Biodiesel production, characterization, diesel engine performance, and emission characteristics of methyl esters from *Aphanamixis polystachya* oil of Bangladesh

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ABSTRACT

This paper presents the prospect of biodiesel derived from *Aphanamixis polystachya* oil in diesel engine. The study deals with the physicochemical properties of *A. polystachya* methyl ester (APME) and its blends followed by evaluation of performance and emission characteristics of APME5 and APME10 in a multi-cylinder diesel engine. It has been observed that the properties of biodiesel and its blends are compatible with the ASTM D6751 and ASTM D7467 standards, respectively. It was found that, APME5 and APME10 showed an average 0.9% and 1.81% reduction in torque and 0.9% and 2.1% reduction in brake power (BP), and 0.87% and 1.78% increase in brake specific fuel consumption (BSFC) compared to diesel. In the case of engine emissions, diesel blends of APME gave an average reduction in carbon monoxide (CO) and hydrocarbon (HC) emissions compared to pure diesel. However, APME blends emitted higher levels of nitrous oxide compared to diesel. It was found that APME5 and APME10 could be used as a diesel fuel substitute without any engine modifications.

1. Introduction

With the increasing stringent environmental legislations and growing energy demand, researchers are looking for environment friendly alternative energy sources among which biodiesel is one potential candidate. Biodiesel refers to the fatty acid alkyl esters (FAAEs), mainly methyl esters which are derived from lipid substances originated from oils, fats, waste greases, recycled oils etc. [1,2]. To produce biodiesel, vegetable oils of edible origin were treated as one of the potential feedstocks once. Due to food vs. fuel controversy of edible oil use for fuel production, other sources e.g. non-edible oils of plant origin with high free fatty acid (FFA) content etc. are now being used for biodiesel production [3–6].

Aphanamixis polystachya (AP) is a widespread species found in Indo-China and western Malaysia. It is native to Indonesia, Malaysia, Singapore and Taiwan. It is commonly known as 'Pithraj' in Bangladesh and 'Amoora' in India. Fig. 1 shows the images of the tree, fruit, and dried seeds. This non-edible oil has been reported to be a potential biodiesel feedstock by some researchers and its use will be acceptable as it will not compete with food supply [7,8]. In the published literature there are handful amount of articles which mainly deals with biodiesel production and its characterization. Kumar *et al.* [9] reported on Indian amoora oil which had 4.62% Free Fatty Acids (FFA) content. Two stage biodiesel production processes was employed for biodiesel production. In acid pretreatment step, the oil was treated with 5% H_2SO_4 and 40:1 methanol to FFA by molar ratio in order to reduce FFA content. After that transesterification process was carried out with 1:6 oil to methanol in presence of more than 3.5 g/L of NaOH at 60 °C temperature which yielded 96% (v/v) biodiesel with 1 h reaction time. Ferdous et al. [10] studied the Bangladeshi pithraj oil which had FFA content of 7.5%. They also carried out two step esterification-transesterification process. For esterification 5% H_2SO_4 and a molar ratio of 1:6 (oil to methanol) were selected for 1 h reaction time at 70 °C. After that, with NaOH at 1 wt% of oil and 1:6 molar ratio of methanol, methyl ester conversion was complete within 1 h at a temperature of 60 °C. Both studies concurred that quality of the biodiesel was found to be comparable with the ASTM D6751, hence its suitability for internal combustion engine application. Till date there is no literature which deals with biodiesel production from *A. polystachya* oil, its characterization along with its effect on engine performance and emission. Thus, the motivation of this work is to establish the suitability of blends of *A. polystachya* biodiesel in diesel engines in terms of its performance and emission characteristics.

