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Cynara cardunculus and coffee grounds as promising biodiesel sources for internal combustion compression ignition engines

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Abstract

In this study, the effect of using two innovative biodiesels - derived respectively from coffee grounds and *Cynara cardunculus* - in blend with neat diesel fuel, on combustion and emissions in a compression ignition engine has been investigated. During tests, load and exhaust gas recirculation were varied and results compared with those obtained with neat diesel fuel and its blends with *Brassica carinata* or waste cooking oil derived biodiesels. Results show a reduction or a comparable NOx and CO emission levels using *Cynara cardunculus* and coffee ground compared to the other fuels tested, while PM and THC emissions are penalized. Fuel consumption, as expected, is slightly reduced. EGR reduces NOx levels, while CO, THC and PM are generally penalized.

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Keywords: renewable fuels; biofuels; biodiesel; transesterification; oil crops

1. Introduction

"The use of vegetable oils as fuel for engines could be insignificant today, but these lubricants over time can become important as oil and coal".

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Since 1900, at the Paris Exposition Universelle, Rudolf Diesel, introducing his compression ignition engine powered by peanut oil, believed that the Diesel engine could also run with improper fuels, made from vegetable oils or animal fats. Nowadays, after more than one century, Diesel's "recipe" is re-discovered and the production of fuels from many kinds of sources - vegetable and animal oils and their derivatives, waste cooking oil, etc… - called biodiesel, is encouraged.

In recent years, the increased fuel price and the shortage of its reserves, in addition to the major restrictions on pollutant and CO_2 (carbon dioxide) emissions, have motivated researchers to use biofuels as an alternative to fossil fuel: in this context, biodiesel is an applicable solution in the immediate future. It is derived from the transesterification of vegetable oils or animal fats, is composed by a mix of long chain fatty acid methyl esters and exhibits chemical-physical characteristics very similar to those of standard diesel fuel. Therefore, biodiesel can be used, alone or in blend with standard diesel fuel, as fuel for compression ignition engines.

The renewability of this fuel is, with no doubt, the main reason behind this research, together with the CO_2 balance emitted throughout the entire biodiesel cycle (i.e. cultivation, production and use), more advantageous than standard diesel fuel. In fact, in the life cycle of one ton of biofuels, 70% CO_2 less, on average, is produced if compared to standard diesel fuels [1,2].

Experiments reported in literature [3,4] have already shown that, despite an overall conversion efficiency comparable or only slightly lower than using standard diesel fuel only, using biodiesel usually leads to a decrease of all regulated polluting emissions at the exhaust, except NO_x levels, whose behavior strongly depends on the amount of oxygen in the biodiesel molecule. Furthermore, from an energetic point of view, the use of biodiesel determines a slight decrease of power and an increase of specific fuel consumption, these effects attributable to the heating value, lower than standard diesel fuel.

The biggest research effort is now addressed to select new and more sustainable sources for biodiesel production. Therefore, in this work, a compression ignition engine has been fed with a blend obtained mixing standard diesel fuel with two new biodiesels derived respectively from *Cynara cardunculus* and coffee grounds with a percentage of biodiesel equal to 20 %vol. The combustion behavior and its effect on engine performance and regulated exhaust emission levels have been compared with the results obtained feeding the engine with standard diesel fuel, alone or in blend with two more "classic" biodiesels, respectively derived from *Brassica carinata* and waste cooking oil. The experimental tests have been carried out varying the engine load and the percentage of exhaust gas recirculation (EGR). The engine speed has been fixed to 1500 rpm while engine loads and EGR levels set during experiments are respectively: 7, 14 Nm; 0, 10, 20%. For each pair of load and EGR levels, the different fuels have been used, keeping constant the start of the single (main) injection.

