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A comparative study on engine performance and emissions of biodiesel and JP-8 aviation fuel in a direct injection diesel engine

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Biodiesel is one of the most important renewable energy sources for diesel engines. Studies have been carried out on different kinds of renewable fuels such as raw vegetable oil, waste cooking oil and biodiesels derived from various vegetable oils. In addition research on biodiesel has gained momentum in recent years because of the increasing environmental issues caused by fossil fuels and depletion of oil reserves. However, problems such as high viscosity, low lower heating value and increase in NO_x emissions due to oxygen content are limiting the scope of biodiesel application. JP-8 is a kerosene-based aviation fuel. JP-8 is a strategically important fuel due to properties such as lower cold filter plugging point and high lower heating value. There are some application problems on existing internal combustion engines because of the low cetane number of JP-8. In this study, diesel, sunflower methyl ester and JP-8 fuel blends are tested in a direct injection diesel engine and the possibility of the use of biodiesel and JP-8 together is investigated. As a result of tests carried out at full load conditions, engine performance and exhaust emissions are compared with those for diesel fuel. By using 25% JP-8 and 75% sunflower methyl ester, engine torque decreased by 3% and brake specific fuel consumption increased by 3.9%. Although it has been ascertained that the NO_x emissions increased, smoke emissions decreased. As a result it has been determined that biodiesel and JP-8 can be used together.

Keywords: Sunflower methyl ester, JP-8, biodiesel, emission, engine performance, combustion

Problems such as air pollution, the risk of the extinction of fossil fuels and, in parallel with this, increasing price and countries depending on others, have directed the researchers to develop alternative fuels and renewable forms of energy. Biodiesel that can be produced from vegetable oil or animal fat is one of these alternative fuels. Biodiesel is an important source of energy which decreases external dependence for countries whose economy depends on agriculture[1].

Biodiesel is an oxygenated, sulphur and aromatic hydrocarbons-free, biodegradable, non-toxic, and environment friendly alternative diesel fuel. Biodiesel hydrocarbon chains are generally 16-20 carbons in length and contain oxygen at one end. Biodiesel contains about 10-12% oxygen by weight[2]. The most important advantage of biodiesel is that it reduces sulphur dioxide (SO_2), carbon monoxide (CO), hydrocarbon (HC) and particulate matter (PM) emissions during the combustion process due to presence of oxygen containing compounds, has a lower sulphur content than other fuels and is aromatic[3-5]. However, the increasing the ratio of biodiesel in fuel blend usually causes increases in nitrogen oxide (NO_x) emissions[6-8]. Another disadvantage of biodiesel is that the lower heating value of biodiesel is lower than the standard diesel fuel[7,9-11]. In addition, the high viscosity and low cold filter plugging point (CFPP) of biodiesel leads to a decrease in application surface area[12,13]. Experimental results indicate that original vegetable oils are not suitable as direct replacement for diesel fuel, due to their longer molecule chains, higher viscosities and higher flash points[14,15]. Although biodiesel has lots of advantages, features such as lower calorific value, lower output power and higher nitrogen oxide emission are require improvement[5].

The idea of using a single military fuel was conceived after the Second World War in order to simplify the logistic supply chain for petroleum products in NATO nations[16]. The idea has now become an official NATO policy, called the Single Fuel Policy (SFC), and the single fuel selected has been JP-8[17]. Therefore, various studies have been performed on the effects of JP-8[18-22]. JP-8 is a kerosene-based jet fuel presently in use by the air force.

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It differs from commercial jet aircraft aviation fuel (Jet A) in that it contains a fuel system icing inhibitor, a corrosion inhibitor and a static dissipater. JP-8 also differs from other military aircraft fuels, such as JP-4, in that it does not contain naphtha (gasoline)[23]. As JP-8 includes fuel system icing inhibitor and corrosion inhibitor, it is more advantageous than standard diesel fuel to use in cold weather conditions. Thanks to this feature, it can be used for military or civilian purposes as a strategic land transport application. In addition, JP-8 has a higher calorific value than the standard diesel fuel[24]. Therefore, when used with diesel fuel, it will not cause excessive power loss and an increase in specific fuel consumption.