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Nomenclature

APME	*Aphanamixis polystachya* methyl ester
ASTM	American society for testing and materials
BP	brake power
BSFC	brake specific fuel consumption
CAPO	crude *Aphanamixis polystachya* oil
CCaO	crude canola oil
CCIO	crude *Calophyllum inophyllum* oil
CI	compression ignition
CIME	*Calophyllum inophyllum* methyl ester
CJCO	crude *Jatropha curcas* oil
CaME	canola methyl ester
CN	cetane number
CO	carbon monoxide
CPaO	crude palm oil
CSO	crude soybean oil
EGT	exhaust gas temperature
FAC	fatty acid composition
GC	gas chromatography
HC	hydrocarbon
IV	iodine value
JCME	*Jatropha curcas* methyl ester
MJ/kg	mega joule/kg
NO	nitrous oxide
NOx	oxides of nitrogen
PaME	palm oil methyl ester
PM	particulate matter
rpm	revolution per minute
SME	soybean oil methyl ester
SN	saponification number

1.1. Objectives of this study

This paper presents the potential of *A. polystachya* as a promising non-edible feedstock for biodiesel production. To achieve this, quantification of fatty acid methyl esters, characterization of physicochemical properties e.g. density, kinematic viscosity, viscosity index, flash point, cold filter plugging point, cloud point, pour point, and oxidation stability etc. of produced biodiesel and its blends with diesel was carried out and compared with corresponding ASTM standards. In addition, to test its suitability in diesel engines, performance and emission study of 5% and 10% by volume diesel/biodiesel blends was carried out and compared with petroleum based diesel fuel in a multi-cylinder diesel engine. The outcome of this study shows the potential of *A. polystachya* as a non-edible biodiesel feedstock for diesel engines.

2. Materials and methods

2.1. Materials and chemicals

The crude AP oil (CAPO) was purchased from Bangladesh. Other chemicals such as methanol, potassium hydroxide (KOH) and anhydrous sodium sulfate (Na_2SO_4) were of Friendemann Schmidt Chemicals, USA. All purchased chemicals i.e. methanol, hydrochloric acid (HCl) etc. were of analytical grade and catalysts were of 99.5% purity.

2.2. List of apparatus

The summary of the equipment used to measure the properties of CAPO, neat biodiesel, and its blends with diesel are shown in Table 1.

2.3. Calculation of the cetane number, iodine value, and saponification number of biodiesel

The cetane number, iodine value, and saponification number of APME were determined empirically using the equations presented in the literature [7,11].

$$\mathrm{SN} = \sum\left(\frac{560 * A_i}{MW_i}\right) \tag{1}$$

$$\mathrm{IV} = \sum\left(\frac{254 * D * A_i}{MW_i}\right) \tag{2}$$

$$\mathrm{CN} = \left(46.3 + \left(\frac{5458}{\mathrm{SN}}\right) - (0.225 * \mathrm{IV})\right) \tag{3}$$

where

$A_i \equiv$ the percentage of each component,

$D \equiv$ the number of double bond and

$MWi \equiv$ the molecular mass of each component.

