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Performance and Emission Analysis of Biodiesel-Kerosene Blends and Their Emulsions in a Modern Small DI Diesel Engine

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ABSTRACT

Researchers are finding alternative ways to deal with the depletion of fossil fuels and global warming. Biodiesel is emerging as one of the alternatives that could be used to cope with both issues efficiently. The biodiesel used was produced onsite by transesterification of canola oil. In this study, we tested blends of biodiesel and kerosene along with their emulsions on a HATZ 2G40 light-duty 2-cylinder modern diesel engine. BK50 (biodiesel 50 vol% and kerosene 50 vol%), BK80 (biodiesel 20 vol% and kerosene 80 vol%) and their emulsions with 2.5% and 5% water were examined. The fuels were tested at three speeds: 1000 rpm (low), 2100 rpm (maximum torque speed), and 3000 rpm (maximum power speed) and at three loads (low, ≈20%, medium, ≈50%, and high, ≈80%) at each speed. The performance parameters studied include brake thermal efficiency (BTE) and brake specific energy consumption (BSEC). For emissions, carbon monoxide (CO), hydrocarbon (HC), oxides of nitrogen (NOx) and smoke were examined. The performance and emission results of biodiesel-kerosene blends and their emulsions are compared with that of diesel and kerosene.

Keywords **-** Diesel engine, biodiesel, canola oil, kerosene, emulsion, emissions.

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Nomenclature

B100	Pure biodiesel
BK50	Biodiesel 50%, kerosene 50%
BK80	Biodiesel 20%, kerosene 80%
BK50W2.5%	2.5% water emulsion in BK50
BK50W5%	5% water emulsion in BK50
BK80W2.5%	2.5% water emulsion in BK80
BK80W5%	5% water emulsion in BK80
BMEP	Brake mean effective pressure
BSEC	Brake specific energy consumption
BTE	Brake thermal efficiency
CO	Carbon monoxide
CO_2	Carbon dioxide
D100	Petroleum diesel
DI	Direct injection
HC	Hydrocarbon
HLB	Hydrophilic-lipophilic balance
K100	Pure kerosene
Naoh	Sodium hydroxide
Nox	Oxides of nitrogen
Span 80	Sorbitan monooleate
Tween 80	Polyoxyethylene sorbitan monooleate

I. INTRODUCTION

Energy is one of the major elements of human existence, which contributes to its progress and development. However, that development must be sustainable in order to ensure a continued supply in the future. Energy is produced by burning a significant amount of fuel. Fuels drive the nation's economy by powering industries, transportation, etc. Society's dependency on fossil fuel has significantly increased in the past few decades, but it will soon run out. Fossil fuel is not a renewable source of energy; it requires millions of years to replenish. Demand for fuel is a much higher than its availability [1].

The increase in demand and consumption leads us to search for alternative sources of fuel. When demand is higher and supply is lower, the price of oil increases. This situation could turn into an economic recession or global crisis [2–5]. The shortageof petroleum diesel makes biodiesel more attractive. Conventional fuels also produce emissions, which contribute to air pollution and global warming. Countries are pressured by one another to keep emissions under control, which mutually affects the entire globe. Air quality management plays a very important role in any government's policy for sustainable development. World powers are developing strict regulations to cope with automotive emissions. As a result, the Kyoto protocol, which was approved in 1997, was used as a legal tool to control air quality. The protocol mandated industrialized countries to reduce greenhouse emissions by 2008 to 2012. Afterwards, the percentage of emissions was set as an aim to reduce emissions in each country, whereby Canada, in December 2011, was the first country to withdraw from the Kyoto protocol [6] because it could not keep up the regulations, or with the gross domestic product. In order to abide by the Kyoto protocol's regulations, industrial output and employment suffered. Canada does, however, have its own regulations to reduce emissions on a provincial and federal level [7].

In the 21st century, the world is facing the expeditious depletion of fossil fuels, as well as an increase in pollution. Researchers are finding alternative ways to deal with both challenges in a sustainable manner. Biodiesel is emerging as one of the alternatives that could be used to address both issues efficiently. It can be used either in its pure form, or blended in any proportion with petroleum diesel, to create a biodiesel blend. If biodiesel is 100% pure, it is referred to as B100; otherwise, a biodiesel blend is termed BXX, where XX represents the amount of biodiesel in the blend. For example, if 20% biodiesel and 80% diesel are blended on a volume basis, it is designated as B20 [8]. The heating values of biodiesel range between 39 to 41MJ/kg [9]. Biodiesel can be run in the same engine (with little or no modification) that is fuelled by petroleum diesel because they both have similar properties.

Currently, biodiesel is produced from vegetable oils, animal fats, and used cooking oil. When choosing which vegetable oil is desirable for biodiesel production, we need to consider topography, weather and economics. Vegetable oils are said to be renewable forms of fuel, and more attractive in an environmentally-friendly aspect. This makes vegetable oil an unlimited source of energy, with a heating value equivalent to that of diesel fuel [10]. Direct use of vegetable oil in a diesel engine is not feasible because it could cause engine operation problems, due mainly to high viscosity, low volatility, and poor atomization. The reason for poor atomization is its high viscosity and surface tension, which increases the droplet size during injection in the combustion chamber [11].

To deal with global warming and air pollution, biodiesel is one of the most promising alternatives to petroleum diesel, in terms of emissions and availability. Biodiesel is a monoalkyl ester of long-chain fatty acids, which can be produced by various methods such as pyrolysis, micro-emulsion, dilution, and transesterification [12]. In our study, we have produced biodiesel through transesterification. This method involves a chemical reaction between vegetable oil (containing mainly triglycerides) and a short-chain alcohol (methanol or ethanol) to yield mono-alkyl esters (biodiesel) and glycerol as a by-product [13]. Petroleum diesel has no oxygen compound [12], while biodiesel has high oxygen content (about 10%). Due to biodiesel's higher oxygen concentration, it emits more NOx with fewer co emissions when it reacts with nascent nitrogen during combustion, compared to petroleum diesel [14].

