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Increasing Cetane Number of the Diesel Fuel by Fuel Additives

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Abstract

Current study uses DieselFX (DFX) additive to increase the cetane number of the diesel fuel used in compression-ignition (CI) engines, reduce carbon monoxide (CO) and hydrocarbon (HC) emissions, and improve engine performance. In this respect, the effects of the additive used in diesel engines were analyzed. A Katana brand, KM 178 FE model, single-cylinder, air-cooled engine was started at a constant engine speed with different loads for the experiments. By adding the additive in 1% and 2% ratios the cetane number was increased to 62 and 75, respectively, furthermore at 3% and 5% additive ratios the cetane number value reached over 76. In result of the experiments, DFX2 offers 12.24% increase on efficiency compared to the diesel fuel and 6.87% increase in specific fuel consumption. As for the emission values, with the use of DFX5 44.23% reduction in HC emission and 50% reduction on average in CO emission was observed at 3000W load compared to additive-free diesel fuel. Moreover, 37.84% increase was observed in carbon dioxide (CO_2) emission at 3000W engine load for DFX2 whereas 52.11% increase was observed in nitrogen oxide (NO_x) emission for DFX5.

Keywords: Diesel engine performance, Emission, Cetane number, Knocking, Combustion

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1. Introduction

Compression ignition engines are preferred for their high momentum, efficiency and lower HC and CO emission advantages. However, diesel fuels produce high amounts of NO_x, particulate matter, and smoke. Besides, the use of low cetane numbered fuels causes knocking and affects the engine performance in a negative way. One of the methods of reducing harmful exhaust emissions and increasing cetane number is the use of additives.

Lu et al. added 2% cetane improver to an ethanol-diesel mixture, and used this fuel in four-cylinder, direct injection CI analyzing its effects on performance and emissions of the engine. In result of the conducted tests, they have concluded that when 2% cetane adjuvant is added to 15% methanol, and 83% diesel fuel ratio the thermal productivity improves, and specific fuel consumption decreases at full load engine parallel to the acquired values with diesel fuel. As for the emission rates, CO, HC, NO_x, and carbon deposit emissions were reduced [1].

In another study, Bang-Quan et al. [2] analyzed the engine performance and emissions by adding cetane adjuvant additive into diesel-ethanol mixed fuels in direct injection, four-cylinder diesel engines. They have added ethanol to standard diesel fuel at 10% and 30% rates. Subsequently, the results accumulated from the burning of the mixture in the engine were compared with the results from the burning of the same mixture, this time with an additional 2% isooctyl-nitrate cetane adjuvant additive. Owing to the fact that adding ethanol in pure diesel fuel lowers the cetane number, an increase was observed in NO_x, CO and CO_2 emissions, however, with the cetane adjuvant additive fuel a reduction was observed in smoke emissions, HC and CO.

Uslu and Aydin [3] added diethyl ether, a cetane improver, to biodiesel / diesel mixtures and used Taguchi method to examine the effects on engine outputs and determine optimum conditions. They stated that the addition of diethyl ether generally improved emissions and slightly reduced performance.

In a study we conducted [4], the effects of adding 2-ethylhexyl nitrate (3%, 2%, 1% and 0%) to biodiesel were experimentally examined, and working conditions and related responses were improved with the response surface methodology. The results showed that after 1% 2-ethylhexyl nitrate ratio, the engine outputs were generally negatively affected, and the optimum 2-ethylhexyl nitrate ratio was 1.1%.

Jong Bon Ooi et al. [5] researched the features of graphite oxide, single flare carbon nanotubes and cerium oxide nanoparticles under various engine loads and their effects on the burning, performance and emission features of a four-stroke, single cylinder CI. The following were obtained with 25 ppm dosage rate of SWCNT nanoparticle addition: ignition delay shortened by 10.3%, improved burning stage (up to 18.5%), shorter burn time (up to 14,7%), BSFC reduced by 15.23%, reduced CO emission (up to 23.40%) and lowered UHC emissions (up to 24.10%). The use of SWCNTs and GO additives for reducing the emissions in diesel engine applications were reported to be an efficient approach in this study.

Many researchers have conducted investigations and experimental work in this area [6-14].

