EXHAUST EMISSIONS OF BIODIESEL AND ITS INFLUENTIAL PROPERTIES ON ENGINE PERFORMANCE CHARACTERISTICS

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ABSTRACT

Biodiesel was extracted from three different individual sources: waste frying oil, palm oil, and castor oil to find out if significant differences exist among biodiesel fuels within their thermo-physical properties and engine performance characteristics and the resulted exhaust emissions. The study investigated the effect of these biodiesels properties on engine performance characteristics, to determine the appropriate biodiesel source for best engine performance. The tested properties were: kinematic viscosity, density, flash point, heat value, and pour point. The tested exhaust emissions elements were: Oxygen, Sulfur dioxide, Carbon dioxide, Carbon monoxide, and Nitrogen oxides. Engine performance characteristics under evaluation were Brake power, Brake specific fuel consumption, and the Air fuel ratio.

INTRODUCTION

Using biodiesel as a renewable fuel source is based on being an alternative liquid fuel produced by chemical reactions between vegetable oils or animal fats and a short-chain alcohol, such as methanol or ethanol in the presence of a catalyst. The main characteristics of biodiesel have been proved quite similar to mineral diesel. Efficient engine performance using a biodiesel fuel depends on the quality of the biodiesel properties. The differences in the chemical compositions and thermo-physical properties of biodiesels from different sources may bring about differences in engine performance characteristics. Biodiesel properties have a significant role for evaluating their adaptability for any engine operation. Few of the important biodiesel properties were determined and found in the comparable range with diesel fuel.

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Shrestha et al. (2005) defined **Flash point** of any fuel as the lowest temperature at which fuel vapor can be ignited by externally supplied ignition, in other words it signifies the temperature at which the fuel self-ignites. Fernando et al. (2007) defined the **cloud point** as the temperature at which wax crystals first becomes visible when the fuel is cooled. **Pour point** is the temperature at which the amount of wax out of solution is sufficient to gel the fuel, thus it is the lowest temperature at which the fuel can flow. Rehman et al. (2009) defined **cloud point** as the temperature where crystal formation in the fuel starts and **pour point** as the temperature where fuel ceases to flow. They also mentioned that one of the major reasons hindering widespread use of biodiesel is its higher filter plugging temperature than regular diesel fuel. Cloud point and pour point temperature are shown to be well correlated with filter plugging point which primarily determines the operability of a diesel engine.

According to Rehman et al. (2009), the **viscosity** of a fuel is an important property which affects fuel atomization during the injection. High viscosity of plant oil was reported to be the main cause of injector chocking problem in C.I. engine. Sonune and Farkade (2012) reported that higher fuel viscosity results in poor atomization and larger fuel droplets followed by inadequate mixing of biodiesel droplets and air.

Buyukkaya (2010) pointed to the higher viscosity of biodiesel fuels, which may affect the engine brake effective power and engine torque especially at full-load conditions, increases the fuel momentum and consequently penetration depth in-cylinder. On the other hand, the higher viscosity and surface tension of biodiesel fuels prevent their sufficient breaking or disintegration during injection process.

Gumus et al. (2012) and Heywood (1988) justified that each biodiesel source may differ from another due to some factors such as air–fuel equivalence ratio, fuel properties, engine performance, chamber design, atomization rate, start of injection timing, injection pressure, engine load and speed which affect **CO** emissions which in fact expresses the lost chemical energy unused in the engine; it is the result of the incomplete combustion of the fuel; **CO** is highly produced from petroleum fuels, which contain no oxygen in their molecular structure. Dwivedi et al. (2014) stated that biodiesel has lower C/H ratio due to its oxygenated

nature and so the total amount of CO_2 is found lower, when biodiesel is used. Kumar et al.(2014) stated that biodiesel injection affects the engine performance characteristics and exhaust emissions of the engine. The start of fuel injection can be influenced by changes in fuel properties like viscosity and in the changes in fuel injection timings. The start of injection is the point at which the injection line pressure matches with the nozzle opening pressure of the injector. The engine performance efficiency of the fuel in the engine can be computed by considering the energy required to produce NOx and the energy losses due to incomplete oxidation of CO to CO_2 and unburnt hydrocarbon (UHC) to CO_2 and H_2O. The increase in NO_x emission may be related to the oxygen content of the biodiesel. The oxygenated biodiesel provides additional oxygen for NO_x formation. According to Aydin and Ilkilic (2010) the more completed engine performance, the higher engine performance temperature, which will cause higher NO_x formation.

According to Peng (2015) Biodiesel fuels can be used in high-pressure engine performance engines, such as common rail injection engines in which high injection pressures allow rapid atomization and engine performance resulting in higher efficiencies and lower emissions. Gomaa et al. (2014) investigated tractor diesel engine performance when engine was fueled with three biodiesels separately; which were extracted from three different individual vegetable oils.

This study aims to investigate the differences that exist among three biodiesel samples obtained from: waste frying oil, palm oil and castor oil, and the possible impacts of biodiesels properties on the characteristics of the diesel engine performance. So the study was carried out to:

1) Determine the variation of the tested biodiesels thermo-physical properties and their resulted exhaust emissions and engine performance characteristics.

2) Determine whether significant differences exist among biodiesels within each property, within each element of their exhaust emissions and within each of their engine performance characteristics.

3) Investigate the effect of the tested biodiesels properties on engine performance characteristics, to obtain best engine performance.

MATERIALS AND METHOD

Preparation of biodiesel samples

In the laboratory of Soil and Agricultural Engineering dept.-Faculty of Agriculture (Saba Basha); three different biodiesels were prepared from three different individual biosources, waste frying oil, palm oil, and castor oil, by transesterification process. They were tested as alternative fuels for tractor engine at the Testing and Research Station for Tractors and Agricultural Machinery, Alexandria.

