer	Borghi &Saveri FE-350S	Measurement: Torque ±3,5 Nm Speed ±1 rpm Controller: ±1.5%
3	Fuel consumption measuring system	AVL-7030 fuel balance	±20 g/h
4	Exhaust gas analyzer system	HORIBA MEXA-8120 F	–
	CO analyzer	AIA-23, NDIR	± 0,002 V/V%
	CO_2 analyzer	AIA-23, NDIR	±0,336 V/V%
	HC analyzer	FIA-22, H FID	± 2,1 ppm
	NO/NO_x analyzer	CLA-53, H CLD	± 42 ppm
5	Smoke meter	AVL 415	3 mg/m^3
6	Fuel temperature controller	–	±5 °C
7	Intake air temperature controller	–	±5 °C
8	Computer	PC-installed with engine loading controls software	–
9	Computer	PC-recording emission data	–
10	Emission sampling	Sampling before DOC	–

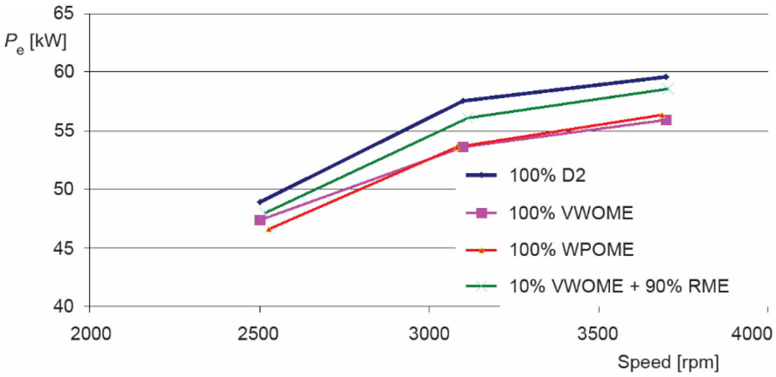

Figure 4. The maximum (full load) brake effective power of the different fuels

The maximum brake effective power decreased, fig. 4, in the case of biofuels (WVOME, WPOME, and 10 V/V% WVOME + 90 V/V% RME). The decreases were different, it was the maximum in the case of WPOME, the average of it was 5.69%, the minimum was in the case of 10 V/V% WVOME + 90 V/V% RME it was 2.06%, but WVOME decrease was near to it, it was 2.39% by the average. These decreases were smaller than the differences of the lower heating value (LHV). The LHV of the WVOME 13%, WPOME 9,8%, and 10 % WVOME + 90 % RMR 15% was lower than the reference D2 fuel's LHV by mass [$MJkg^{-1}$]. These results could be attributed to higher CN number, higher density and viscosity, and improved combustion [30].

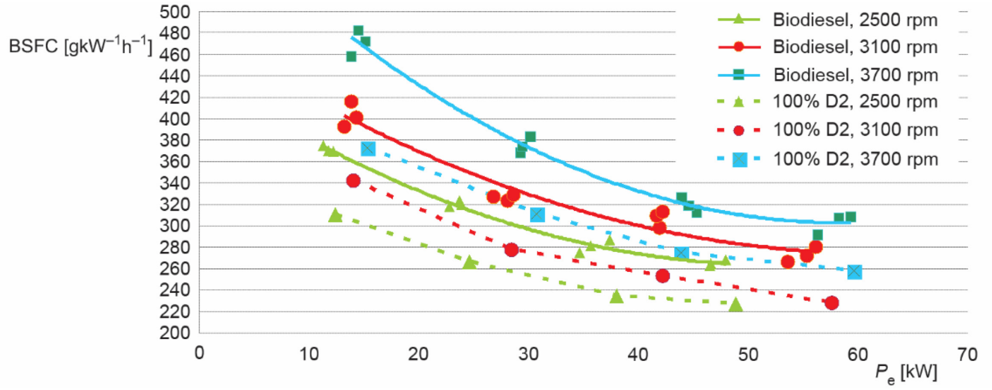

Figure 5. The BSFC of the different fuels at different loads and speeds

Compared BSFC of the bio based fuels was higher, fig. 5, in the case of WVOME it was 19,5%, 10 V/V% WVOME + 90 V/V% it was 21.8%, and in the case of WPOME, it was 14.9%, by the average. The differences between the biofuels were small, the maximum deviation was 11.8 g/kWh, which was less than 3%. These increases were higher than the differences of the LHV, the reason could be the lower BTE than that of D2 reference fuel. The reason of higher fuel consumption could be the higher density and viscosity.