Lee and Bae[16] conducted a comprehensive experimental investigation on the combustion and emission of a heavy duty diesel engine burning JP-8 aviation fuel. They found that JP-8 had a shorter spray tip penetration and wider spray angle than diesel fuel mainly due to the faster vaporization characteristic of JP-8. While JP-8 enabled a reduction in smoke, HC and NO_x emissions increased[16]. Kouremenos ***et al***.[20] compared the emission characteristics of a diesel engine fueled with JP-8 and diesel. NO_x, HC and CO emissions were investigated under different engine operating conditions. They found that the exhaust emission levels were not much different for operation with the two fuels.

The main disadvantages of JP-8 and jet-1 aviation fuels are that their lubricity properties are less than commercial distillate diesel fuel. This can arise from the fact that diesel, which has a higher boiling temperature range than kerosene, contains higher proportion of natural lubricant[25]. Because of this feature of JP-8, engine-wearing can increase rapidly on very high speed engine components such as injection pump and injector. Guru ***et al***.[25] used ten mono-carboxylic acid esters to make JP-8 a compatible fuel type. They found that all esters tested were suitable for increasing the kerosene lubricity to a satisfactory level[25]. Due to resultant later injection and bulk modulus, JP-8 combustion occurs later in the engine, thus lower combustion efficiency and NO_x emissions result[26]. Jayakumar[27] made comparisons between the autoignition, combustion, performance and emissions of soybean-derived biodiesel, JP-8 and ultra low sulphur diesel in a single cylinder research diesel engine. His research demonstrated the effects of these fuels' properties on engine performance, fuel economy and emissions. The NO_x and particulate matter emissions produced by biodiesel are lower than those produced by diesel fuel and JP-8.

The features of biodiesel and JP-8 can supplement each other. Not only can the loss of power that occurs by usage of biodiesel not be compensated by JP-8 but also it can be compensated for by the NO_x emissions of biodiesel that increase with the usage of JP-8. In this study, sunflower oil methyl esters and JP-8 blends in different ratios have been tested in a single cylinder direct injection diesel engine. JP-8 is used for improving biodiesel properties such as its CFPP and viscosity. This experimental study gives us the opportunity to compare methyl ester and diesel fuel mixture with aviation fuel JP-8. Engine performance, NO_x emissions and smoke emissions have been discussed according to the experimental results.

Materials and Method

Test fuels

Engine performance and emission tests were carried out with five different fuels. Diesel and sunflower methyl ester - JP-8 aviation fuel blends were used in the experiments. The volumetric percentages and abbreviations of fuels used in the experiments are given in Table 1.

As mentioned earlier, the high viscosity of biodiesel, which is one of its main disadvantages and the low lubricity feature of the JP-8 may lead to a breakdown of the fuel injection system and some other engine components. Additionally, it can be useful to know about lower heating value. Some properties of test fuels that have been used at the experiments are given in Table 2. Fuel properties were determined at the Turkey Petroleum Refineries Co. (TUPRAS) laboratories and the JP-8 fuel was provided by TUPRAS**.**

Table 1 – The volumetric percentages of fuel used in the experiments

Abbreviation	Percentages of fuel
D0	100% Diesel
B0	100% Methyl ester
BJ1	95% Methyl ester + 5% JP-8
BJ2	90% Methyl ester + 10% JP-8
BJ3	75% Methyl ester + 25% JP-8

Table 2 – Properties of test fuels

Fuel Type	Diesel	JP-8	Methyl ester	Method
Density (g/cm^3, 15^{o}C)	0.8372	0.7950	0.8893	ASTM D 1298
Viscosity (cSt,	2.8(40°C)	3.87(-20°C)	4.391(40°C)	ASTM D 445
CFPP (^{o}C)	-5	-48.5	-2	ASTM D 2386
Flash point (^{o}C)	73	41	110	ASTM D 93
Lower heating value (kcal/kg)	10450	10200	9189	ASTM D 2015
Cetane number	54	45	58	ASTM D 976

Table 3 – Test engine specifications

Item	Specification
Number of cylinders	4
Cylinder diameter	100 mm
Stroke	100 mm
Compression ratio	16.1
Maximum engine speed	2400/min
Maximum power	46 kW (2400/min)
Maximum torque	216 Nm (1400/min)

Experimental set-up

Experiments were carried out in a single cylinder direct injection diesel engine. The test engine technical specifications and schematics illustration are shown in Table 3 and Fig. 1, respectively. Engine speed was controlled constantly by a DC dynamometer Cussons P8160. DC electric dynamometers with the engine test facility are able to absorb 10 kW power at a maximum 4000/min. Motor load was measured by a strain gauge load cell. Engine speed was measured with a magnetic sensor on the gear wheel on the shaft. A sensitive scale and a stopwatch were used for the measurement of fuel consumption. Experiments were carried out at full load conditions.