Density measurement:

Density of each pure biodiesel was measured in the laboratory of Soil and Agricultural Engineering dept.- Faculty of Agriculture (Saba Basha) according to the standard steps and replications to determine the mass of a hypothetical volume of 20 ml biodiesel :

$$\textbf{Density} = \frac{\textbf{Biodiesel mass}}{\textbf{20}} \quad (\frac{\textbf{gm}}{\textbf{cm}^3}) \textbf{ or } (\frac{\textbf{kg}}{\textbf{l}})$$

The whole steps were repeated each time temperature was raised 20 ºC until 100 ºC.

Dynamic viscosity measurement:

The variation of the prepared biodiesels viscosities with raising temperature, were measured at the SOUTH REFINERIES - MINISTRY OF OIL - REPUBLIC OF IRAQ. Biodiesel viscosity was determined by using a viscometer, to measure the time of both biodiesel and distilled water flow through a definite distance in a tube of glass. The following equation was used:

$$\frac{\eta_1}{\eta_2} = \frac{d_1.t_1}{d_2.t_2}$$

Where, t_1 : measured flow time of the unknown biodiesel viscosity - **s**.

t_2 : flow time of water - **s**.

η_1 : unknown biodiesel viscosity

η_2 : Viscosity of water 0.891 **ml Pa.s**, or 0.01**poise**.

d_1 : Biodiesel density - **gm/cm³**

d_2 : density of water - 1 **gm/cm³**

Kinematic viscosity **(mm²/s)** was then calculated as the quotient of the dynamic viscosity (**ml Pa.s**) and density (**kg/l**):

$$\textbf{Kinematic viscosity (mm}^2/\textbf{s}) = \frac{\textbf{Dynamic viscosity (ml Pa.s)}}{\textbf{Density (kg/l)}}$$
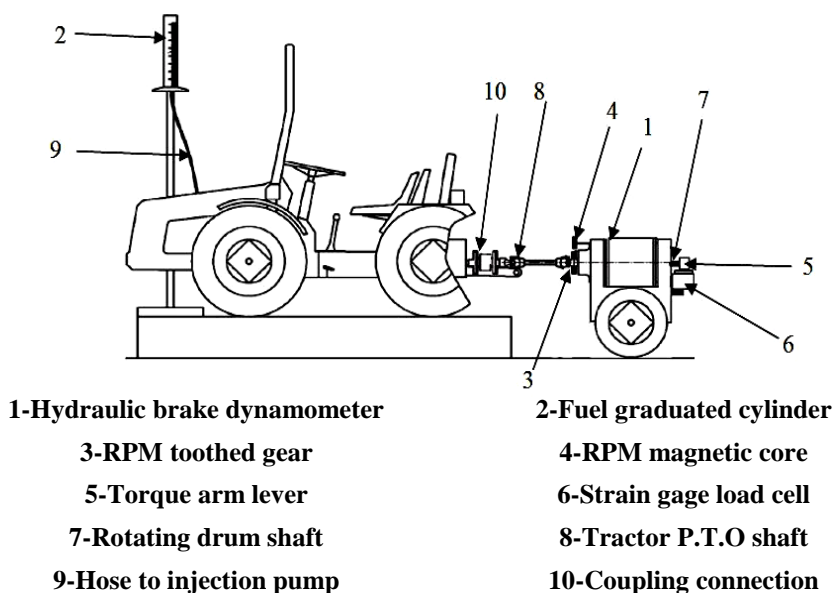
Measurements of the rest of the biodiesel properties were accomplished in Misr Petroleum Co. laboratory as displayed in Table (4).

The analysis of variance (ANOVA) was applied to determine whether significant differences in their operational properties exist among biodiesel samples obtained from three different individual sources of vegetable oil, FO, PAO, and CAO. Exhaust emissions and thermo-physical biodiesel properties(or operational properties) and their related engine performance characteristics; they all were subject to ANOVA of two - factor with replication, except flashpoint, heat value, and pour point which were subject to ANOVA of single factor.

Based on all of the above applied ANOVA the deduced judgement is based on the following principle: The absence of any significant differences among the tested biodiesels within any property can justify their common graphical trend within any engine performance characteristic BP, BSFC, and AFR; and vice versa.

Engine torque and power measurements:

A hydraulic brake stationary dynamometer 90 kW was hooked to 67 kW tractor to measure both torque and rpm exerted on the tractor power take off shaft (PTO) at different loads when operating the tractor engine on biodiesel as shown in Fig. (1).

|	
1-Hydraulic brake dynamometer	2-Fuel graduated cylinder
3-RPM toothed gear	4-RPM magnetic core
5-Torque arm lever	6-Strain gage load cell
7-Rotating drum shaft	8-Tractor P.T.O shaft
9-Hose to injection pump	10-Coupling connection

Fig.(1): Schematic view of the engine test arrangement.

Technical specifications of the tractor and the hydraulic brake stationary dynamometer are given in Table (1):

Table (1) Technical specifications of the tractor and dynamometer

Model	Kubota M$_1$-100S-DT
Type of engine	Four stroke, indirect injection ,Turbocharged , liquid cooled diesel
Engine power , kW (HP)	73.6 (100)
Rated Engine speed , rpm	2600
Compression ratio	21.8:1
Number of cylinders	4-cylinder
Bore * stroke , mm	100 x 120 mm
Technical specifications of the hooked hydraulic brake stationary dynamometer.	
Model	NEB600
Serial number	CD6190C5
Range	300 kW at 540rpm
	600 kW at 1000 rpm
Capacity of torque	4338 Nm

A daytronic data PAC model 10k4 was used to record data measured by the torque cell sensor and the magnetic pick-up frequency sensor as shown in Fig (2). These two sensors are engaged to the AW dynamometer; The sensing torque cell has a full whinstone bridge of strain gage for recording the torque applied to P.T.O. during test; while a magnetic pick-up frequency sensor consists of a toothed wheel, (60 teeth), coil, and iron core was used to record the P.T.O shaft rpm, as the toothed wheel rotates, the magnetic field of the magnetized source is detected, and displayed as RPM.
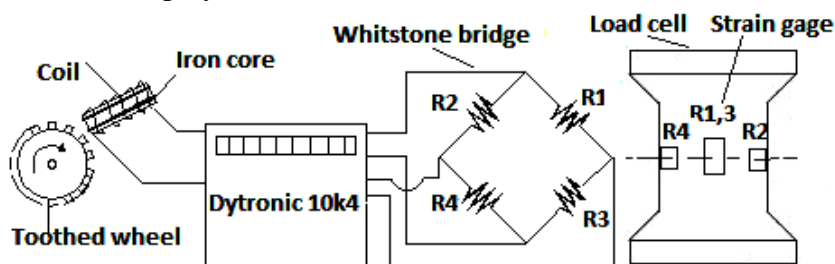
Fig. (2) Daytronic and AW sensors wiring diagram.

