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Performance and Emissions of a Small Agricultural Diesel Engine Fueled with 100% Vegetable Oil: Effects of Fuel Type and Elevated Inlet Temperature

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Abstract: The paper presents the results of a research project to evaluate performance and emissions of a small direct injection, naturally aspirated, agricultural diesel engine using vegetable oils. Semi-refined palm and soybean oils were solely used as fuel. The two types of vegetable oil appeared to affect the engine performance and emissions in a similar way and compared well with diesel fuel. Tests were also performed to investigate the effect of fuel inlet temperatures or temperatures at the injector prior to injection, ranging from 40 – 100^{o}C, on brake specific fuel consumption, black smoke and NO_x emissions. It was found that the engine tended to improve in its

NO_x emissions as the warm-up temperature of vegetable oil increased while its performance and black smoke emission were not found to have any significant change with inlet temperature.

Keywords: Small diesel engine, Vegetable oil combustion, Biodiesel, NO_x, Alternative fuel.

Introduction

The use of vegetable oils as a source of energy has been known for a long time since the very first creation of the Diesel engine. Vegetable oils are biodegradable and nontoxic, have low emission profiles, are made from renewable resources and so are environmentally beneficial [1]. They have been used as an alternative to the partial or total substitution of diesel fuel without requiring extensive engine adjustments or modifications. However, due to differences in characteristics of vegetable oils and diesel fuel, such as heating value, viscosity, chemical composition, boiling point, etc., there exist a few difficulties in obtaining acceptable engine operations. Some technical aspects of using vegetable oils as diesel fuel extenders or replacements require further study.

Considerable research has been conducted on vegetable oils as alternatives to, or blends with, diesel fuel. This included palm oil, rapeseed oil, coconut oil, sunflower oil, olive oil and soybean oil. Because of the reported problems, such as carbon deposits in the engine, engine durability and lubricating oil contamination, associated with the use of vegetable oils, they should be modified to be compatible with existing engines. The technologies involved are direct use or blending of oils, microemulsion, pyrolysis, and transesterification [1]. Fundamentally, high viscosity appears to be a property at the root of many problems associated with direct use of these oils as engine fuel. High viscosity has the effect of increasing fuel droplet size on injection into the combustion chamber, leading to poor combustion and formation of deposits on the chamber wall, valve seat and injector. Some of vegetable oils may then be introduced into the lubricating oil, causing fuel dilution. Because of their unsaturated state, fuel dilution by vegetable oils results in excessive thickening of the lubricating oil and the problem of inadequate engine lubrication over a portion of the temperature range [2]. Another point of concern is that, at relatively cold or room temperatures, vegetable oils tend to solidify. This problem may be partially overcome by some type of heating or blending with diesel fuel [3].

Several other approaches to reduce viscosity and its associated problems are microemulsion with solvents, pyrolysis or thermal cracking, and transesterification. Esterified vegetable oils in the form of methyl ester or ethyl ester (known as biodiesel) have been the predominant vegetable oil fuels used in the US and Europe because of their similar characteristics to diesel. In the last several years, many studies have focused on the potential of biodiesel as an alternative fuel for compression ignition engines. Sharp [4] examined performance and transient exhaust emissions from three modern diesel engines fueled with blends of diesel and biodiesel. The use of biodiesel resulted in a slight loss in engine power, lower emissions of unburned hydrocarbons (HC), carbon monoxide (CO), and particulate matter. Marshall *et al.* [5] reported the effect of biodiesel/ alkylate/diesel blend on emissions from a Cummins L10E engine. The engine was found to perform well with little power change and all regulated emissions were reduced below the baseline diesel fuel. Serdari and co-workers [6] investigated four different types of biodiesel blended with diesel in comparison with diesel using a single cylinder, stationary diesel engine. They found that irrespective of the raw material and origins, the four types of biodiesel performed in a similar way. Biodiesel improved particulate emissions at almost all conditions of speed and loads. Wang *et al.* [7] examined and compared emissions from nine in-use heavy trucks fueled with diesel and biodiesel blend. The trucks were found to perform well and fuel economy was comparable for both fuels. Particulate matter, CO and HC were lower whereas oxides of nitrogen (NO_x) were found to be unchanged.