In the use of fuel additives, the analysis of the effects of physical and chemical properties of the fuel on burning features is important with respect to engine performance and engine lifetime. When the related literature was researched, a limited number of studies were found regarding the reduction of carbon amount and increasing cetane number in compression ignition engines. Current study investigates the chemical and physical properties of the DFX additive. The work aims to increase cetane number, improve combustion and reduce knocking. In addition, by mixing 1%, 2%, 3% and 5% DFX additive in diesel engine fuel increasing cetane number, reducing carbon monoxide and HC emissions and improving engine performance were targeted.

2. Material and method

2.1 Fuels used in experiments

Four different fuels were prepared to be used in the experiments by mixing DieselFX additive and diesel fuel in various volume ratios. These ratios are DFX0 (0% DieselFX + 100% Diesel), DFX1 (1% DieselFX + 99% Diesel), DFX2 (2% DieselFX + 98% Diesel), DFX3 (3% DieselFX + 97% Diesel) and DFX5 (5% DieselFX + 95% Diesel). The analyses of the diesel fuel and the DieselFX additive that are used in the experiments were conducted in TUBITAK Marmara Research Center laboratories. The results of these tests are given in Table 1. The physical and chemical properties of the DieselFX additive used in the experiments are given in Table 2. The distillation analysis results of the DieselFX additive used in the experiments are given in Table 3.

Table 1. Chemical composition and physical characteristics of diesel fuel and DieselFX

	Density (g/cm^3)	Higher Heating Value (kJ/kg)	Lower Heating Value (kJ/kg)	Sulphur (mg/kg) EN ISO 20846	Cetane Number
DFX0	829.04	46106	43198	5.5	54
DFX100	957	34248	33666	56	>76
DFX1	830.2	46012	43058	8.1	62
DFX2	831.59	45673	42894	9.9	75
DFX3	832.06	45432	42803	11.7	>76
DFX5	834.73	44958	42508	15.3	>76
Analysis compliant to	EN ISO 12185	ASTM D 240	(Calculated)	TS EN ISO 20646	EN ISO 5165

Table 2. Physical and Chemical Properties of DieselFX

Physical State of DieselFX	Liquid
Odor Threshold	Not defined
Appearance	Clear, Amber
Auto-ignition (the lowest known value)	130- 215°C (2-ethylhexyl-nitrate)
Flash Point (Closed container)	72.778°C
Specific Weight	0.957 [ASTM D 4052]
Vapor Density (the highest known value)	4.6 - 5.5 (Air = 1) (solvent naphtha (crude oil), intense aroma)
Vapor Pressure of DieselFX	0.1 kPa (0.81 mm Hg) (20 °C'de) [solvent naphtha (petrol-crude oil), intense aroma.] Weighted mean: 0.04 kPa (0.31 mm Hg) (at 20°C)
Weighted Mean	1.71 (Air = 1)
Boiling Point	The lowest known value: 168.4-170.85°C (2-butoxyethanol). Weighted mean: 191.5°C
Evaporation Rate	<1($C_8H_{17}NO_3$) Weighted mean: 0.76 (when mixed with Butyl acetate)
Pour Point	Possible solidus: <-20°C Provided by the following components: solvent naphtha (crude oil), intense aroma. Weighted Mean: - 47.06°C
Water Solubility	Easily soluble in following materials: hot water and cold water.

Table 3. Diesel FX additive distillation analysis results

View	Clear, Amber, Liquid
Specific weight, 15.6/15.6	0.959
Density, kg/m^3, 15.6 °C	7.99
Flash point, TCC, °C	72.8
Dropping point, °C	<-40
Viscosity, mm^2/s, 37.8 °C	5
Viscosity, mm^2/s, 20 °C	8
Viscosity, mm^2/s, 0 °C	16
Viscosity, mm^2/s, -17.8 °C	37
Viscosity, mm^2/s, -28.9 °C	72
Viscosity, mm^2/s, -40 °C	164

2.2 Experimental procedure

An internal combustion engine, naturally aspirated, four-stroke, air cooled, single-cylinder, and direct injection diesel engine was used during the experiments at 3000 rpm fixed engine speed. The related technical properties of the engine and the generator connected to the engine are given in Table 4.