Nomenclature

ATDC	After Top Dead Center
CAD	Crank Angle Degree
CO	Carbon Monoxide
HRR	Heat Release Rate
EGR	Exhaust Gas Recirculation
NO_x	Nitric Oxides
SOI	Start Of Injection
THC	Total HydroCarbon
PM	Particulate Matter
ICE	Internal Combustion Engine

1.1. Biodiesels properties

The raw materials used for biodiesel production originate from dedicated oil crops or from the filtered collection of waste cooking oils. The chain from dedicated crops is articulated in the extraction of oils from oily seeds, refining and chemical conversion, transesterification to biodiesel. The transesterification process represents the synthesis of biodiesel, in which reactants are vegetable oil and methanol (or ethanol), in presence of a catalyst, usually potassium hydroxide or sulfuric acid. The reaction products are biodiesel (90% by weight) and glycerol (10% by weight). Furthermore, after extraction, the oil seeds are pretreated in order to remove residues due to harvesting, while the transesterification process is followed by a stripping step, in which the residual methanol and glycerol are separated.

If the raw material is made up of vegetable oils and fats and/or organic waste of food origin, the first two phases (extraction and pretreatment) are replaced by a regeneration phase to reduce their acidity. In fact, waste oils and fats can have acid values ranging between 2% and 15%, while for conversion to biodiesel these values must not exceed 4%.

Biodiesel is characterized by some physical and chemical properties that make it similar to standard diesel and suitable to be used in substitution or, alternatively, in combination with standard diesel in compression ignition engines.

1.2. Biodiesel tested

Biodiesels tested in this work have been provided by Istituto di Scienze delle Produzioni Alimentari (ISPA) – National Research Council (CNR). The utilization of biodiesel derived from *Cynara carduculus* and from Coffee grounds for feeding an internal combustion engine is new to the best of the Authors's knowledge, while the biodiesel derived from *Brassica carinata* and waste cooking oil have been massively investigated and will be considered here for comparison purposes.

Brassica carinata was considered since the very beginning as viable for biodiesel production, thanks to favorable energy balance and environmental impact [8].

Cynara cardunculus as source of biodiesel was selected for the activities reported in this work since it requires low irrigation, thanks to its biological cycle taking place mainly in autumn-winter and followed by a quiescent phase in summer. The oil extracted from its seeds has characteristics that make the obtained biodiesel particularly suitable to be used as fuel [9].

Coffee grounds, on the other hand, were selected since the extraction process of oil from coffee requires low energy amount and it is usually characterized by a high efficiency [10].

The high cost of vegetable oils has led to the production costs of biodiesel becoming 1.5 times higher than that for diesel [11], [12] but there is an attractive resource in which the price is 2-3 times cheaper than vegetable oils, therefore, the total production cost of biodiesel can be reduced [12]. This resource is the waste cooking oil (or used frying oil). Increasing food consumption has increased the production of waste cooking oils/fats. Its conversion into fuel also eliminates the environmental impacts caused by the harmful disposal of these waste oils, such as into drains [13].

Data related to the chemical-physical properties for each biodiesel are reported in Table 1. In the same table, the measured Lower Heating Value (LHV) and the estimated stoichiometric air-fuel ratio are also reported. The latter was estimated by knowing the carbon, hydrogen and oxygen concentrations derived from biodiesel chemical formula and calculated as reported in [4].

Table 1. Chemical-physical properties of tested Biodiesels and standard diesel.

Parameter	**WCO**	**Brassica Carinata**	**Cynara Cardunculus**	**Coffee Grounds**	**Standard Diesel**
Cetane Number (ASTM D 613)	57.12	56.44	57.44	56.11	48
Kinematic Viscosity (40°C) [mm^2/s] (ASTM D445)	6.1	6.0	9.5	5.7	3.3
Low Heating Value [MJ/kg]	39.77	40.69	39.18	40.10	44.80
Flash Point [°C] (ASTM D93)	302	296	309	292	72
Surface Tension [mN/m]	40.52	42.05	40.99	37.62	30
Stoichiometric air-fuel ratio, α_{st}	12.6	12.75	12.44	12.39	14.5