The diesel engine gas emissions were measured by a gas analyzer. This gas analyzer consists of electrochemical sensors, and infrared flue gas analyzers. The temperature and the gas emissions concentrations (CO_2, CO, NO, NO_x, O_2, and SO_2) elements were detected by independent electrochemical sensor. Fig.(3) illustrates the connection of the gas analyzer to the tractor exhaust pipe during the test.

Fig.(3) The stack gas analyser connected to the tractor exhaust pipe

The tractor was kept running for one hour before start the measurements to warm up all parts and liquids to reach the best working temperature. At the same time and before each measurement for each fuel type, the whole system was running for 10 min at full throttle. Every measurement of torque and rotational speed of PTO was recorded at tractor full throttle. During the experiments, the time required for consuming 100 cm3 of each fuel was also recorded; the first measurement was carried out at no load, then at a standard PTO speed of 540 rpm, and finally at maximum load. For every subsequent measurement, the load on the AW hydraulic brake was increased in order to decrease the rotational speed of the PTO. All engine settings (throttle, cooling...) remained unchanged during the whole experiment for each particular fuel type. When testing a new fuel it was made sure that, the previously tested fuel was completely removed from the pipelines and filter system by running the engine on the new fuel for 10 min at full throttle before doing any new measurements.

Engine Performance Characteristics:

1. PTO Torque and Power:

Both PTO torque in N.m and rotational speed in rpm, were measured in the lab using the AW hydraulic brake stationary dynamometer for tractor power take off shaft calculation, , at different PTO speed, using the following equation.

$$P = 2 \pi n \tau / c \qquad kW \dotsc\dotsc\ (1)$$

Where:

P	Power take-off shaft P.T.O	kW
n	Measured rotational speed of P.T.O	rpm
τ	Measured torque of P.T.O in	N.m
c	constant, equals 60000	

2. Engine Brake Power BP:

According to KUBOTA tractor technical data, PTO power is 88.9% of the engine BP. For a used tractor the PTO power was considered as 88% of the engine BP; and the ratio between the engine and PTO shaft speeds (rpm) is (2205/540) or 4.0833:1.

$$BP = \frac{PTO\ power}{0.88}\quad kW \ldots\ldots (2)$$

3. Fuel Consumption:

The volume of fuel consumption (cm^3) was measured during each test run at no load, at the standard PTO speed, and at full load. Consumption time for each test was also measured and the volumetric fuel consumption rate was calculated for each load as follows:

$$VFC = (V * 3600)/(t * 1000)\quad l/h \ldots\ldots (3)$$

Where:

VFC: Volumetric fuel consumption rate, $l.h^{-1}$

V: volume of consumed fuel in glass bulb, cm^3

t :Time of running the test, s

4. Brake thermal efficiency BTE:

This parameter is obtained by dividing the effective power from the engine by the amount of energy given to the engine.

$$BTE = \frac{BP \times 3600}{VFC \times \rho_f \times HV} \ldots\ldots (4)$$

Where:

BP = Brake power, kW

ρ_f = density of the tested fuel, kg/l

VFC= volumetric Fuel consumption rate, l/h

HV = heat value of the tested fuel, kJ/kg.

5. Brake Specific Fuel Consumption BSFC:

BSFC is the quotient of the fuel consumption rate (l/h) and the corresponding BP (kW) at the same loading conditions represented by the different levels of engine speed (rpm) starting from 408.33 to 2858.31(100 to 700 PTO rpm).

$$BSFC = \frac{VFC}{BP} \quad l/(kW.h) \,\ldots\ldots\ldots (5)$$

6. Brake Mean Effective Pressure BMEP:

BMEP is a useful term which can be obtained if the standard expression for computing indicated power IP is applied to brake power BP instead of IP. So BP in kW can be expressed as follows:

$$BP = \frac{BMEP \times L \times A \times n \times N}{60 \times 2} \quad kW \,\ldots\ldots\ldots (6)$$

Where, BMEP: Brake Mean Effective Pressure, kPa.

L: Piston displacement, m.

A: Piston cross-sectional area, m2.

N: Engine rotation speed, rpm.

n: Number of engine cylinders,

2: Constant associated with a 4 stroke engine.

60: Constant for unit conversion, s.

BMEP gives an indication of the engine state at a certain loading level, which expresses the output per piston displacement. As BMEP increases, the engine develops greater power, where its BMEP changes in direct proportion with load as follows:

$$BMEP = \frac{BP \times 120}{L \times A \times n \times N} \,\ldots\ldots\ldots (7)$$

7. Air Fuel Ratio AFR:

AFR is defined as the ratio of the mass of air to the mass of fuel in the engine. Hence, the following steps had to be measured:

1- Air mass flow rate.

2- Fuel mass flow rate from the system measurement equipment.