Table 4. Specifications of the engine and the generator used in the experiment

Engine Specification	
Brand	Katana
Type	KM 178
Total Volume	296 cm³
Bore & Stroke	78x62
Maximum Horsepower	6.7 hp
Continuous-Duty Horsepower	6.01 hp
Starting System	Kick-starter/Recoil
Engine Speed	3000 rpm
Air Filter	Dual-Element/Dry
Electrical System	12 V – 36 Ah
Fuel Type	Diesel
Sump Capacity	1.1 Lt
Fuel Storage Capacity	11 Lt
Generator Specification	
Brand	Katana
Prime Power	4.2 kVA
Continuous Power	3.36 kVA
Frequency	50 Hz
Phases	1
Voltage	230 V

The engine was operated until it reaches the running temperature before measuring the engine performance and exhaust emission values. The test engine was loaded with 500W, 1000W, 1500W, 2000W, 2500W and 3000W halogen lamps during the experiments, respectively. The test engine was started at the above-mentioned loads for volumetrically prepared DFX0, DFX1, DFX2, DFX3 and DFX5 fuels and its performance and emission values were measured. Exhaust temperature, oil temperature and engine speed sensors were connected to the engine. The specific fuel consumption, effective efficiency, and emissions (NO$_x$, HC, CO$_2$, CO, and Smoke) were measured and recorded during the experiments. A schematic image of the experiment mechanism is given in Figure 1.

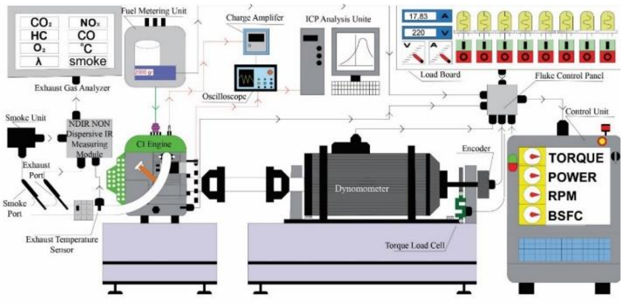

Fig. 1. Schema of experiment setup

The Bilsa MOD 2210 WINXP-K brand exhaust gas analyzer was used for measuring O$_2$, CO, CO$_2$, HC, NO$_x$, Smoke emissions and lambda as accurately as shown in Table 5.

Table 5. Ranges for exhaust gas analyzer measurement

Parameters	Precision	Measurement Limit
CO	0.001%	0-10.0 % vol.
HC	1 ppm	0-10.000 PPM vol.
CO$_2$	0.001%	0-20.0 % vol.
O$_2$	0.01%	0-10 % vol.
NO$_x$	1 PPM	0-5000
Smoke	± 0.1%	0-100%
Lambda	0.001	0.5 – 2.00

3. Results and Discussions

3.1 Effective Efficiency

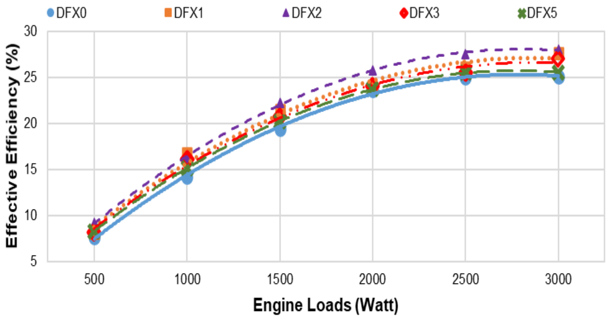

Fig. 2. Effective efficiency changes with engine loads

Figure 2 shows the effective efficiency changes of DFX0 and DFX1, DFX2, DFX3 and DFX5 depending on engine load. When the effective efficiencies of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel an increase was observed by 7.83%, 12.27%, 5.74% and 3.08% on average, respectively and as for 3000W engine load, an increase was seen for the prepared fuels by 9.98%, 11.56%, 7.57%, 1.85% rates, respectively. During the experiments, DFX additive was found to increase the effective efficiency in all mixtures compared to diesel fuel. The results show that the addition of DFX has a positive function in increasing the cetane number, shortening the diesel injection delay and the burn time. Despite increasing the cetane number, the increase in the DFX rates is thought to cause effective efficiency to drop for DFX3 and DFX5 due to decreasing the lower heating value. One can see that there is a reasonable compatibility between the effective efficiency obtained within this study and the other research results [6, 16-21].