A VLT 2600 S smoke opacimeter was used for the smoke emissions measurement. For NO_x measurements, the Testo 350XL gas analyzer was used. The technical specifications of these devices are given in Tables 4 and 5, respectively.

Results and Discussion

The tests were carried out on a direct injection diesel engine to investigate the variations in the engine performance and exhaust emissions for diesel, biodiesel and biodiesel-JP-8 blends. During the experiment, the engine speed variation range was 1750-3000 1/min and values were selected with 250 1/min intervals.

Table 4 – The technical features of the VLT 2600 S smoke density measuring device

Parameter	Measuring range	Accuracy
Exhaust smoke density	0-99 %	0.01
k smoke factor (1/m)	0-10	0.01
Engine speed	0-9999/min	1/min

Performance characteristics

The torque variations depending on engine speed for D0, B0, BJ5, BJ10 and BJ25 fuels are shown in Fig. 2. The maximum engine torque obtained was 2250/min for all fuel blends. Maximum engine torque was measured with D0 fuel at 2250/min as 21.77 Nm. By using sunflower oil methyl ester, the engine torque was reduced averagely 15.2% compared with D0 fuel. The higher viscosity of biodiesel, which may affect the engine brake effective power and engine torque especially in full-load conditions, increases the mixture momentum and consequently the penetration depth in-cylinder. On the other hand, the higher viscosity and surface tension of biodiesel prevent sufficient breaking of the biodiesel during the injection process[6]. Additionally, torque loss can be observed with the addition of biodiesel fuel because of its oxygen content and lower heating value when compared with diesel fuel[25,28].

It has been seen that the mixture of JP-8 aviation fuel and sunflower oil methyl ester provides more torque than B0 fuel. When BJ1, BJ2, BJ3 fuels are used, the engine torque increased 3%, 3.9% and 6.5%, respectively, compared with B0 fuel. Engine torque has increased with the increase of JP-8 ratio in blends. The lower heating value of JP-8 is higher and its viscosity is lower than the sunflower methyl ester. It has been seen that the low torque characteristic of the biodiesel, which occurs due to its low calorific value and high viscosity, can be improved with JP-8 fuel. Also when D0 fuel and BJ3 fuel that contain 25% JP-8 were compared in terms of volume torque

Table 5 – Technical features of the Testo 350 XL emission measuring device

Combustion products	Measuring range	Accuracy
Oxygen (O_2)	0-25% vol	+/- 0.2 m.v
Carbon monoxide (CO)	0-10000 ppm	5 ppm (0-99 ppm)
Carbon dioxide (CO_2)	0-50% vol	± 0.3%vol +1%mv (0-25%vol)
Hydrocarbon (HC)	0.01-4%	< 400 ppm (100-4000 ppm)
Nitrogen oxide (NO_x)	0-3000 ppm	5 ppm (0-99 ppm)