In previous works [14]-[15], the Authors performed preliminary tests with biodiesel in order to assess their suitability for the utilization as fuel in internal combustion engines. In particular, in [14] the biodiesels were examined in terms of oil quality and impact of different agronomic techniques (fertilisation, sowing density) and then tested in a constant-volume vessel in order to characterize the spray morphology. The spray penetration and width demonstrated similar behaviour between biodiesel and standard diesel fuel measured for different injection pressures, durations and backpressures. In [15], a first comparison among biodiesels has been carried out on a compression ignition engine and results showed that an overall conversion efficiency comparable or only slightly lower compared to that characterizing an engine fed with standard diesel fuel is observed using the biodiesel blends. Moreover, unburned hydrocarbons, carbon monoxide and particulate matter were all lowered with biodiesel. On the other hand, nitrogen oxides increased. In this work, the previous experimental campaign has been extended analyzing also the behavior of biodiesel derived from waste cooking oil and introducing the effect of EGR.

2. Experimental method

A single cylinder, 4-stroke, common-rail Diesel research engine (AVL model 5402) was used to analyze the effects of the biodiesels on combustion process and regulated emission levels. The technical features of the engine are reported in Table 2, while in Fig. 1 the scheme of the experimental layout is reported.

Table 2: Main specification of single cylinder diesel engine.

Maximum power	18 kW
Bore	85 mm
Stroke	90 mm
Displacement	510 cm^3
Compression ratio	17.1:1
Combustion chamber	Bowl with valve pockets and flat head
Injection system	Common rail
Max. injection pressure	1300 bar

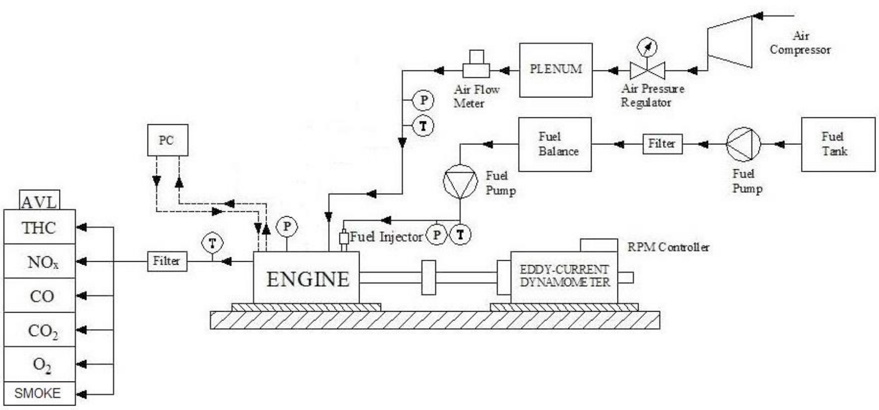

Fig. 1 Experimental layout.

During the experiments, data acquisition started only when the engine had reached steady conditions in terms of speed, load, EGR and cooling water temperature. The cylinder pressure was acquired by means of an AVL piezoelectric pressure sensor model QC33C. The sensor signal was sampled triggering it through an AVL angle encoder model 364C every 0.2 CAD. The absolute cylinder pressure, $p_{cyl,abs}$ was stored for 10 consecutive cycles and then averaged. The linearity error of the pressure transducer was less than 0.4%, while the sensitivity shifts and the range error of the pressure amplifier (AVL model 3066A01) was less than 1%. The measurement error in analogue/digital data conversion and acquisition has been evaluated equal to 0.3%. The maximum error in this calculation, due to the errors in the pressure measurement, is around 2%. In particular the total Heat Release Rate

(HRR) was calculated, as described, for example, in [16]. Other investigated combustion parameters were: the ignition delay, defined as the crank angle interval between the angle at which the 10% of the total heat has been released and the angle at which injection starts; the combustion duration, defined as the crank angle interval between the angles at which respectively 90% and 10% of the total heat has been released. Based on cylinder pressure, it was possible to estimate the indicated power P_i supplied by the engine and also the fuel conversion efficiency as described in [15] measuring the fuel average mass flow rate by means of a AVL 733S Fuel Balance, characterized by a maximum measurement error in the testing conditions equal to 3%.