3- The quotient of step 1 by step 2 is the AFR. Volumetric efficiency η_v is defined as the ratio of air volume input / minute, v_a, measured at the inlet air conditions, to the number of cylinder swept volume / minute, v_s:

$$\eta_v = \frac{v_a}{v_s} \,\ldots\ldots\ldots (8)$$

The η_v of the KUBOTA tractor supercharged engine, could be determined at any operating point (engine speed) As later shown and

explained from Fig.(15), from which the actual air volume flow rate, v_a (m^3/(min · cyl)) could also be determined per one single cylinder from equation (8) as follows:

$$v_a = \eta_v \times v_s \ \ldots\ldots\ (9)$$

Where,

$$v_s = \left(\frac{\text{number of suction strokes}}{\text{min} \cdot \text{cyl}}\right) \times \text{piston surface area} \times \text{displacement}$$

$$v_s = \left(\frac{\text{Engine revs.}}{\text{min} \cdot 2 \cdot \text{cyl}}\right) \times \frac{cm^2 \cdot cm}{10^6}$$

$$\text{Air mass flow rate} \left(\frac{kg_{ma}}{\text{min} \cdot \text{cyl}}\right) = v_a\left(\frac{m^3}{\text{min} \cdot \text{cyl}}\right) \times \text{air density} \left(\frac{kg_{ma}}{m^3}\right) ..(10)$$

An average air density is considered of 1.205 kg/m^3 at sea level (p = 101.3 kP$_a$, t = 20°C). Table (1) shows the measured density data for all tested fuels in (kg$_m$/l). The measured fuel consumption rate for all tested fuels was divided by 4 cylinders to determine the fuel consumption rate v_f per one single cylinder in (l/min.cyl). Then the mass flow rate of all tested fuels is determined as follows:

$$\text{Fuel mass flow rate} \left(\frac{kg_{mf}}{\text{min} \cdot \text{cyl}}\right) = v_f\left(\frac{l}{\text{min} \cdot \text{cyl}}\right) \times \text{fuel density} \left(\frac{kg_{mf}}{l}\right) \ldots (11)$$

$$\text{AFR} = \ \text{Air mass flow rate} \left(\frac{kg_{ma}}{\text{min} \cdot \text{cyl}}\right) \Big/ \text{Fuel mass flow rate} \left(\frac{kg_{mf}}{\text{min} \cdot \text{cyl}}\right) \ldots\ldots\ (12)$$

The detailed description of test procedure concerning the variation of AFR with engine speed is presented in the next section: Results and Discussion.

RESULTS AND DISCUSSION

1- Biodiesel properties

1.1 - Operational properties

Operational properties of biodiesel samples considered under the present study are: density, kinematic viscosity, Flashpoint, Heat value, and Pour point.

1.1.1- Density and Kinematic viscosity (properties subject to two – factor with rep. ANOVA) **:**

Figs (4&5) illustrate the variation of biodiesels Density and Kinematic viscosity resp. with temperature levels. Density trends for all tested biodiesel fuels are common and close together; this behavior is

confirmed by their related ANOVA shown in Table (2) which confirmed the absence of significant density differences among Biodiesel fuels; which in turn can participate in the resulted common Biodiesel fuels trends and the absence of significant differences between them within all engine performance characteristic BP, BSFC, and AFR.
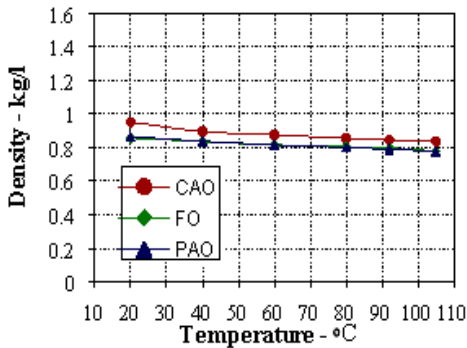

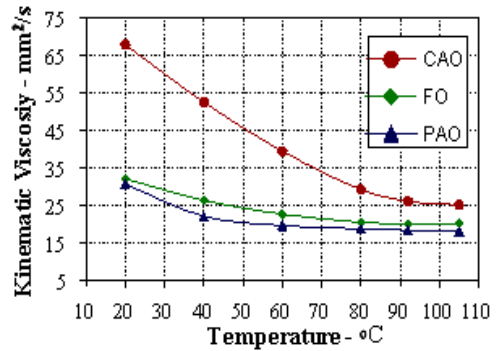Fig.(4): Variation of density with temperature of biodiesel from three different sources.

Fig.(5): Variation of kinematic viscosity with temperature of biodiesel from three different sources.

Kinematic viscosity trends of the same tested biodiesels were not totally in harmony; while biodiesel trends originated from Palm and Fried oil were adjacent, Castor oil was quite higher than them. These mixed viscosity trends of the tested biodiesels resulted in significant Kinematic viscosity differences among biodiesel fuels as confirmed by their ANOVA in Table (3). But this case of existing viscosity significant differences didn't reflect any particular difference in the complete common sources behavior shown by the engine performance characteristic BP, BSFC, and AFR (Figs(11,12,&13)), which also didn't contain any significant differences among biodiesel fuels.

Table (2): Analysis of Density Variance – kg/l.

Source of Variation	SS	df	MS	F	P-value	F crit
Temperature Levels	0.05243	5	0.010486	0.375138	0.862379	2.477169
Among Biodiesel fuels	0.045923	2	0.022961	0.821455	0.447865	3.259446
Interaction	0.002355	10	0.000236	0.008426	1	2.106054
Within	1.006277	36	0.027952			
Total	1.106984	53				

Table (3): Analysis of Kinematic Viscosity Variance - mm²/s.

Source of Variation	SS	df	MS	F	P-value	F crit
Temperature Levels	3500.567	5	700.1135	18.13456	5.8E-09	2.477169
Among Biodiesel fuels	3757.307	2	1878.653	48.66146	5.82E-11	3.259446
Interaction	1574.31	10	157.431	4.077826	0.000847	2.106054
Within	1389.837	36	38.6066			
Total	10222.02	53				

1.1.2 – Flashpoint, Calorific or Heat value, and pour point (properties subject to single factor ANOVA)**:**

Table (4) displays the average values of biodiesels operational properties subject to single factor ANOVA; which were measured at Misr Petroleum Co. laboratory. ANOVA was determined for each property and presented by Tables (5, 6 and 7). Referring to Tables (5&6), no significant differences were found among biodiesel fuels neither in their flashpoint nor in their heat value. In spite of the pour point similar average measured values in both of PAO & CAO, pour point ANOVA in Table (6) indicated significant differences between all biodiesel fuels due to the far FO value.