3.2 Specific fuel consumption

Figure 3 shows the changes in the specific fuel consumption for DFX0 and DFX1, DFX2, DFX3 and DFX5 fuels depending on engine load. When the specific fuel consumptions of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel an increase was observed by 3.41%, 5.87%, 7.76% and 10.87% on average, respectively and as for 3000W engine load, an increase was seen for the prepared fuels by 2.92%, 6.83%, 9.63%, 22.80% rates, respectively. When the lower heating value of diesel is 43198 kJ/kg, DFX lower heating value is 34248 kJ/kg, and in result of this, the decrease in lower heating value depending on the increase of the additive rate also increases the specific fuel consumption to a degree.

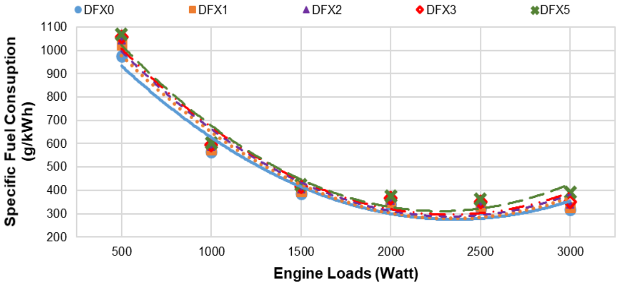

Fig. 3. Specific fuel consumption changes with engine loads

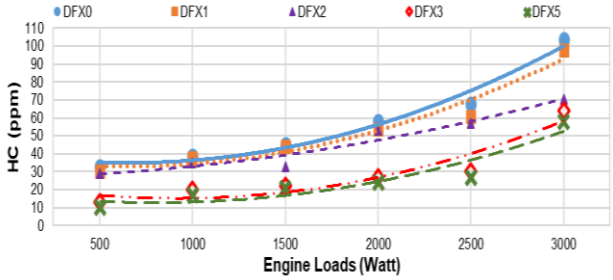

Fig. 4. HC emission changes with engine loads

3.3 Hydrocarbon

Figure 4 shows the changes in the HC emissions for DFX0 and DFX1, DFX2, DFX3 and DFX5 fuels depending on engine load. When the HC emissions of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel a reduction was observed by 6.24%, 19.90%, 49.22% and 54.71% on average, respectively and as for 3000W engine load, a reduction was seen for the prepared fuels by 5.76%, 32.37%, 38.46%, 44.23% rates, respectively. The improvement that the DFX mixtures provide for the viscosity and the intensity of the fuel also improves the quality of burning and injection since it increases the evaporation speed depending on the increase of the cetane number [1,6]. The volumetrically increase of DFX rates in the mixtures also increases the cetane number. DFX was found to increase the burning speed due to its oxygen component, and thus provide higher burning temperature and reduce the HC amount. One can see that there is a reasonable compatibility between the effective efficiency obtained within this study and the other research results [9, 22-25].