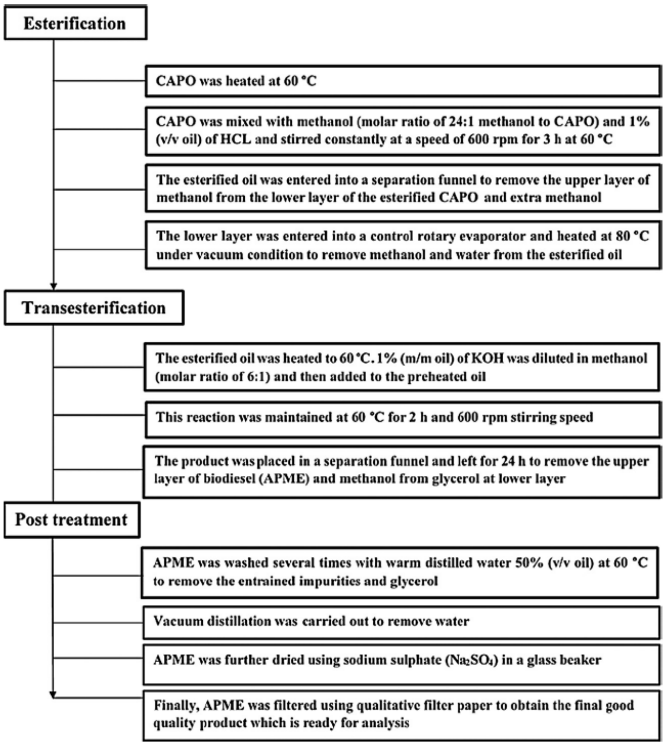
2.4. Biodiesel production from CAPO

The high acid value of CAPO, 26.1 mg KOH/g of oil, prevents the use of a single-step alkaline-transesterification process. Therefore, a two-step process of acid-base catalysis was used to produce biodiesel. In the first stage, the esterification process was used to reduce the high acid value of the crude oil, while in the second stage; the transesterification process was used to convert the esterified oil to methyl ester or biodiesel (APME). Fig. 2 shows a detailed flow chart of the production of biodiesel from CAPO.

Fig. 1. *Aphanamixis polystachya* tree, fruit and dried seeds.

Table 1
Summary of the apparatus used to measure the properties.

Property	Equipment	Manufacturer	Test method
Kinematic and dynamic viscosity at 40 °C	SVM 3000	Anton Paar, UK	ASTM D7042
Density at 40 °C	SVM 3000	Anton Paar, UK	ASTM D7042
Density at 15 °C	DM 50	Mettler Toledo, Switzerland	ASTM D1298
Oxidation stability	873 Rancimat	Metrohm, Switzerland	EN ISO 14112
Flash Point	Pensky-martens NPM 440	Norma lab, France	ASTM D93
Cloud and Pour point	Cloud and Pour point tester NTE 450	Norma lab, France	ASTM D2500, ASTM D97
Cold filter plugging point	Cold filter plugging point tester NTL 450	Norma lab, France	ASTM D6371
Calorific value	C2000 basic calorimeter	IKA, UK	ASTM D240
Viscosity index	SVM 3000	Anton Paar, UK	N/A
Transmission and absorbance	Spekol 1500	Analytical Jena, Germany	N/A
Refractive index	RM 40 Refractometer	Mettler Toledo, Switzerland	N/A



CAPO was heated at 60 °C

CAPO was mixed with methanol (molar ratio of 24:1 methanol to CAPO) and 1% (v/v oil) of HCL and stirred constantly at a speed of 600 rpm for 3 h at 60 °C

The esterified oil was entered into a separation funnel to remove the upper layer of methanol from the lower layer of the esterified CAPO and extra methanol

The lower layer was entered into a control rotary evaporator and heated at 80 °C under vacuum condition to remove methanol and water from the esterified oil

The esterified oil was heated to 60 °C. 1% (m/m oil) of KOH was diluted in methanol (molar ratio of 6:1) and then added to the preheated oil

This reaction was maintained at 60 °C for 2 h and 600 rpm stirring speed

The product was placed in a separation funnel and left for 24 h to remove the upper layer of biodiesel (APME) and methanol from glycerol at lower layer

APME was washed several times with warm distilled water 50% (v/v oil) at 60 °C to remove the entrained impurities and glycerol

Vacuum distillation was carried out to remove water

APME was further dried using sodium sulphate (Na_2SO_4) in a glass beaker

Finally, APME was filtered using qualitative filter paper to obtain the final good quality product which is ready for analysis

Fig. 2. Flow chart of biodiesel production from CAPO.

2.5. Gas chromatography method

The fatty acid composition (FAC) of APME was determined using a GC setup (Shidmadzu, Japan) equipped with a flame ionization detector, and compared with other feedstocks such as JCME, CIME, PME, SME and CME. Table 2 shows the GC operating conditions.

Table 2
GC operating conditions.