Table (4): Av. values of biodiesels operational properties subject to single factor ANOVA.

Property	FO	PaO	CaO
Flash point °C	140	185	170
Pour point °C	-6	12	12
Calorific value (MJ/kg)	42.3	42.3	42.5
Ash content (% by weight)	Nil	Nil	Nil

Among all of the above analyzed biodiesels operational properties, only Kinematic viscosity and Pour point showed significant differences among biodiesel fuels; while the effect within the majority or the rest of the tested properties didn't result any significant differences among biodiesel fuels, and this can strongly participate in supporting the common graphical behavior of all of the evaluated engine performance characteristics BP, BSFC, and AFR, (Figs(11,12,&13)), which also didn't contain any significant differences among biodiesel fuels.

Table (5) Analysis of Flashpoint variance °C

Source of Variation	SS	df	MS	F	P-value	F crit
Among Biodiesel fuels	3150	2	1575	1.427924	0.311002	5.143253
Within Biodiesel fuels	6618	6	1103			
Total	9768	8				

Table (6) Analysis of Heat value variance MJ/kg

Source of Variation	SS	df	MS	F	P-value	F crit
Among Biodiesel fuels	0.08	2	0.04	0.000557	0.999443	5.143253
Within Biodiesel fuels	430.7864	6	71.79773			
Total	430.8664	8				

Table (7) Analysis of pour point variance °C

| Source of Variation	SS	df	MS	F	P-value	F crit
Among Biodiesel fuels	648	2	324	75	5.68958E-05	5.143253
Within Biodiesel fuels	25.92	6	4.32			
Total	673.92	8				

1.2 Exhaust emissions

1.2.1 - O_2 Emission

O_2 emission from tractor diesel engine is shown in Fig. (6); O_2 emission was almost in direct proportion with Engine Rotation Speed and of common trend for all tested biodiesels; it is observed that FO, CAO, and PAO contain higher amounts of O_2 than pure diesel at any level of the Engine Rotation Speed which lead to greater oxidation than diesel fuel. This high amount of O_2 in biodiesels helps to contribute in higher engine performance; the exceeded O_2 is swept out of the engine cylinder through exhaust process. The common trend of the tested biodiesels is justified by the absence of significant O_2 emission differences among biodiesel fuels as confirmed by their related ANOVA in Table (8).

1.2.2 - SO_2 Emission

Fig.(7) showed that the concentration of SO2 in the engine exhaust is almost nihilistic for all tested biodiesels; while it was reduced from over 20 ppm at no load to almost 4 ppm for diesel fuel at maximum load.
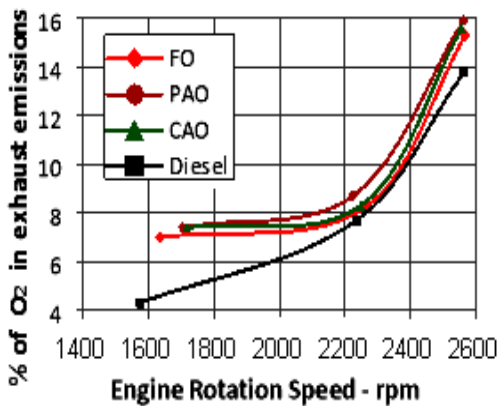
Fig.(6): Variation of O_2 emission with load increase for all tested biofuels & diesel fuel
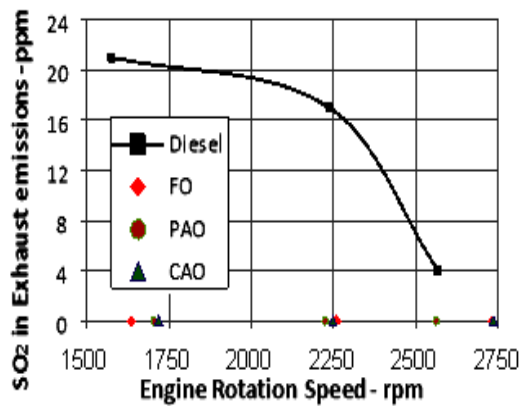
Fig.(7): Variation of SO_2 emission with load increase for diesel fuel & zero SO_2 emission for all tested biofuels

1.2.3 - CO & CO_2 Emission

Figs.(8&9) present the variation in CO_2 and **CO** emission resp. with load increase for all tested biodiesels and diesel fuel, their content in diesel fuel always exceeded which of biodiesels especially at low loading levels. All tested biodiesels were subjected to a common trend, this is due to the absence of significant CO_2 emission differences among biodiesel fuels as confirmed by their ANOVA in Table (9); biodiesels trends of their **CO** emission were not in complete harmony which are justified by the presence of their significant differences among biodiesel fuels as shown by their ANOVA in Table (10). This is discussed and justified in the above introduction by Gumus et al. (2012) and Heywood (1988).
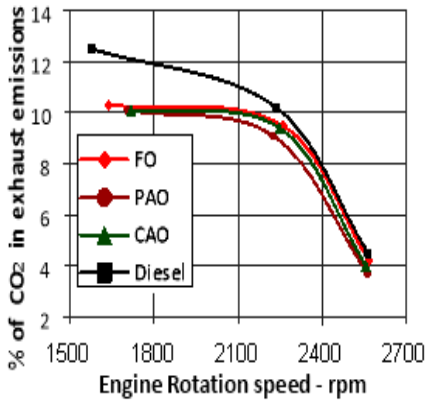