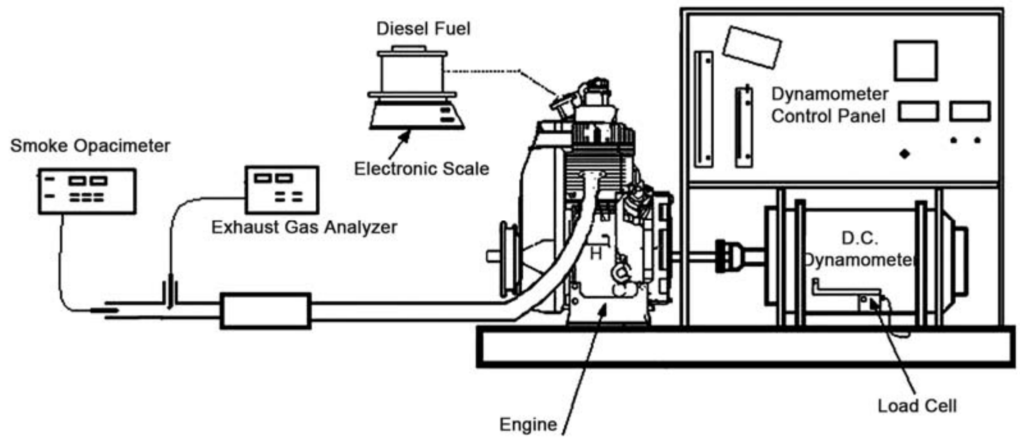

Fig. 1 – Schematic representation of the experimental apparatus

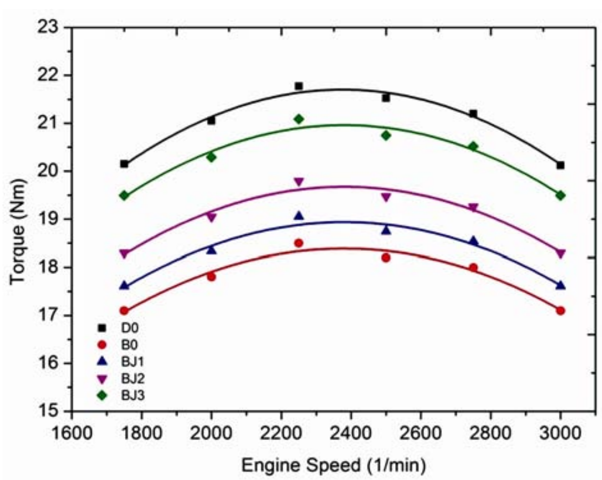

Fig. 2 – Engine torque variations by engine speed at full load

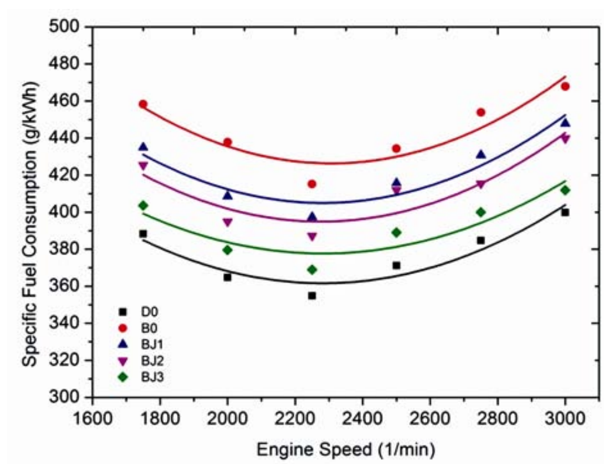

Fig. 3 – Brake specific fuel consumption variations by engine speed at full load

characteristics, there was only a 3.3% reduction in engine torque. Thanks to the fact that JP-8 is more easily vaporized, JP-8 and methyl ester blends can be better atomized[16]. Therefore combustion efficiency and torque characteristics may improve. However, JP-8 has a lower cetane number than the biodiesel[20]. Accordingly, increasing the JP-8 proportion in blends may lead to a decrease in engine torque at the same injection timing.

Figure 3 shows the variations in the brake specific fuel consumptions (BSFC) with engine speed at full-load condition. BSFC is the ratio of the engine fuel consumption to the engine power output as measured at the flywheel. The minimum BSFC was obtained at 2250/min with all fuel blends. The BSFCs of D0 and B0 fuels were measured to be 354.9 and 415.3 g/kWh, respectively at 2250/min. The BSFCs of B0, BJ1, BJ2 and BJ3 blends was higher than D0 fuels at 17.8%, 12%, 9.32% and 3.9%, respectively. The density, viscosity, calorific value and amount present of the injected fuel affected specific fuel consumption. Regarding specific fuel consumption, a greater fuel mass flow rate is required to provide the same engine output due to the lower energy content of biodiesel and this results in higher specific fuel consumption[25,28]. It has been apparent that use of the sunflower oil methyl ester has caused an increase at BSFC. This may be due to higher density and lower heating value of biodiesel compared to diesel fuel. A large majority of researchers have found enhancement in biodiesel fuel consumption according to the percentages of the biodiesel content in the blends and to the loss of heating value[6,25-29]. BSFC decreased with increase in the JP-8 proportion in the blends. This may be attributable to the fact that the lower heating value of JP-8 is higher than biodiesel.