It can be seen that biodiesel in the form of esters has been studied and used widely in developed countries. However, it is an expensive product due to the high processing costs which may not be appropriate for the Thai economy. Alternatively, current interest in vegetable oils as fuel is more likely to focus on high quality, nonesterified vegetable oils. McDonnell and co-workers [8] reported their research on crude, degummed and filtered rapeseed oil. Short term and long term engine tests were carried out using vegetable oil blended with diesel. The short-term tests showed no significant differences between fuels, while in the endurance test, the injectors was found to require more frequent servicing compared to diesel operation. Nwafor and Rice [9] investigated the effect of three nonesterified vegetable oil blends on the performance of a diesel engine. It was found that operation with vegetable oil fuels offered a net reduction in emissions and maximum power output, and also improvement in brake thermal efficiency. Generally, the blend compared favorably with diesel and offered a reasonable substitute for diesel fuel.

In Thailand, because of their relatively high yields and widespread production, palm and soybean oils are seen as potential alternatives to diesel fuel. A lot of attention has been paid to study their characteristics and effects on engines [for example, 10, 11, 12]. However, there remains some concern over the suitability and feasibility of direct use of vegetable oil in compression ignition engines due to problems associated with high viscosity. One way to avoid these problems is to reduce viscosity by pre-heating of the vegetable oils. In this project, our research efforts have been directed to improvement in the use of vegetable oils as fuel with minimum fuel processing and engine modifications. This paper reports our investigation on the effect of elevated fuel inlet temperatures on performance and emissions of a small direct injection diesel engine. Two neat vegetable oils, namely, palm and soybean, were used. Test runs were also made for diesel fuel. The engine performance and emissions were compared and are presented.

Materials and Methods

1. Fuel preparation

Two different types of vegetable oil have been chosen for use in this project. They include soybean and palm derived oils. The processed oils were obtained from commercial suppliers (Lanna Agri-business Co. Ltd., Lamphun, and Olene Co. Ltd., Bangkok) for all cases. The processing undertaken was filtration, degumming, deacidification and dehumidification. Properties of the processed oils along with commercially available diesel fuel are shown in Table 1 below.

Table 1. Selected properties of diesel and vegetable oil fuels.

Fuel properties	Unit	Diesel	Palm	Soybean
specific gravity @ 15.6°C		0.81-0.87	0.918	0.9150
cetane number		> 47	43	-
kinematic viscosity @ 40°C	cSt	1.8-4.1	42	41.2
pour point	°C	<10	6	-0.5
sulphur content	% mass	<0.05	-	-
water/sediment	% vol	<0.05	0.02	-
flash point	°C	>52	173	185
heating value	MJ/kg	46.2	38.0	37.9
lubricity (HFRR)	µm	<460	157	-

The fuel system, combining a fuel pump and an injector, was modified by installing an additional filter and a three-way, two-position directional manually controlled valve, which allowed for rapid switching between diesel and vegetable oil fuels. In a vegetable oil tank, a heater with temperature controller was installed to provide necessary heating to achieve pre-determined set-point temperature. Fuel was fed under gravity to the injector and the fuel flow rate was measured using a Plint graduated burette and stopwatch. This procedure was repeated a number of times during a test and an average value was subsequently calculated.

2. Engine setup

The research engine used in this project was a Mitsubishi DI-800, model year 1995. The engine is a 411cc, single cylinder type with overhead poppet valves, and has a bore of 82 mm and a stroke of 78 mm. The combustion chamber is cylindrical in shape with a compression ratio of 18:1. The 4-stroke, naturally aspirated, air-cooled, compression ignition engine is nominally rated at 6 kW at 2400 rpm and develops 25.5 N-m of torque at 1900 rpm. The engine is coupled to a 5 kW, 220 volt, one phase, AC, 50 Hz Aden alternator acting as a dynamometer to allow for accurate manual speed and load control. The electrical loading is obtained through a load bank, consisting of one 500 W, three 1000 W, and one 1500 W resistance heaters. The main characteristics of the engine are listed in Table 2 below.

Table 2. Engine specifications.