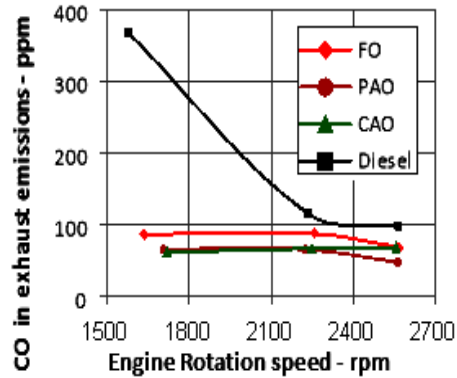Fig.(8)Variation of CO_2 emission with load increase for all tested biofuels & diesel fuel

Fig.(9)Variation of CO emission with load increase for all tested biofuels & diesel fuel

1.2.4 – NO_x Emission

Fig. (10) shows the variation of NOx emissions at different loads expressed by engine speed for biodiesels and diesel fuel. Nitrogen oxides (NOx) in the exhaust emissions contain nitric oxide (NO) and nitrogen dioxide (NO2). It is quite high with biodiesel compared to diesel fuel at load increase. All tested biodiesels had a common
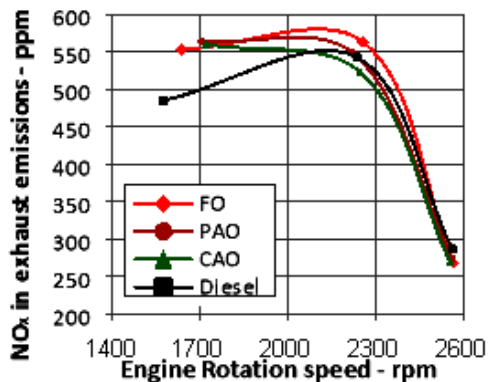

Fig.(10)Variation of NO_x emission with load increase for all tested biofuels & diesel fuel

trend which is justified by the absence of significant NO_x emission differences among biodiesel fuels as confirmed by their ANOVA in Table (11).

Table (8) Analysis of O2 variance in tractor exhaust emissions - %.

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	367.7067	2	183.8533	37.58586	3.75E-07	3.554557
Among Biodiesel fuels	1.126667	2	0.563333	0.115164	0.891871	3.554557
Interaction	0.153333	4	0.038333	0.007837	0.999865	2.927744
Within	88.048	18	4.891556			
Total	457.0347	26				

Table (9) Analysis of CO2 variance in tractor exhaust emissions - %.

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	203.8067	2	101.9033	37.04917	4.16E-07	3.554557
Among Biodiesel fuels	0.606667	2	0.303333	0.110283	0.896181	3.554557
Interaction	0.113333	4	0.028333	0.010301	0.999768	2.927744
Within	49.5088	18	2.750489			
Total	254.0355	26				

Table (10) Analysis of CO variance in tractor exhaust emissions - ppm

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	700.6667	2	350.3333	1.784017	0.196407	3.554557
Among Biodiesel fuels	2178.667	2	1089.333	5.547257	0.013279	3.554557
Interaction	711.3333	4	177.8333	0.905588	0.481516	2.927744
Within	3534.72	18	196.3733			
Total	7125.387	26				

Table(11) Analysis of NOx variance in tractor exhaust emissions – ppm.

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	472402.7	2	236201.3	26.26541	4.59E-06	3.554557
Among Biodiesel fuels	640.6667	2	320.3333	0.035621	0.965074	3.554557
Interaction	2005.333	4	501.3333	0.055748	0.993688	2.927744
Within	161871.6	18	8992.867			
Total	636920.3	26				

2. Engine performance characteristics

Since some of the engine performance characteristics are functions of, or implied in some others having their same trends and indications. We'll just discuss BP, BSFC, and AFR to express engine performance characteristics as affected by the above discussed biodiesel properties (Full evaluation of engine performance characteristics was accomplished by Gomaa et al. (2014)):

1. Brake Power (BP)

In Fig.(11) the Brake Power increases with the increase of engine speed due to mass increase of burning fuel; the highest power values were obtained at 1900-2000 rpm engine speed. Conventional diesel fuel was of the highest output power (53 kW) because of its higher heat value than those of the tested biodiesels; power levels obtained from the tested biodiesel fuels were close to each other (around 45 kW). The higher values of viscosity and density of biodiesels can partially explain this result as above explained by Buyukkaya (2010). The common BP trends of the tested biodiesels explain the absence of significant BP differences among biodiesel fuels as shown by their ANOVA in Table (12).
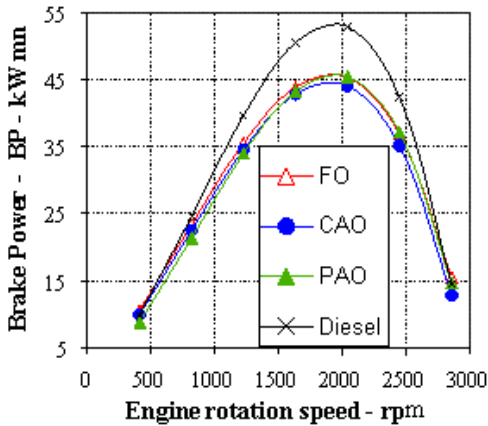

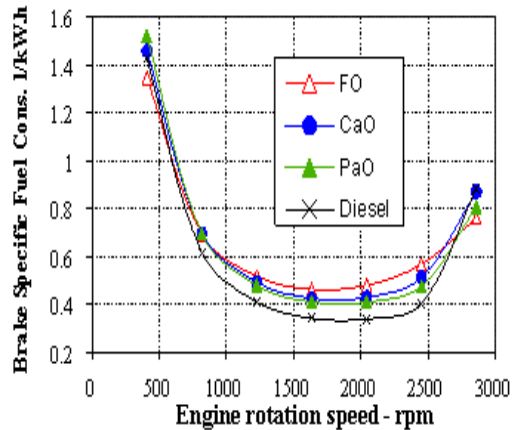Fig.(11): Variation of Engine Brake Power BP with engine speed.