3.4 Carbon monoxide

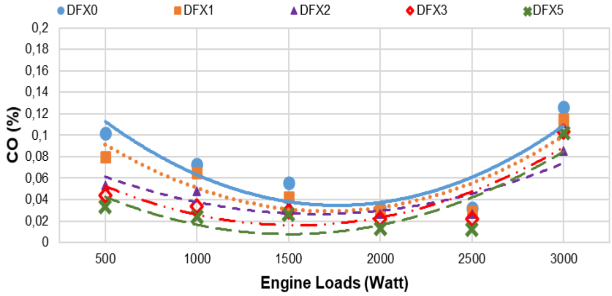

Fig. 5. CO emission changes with engine loads

All emissions generating from internal combustion engines affect engine running parameters, such as fuel type, combustion chamber design, atomization rate, engine speed and air fuel rate. Figure 5 shows the changes in the CO emissions for DFX0 and DFX1, DFX2, DFX3 and DFX5 fuels depending on engine load. When the CO emissions of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel a reduction was observed by 14.28%, 34.28%, 40%, and 50% on average, respectively and as for 3000W engine load, a reduction was seen for the prepared fuels by 8.3%, 32.53%, 18.25%, and 19.04% rates, respectively. CO emission is a pollutant emission generated due to poor combustion. Due to containing nanoparticles in its content (2-ethylhexyl-nitrate, Butyl acetate and 2-Butoxyethanol), DFX additive may have affected the fuel distribution in combustion chamber. The increase in the usability of oxygen, increases burning, and thus reduces CO emission. CO emissions are relatively less for all situations except for pure diesel. The increase DFX mixtures provided in cetane number also increased the burning speed and yielded higher burning temperatures. DFX was found to improve burning speed due to its oxygen component and evaporation speed; corresponding reductions were reported for the emitted CO amount.

3.5 Carbon dioxide

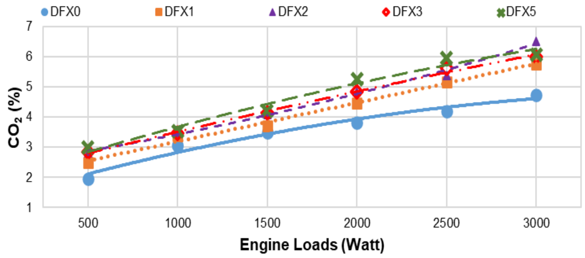

Fig. 6. CO_2 emission changes with engine loads

Figure 6 shows CO_2 emission change graphic for diesel fuel and DFX mixtures. As seen in the figure, CO_2 emission increased with the increasing engine load and DFX mixtures reached higher CO_2 emission values compared to diesel fuel. The increasing of CO_2 emission with the increasing engine load is a result of DFX mixtures increasing the cetane number of the fuel together with its evaporation speed [1, 6, 12, 19, 31]. When the CO_2 emissions of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel an increase was observed by 17.56%, 28.04%, 26.91% and 32.29% on average, respectively. As for 3000W engine load, an increase was seen for the prepared fuels by 21.98%, 37.84%, 26.84%, 28.54% rates, respectively.

3.6 Nitrogen oxides

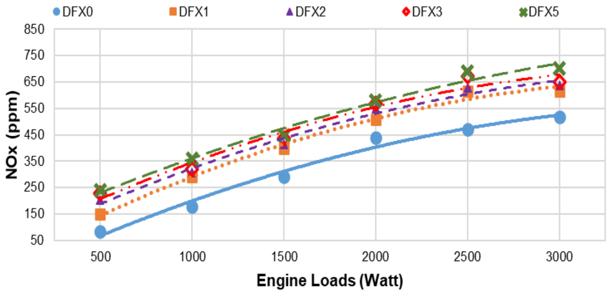

Fig. 7. NO_x emission changes with engine loads

Figure 7 shows the graphic of the change in NO_x emission of diesel and DFX mixtures depending on engine load. With the increase in engine load and increase was observed in the NO_x emissions of the DFX mixtures compared to diesel fuel. Maximum NO_x emission values were obtained at 3000W engine load. When the NO_x emissions of the DFX1, DFX2, DFX3 and DFX5 fuels were compared with DFX0 fuel at 3000W engine load, an increase was seen by 19.11%, 23.16%, 25.41% and 35.32% rates, respectively, and on average, an increase was observed by 30.22%, 38.19%, 45.03% and 52.12%, respectively. Owing to the increasing cetane number, evaporation speed increases and therefore burning speed also increases yielding higher burning temperature and reducing the amount of HC emission. The reduction in HC emission, on the other hand, causes a rise in temperature within the cylinder, and owing to this reason, increases were detected in NO_x amounts [32]. One can see that there is a reasonable compatibility between the nitrogen oxides obtained within this study and the other research results [26-30].