Engine type	Diesel, single cylinder, 4-stroke, 4 valve cylinder head
Model	Mitsubishi Direct Injection – 800
Bore x Stroke	82 mm x 78 mm
Displacement	411 cc
Compression ratio	18
Fuel pump	Bosch plunger type

Engine speed was measured by a strobe light tachometer and the air mass flow rate was estimated using a TSI hot wire anemometer. Coolant flow rate was monitored using a Micronics Portaflow 300. Type K thermocouples, connected to a Eurotherm chessel datalogger, were installed to measure gas temperatures at the inlet, outlet pipes and the cylinder wall temperature, as well as coolant, lube oil and fuel inlet temperatures. NO_x measurements were taken using a Kane-may KM 9106 gas analyzer. CO emissions were measured using a non-dispersive infrared detector. Black smoke was obtained, based on opacity measurements using a Diesel Tune Model 114. Each of these values was recorded at 2 minute intervals and the average value was computed. For each condition, emissions were captured a number of times, and up to 30 readings were taken each time.

3. Test procedures

Preliminary engine conditioning was necessary to prepare the engine at steady operating condition. Initially, the engine was run through a warm-up procedure on diesel fuel. The procedure began with normal operation at idling speed for about 10 minutes. The engine speed was then increased gradually to 2400 rpm. After a period of transition, the engine was left running for a further 30 minutes to stabilize. For the baseline test, once stability was attained, testing was carried out by applying a fixed load and varying the engine speeds and the data acquisition was then undertaken. Baseline tests were conducted with 100% diesel fuel.

A pure palm oil was used in the engine to compare with the baseline data. The vegetable oil was heated to a stable temperature of 40^{o}C. After engine stabilization was reached, the vegetable oil was mixed in the fuel line with diesel while the engine was kept running for another 10 minutes. The diesel fuel supply was then shut off, leaving the engine running with vegetable oil as the only fuel for a period of at least 60 minutes to ensure that the fuel system was clear of diesel fuel. The experimental data measurements could then be performed for different oil inlet temperatures within the 40 – 100^{o}C range. The testing procedure described above was repeated with soybean oil at the same operating conditions.

Results and Discussion

The experiments in the unmodified Mitsubishi DI-800 engine fueled with two types of semi-refined vegetable oils included fuel consumption and emission measurements, under various speeds and a fixed 50% of rated maximum load. Test runs were made on straight diesel fuel in order to make comparative assessments. The impact of different vegetable oil warm-up temperatures was also examined. Since a large amount of data was collected, only summary data is reported here in this paper.

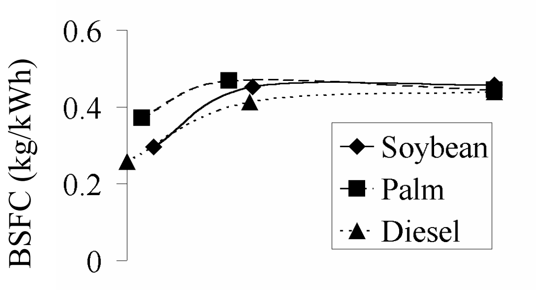
Effect of fuel types

Figures 1 and 2 (a, b and c) show the effect of fuel types, namely soybean oil, palm oil and diesel on engine brake specific fuel consumption (BSFC), NO_x and smoke emissions, respectively. Diesel was at room temperature (about 30^{o}C) whereas the two vegetable oils were kept constant at 40^{o}C. At these corresponding conditions, the difference in viscosity between the vegetable oils and diesel was about tenfold. It can be seen that diesel had lower BSFC than the two vegetable oils. The explanation for this behavior lies in the lower energy content of the oils. It should be noticed that soybean oil seemed to perform better than palm oil in terms of engine performance. At low speed operation, there was a relatively large difference in BSFC between fuels but as the engine speed increased to 2400 rpm the value was not much different. Changes in fuel consumption between 1800 to 2400 rpm were relatively marginal in absolute values. Similar findings were also obtained for different loads up to 50 % maximum rated power at a fixed speed. The results obtained implied that the overall combustion rate for the vegetable oils was somewhat slower than that for the diesel fuel. One possible reason for this may be the viscosity of the oils as this property alters spray characteristics at the time of injection and can delay the combustion process in the engine. The lower cetane number also has the effect of increasing the ignition delay. Exhaust temperature for the oils was consistently higher than for diesel by about $10^{o}C$, indicating higher energy loss in the exhaust.