Fig.(12) Brake Specific Fuel Consumption BSFC variation with engine rotation speed, for all tested fuels.

Table (12) Analysis of Engine Brake Power variance - kW

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	10571.91	6	1761.985	42.64158	2.58E-16	2.323994
Among Biodiesel fuels	18.45735	2	9.228675	0.223342	0.800785	3.219942
Interaction	19.11213	12	1.592678	0.038544	1	1.991013
Within	1735.475	42	41.32082			
Total	12344.96	62				

2. Brake Specific Fuel Consumption (BSFC)

In all tests the fuel consumption rates for biodiesels were higher than that of diesel fuel. Fig.(12) showed that the BSFC of the biodiesel fuels were higher than that of conventional diesel. This behavior is attributed to their noticeably lower heating value per unit mass, than that of the diesel fuel. Therefore, the amount of fuel introduced into the engine cylinder for a
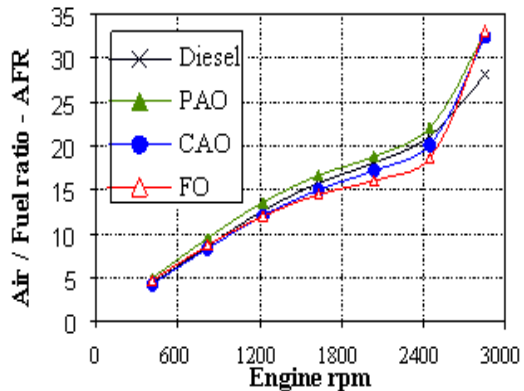
desired fuel energy input has to be greater with the biodiesel. The loss of heat value of biodiesels is compensated with higher fuel consumption to maintain the similar trend of power. The common BSFC trends of the tested biodiesels explain the absence of significant BSFC differences among biodiesel fuels as shown by their ANOVA in Table (13).

Table (13) Analysis of Engine Brake Specific Fuel Consumption variance - l/kW.h

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	6.985354	6	1.164226	49.40728	1.83E-17	2.323994
Among Biodiesel fuels	0.001755	2	0.000877	0.037232	0.963484	3.219942
Interaction	0.09193	12	0.007661	0.325108	0.980365	1.991013
Within	0.989682	42	0.023564			
Total	8.068721	62				

3. AFR

Fig.(13) shows the variation of AFR with engine speed. At test beginning, the tractor engine is set at full throttle position without any load, then the dynamometer is gradually started to exert loading on PTO shaft while engine is freely running at maximum rotation speed. At "No load" conditions, AFR values reached their maximum for all

Fig.(13): Variation of AFR with engine speed.

tested fuels (28:1 - 33:1) despite the diminishing ηv in this stage; this can be referred to the little amount of fuel used under no load conditions; but they sharply decreased with load increase and corresponding fuel increase to reach 18:1 – 22:1. The ascended load caused more fuel consumption, and engine speed reduction to reach 2000 - 1500 rpm where maximum BP & BTE, minimum BSFC, are satisfied under maximum ηv, and decreased AFR. The ascended load continuation leads to more of AFR decrease until reaching its minimum at full load conditions which almost braked engine speed due the braking effect of dynamometer loading, which in turn:

1) Reduced the amount of fuel used

2) Significantly reduced the air flow rate due to the sharp reduction in engine speed and the corresponding low ηv in this stage.

Table (14) Analysis of Engine Air/ Fuel ratio variance - (kg air/kg fuel).

Source of Variation	SS	df	MS	F	P-value	F crit
Engine Speed Levels	4449.307	6	741.5512	56.8229	1.41E-18	2.323994
Among Biodiesel fuels	28.98082	2	14.49041	1.110358	0.338918	3.219942
Interaction	16.89678	12	1.408065	0.107896	0.999902	1.991013
Within	548.1091	42	13.05022			
Total	5043.294	62				

The AFR level of the conventional diesel along the whole engine speed range wasn't the highest as it usually was in the precedent engine performance characteristics. The biodiesel from palm oil was of the highest AFR. However the general behavior of AFR shown in this study for all tested fuels was corroborated by which was described by Gupta (2009). Mohammadi et al.(2012) pointed to that poor ratio of fuel to air (which is high AFR) was more visible at higher engine speeds, and increasing torque resulted in poor AFR, which also corroborate the present study results. The common AFR trends of the tested biodiesels explain the absence of significant AFR differences among biodiesel fuels as shown by their ANOVA in Table (14).

All checked biodiesels operational properties, didn't show any significant differences among biodiesels except for **kinematic viscosity** and **pour point**. Viscosity is a common distinctive property caused all biodiesels to be known as fuels of higher viscosity which results in poor atomization and larger fuel droplets followed by inadequate mixing of biodiesel droplets and air; higher viscosity and surface tension of biodiesels prevent their sufficient disintegration during injection process which may affect engine torque and BP especially at full-load conditions. CAO is of the highest viscosity with respect to which of FO & PAO (Fig.(5)); their **kinematic viscosity** ANOVA showed significant differences between the tested Biodiesels; while each of them had the same common viscosity impact on engine performance characteristics; which is corroborated by the convergent trends of the tested biodiesels within each of the engine performance characteristics BP, BSFC, and AFR which none of them contained any significant differences between Biodiesels sources. Anyway CAO cannot be recommended as a vegetable oil source to produce biodiesel due to its upper viscosity.

Similarly, ANOVA within **pour point** revealed significant differences among biodiesel fuels; while all of their engine performance characteristics BP, BSFC, and AFR didn't show any significant differences among biodiesel fuels; this could signify that pour point variance among biodiesels didn't affect their engine performance characteristics behavior. It could be noticed that the above related literature didn't identify a particular pour point difference which directly affect the engine performance characteristics behavior. So we may suppose that the pour point effect is implied within viscosity and participating its effect. Otherwise than **kinematic viscosity**, and **pour point**; the absence of the significant differences among biodiesels in the rest of their operational properties could be strongly the cause of the resulted convergence of the tested biodiesels trends which is confirmed by their unified behavior represented by BP, BSFC, and AFR as engine performance characteristics which in turn didn't show within each of them any significant differences between their Biodiesels Sources.