Property	Specifications
Carrier gas	Helium
Linear velocity	24.4 cm/sec
Flow rate	1.10 mL/min (column flow)
Detector temperature	260.0 °C
Column head pressure	56.9 kPa
Column dimension	BPX 70, 30.0 m × 0.25 μm × 0.32 mm ID
Injector column oven	240.0 °C
Temperature ramp	140.0 °C (hold for 2 min)
	8 °C/min 165.0 °C
	3 °C/min 192.0 °C
	8 °C/min 220.0 °C (hold for 5 min)

2.6. Biodiesel–diesel blending

APME was blended with diesel at 5%, 10%, 20%, 30%, 40%, 60%, and 80% by volume, using a magnetic stirrer (IKA C-MAG HS 7) at 2000 rpm for 30 min and a shaker (IKA KS 130 basic) at 400 rpm for 30 min.

Table 3
Detailed technical specification of the tested engine.

Parameter	Specification
Type	Four cylinder IDI diesel engine
Displacement (L)	2.5
Cylinder bore × stroke (mm)	92 × 96
Compression ratio	21:1
Maximum engine speed (rpm)	4200
Fuel system	Distribution type jet pump
Lubrication system	Pressure feed
Combustion chamber	Swirl type
Cooling system	Radiator cooling

2.7. Engine tests

The engine testing was carried out on a 2.5 L turbocharged four-cylinder indirect injection (IDI) diesel engine. The detail of the engine is described in Table 3. The test engine was directly coupled to Froude Hofman AG250 eddy current dynamometer. Engine oil, cooling water, exhaust gas and inlet air temperatures were measured using K type thermocouples. Fuel flow was measured using KOBOLD ZOD positive-displacement type flow meter. REO-dCA Data Acquisition System collects the data. A flow diagram of the engine test bed is shown in Fig 3. To allow rapid switching between fuels, the engine fuel system was modified by adding separate tanks with two way valve. The exhaust gas emissions CO, CO_2, HC, and NO emissions were measured by gas analyzer (BOSCH BEA350). The CO, CO_2 and HC measuring instrument uses the non-dispersive infrared (NDIR) detectors and the NO analyzer uses electrochemical detectors. Details of the exhaust gas measurement are shown in Table 4.

To carry out tests using biodiesel blends, steady operating condition was first attained by running engine with diesel. Then fuel was changed to a biodiesel blend. The engine was run for 10 min to ensure the removal of residual diesel in the fuel line. After that the data acquisition was started. After each test engine was again run with diesel to drain out all the blends in the fuel line. This procedure was followed for all the blends. The test fuels were diesel, 95% diesel and 5% biodiesel (B5), and 10% biodiesel and 90% diesel (B10) blends. Test fuels were blended using a homogenizer device at a speed of 3000 rpm for 10 min. The engine was operated between 1000 rpm and 4500 rpm with a step of 500 rpm at 100% load condition. The performance and emission measurements were repeated more than 10 times to carry out Student's t-test. Statistical analysis was carried out by applying two-sided Student's t-test for independent variables to test for significant differences between samples set means using Microsoft Excel 2013. Differences between mean values at a level of $p = 0.05$ (95% confidence level) were considered statistically significant.

Table 4
Specifications of the exhaust gas analyzer (BOSCH BEA350).

Measurement	Measurement range	Accuracy	Percentage uncertainties
CO	0–10.00 vol.%	±0.01 vol.%	±0.20
CO_2	0–18.00 vol.%	±0.001 vol.%	±0.16
HC	0–9999 ppm	±1 ppm	±0.50
NO	0–5000 ppm	±1 ppm	±0.50

3. Results and discussion

3.1. Characterization of CAPO

Table 5 shows the physicochemical properties of CAPO. In this table, a comparison with other crude oils such as *Jatropha curcas* oil (CJCO), *Calophyllum inophyllum* oil (CCIO), palm oil (CPaO), canola oil (CCaO) and soybean oil (CSO) is presented.