Pollutant emissions levels at the exhaust and along the EGR line have been measured by means of an AVL AMAi60 emission analyzer and the EGR rate was calculated as follows:

$$EGRrate = \left(\frac{CO_{2\_int} - CO_{2\_amb}}{CO_{2\_exh} - CO_{2\_amb}}\right) * \% \quad (1)$$

where CO_{2_amb}, CO_{2_exh} and CO_{2_int}, are respectively the CO_2 levels in the ambient air, in exhaust line and the CO_2 levels after recirculation in the intake system.

On the other hand, Particulate Matter (PM) has been measured using an AVL Smoke Meter 415S.

The experiments allowed to study the effect of biodiesel-standard diesel blends with 20%vol. of biodiesel on combustion process and exhaust emissions and compare them with those obtained using standard diesel fuel.

In particular, the engine speed has been fixed to 1500 rpm, while engine load and EGR set during experiments were respectively: 7 and 14 Nm; 0, 10 and 20%. For each pair of load and EGR, the four different fuels have been used, keeping constant the start of single (main) injection (SOI), while the amount of total fuel injected per cycle has been adjusted, for each biofuel tested, in order to reach the same engine load obtained with standard diesel fuel. Although the different combustion development determined by the different fuels could impact differently on performance, noise, fuel conversion efficiency and emission levels for different values of SOI, results obtained varying SOI are not presented here. In the following table, factors and corresponding levels varied during tests are reported.

Table 3: Factors and corresponding levels varied during tests.

Description	Abbreviation	Tested levels
Engine Speed	n	1500 [rpm]
Rail injection pressure	p_{rail}	500 [bar]
Injection timing	SOI	-6 [CAD ATDC]
Engine load	EL	7 / 14 [Nm]
Exhaust Gas Recirculated rate	EGR	0 / 10 / 20 [%]

3. Results and discussion

As previously said, from the in-cylinder pressure, it was possible to calculate the combustion process parameters. In particular, in Fig. 2 the *fuel conversion efficiency* is reported for several fuels tested varying the EGR rate for low (equal to 7 Nm, a) and medium (equal to 14 Nm, b) engine load.

It is possible to note that the fuel conversion efficiency for biodiesel blends tested is slightly lower and sometimes comparable or higher compared to that of standard diesel. In Fig.2b, increasing engine load, the fuel conversion efficiency increases with respect to low load conditions. Furthermore, it is also possible to note a slight decrease in fuel conversion efficiency increasing the EGR rate. The decrease in fuel conversion efficiency could be due to the lower combustion temperature and reduction in air-fuel ratio as results of EGR.

In Fig. 3, HRR peak, ignition delay and combustion duration varying the EGR rate are compared using different fuels at low (a-a'-a'') and medium (b-b'-b'') loads. From Fig. 3 is visible that, using biodiesel blends, HRR peak (a) is lower than using standard diesel fuel, first of all because their LHV is lower compared with that of standard diesel fuel but also because the ignition delay (a') is shorter, due to the higher cetane number of biodiesel.