O. Can et al. [15] tested canola biodiesel blends in four proportions (5%, 10%, 15% and 20%) at four different loads (4.8, 3.6, 2.4 and 1.2 bar BMEP) in a single cylinder di diesel engine. They concluded that there was an increase in NOx emissions at all loads in proportion to the blend ratio. HC and CO emissions were reduced with the increase in biodiesel concentration at all loads. Biodiesel has ahigher viscosity than petroleum diesel, which leads to high surface tension, larger droplet size, and poor atomization while fuel is injected into the cylinder. High viscosity also resulted in lower injection velocity of the biodiesel [11]. This problem can be resolved by blending biodiesel with kerosene, which has low viscosity, low density, and high volatility. Kerosene has an advantage of high miscibility and good stability at any mixing ratio [16].

H. Aydin et al. [17] tested three different fuel types: D100, B20, and BK20 in a single cylinder, 4-stroke, direct-injection compression engine. They concluded that the addition of kerosene increased engine power and decreased brake-specific fuel consumption. NOx was reduced by 6-10% in BK20, compared to B20. There are three different methods of adding water: spraying water into the intake manifold, which is known as manifold fumigation [18–20]; injecting water directly into the combustion cylinder [21, 22]; and introducing water into the diesel emulsion fuel. The direct injection method reduces more NO_x than manifold fumigation because water droplets are closer to the flame during combustion, which enhances fuel penetration [23]. With the introduction of water into diesel fuel, a micro-explosion occurs and, due to this phenomenon, the spray characteristics are enhanced, which in turn improves the pace of combustion and reduces emissions [24]. However, manifold fumigation and direct injection tend to increase NOx and HC emissions [25, 26]. Of the three methods, the blending method proved to be more effective in reducing emission because it can reduce NOx and PM emissions simultaneously, and improve efficiency [27–30].

Introducing water into a diesel engine is a convincing concept that can reduce NOx and PM emissions [31, 32]. H. Raheman et al. [33] studied performance and emission of a 10% blend of jatropha biodiesel and 90% petroleum diesel, with its emulsions. They concluded that, by increasing the percentage of water in an emulsion at all engine loads, ignition delay was longer. BSFC was higher with 15% water content compared to emulsified fuel with 10% water content; whereas BTE was lower. CO, CO_2, NOx were also reduced when the engine was operated with emulsified fuel. In this study, we attempted to reduce emissions using emulsions. Emulsion with 2.5% and 5% water concentration in biodiesel-kerosene was expected to reduce its NOx emissions due to the quenching action of water.

II. METHODS AND MATERIALS

2.1 Materials

To carry out this experimental study, we used canola biodiesel (produced in the lab), kerosene, sorbitan monoleate (span 80) and polyoxyethylene sorbitan monoleate (tween 80). To produce the biodiesel, we used canola oil, methanol and sodium hydroxide (NaOH).

2.1.1 Biodiesel Production

In our lab, we produced biodiesel through transesterification, with the help of canola oil and methanol, using NaOH as a catalyst. First, canola oil was heated to about 60˚C (because the boiling point of methanol is 64.7˚C). We needed to heat the canola oil to reduce its viscosity and make it more soluble, using methanol for a reaction. For each litre of canola oil, we needed 200 millilitres of methanol. Sodium hydroxide (catalyst) was dissolved with methanol separately; for one litre canola oil (one batch), we used 3.5g of NaOH pellets. After blending these three ingredients, glycerine (by-product) formed after the mixture settled for 5-7 hours. We then separate the glycerol from the rest of the oil. At this point, the fuel contained fatty acids (by-product) and needed to be purified further; with 500 ml of water for first wash, and 300 ml for second wash. After the second wash, the resulting biodiesel contained water, which was removed by heating the biodiesel to 105°C; its final colour was golden yellow. The volumetric collection efficiency was calculated to be approximately 80%, according to the following equation.

$$\text{Volumetric collection efficiency (\%)} = \frac{Vol.of\ Produced\ Biodiesel}{Vol.of\ Initial\ Canola\ Oil}$$

2.2 Test Engine

We used an air-cooled, 2-cylinder, 4-stroke diesel engine (HATZ 2G40) with direct fuel injection. This engine had a minimum idling speed of 1000 rpm. Detailed engine specifications are shown in Table 1. A schematic for experimental engine setup is outlined in Fig. 1.

2.3 Equipment to Record Test Parameters

2.3.1 Dynomite Data Acquisition Computer and Water Brake Dynamometer

Dynomite water-brake absorbers are low-cost and low in inertia, with high rpm limits. Load is controlled by varying the volume of water circulating within the brake, with adjustable inlet and/or outlet valves and orifices. The stream of water flowing through it can be controlled in two ways: by using a valve, or working with dyno-max software. By using this software, we recorded the operating conditions of the entire experiment and controlled the applied torque on the engine. Recorded data was later used to determine brake power at a specific engine speed and load.

2.3.2 Emission Measurement

For emissions testing, three devices were used: NovaGas 7466-K analyzer - to measure carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC), nitric oxide (NO) and nitrogen dioxide (NO_2); a Dwyer 1205A (to measure CO precisely); and a smart 1500 (to measure smoke opacity). A NovaGas 7466-K analyzer was used for the simultaneous measurement of emissions from the exhaust from the engine. CO, CO_2 and HC were measured using a dual-wavelength infrared sensor, whereas O_2, NO and NO_2 levels were determined by an electrochemical sensor. A Dwyer 1205A is an electrochemical analyzer that tests co levels precisely. The smart 1500 smoke opacity analyzer is fully computerized, and integrated into an automated and computerized smoke opacity analysis system. It is an accurate and repeatable system that complies with ISO standards, as well as to industry-specific standards in Europe and North America. Detailed specifications of emission measurement equipment are shown in Table 2.