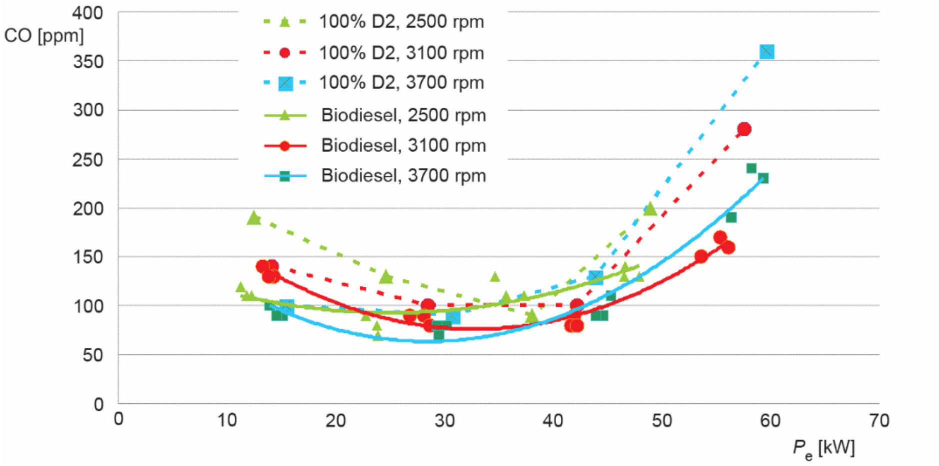

Figure 6. The CO emissions of the different fuels at different loads and speeds

The measured CO [ppm] emissions, fig. 6, developed in the function of the power. At low power region it had a high value, around the medium brake effective power the emissions had a minimum region. At maximum brake effective power the CO emissions had the highest values. At low (25%) and medium (50%) power the CO emissions were similar for all of the fuels, except at low speed (2500 rpm) and low load, in this case the CO emission of the reference D2 fuel had higher emission. At full load at all speeds the D2 fuel had higher emission, the bio based fuels had lower emissions, the reason of it could be the oxygen content of the biofuels. The differences between biofuels were smaller or near the same as the accuracy of the CO analyzer.

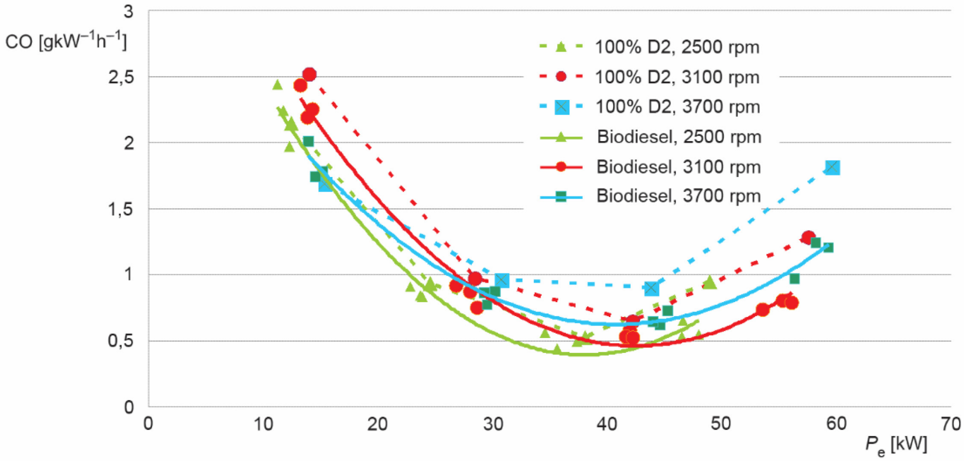

Figure 7. Specific CO emissions of the different fuels at different loads and speeds

The specific CO emissions of the biofuels and reference D2 fuel are shown in fig. 7. The specific CO emission [gkW^{-1}h^{-1}] trends in the function of the power were different than direct emissions, the highest specific CO emissions were in the low brake effective power region. There were no clear trends in the function of the speed. The 100% WVOME, the 100% WPOME, and the 10% WVOME + 90% RME had lower values at full load, in other points the differences were near the same as the accuracy of the CO analyzer and the measuring system.