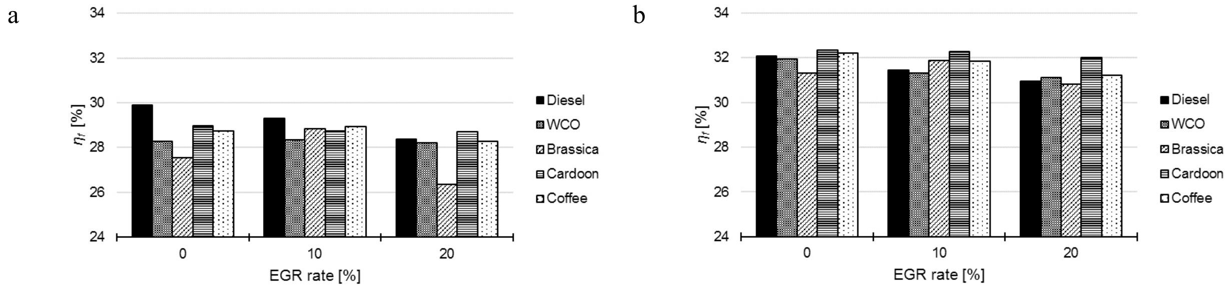

Fig. 2. Fuel conversion efficiency for engine load equal to 7 Nm (a) and 14 Nm (b) varying the EGR rate for different biodiesel blends and standard diesel.

The combustion duration (a'') with biofuels is higher than standard diesel fuel due to a higher amount of fuel injected and, presumably, because of higher values of fuel viscosity and surface tension, both leading to a bigger dimension of spray droplets. Same trends have been observed for HRR peak (b), ignition delay (b') and combustion duration (b'') at medium load.