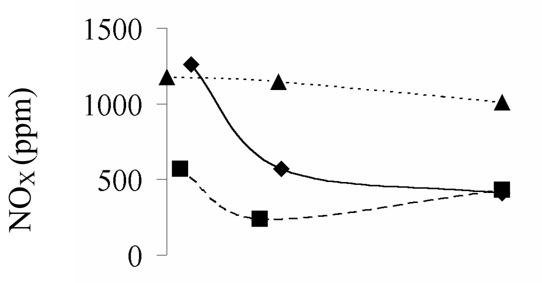
For a given fuel type, NO_x emissions was found to decrease with an increase in engine speed, as shown in Figure 1b, and vegetable oils proved to exhibit a sharper decline than diesel. NO_x was found to be significantly higher for diesel fuel, especially at 2400 rpm. At different loads, NO_x (Figure 2b) did not vary significantly for the vegetable oils and was smaller than that for diesel. This was expected because, in the combustion process, NO_x formation is related to the local availability of oxygen and the temperature in local regions. Vegetable oil spray was expected to produce relatively larger droplet sizes. This would result in lower local temperature and lower NO_x.

The effect of vegetable oil on the exhaust smoke is illustrated in Figures 1c and 2c. Smoke levels were found to be consistently lower for the vegetable oils than for the diesel fuel, except for palm oil at low speed operation. Smoke is usually associated with the presence of unburned fuel and soot. The kinetics of the formation and decomposition of soot in the combustion chamber of a diesel engine is highly complex.

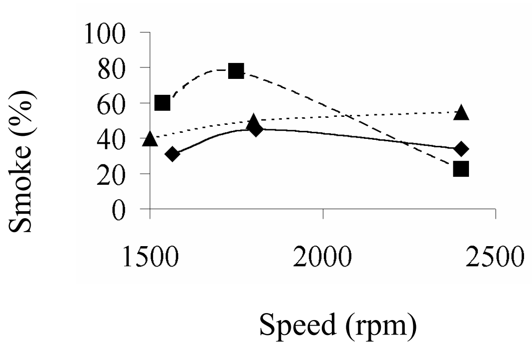
Various explanations have been proposed and it is generally agreed that the excess oxygen tends to suppress the formation of soot, hence smoke level.



(a) Brake specific fuel consumption

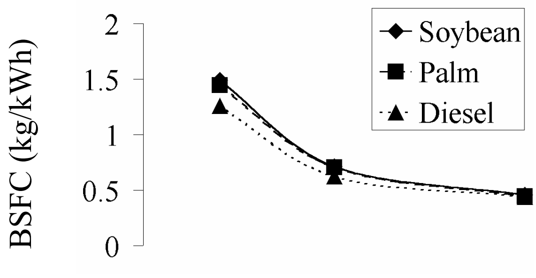


(b) NO_X

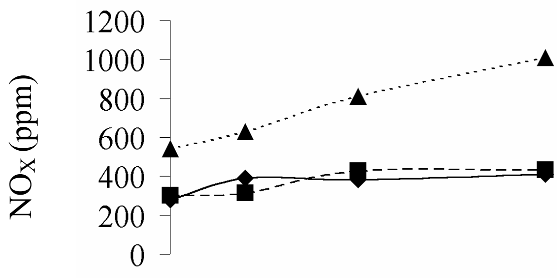


(c) Black smoke

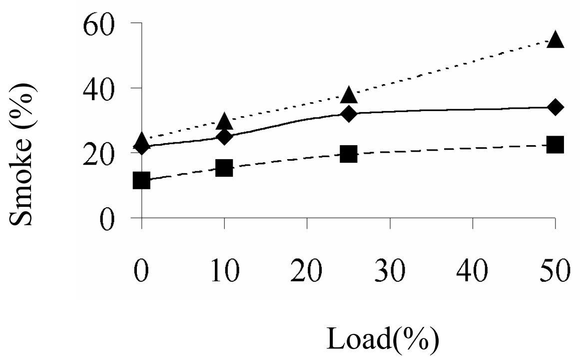
Figure 1. Effect of fuel types on engine performance and emissions at different engine speeds, fixed load = 50% of maximum rated power: comparison between palm and soybean oils and diesel fuels.