3.2. Fatty acid composition and characterization of APME

The FAC of APME, and a comparison with the FAC of different methyl esters e.g. *Jatropha curcas* (JCME), *Calophyllum inophyllum* (CIME), palm (PaME), canola (CaME) and soybean (SME), is shown in Table 6. It is observed that APME is mainly comprised of oleic acid (18.3%), linoleic acid (26.7%) and linolenic acid (23.3%), while PaME mainly consists of Palmitic acid (42.8%) and Oleic acid (40.5%). CIME and JCME are dominated by oleic acid (34.09% and 44.6%, respectively) and linoleic acid (38.26% and 31.9%, respectively). The saturated fatty acid content of APME is 30.7%, while it is 48.4% for PaME, 22.7% for JCME and 24.96% for CIME, respectively. In general, APME shows a trend comparable to that of CIME and JCME. Therefore, it can be understood that non-edible biodiesel feedstock's exhibit similar fatty acid compositions.

The significant physicochemical properties of APME were studied and compared with those of PaME, SME, CaME, JCME, CIME, and the ASTM D6751 standard specification. The detailed physicochemical properties are shown in Table 7.

3.3. Physicochemical properties of APME-diesel blends

In this paper, the properties of B5, B10, B20, B40, B60, and B80 blends were determined and compared with the ASTM D7467 standard. In addition Table 8 shows the physicochemical properties of diesel, APME, and APME-diesel blends.

3.4. Engine performance

Biodiesel comprises of high molecular weight fatty acids of varying carbon chain length and number of double bonds along

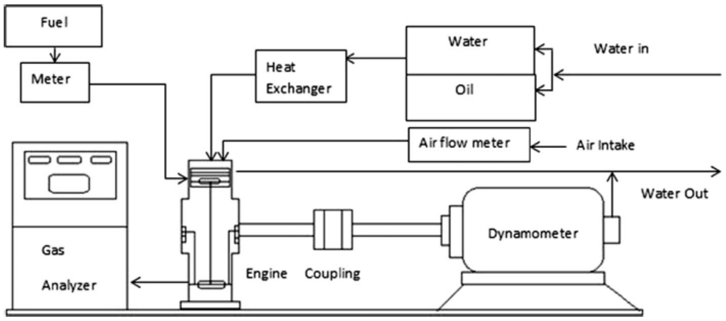


Fig. 3. Flow diagram of engine test bed.

Table 5
Properties of CAPO.

Property	Unit	CAPO	CJCO[a]	CCIO[a]	CPaO[a]	CCaO[a]	CSO[a]
Kinematic viscosity at 40 °C	mm^2/s	35.093	48.091	55.677	41.932	35.706	31.739
Kinematic viscosity at 100 °C	mm^2/s	7.2547	9.1039	9.5608	8.496	8.5180	7.6295
Dynamic viscosity at 40 °C	mPa s	32.159	43.543	51.311	37.731	32.286	28.796
Viscosity Index (VI)	–	177.9	174.10	165.4	185.0	213.5	223.2
Cloud point (CP)	°C	5	–	–	–	–	–
Pour point (PP)	°C	4	–	–	–	–	–
Density at 40 °C	kg/m^3	916.4	–	–	899.8	904.2	907.3
Density at 15 °C	kg/m^3	934	915	951	–	–	–
Calorific value	kJ/kg	38,729	38,961	38,511	39,867	39,751	39,579
Oxidation stability	h at 110 °C	0.09	0.32	0.23	0.08	5.64	6.09
Acid value	mgKOH/g	26.7	17.63	41.74	N/D	N/D	N/D
Refractive index	–	1.4789	1.4652	1.4784	1.4642	1.471	1.471
Transmission	%	61.6	61.8	34.7	63.2	62.9	65.2
Absorbance	Abs	0.209	0.209	0.46	0.199	0.202	0.186

[a] Data taken from Ref. [12].

Table 6
FAC of APME and comparison with other methyl esters (wt.%).