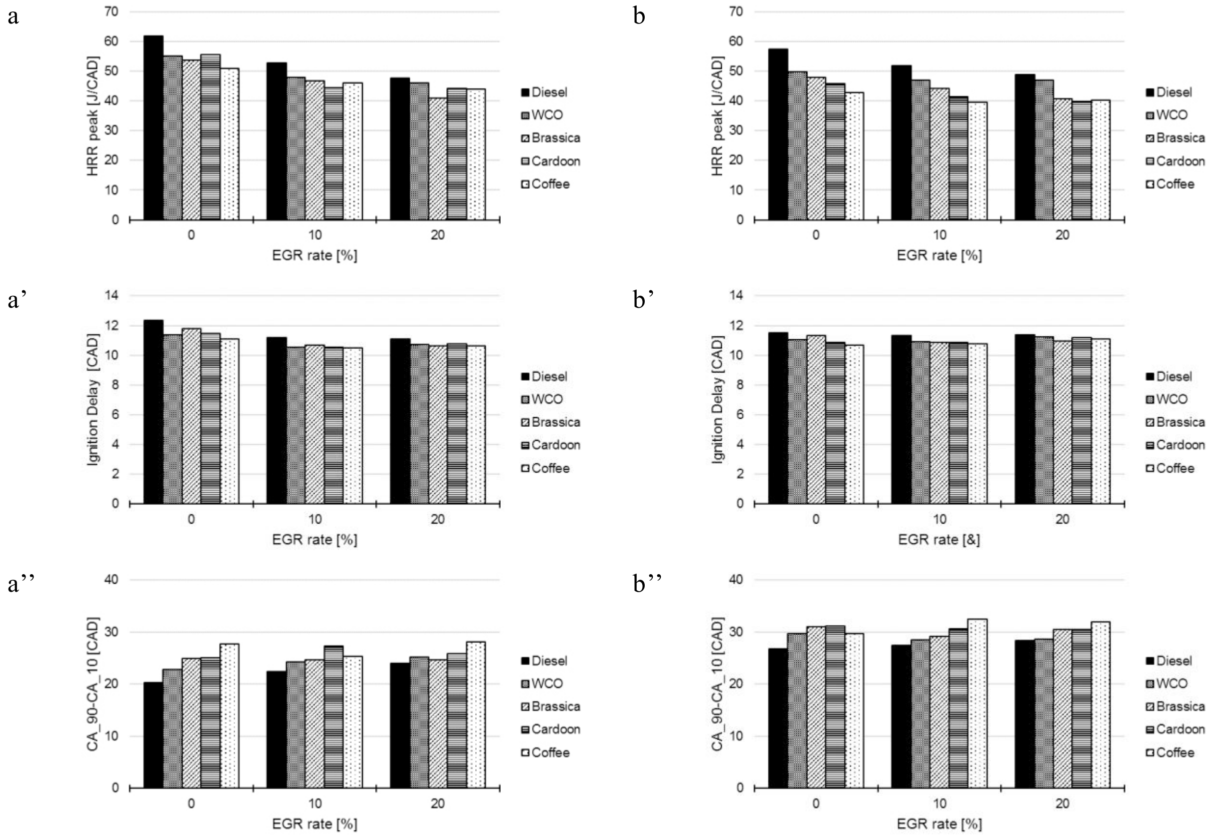

Fig. 3. HRR peak (a), ignition delay (a'), combustion duration (a'') for 7 Nm engine load; HRR peak (b), ignition delay (b'), combustion duration (b'') for 14 Nm engine load, varying the EGR rate for biodiesel blends and standard diesel tested.

In Fig. 4, THC, CO, NO_x and PM levels varying the EGR rate are compared using different fuels at low (a, a', a'', a''') and medium (b, b'. b''. b''') loads. A slight increase in THC and PM emissions is generally noted with biodiesel fuels in both engine load condition, similarly to what reported in [17], while lower or comparable NO_x and CO emission levels have been noted using Cardoon and coffee biodiesel compared to the other fuels tested, this being more evident as EGR rate is increased. The behaviours are determined based on the following considerations. On one hand, the fuel composition, and in particular the oxygen content, positively affects the oxidation of CO and THC species, resulting in a more complete combustion process. On the other hand, NO_x emissions increase, as directly affected by oxygen concentration. Applying EGR lowers the oxygen concentration in the cylinders, resulting in a reduction of NO_x and an increase of CO and THC emissions with increasing EGR rate.