(a) Brake specific fuel consumption



(b) NO_X



(c) Black smoke

Figure 2. Effect of fuel types on engine performance and emissions at different loads, constant speed of 2400 rpm: comparison between palm and soybean oils and diesel fuel.

Due to differences in physical properties between the fuels used, the engine performance and emission parameters for the vegetable oils were expected to differ from that for the diesel fuel. This was, indeed, the case here. Nonetheless, the differences were found not to be relatively large. In general, vegetable oils and diesel appeared to exhibit trends similar to those in previously reported literature [for example, 8, 13, 14].

Effect of fuel inlet temperature

Variation of engine BSFC and emissions with temperatures under different engine speeds are presented in Figures 3 and 4 for soybean and palm oils, respectively. For both vegetable oils, BSFC did not change much for a given engine speed, as shown in Figures 3a and 4a. Elevated fuel inlet temperatures proved not to have any significant effect on engine fuel consumption. This finding was anticipated because energy content or heating value of oils was unchanged as it is independent of temperature. The findings here were in agreement with those reported by Bari et al [14]. A similar trend was also obtained by Nwafor [15] at low and high loading conditions.

Figures 3b and 4b depict the effect of fuel temperatures on NO_x emissions. For the case of soybean oil, increasing temperature tended to reduce NO_x. The effect was particularly obvious at low engine speed (1500 rpm). However, for the case of palm oil, variation of NO_x with temperature was not conclusive. With respect to exhaust smoke (Figures 3c and 4c), an increase in fuel temperature resulted in a slight increase in black smoke level.

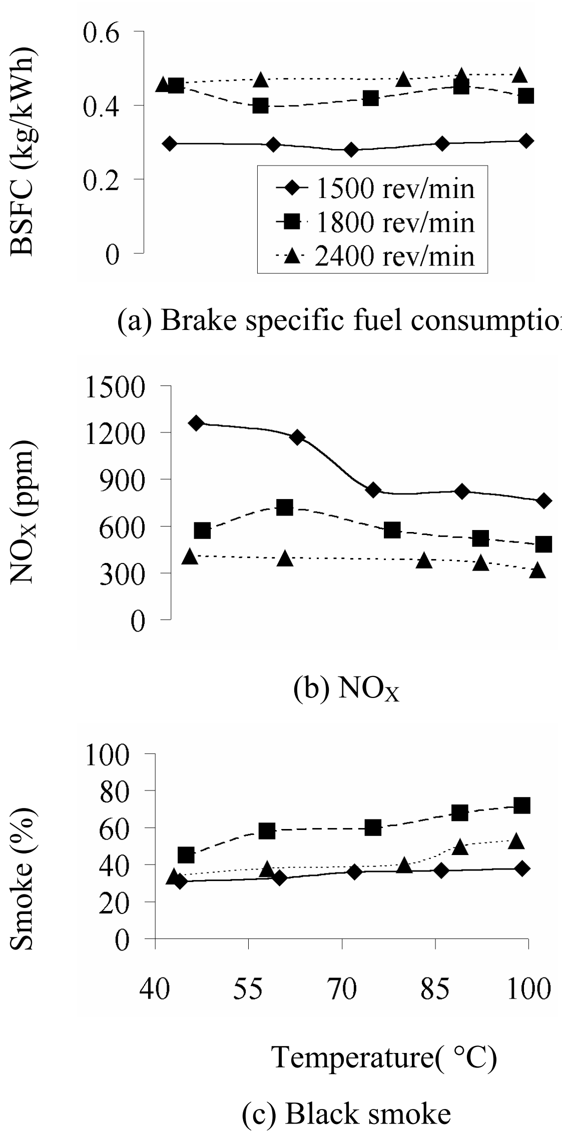


Figure 3. Effect of fuel (soybean oil) inlet temperature on engine performance and emissions at different engine speeds, fixed load = 50% of maximum rated power.