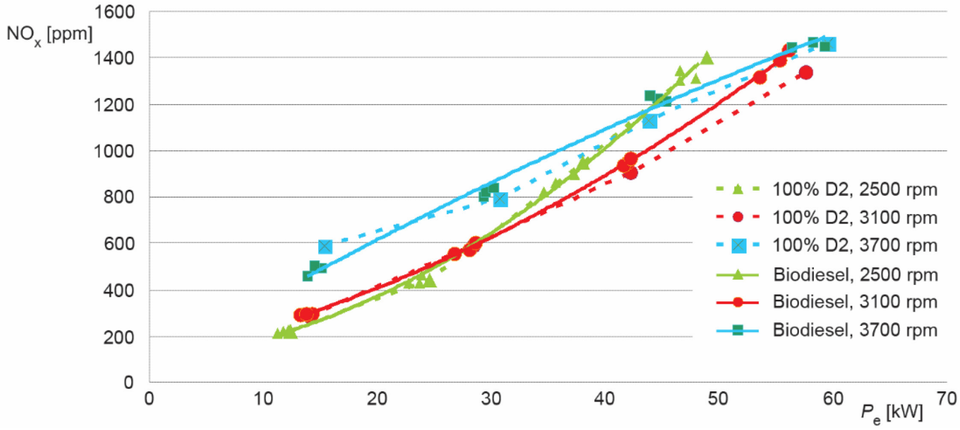

Figure 8. The NO$_x$ emissions of the different fuels at different loads and speeds

The NO$_x$ emissions in the four different fuels are shown in fig. 8. The measured NO$_x$ emissions increased in the function of the power. The highest NO$_x$ emissions were measured at high speed (3700 rpm) and full load. Usually, methyl esters had higher emission values, but the differences were near the same as the accuracy of the NO_x analyzer.

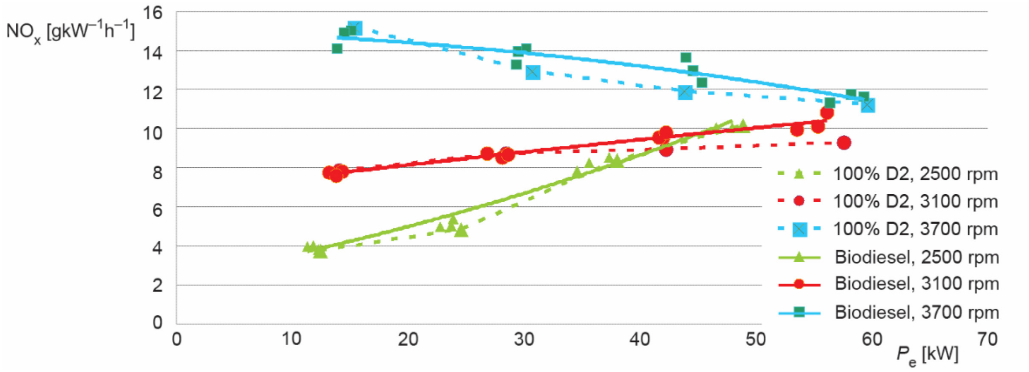

Figure 9. The specific NO_x emissions of the different fuels at different loads and speeds

The differences of the specific NO_x emission of the four different fuels are shown in fig. 9. The specific NO_x emission [$gkW^{-1}h^{-1}$] trends were different. At 2500 rpm and at 3100 rpm the specific NO_x emissions increased with the power, but at 3700 rpm they decreased. Waste vegetable methyl esters and RME blend had similar values, the differences are smaller or near the same as the accuracy of the NO_x analyzer and the measuring system too.

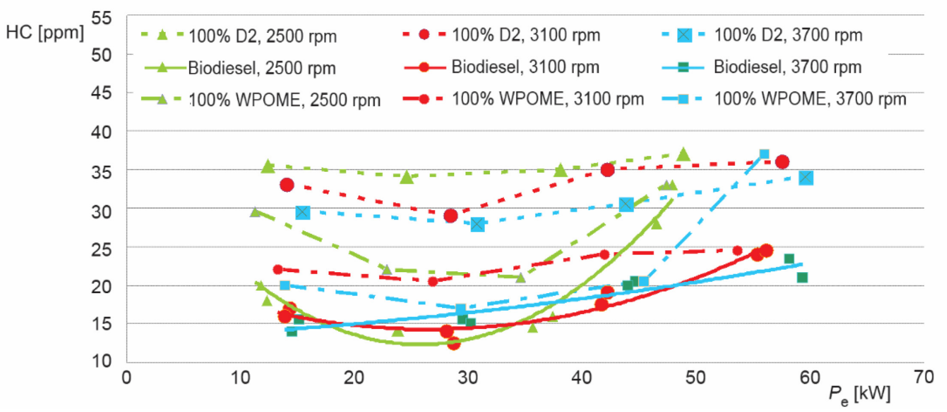

Figure 10. The HC Emissions of the different fuels at different loads and speeds

The differences of the HC emission of the different fuels are shown in fig. 10. The measured HC emissions had a maximum at full load, in the function of the power at constant speed the emissions slightly increased with the power, The bio based fuels had a lower HC emission, it is important to note that the 100% WPOME had higher emission than the other two biodiesels, which was possible to attribute to the worse combustion process due to higher viscosity of the WPOME fuel.