Table 1: Engine Specifications

Engine Manufacturer & Model	HATZ 2G40
Engine Type	Air Cooled , 4 Stroke Diesel Engine
Combustion System	Direct Injection
Number of Cylinders	2
Bore/Stroke	92 mm/75 mm
Displacement	997 cc
Lowest Idling Speed	1000 rpm
Compression Ratio	20.5 : 1
Maximum Rated Power	17 kW @ 3600 rpm
Maximum Torque	53.6 N.m

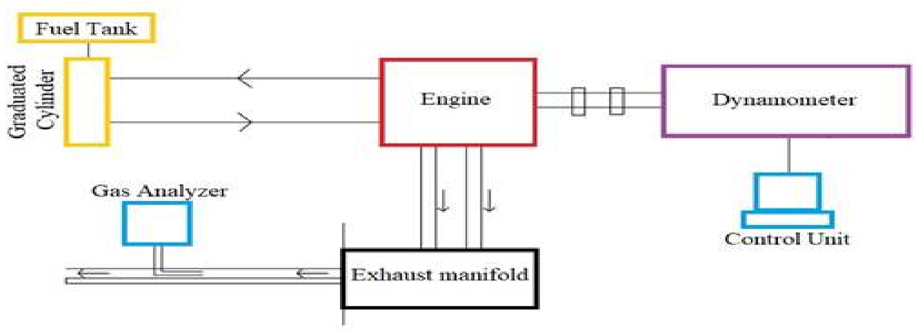

Fig. 1: Schematic diagram of engine setup

Table 2: Emission Measurement Equipment Specifications

Measurement Device/Species	Method of Detection	Measurement Unit	Range	Resolution	Accuracy
Novagas 7466 K					
CO	Electrochemical & Infrared Detector	%	0 – 10 %	0.10%	±1%
CO_2	Infrared Detector	%	0 – 20 %	0.10%	±1%
NO	Electrochemical	ppm	0 – 2000	1 ppm	±2%
NO_2	Electrochemical	ppm	0 – 800	1 ppm	±2%
O_2	Electrochemical	%	0 – 25%	0.10 %	±1%
HC	Infrared Detector	ppm × 10	0 – 20,000	10 ppm	±1%
Dwyer 1205 A					
CO	Electrochemical	ppm	0-2000	1 ppm	±5%
Smart 1500					
Opacity		%	0–100%	0.1%	±2%

2.4 Emulsification

Emulsion is a process by which two immiscible phases are mixed together in the presence of surfactants. The primary role of surfactants in the emulsification process is to reduce surface tension of oil/fuel and water. Its secondary role is to stabilize the emulsion and avoid coagulation of the water phase. Firstly, a blend of sorbitan monoleate (span 80) and polyoxyethylene sorbitan monoleate (tween 80) was stabilized at 8 HLB, which was tested to be most stable with biodiesel-kerosene-water emulsion. It was added to the fuel in a volumetric percentage of 2% of the total fuel volume. The fuels used as emulsions were biodiesel and kerosene as BK20, and as BK50 with a water percentage of 5% and 2.5%. Secondly, water was added to the fuel in a mixer (running at 4000 rpm) for 15 minutes, after which emulsifiers were added at the rate of 1.25 ml per minute.

III. RESULTS AND DISCUSSION

3.1 Fuel Properties

In this study, we needed to know the properties of nine fuels: D100, B100, K100, BK80, BK50, BK80W2.5%, BK80W5%, BK50W2.5% and BK50W5%. Viscosity plays a vital role inthe complete combustion of fuel. Fuel atomization is influenced by its viscosity, which means low viscosity leads to high atomization. If a fuel is well atomized, flame propagation would be better, ignition delay would be shorter, and the fuel would ignite completely. The calorific value of the fuels was tested by a bomb calorimeter, whereby it was observed that the calorific value decreased with the increase in water concentration. Low calorific value resulted in low combustion temperature. The properties of the fuels used are outlined in Table 3.

3.2 Engine Performance

3.2.1 Brake Thermal Efficiency (BTE)

Figure 2 shows brake thermal efficiency of the engine for different blends and their emulsions. It was observed that BTE increased with an increase in load, as did brake power. Biodiesel showed higher BTE than petroleum diesel because of oxygen content (about 10%) in it, which produces better combustion. Kerosene had the highest BTE, indicating that kerosene is a very good fuel in diesel engine. With the increase in kerosene concentration in the blends, BTE increased. On average, about 2% increase in BK80, compared to BK50, was noted. The emulsion with higher water concentration had higher BTE because of the micro explosion phenomenon, which improved air-fuel mixing at different engine running conditions [33]. For 5% water concentration in BK80 and BK50, there was an average increase of about 4%, compared to D100 at various engine conditions.

3.2.2 Brake-Specific Energy Consumption (BSEC)

Figure 3 outlines the BSEC of different blends and their emulsions at three different speeds and loads. BSEC is energy consumed by engine to produce unit brake power. BSEC decreased with the addition of kerosene due to the kerosene's high heating value and better thermal efficiency as compared to D100. It was seen that BSEC increased with the increase in water concentration in the emulsion due to the low combustion temperature; the engine consumed more energy to balance it. There was an average decrease in BSEC of 2-3% for BK80 with 5% water concentration compared to D100 at different loads and speeds. It was also clear that BSEC followed the same trend for both kerosene and emulsion: it decreased with an increase in engine speed and load.