Emission characteristics

NO_x emission variations by engine speed are presented in Fig. 4 for different fuel blends at full load condition. NO_x emissions decreased with increase in engine speed for all fuel types. This is primarily due to the increase in volumetric efficiency and gas flow motion within the engine cylinder under higher engine speeds, leading to faster mixing between fuel and air, and shorter ignition delay. The reaction time of each engine cycle was thereafter reduced so that the residence time of the gas temperature within the cylinder was shortened. This led to lower NO_x emissions under higher engine speeds[6,30]. The lowest NO_x emission was obtained with D0 fuel. According to the D0 fuel, with use of B0, BJ1, BJ2 and BJ3 fuels, the NO_x emissions increased 39%, 27%, 17% and 10%, respectively. Biodiesels contain oxygen components ranging from 9% to 10%. So it is evident that there is higher oxygen content available in the biodiesel to react with the nitrogen component in the surrounding air, resulting in a larger amount of NO_x formation[25,30]. The high oxygen content in biodiesel results in the improvement of its burning efficiency, a reduction in PM, CO and other gaseous pollutants, but at the same time, greater NO_x formation, particularly under a high temperature burning environment[31,32]. However, it has been seen that increases in the JP-8 proportion in blends has resulted in an increase in NO_x emissions. This situation may arise from the increase of maximum temperature that occurs as a result of the combustion of JP-8, the lower heat value of which is high, as well as the reduction of the amount of oxygen in the mixture that arises from biodiesel. The higher evaporation rate and longer ignition delay of JP-8 provided a greater chance for the formation of a premixed mixture close to the stoichiometric condition. This larger portion of premixed burn resulted in higher in-cylinder temperature and finally more NO_x, which is known to be strongly influenced by local temperature and to be proportional to the flame temperature[16].

The smoke is formed due to incomplete combustion. Improvement of combustion will cause a decrease in smoke density[33]. In Fig. 5, the change of emission that depends on full speed engine speed for different fuel types are shown. The lowest smoke emission was generated with B0 fuel. For all kinds of fuel, emission was reduced depending on increase in engine speed. This situation may arise from