3.7 Smoke emission

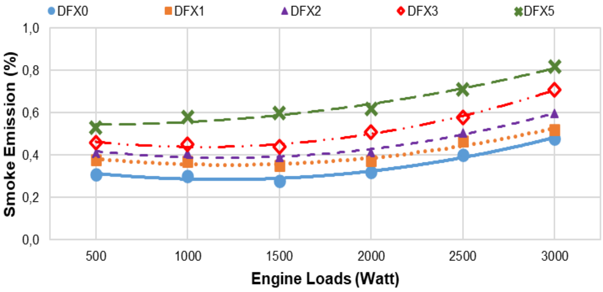

Fig. 8. Smoke Emission changes with engine loads

Figure 8 shows the smoke emission graphic of diesel and DFX mixtures. Since the cetane number of the fuel mixture improves combustion to a degree (~70), the inclination of smoke generation in the fuel decreases. Above a certain value, cetane number negatively affects smoke generation. The Sulphur rate in the mixtures was observed to increase depending on the increase of the cetane number. Correspondingly, the increase in Sulphur rate negatively affected the smoke emission. The cetane number in DFX3 and DFX5 showed high rates of increase and thereof a parallel increase was observed in fuel consumption and smoke emission values. Minimum smoke rate was obtained at 1500W engine load. When added to diesel fuel, DFX1, DFX2, DFX3 and DFX5 fuels demonstrated an increase in smoke emission values by 19.43%, 30.14%, 51.83% and 99.43% on average, respectively.

4. Conclusions

The DFX additive was preferred in diesel engine experiments due to its intensity, viscosity, and contribution to burning. When its physical and chemical properties were analyzed, DFX additive was found to have a dark brown color with a higher intensity than diesel fuel. The evaporation rate of DFX additive being 0.76 with an evaporation pressure weighted mean of 0.04 kPa improves burning, and thus increases the effective efficiency of the engine. In addition, DFX additive is thought to increase the cetane number of diesel fuel and shorten the time between injection and combustion and therefore to reduce the HC and CO emissions.

The cetane number of the used diesel fuel was 54; with DFX1 mixture rate this number increased to 62 and with DFX2 mixture rate to 75. As for DFX3 and DFX5 mixture rates, the cetane number could not be measured since it was higher than the maximum measurement value of CFR engine, 76. The cetane number being above a certain rate increased the smoke emissions. In DFX3 and DFX5 mixtures, the high rates of cetane number caused engine knocking at partial loads. Some subsiding was observed with the increase of additive in Diesel and DFX mixtures.

When engine performance and exhaust emission data were analyzed, DFX additive has shown improvement with DFX1, DFX2, DFX3 and DFX5 proportions in cetane number, evaporation rate and evaporation pressure demonstrating increase at every rate in effective efficiency. Parallel to these, an increase was observed in specific fuel consumption to a degree. This increase in fuel consumption together with the increase in Sulphur due to the use of DFX additive had a negative impact on smoke emission while causing NO_x emission increase at the same time. Depending on the accumulated data from the experiments, the values of the compared parameters are as follows:

- The additive used in Diesel fuel has increased the effective efficiency of the engine. In result of the experiments, the effective efficiencies of DFX1, DFX2, DFX3 and DFX5 fuels were observed to increase by 7.81%, 12.24%, 5.73% and 3.05% rates on average, respectively. DFX2 fuel which has yielded 29.99% effective efficiency at 3000W engine load was found to be 12.24% more efficient compared to diesel.

- When compared to diesel fuel, specific fuel consumption rates of DFX1, DFX2, DFX3 and DFX5 fuels were observed to increase by 3.76%, 6.87%, 9.51% and 12.77% respectively at 2500W engine load.

- When compared to diesel fuel, the CO emissions of DFX1, DFX2, DFX3 and DFX5 fuels were observed to decrease by 14.28%, 34.28%, 40% and 50% rates, respectively.

- At 3000W engine load, the CO_2 emissions of DFX1, DFX2, DFX3 and DFX5 fuels were observed to increase by 21.98%, 37.84%, 26.84% and 28.54% rates, respectively.

- NO_x emissions reach their maximum level at 3000W load. Compared to diesel fuel, NO_x emissions of DFX1, DFX2, DFX3 and DFX5 fuels were observed to increase by 30.22%, 38.19%, 45.03% and %52.11 rates, on average, respectively.

- The minimum smoke rate is obtained at 1500W load. With the use of DFX1, DFX2, DFX3 and DFX5 fuels, an increase by 19.43%, 30.14%, 51.83% and 99.43% rate were observed, respectively.

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