3.3 Emissions

3.3.1 CO Emissions

Table 3: Properties of Fuel

Fuel	Calorific Value (kJ/kg)	Kinematic Viscosity (cSt)	Density kg/m^3
D100	44681	2.40	838
B100	40225	5.72	873
K100	45600	1.36	774
BK80	44520	2.01	794
BK50	42910	3.06	824
BK80W2.5%	43850	2.69	805
BK80W5%	44100	3.15	826
BK50W2.5%	42300	3.52	841
BK50W5%	42190	4.23	858

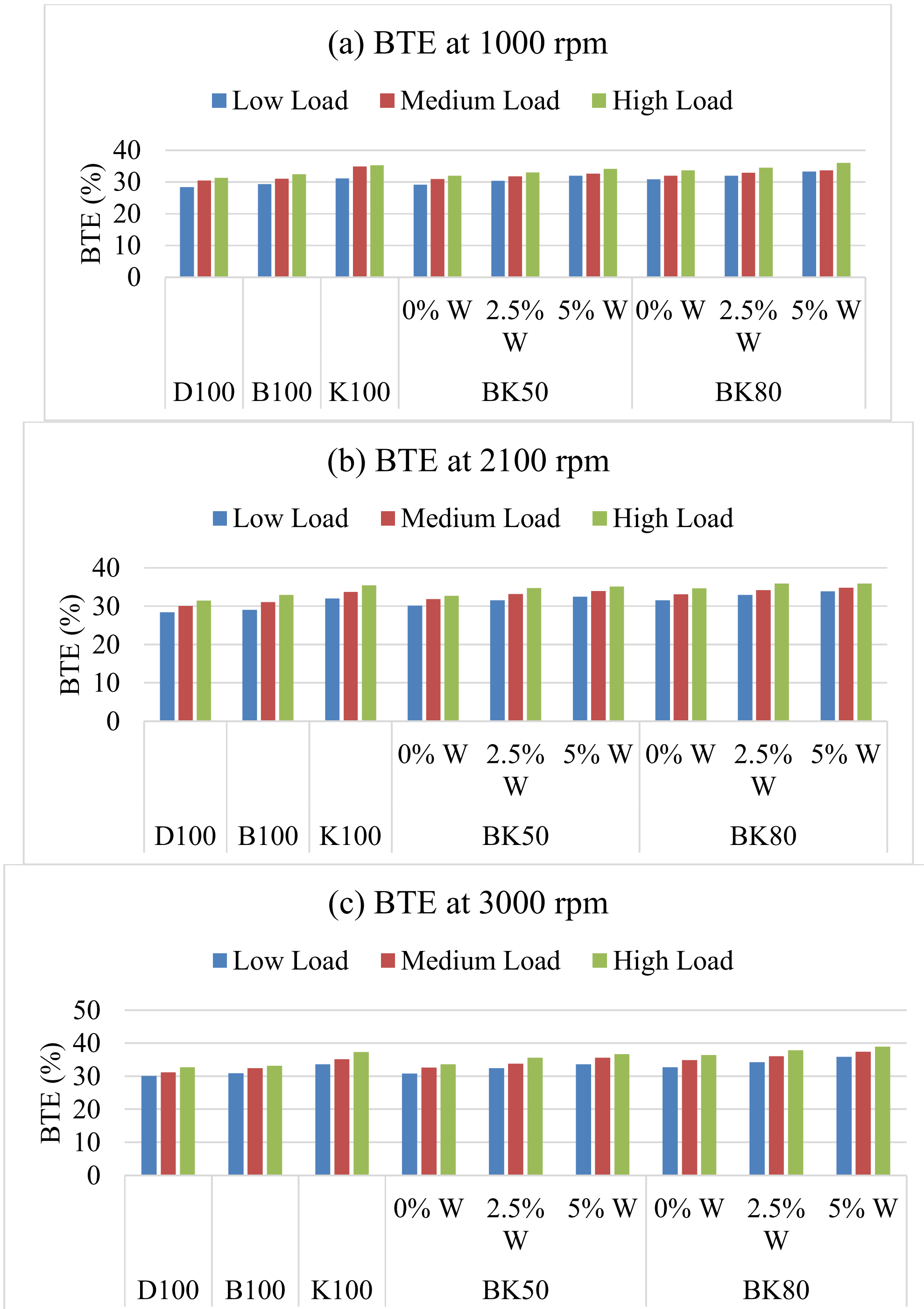

Fig. 2: BTE of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

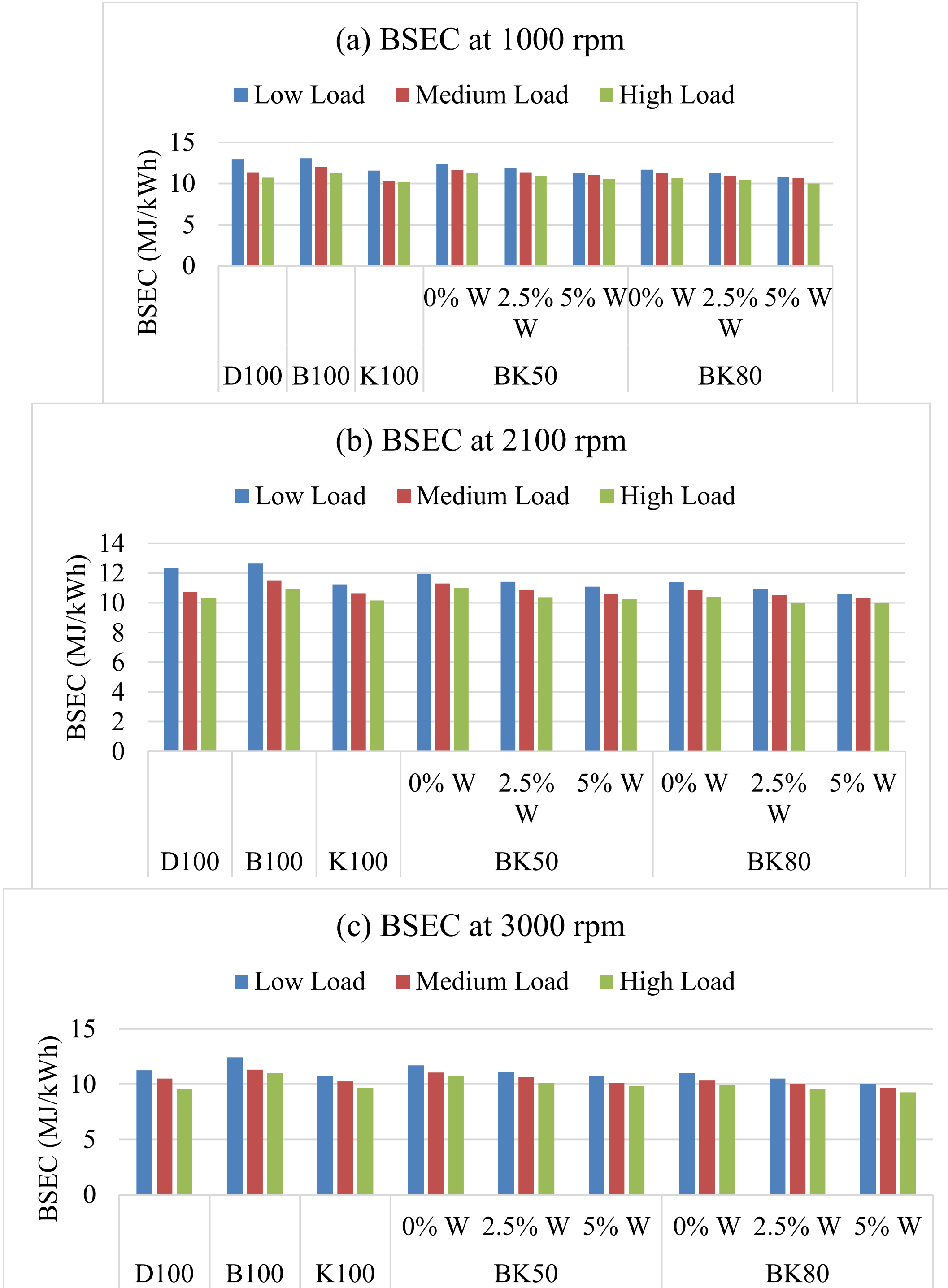

Fig. 3: BSEC of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

Figure 4 shows CO emission of different fuels and their emulsions, at various engine loads and speeds. CO and HC are products of incomplete combustion. Neat biodiesel (B100) has more oxygen content (about 10%) than petroleum diesel (D100); hence, more complete combustion takes place and therefore less CO and unburnt hydrocarbon (HC) were expected. It is found that CO with B100 is approximately 55-60% less than D100 at different loads and speeds. Kerosene has a little lower CO than D100, and with the addition of kerosene in biodiesel, there was a perceivable increase in CO. However, still the CO emissions for kerosene-biodiesel blends are almost 50% lower than that of diesel. The combustion temperature rose with the increase in engine load and rpm, which resulted in decreased CO emissions. With the introduction of water as an emulsion with biodiesel blend, CO increased with the increase in water concentration due the lower combustion temperature.

3.3.2 HC Emissions

Figure 5 illustrates HC emissions at different loads and engine speeds. It is clear that HC emission decreased with the increase in load and engine speed. HC is measured as C1. This decrease in HC emission is attributed to the increase in combustion temperature and complete fuel combustion. HC's trend is quite similar to that of CO, there was about 50-65% HC reduction for B100 than D100. Adding kerosene in biodiesel increased the