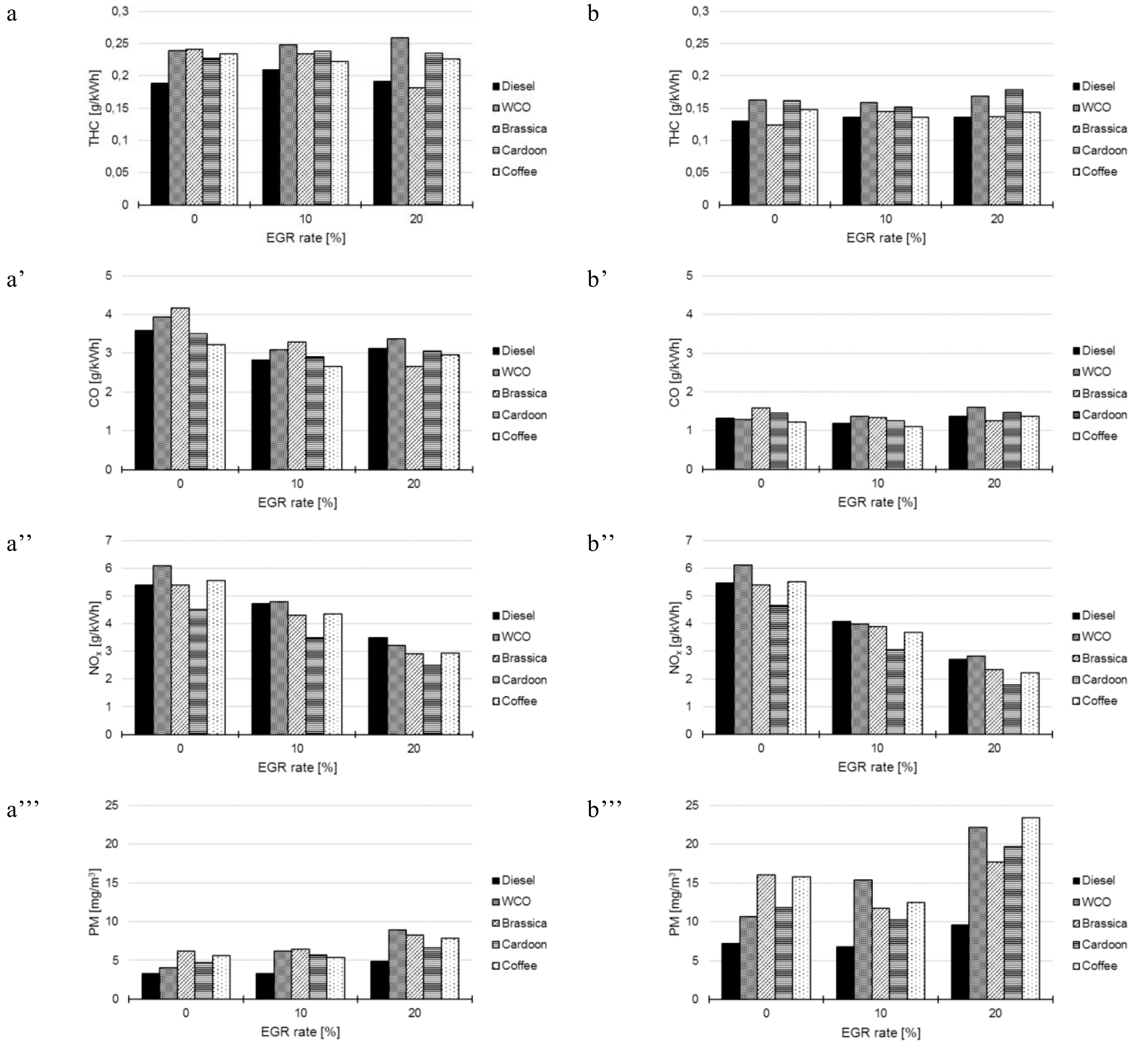

Fig. 4. THC (a), CO (a'), NO_x (a''), PM (a''') for 7 Nm engine load; THC (b), CO (b'), NO_x (b''), PM (b''') for 14 Nm engine load varying the EGR rate for biodiesel blends and standard diesel tested.

PM is produced by unburned carbon particles in rich (fuel excess) zones. PM emissions increased for all the different biodiesel tested; also EGR rate had a detrimental effect on PM levels, due to further reduction of oxygen availability deriving from EGR utilization. This behaviour could be attributed to different chemical-physical properties and, in particular, the higher surface tension and viscosity of biodiesels (see Table 1) that may have affected the droplet size distribution of sprays, in particular determining bigger fuel droplets and therefore a slower fuel evaporation and a not perfect mixing with air.

4. Conclusions

Aim of this work was to assess the feasibility of using biodiesel derived from *Cynara cardunculus* and *Coffee grounds* as fuels in internal combustion compression ignition engines. Therefore, blends of 20% by volume of *Cynara cardunculus*, coffee grounds, waste cooking Oil and *Brassica carinata*, biodiesels in standard diesel were investigated, the last two for comparison purposes. During the experimental campaign, one single injection, one rail injection pressure, one injection timing, three EGR rates and two engine loads were tested.

Results show a reduction or a comparable NO_x and CO emission levels using *Cynara cardunculus* and coffee ground compared to the other fuels tested, while PM and THC emissions are penalized. Fuel consumption, as expected, is slightly reduced. EGR reduces NO_x levels, while CO, THC and PM are generally penalized.

It can be concluded that biodiesel derived from *Cynara cardunculus* and *Coffee grounds* are potentially good candidates for feeding compression ignition engines.

From the presented results, it can be argued that fuel properties have great influence on emission level and combustions development. Therefore, an ad hoc experimental campaign will be performed, addressed at better understanding of the observed phenomena and at improving biodiesels benefits.

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