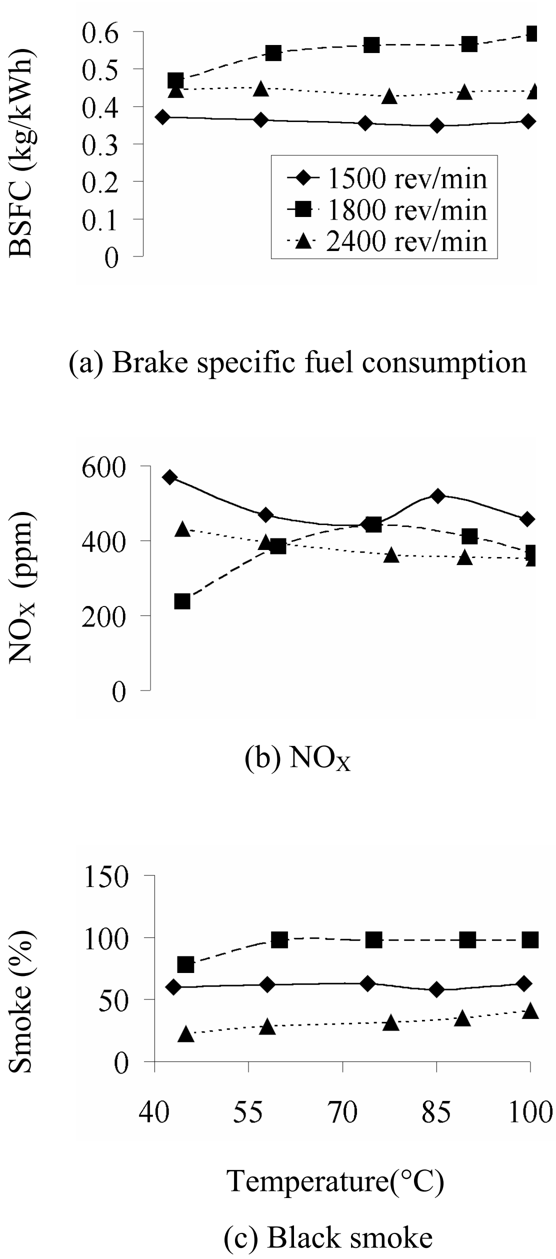


Figure 4. Effect of fuel (palm oil) inlet temperature on engine performance and emissions at different engine speeds, fixed load = 50% of maximum rated power.

Viscosity is a function of temperature. Hence, the fuel inlet temperature or temperature at the injector prior to injection was expected to have significant influence on engine emissions. The higher the temperature, the fuel becomes less viscous, and as a result, better atomization and finer spray droplets are produced. This should, in turn, lead to better in-cylinder combustion and improved emissions. However, from the results obtained, this was not exactly the case. Any significant improvement in emissions was not observed. On the contrary, a slight increase in emissions was obtained. The reasons may be that (1) the resulting decrease in viscosity may not be low enough to have any significant effect on spray and eventual combustion characteristics of the fuel. To reach the same level of viscosity as diesel, the vegetable oil would have to be heated to about 150^{o}C at the injector; (2) there may be rapid transfer of heat away from the injector to the engine head and away from the fuel lines, preventing the fuel temperature at the injector from increasing significantly. After a re-evaluation of the rig arrangement, it was found that a 70^{o}C increase in fuel temperature at the fuel tank resulted in only about 30^{o}C increase at the injector. This amount of temperature change was not expected to significantly alter the oil properties.

Conclusions

Tests were carried out in a small direct injection compression ignition engine fueled with diesel and then vegetable oils, namely palm and soybean. The engine was not modified in any way and the results obtained were analyzed in terms of performance and emissions. Engine performance in terms of brake specific fuel consumption and engine exhaust emissions in terms of black smoke and NO_x have been shown to depend on the properties of vegetable oils and diesel fuel. The two types of semi-refined vegetable oils performed reasonably well in comparison with the diesel fuel. Between the two oils, they did not show a significant difference in emission and performance characteristics.

The most detrimental parameter in the use of vegetable oils is their high viscosity. Heating of the vegetable oils prior to injection into the engine's combustion chamber results in a reduction in viscosity, leading to better atomization and improved performance and emissions. An increase in fuel inlet temperature was therefore expected to decrease emissions and improve engine performance. However, from the results obtained in this test, the expected improvement was found not to be significant. Pre-heating the vegetable oils did not appear to benefit the performance. The tests also revealed that heated vegetable oils gave a slight increase in emissions, compared to diesel. At any rate, even though heating the vegetable oils offered no significant advantages in terms of performance and emissions, it was necessary for a smooth fuel flow in the fuel lines.

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