HC significantly. Additional water in the fuel as emulsion further lowers the combustion temperature, resulting in an increase in HC emissions. However, BK50 and BK80 with 2.5% water emulsion always produced lower HC than D100, and with 5% water in those blends, HC is slightly higher than D100.

3.3.3 NOx Emissions

Figure 6 shows NOx emission of different fuels and their emulsions at various engine speeds and loads. Reasons for high NOx emission are high combustion temperature and oxygen content in fuels. Due to 10% oxygen content in biodiesel, B100 produced about 15-25% more NOx than D100 at different engine running conditions. Kerosene emitted pretty much similar NOx to that of diesel. Adding kerosene in biodiesel helped reducing NOx emissions. Adding water in biodiesel further helped more NOx reduction due to lower combustion temperature. With BK80 for 5% water emulsion, the NOx emission is very similar to that of diesel. It was seen that with 2.5% and 5% water concentration, there was an average5-7%, and a8-11% decrease in NOx, respectively, over their base fuels.

3.3.4 Smoke Emissions

Figure 7 shows smoke opacity of different fuels and their emulsions at various engine loads and speeds. It has been observed that biodiesel produced about 15-25% higher smoke than diesel. This might be due to higher viscosity of biodiesel, which causes higher fuel pressure and penetration to the combustion chamber wall for this small diesel engine. At lower engine speed (1000 rpm), the smoke difference between diesel and biodiesel is more (25%). The smoke density in exhaust is decreased with the decrease in biodiesel concentration. Addition of water leads to micro explosion which improves the mixing of fuels, fuel atomization and vaporization, hence it reduces the smoke emission. At 3000 rpm, an average decrease of more than 20% and 10% has been observed in BK80 with 5% and 2.5% water concentration, respectively, as compared to petroleum diesel.