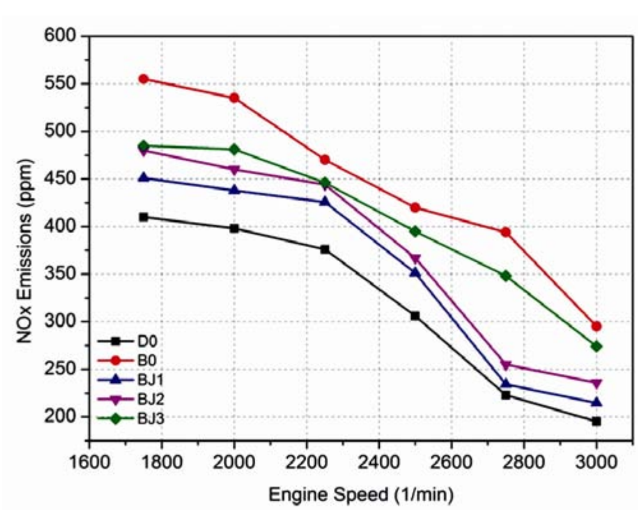

Fig. 4 – NO_x emissions variations by engine speed at full load

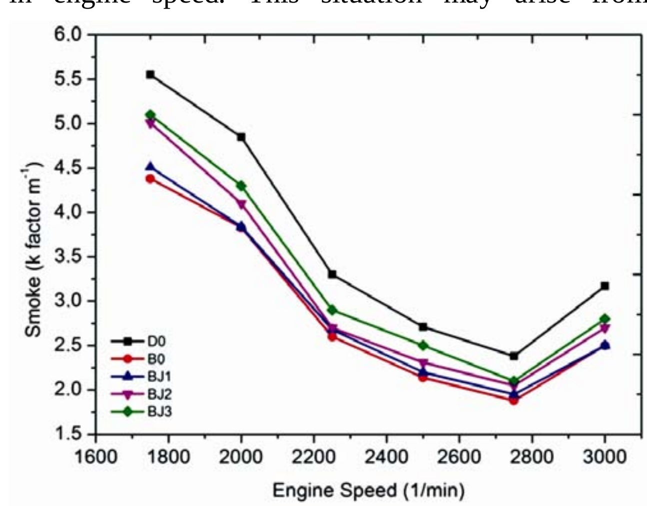

Fig. 5 – Smoke emissions variations by engine speed at full load

recovering of combustion and the shortening of the delay time of ignition that is the result of increase in engine speed. It was seen that the highest emission values were generated with D0 fuel. This may be because of the fact that diesel engines are mostly operated in fuel-lean burning conditions[30]. Smoke emission has been reduced thanks to usage of biodiesel and the mixture of it with other fuels. In the cases of the usage of B0, BJ1, BJ2 and BJ3 fuels, smoke emission was reduced 21%, 19.5%, 14% and 10.3%, respectively in comparison with D0 fuel. These findings show that the amount of unburned hydrocarbon in exhaust gas was reduced. Reduction in smoke emissions is principally based on the oxygen content of biodiesel as well as its lower aromaticity and sulphur content. With the combustion of biodiesel, fuel-bounded oxygen enhances fuel oxidation in these regions and that leads to a reduction in the formation of soot precursors[31-33]. Additionally, the fact that JP-8 is easily vaporized makes possible the formation of mixture that is similar to stoichiometric conditions. In this situation, as the process of combustion improves, the smoke emission reduces. However; the delay of ignition that arises from the low cetane number of JP-8 causes an increase in smoke emission, especially in situations where dynamic advance is insufficient. Smoke formation was minimum in the range of 2500-2750/min and increased again after 2750/min as shown in Fig. 5. In an internal combustion engine the air taken into the cylinder decreases after maximum torque speed. In addition increasing engine speed worsens the turbulence and adversely affects the formation of a homogeneous mixture[34,35]. As a result of this soot emissions may increase. The increase of soot emissions after 2750/min as shown Fig 5 may be caused from the reducing volumetric efficiency and quite worsening turbulence.

Conclusions

In this study, diesel, biodiesel and JP-8-biodiesel fuel blends have been tested in a direct injection single cylinder diesel engine at full load condition. Sunflower oil methyl ester was used as the biodiesel. Engine torque, brake specific fuel consumption, NO_x and soot emissions were evaluated comparatively.

The highest engine torque was obtained with D0 fuel and the engine torque decreased with the use of biodiesel. However, the use of JP-8 has approached the engine torque of the reference fuel. The use of biodiesel fuel BJ3 led to a decrease of 3% in engine torque when compared to D0. This is a result of the low energy content and high density of biodiesel fuel.

The lowest brake specific fuel consumption was obtained using D0 compared to the other fuels. Brake specific fuel consumption was increased by using biodiesel but, contrarily, increasing the rate of JP-8 in the blends reduced the brake specific fuel consumption. Using 25% JP-8 and 75% biodiesel (BJ3) increased brake specific fuel consumption by 3.9%. This variation is a result of viscosity differences between the test fuels.

While the NO_x emissions increased, there was a decrease in smoke emissions according to the D0 fuel. Increasing the rate of JP-8 in the mixtures reduced NO_x emissions but, contrarily, increased smoke emission. The lowest smoke emission was obtained using B0 fuel and the lowest NO_x emission was obtained using D0 fuel. Smoke emission variation is mainly related with the oxygen content of the test fuels. The NO_x emissions decreased 10.3% and the smoke emissions increased 10% according to the results of the D0 fuel sample which used BJ3 fuel.

As a result, the kerosene-based JP-8 aviation fuel has partly compensated for the lower torque characteristics of biodiesel resulting from its lower heating value. In addition, the NO_x emissions increase with the use of biodiesel approached the standard value when JP-8 was included in the blend. Possible increase in smoke emission which could arise from the low cetane number of JP-8 has been kept under the standard value using biodiesel. Therefore, it was seen that the combination of biodiesel and JP-8 aviation fuel can be used together. Due to the fact that JP-8 fuel has a low cold filter plugging point value; it has a positive impact on the usage of biodiesel fuel in winter conditions.

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