On the other hand, exhaust emissions are not related to biodiesel properties, they are mainly depending on the biodiesel chemical composition and combustion. ANOVA within **CO** emission indicated significant differences among biodiesel fuels; This case is already justified by Gumus et al. (2012) and Heywood (1988) that each biodiesel source may differ than another due to different factors effect as discussed in the above introduction.

Gomaa et al. (2014), reported that engine performance characteristics always showed the superiority of conventional diesel and the resemblance of the tested biodiesels trends. So, there is no any distinctive biodiesel source can be recommended among the three different tested fuels. The decision of selecting a specific biodiesel (from a specific source) depends mainly on its best economic feasibility wherever is used and on its BioSource availability. On the basis of the present study results, the previous decision could be applied at one condition that the selected biodiesel source should be neither of high viscosity, nor of high pour point in order to insure the correct selection of biodiesel source.

5. CONCLUSION

Three Biodiesel samples were extracted from three different and separate vegetable oils to determine their thermo-physical properties impact on

engine performance characteristics and analyze their resulted exhaust emissions elements. The analysis of variance (ANOVA) was used to detect if any significant differences exist between these biodiesels of different individual sources. This statistical standard was applied to determine the probable significant differences presence or absence among biodiesel fuels in the resulted exhaust emissions and the thermo-physical properties which affect engine performance characteristics. The judgement is based on the following principle: The absence of any significant differences among biodiesel fuels within any property can justify the resulting common graphical behavior among biodiesel fuels within any engine performance characteristic and vice versa.

After reviewing the whole results all checked biodiesels operational properties didn't show any significant differences among biodiesels except for **kinematic viscosity** and **pour point**. Despite the above discussed negative effect of both properties on biodiesel atomization and combustion, it didn't show any particular disturbance on the common graphical behavior among biodiesel fuels within each engine performance characteristics. This could be referred to the properties major common effect originated from their absence of any significant difference among biodiesel fuels. Similar behavior is recorded from all biodiesels exhaust emissions which didn't contain any significant differences among biodiesels except within **CO** emission. Finally, the decision of selecting the correct biodiesel source should depend mainly on its best economic feasibility wherever is used and on its Bio source availability, and should be neither of high viscosity, nor of high pour point.

Nomenclature:

FO: Fried oil biodiesel	BTE: Brake thermal efficiency
CAO: Castor oil biodiesel	VFC: Volumetric Fuel Consumption rate
PAO: Palm oil biodiesel	BSFC: Brake Specific Fuel Consumption
O_2: Oxygen	BMEP: Brake Mean Effective Pressure
SO_2: Sulfur dioxide	AFR: Air Fuel Ratio
CO_2: Carbon dioxide	ml : milli or 1/1000.
CO: Carbon monoxide	Pa : Pascal (N/m^2)
NO_x: Nitrogen oxides	s : second
ppm: parts per million	kg : kilogram mass
BP: Brake Power	l : liter

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الملخص العربى

انبعاثات العادم للديزل الحيوي وخواصه المؤثرة على خصائص أداء المحرك

ا.د/ احمد السيد علي جمعه[1]، د/ هيثم حسين يوسف محمد [2] و م/ مناف ذياب فندي العصيب[3]

تم استخراج ثلاث عينات من وقود الديزل الحيوي من ثلاثة زيوت نباتية مختلفة ومنفصلة لدراسة خصائصها الحرارية الفيزيائية وتأثيرها على خصائص أداء المحرك ولتحليل عناصر انبعاثات العادم الناتجة. تم استخدام تحليل التباين (ANOVA) لاكتشاف ما إذا كانت هناك فروق معنوية بين هذه العينات من البيوديزل المختلف المصادر المنفردة. تم استخدام هذا المعيار الإحصائي لإيجاد الفروق المعنوية المحتملة في انبعاثات العادم الناتجة بين المصادر المختلفة للزيوت النباتية؛ وتحديد وجود الفروق المعنوية من إنعدامها للخواص الحرارية الفيزيائية وتأثيرها على خصائص أداء المحرك. يعتمد الحكم على المبدأ التالي: انعدام الفروق المعنوية بين مصادر الديزل الحيوي داخل أي خاصية يبررالسلوك البياني المتقارب المشترك بين مصادر الديزل الحيوي داخل أي خاصية من خصائص أداء المحرك والعكس بالعكس.

بعد مراجعة كل النتائج، لم تظهر جميع الخصائص التشغيلية التي تم فحصها أي فروق معنوية بين عينات البيوديزل المختلف المصادر باستثناء اللزوجة الحركية ونقطة الإنسكاب. وعلى الرغم من التأثير السلبي السابق مناقشته من كلتا الخاصيتين من سوء تجزيئ وترذيذ الديزل الحيوي واحتراقه، فإنه لم يظهر أي اضطراب معين في السلوك البياني المتقارب المشترك بين مصادر الديزل الحيوي داخل كل خاصية من خصائص أداء المحرك. يمكن إرجاع السبب في ذلك إلى التأثير المشترك لأغلبية باقي الخواص الأخرى التي سجلت داخلها أنعدام الفروق المعنوية بين مصادر البيوديزل. تم رصد سلوك مشابه من جميع انبعاثات العادم التي أيضا لم تسجل خلالها أي فروق معنوية بين مصادر الديزل الحيوي إلا داخل انبعاثات أول أكسيد الكربون فقط. وأخيرًا، يجب أن يعتمد القرار الصحيح لإختيار مصدر الديزل الحيوي بشكل أساسي على أفضل جدوى اقتصادية له أينما تم استخدامه وعلى توفر مصدره الحيوي، ويجب ألا يكون ذو لزوجة مرتفعة أو ذو نقطة إنسكاب مرتفعة.

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