IV. CONCLUSIONS

Experimentation and analysis for engine performance and emissions were conducted on various biodiesel-kerosene blends and their emulsions. It was concluded that brake thermal efficiency (BTE) increased with the increase in water concentration, among which BK80W5% had the maximum BTE. With respect to kerosene, the increase in its concentration increased the calorific value, which tended to increase its BTE. For all engine loads and speeds, BTE increased with an increase in engine load and speed. Brake-specific energy consumption (BSEC) was initially high for pure biodiesel (B100) because of its low heat content, but subsequently decreased with the kerosene concentration. With the addition of water, BSEC increased again with the increase in water concentration. As for emissions, carbon monoxide (CO) and hydrocarbons (HC) showed similar trends, as both are produced as a result of incomplete combustion. Both CO and HC increased with the increase in kerosene concentration, but decreased with engine speed and load. CO in the biodiesel-kerosene blend further increased with the increase in concentration of water in the emulsion. NOx is considered to be the major challenge in using pure biodiesel as the alternative fuel. NOx decreased with the increase in kerosene concentration, and further decreased with the increase in water percentage. In this experimental analysis, we achieved NOx reduction by 15-20% in the emulsions that contained 5% water as compared to pure biodiesel. A significant decrease in smoke emission (20% or more) has been achieved for BK80 with 5% water concentration than diesel.