The differences of the specific HC emissions in the different fuels are shown in fig. 11. The measured specific HC emissions in the function of the power decrease, except at

2500 rpm in the case of bio based fuels. The specific emissions increased in the function of the speed except at 2500 rpm at full load in the case of bio fuels.

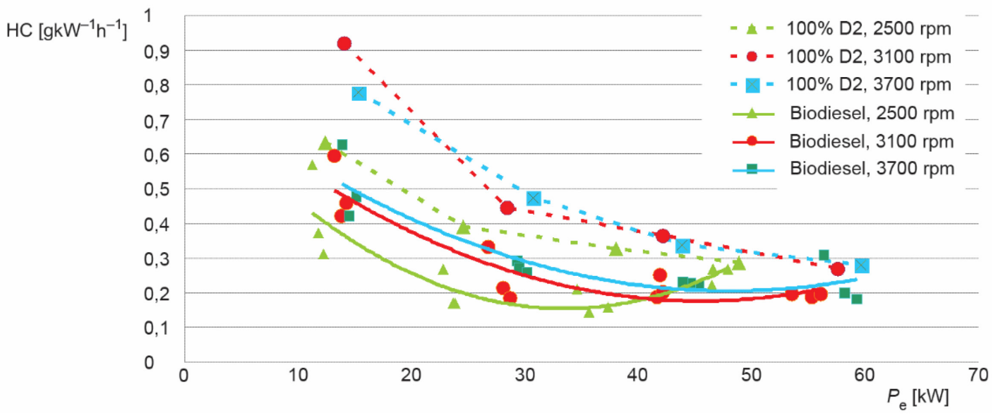

Figure 11. The specific HC emissions of the different fuels at different loads and speeds

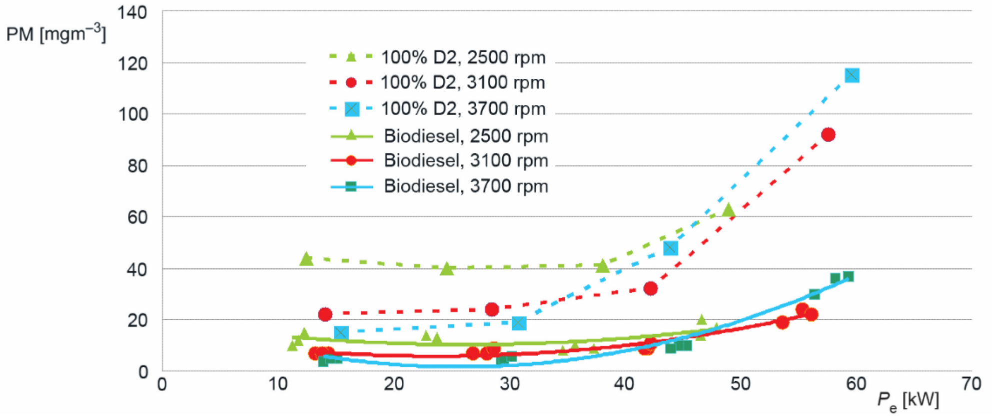

Figure 12. The measured PM emissions of the different fuels at different loads and speeds

The measured particulate matter (PM) emissions increased in the function of the brake effective power, fig. 12. At low load the highest values belong to the low speed. The 100% WVOME, the 100% WPOME, and the 10% WVOME + 90% RME fuels had lower values, possibly attributed to the oxygen content of the bio based fuels. The differences between the bio fuels were lower than the accuracy of the analyzer.

The differences of the specific PM emission of the four different fuels are shown in fig. 13. The specific PM emissions had high values in the function of the brake effective power at low load, at medium load there were the lowest emissions, and then they increase with the load, while the highest values belong to the full load. The methyl esters have lower values, the differences between the different fuels were near to the accuracy of the analyzer.

After the measurements the author performed the weighted calculation of averages according to the standard ESC [21]. The results are in tab. 4.