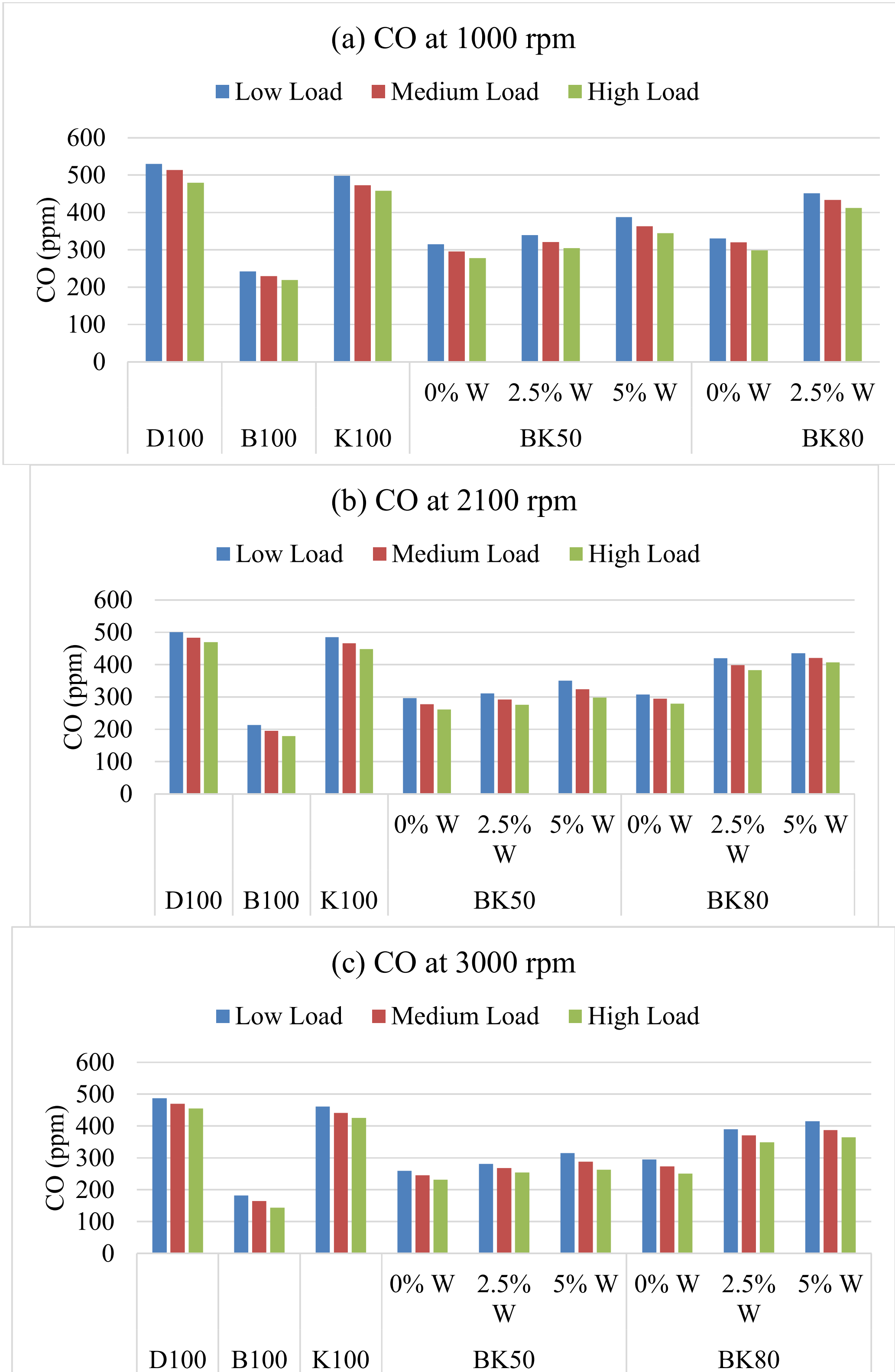

Fig. 4: CO of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

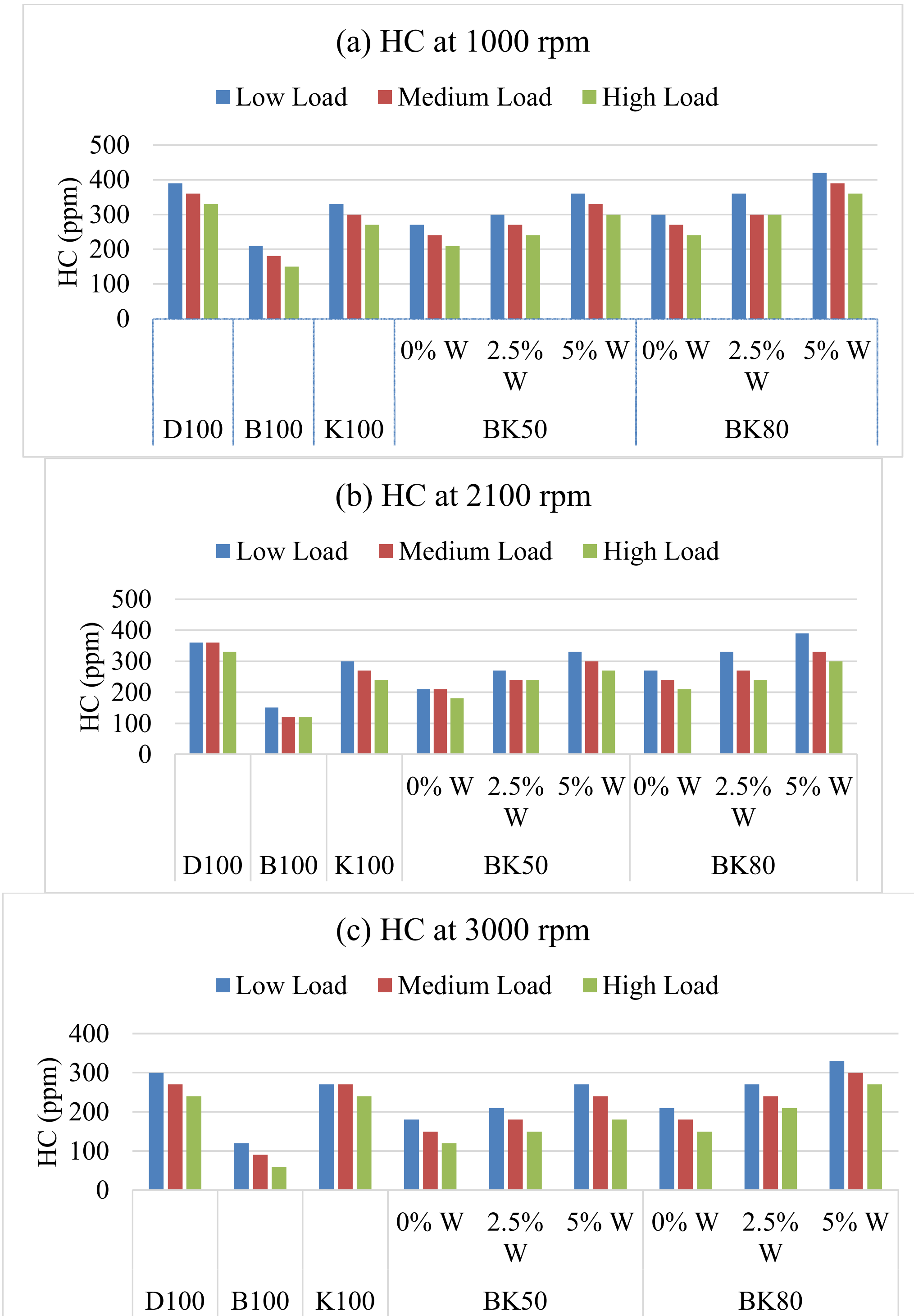

Fig. 5: HC of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

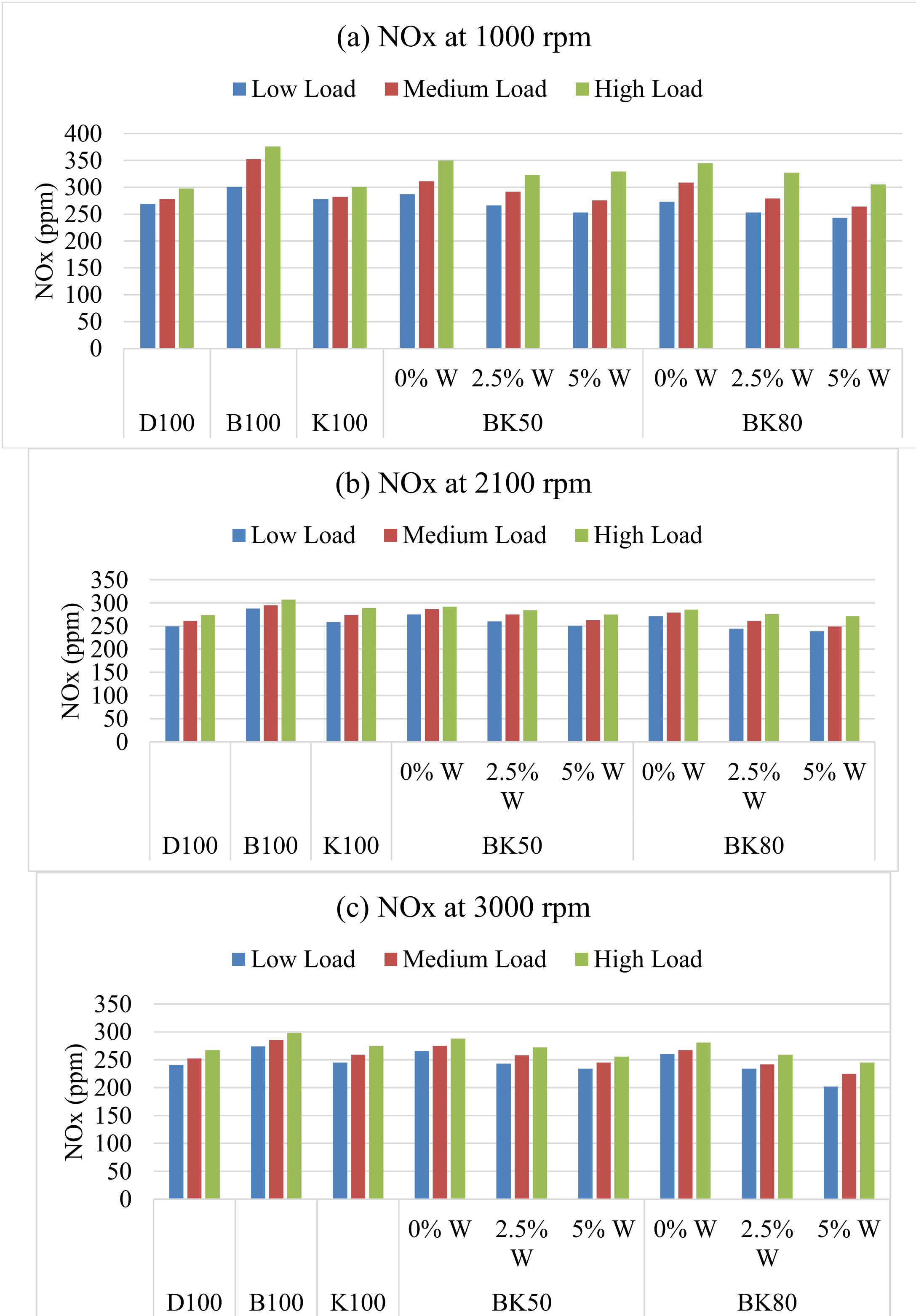