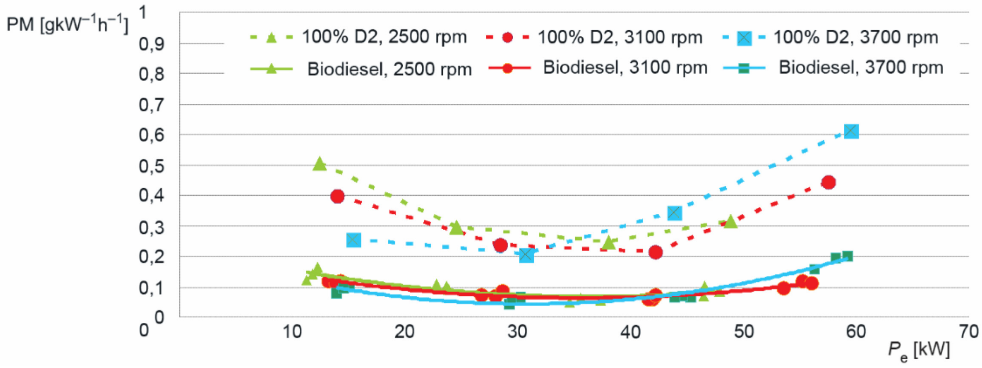

Figure 13. The specific PM emissions of the different fuels at different loads and speeds

Table 4. The different weighted specific emissions of the different fuels own edition

	CO [gkW^{-1}h^{-1}]	HC [gkW^{-1}h^{-1}]	NO$_x$ [gkW^{-1}h^{-1}]	PM [gkW^{-1}h^{-1}]
D2	1.34	0.40	9.73	0.37
100% WPOME	0.95	0.30	9.94	0.09
100% VWOME	0.96	0.23	10.14	0.10
10% VWOME + 90% RME	0.93	0.23	10.32	0.11

Conclusions

The paper theoretically and experimentally investigated the economic and environmental effects of WVOME usage in compression ignition type internal combustion engines.

From the macro economical investigation the author found that with the help of WVOME, biofuel dependency can be decreased and agriculturally based biofuel production can be partly substituted. Agriculture has an important role in the future biodiesel production and in the conservation of non-agricultural areas. One tool can be the usage of WVOME.

For the experimentally environmental investigation pure WPOME made from pure waste palm oil, WVOME made from used cooking oil and a blend rapeseed oil methyl ester blend were tested. These blend tests were important to compare the influence of the WVOME on the RME.

The maximum brake effective power decreased, in the case of WPOME, the average decrease was 5.69%, the minimum in the case of WVOME was 2.39%, and the 10 V/V% WVOME + 90 V/V% RME decrease was near to the WPOME, which was 2.06% by the average. These decreases were smaller than the differences of the LHV.

The BSFC of the biofuels was higher, the increase was higher than the decrease of LHV, so it was suppose that the BTE.

The weighted calculation of the averages according to the ESC standard, the environmental impacts of the fuels are as follows.

- The weighted specific CO emissions by the ESC, decreased with the used bio base fuels, the average decreases were less than 30%, the difference between the three biodiesel fuels was around 2%.

- The weighted specific HC emissions clearly decreased with the investigated renewable fuels, by nearly 38%, the WPOME had the maximum value, where the decrease was only 27%. In the case of 100% WVOME and 10% VWOME-90 % RME, the decrease was around 43%.
- The weighted specific NO_x emissions slightly increased with bio base fuels, where the average decrease was less than 5%.
- The weighted specific PM emissions decrease with the investigated renewable fuels, namely more than 70%.

Regardless of the previously mentioned advantages, there are some disadvantages of the use of cooking oils as well. A limited volume of supply of used cooking oil is available for collection that requires some treatment.

Acknowledgment

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Nomenclature

a, α – constants of the demand function
b, β – constants of the supply function
P_e – effective (brake) power
p_t – price in time
$\hat{p}$ – market equilibrium price
$\tilde{p}$ – actual price
t – time
x_t – the demand function in time
y_t – supply function in time

Acronyms

BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CFPP – cold filter plugging point
CN – cetane number
D2 – diesel fuel
DOC – diesel oxidation catalyst
ESC – European stationary cycle
H CLD – heated chemiluminescence detector
H FID – heated flame ionization detector
LHV – lower heating value
NDIR – non-dispersive infrared (detector)
PM – particulate matter
RME – rapeseed methyl ester
TDI – turbo direct injection
WPOME – waste palm oil methyl ester
WVOME – waste vegetable oil methyl ester

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