Fig. 6: NOx of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

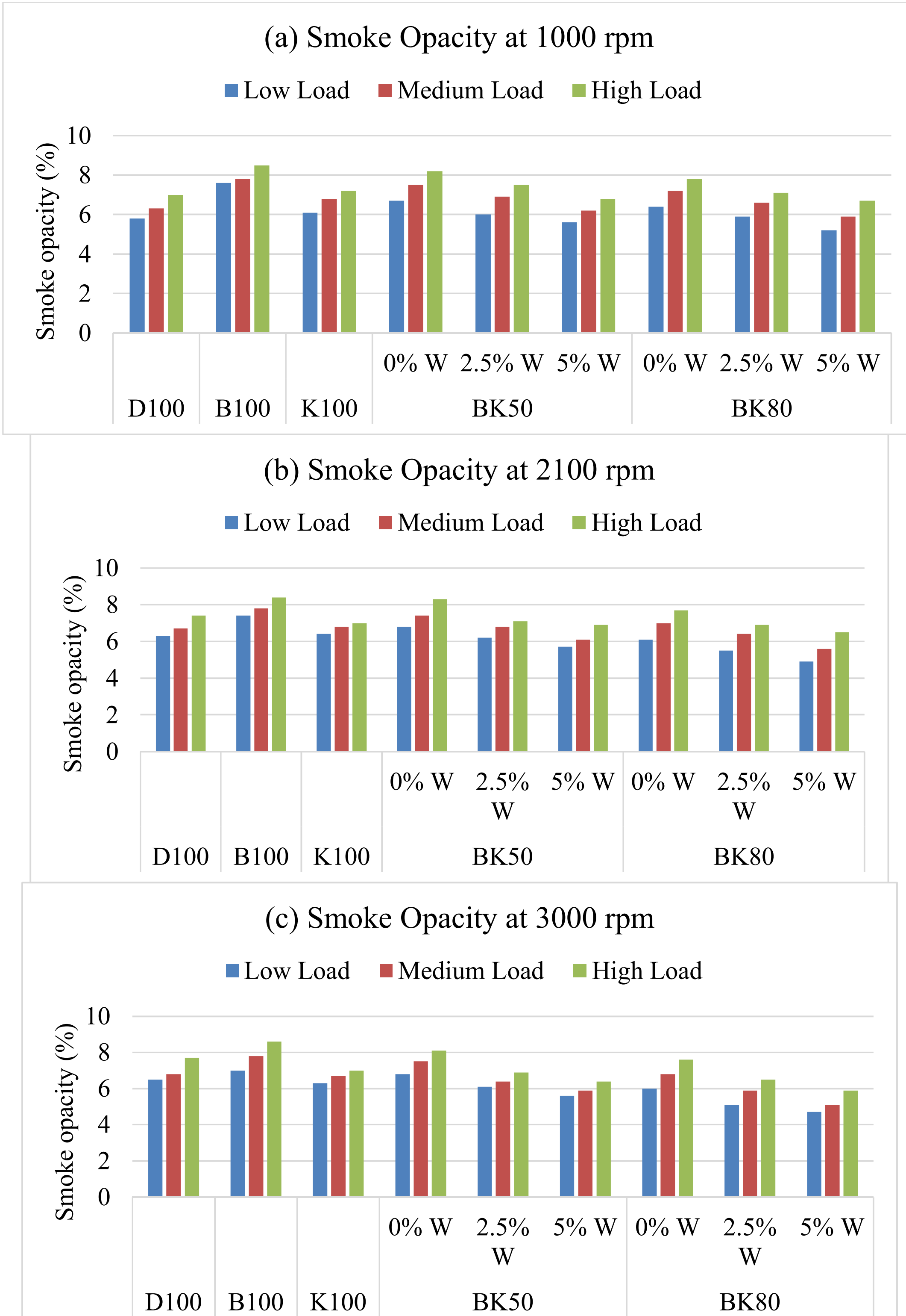

Fig.7: Smoke of biodiesel-kerosene blends and their emulsions at (a) 1000 rpm, (b) 2100 rpm, and (c) 3000 rpm

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