No	Fatty acid	Molecular weight	Structure	Systematic name	Formula	APME	JCME[a]	CIME[b]	PaME[c]	CaME[c]	SME[c]
1	Caprylic	144	8:0	Octanoic	$C_8H_{16}O_2$	N/D	N/D	N/D	N/D	N/D	N/D
2	Capric	172	10:0	Decanoic	$C_{10}H_{20}O_2$	N/D	N/D	N/D	N/D	N/D	N/D
3	Lauric	200	12:0	Dodecanoic	$C_{12}H_{24}O_2$	N/D	0.1	N/D	0.1	N/D	0.1
4	Myristic	228	14:0	Tetradecanoic	$C_{14}H_{28}O_2$	N/D	0.1	N/D	1.0	N/D	0.1
5	Palmitic	256	16:0	Hexadecanoic	$C_{16}H_{32}O_2$	18.4	14.6	12.01	42.8	3.5	10.2
6	Palmitoleic	254	16.1	hexadec-9-enoic	$C_{16}H_{30}O_2$	0.3	0.6	N/D	N/D	N/D	N/D
7	Stearic	284	18:0	Octadecanoic	$C_{18}H_{36}O_2$	11.8	7.6	12.95	4.5	0.9	3.7
8	Oleic	282	18:1	cis-9-Octadecenoic	$C_{18}H_{34}O_2$	18.3	44.6	34.09	40.5	64.1	22.8
9	Linoleic	280	18:2	cis-9-cis-12 Octadecadienoic	$C_{18}H_{32}O_2$	26.7	31.9	38.26	10.1	22.3	53.7
10	Linolenic	278	18:3	cis-9-cis-12	$C_{18}H_{30}O_2$	23.2	0.3	0.3	0.2	8.2	8.6
11	Arachidic	312	20:0	Eicosanoic	$C_{20}H_{40}O_2$	0.5	0.3	N/D	N/D	N/D	0.3
12	Gondoic	310	20:1	11-Eicosenoic	$C_{20}H_{38}O_2$	0.2	N/D	N/D	N/D	N/D	N/D
13	Behenic	340	22:0	Docosanoic acid	$C_{22}H_{44}O_2$	N/D	N/D	N/D	N/D	N/D	0.1
14	Erucic	339	22:1	(Z)-Docos-13-enoic acid	$C_{22}H_{42}O_2$	0.6	N/D	N/D	N/D	N/D	N/D
Saturated						30.7	22.7	24.96	48.4	4.4	14.5
Monounsaturated						19.4	45.2	34.09	40.5	64.1	22.8
Polyunsaturated						49.9	32.2	38.56	10.3	30.5	62.3
Total						100	100	97.61	99.2	99.0	99.6

[a] Data taken from Ref. [13].
[b] Data taken from Ref. [14].
[c] Data taken from Ref. [15].

Table 7
Physicochemical properties of APME.

Property	Unit	APME	JCME[a]	CIME[a]	PaME[a]	CaME[a]	SME[a]	ASTM D6751
Kinematic viscosity at 40 °C	mm^2/s	4.7177	4.9476	5.5377	4.6889	4.5281	4.3745	1.9–6.0
Kinematic viscosity at 100 °C	mm^2/s	1.8239	1.8557	1.998	1.7921	1.7864	1.764	N/A
Dynamic viscosity at 40 °C	mPa s	4.1210	4.2758	4.8599	4.0284	3.9212	3.8014	N/A
Viscosity Index (VI)	–	220.7	194.6	183.2	203.6	236.9	257.8	N/A
Cloud point (CP)	°C	8	10	12	16	−3	1	Report
Pour point (PP)	°C	8	10	13	15	−9	1	Report
Cold filter plugging point(CFPP)	°C	5	10	11	12	−10	−3	Report
Density at 40 °C	kg/m^3	873.5	864.2	877.6	859.1	866	869	–
Density at 15 °C	kg/m^3	893	–	–	–	–	–	–
Specific gravity (f/t) at 15 °C	–	0.8938	–	–	0.873	–	0.882	0.86
Flash point	°C	188.5	186.5	–	214.5	186.5	202.5	130 (min)
Acid value	mg KOH/goil	0.448	–	–	0.24	–	0.266	0.80 (max)
Calorific value	kJ/kg	39,960	39,738	39,513	40,009	40,195	39,760	N/A
Oxidation stability	h at 110 °C	0.16	4.84	6.12	23.56	7.08	4.08	3 h (min)
Cetane number	–	44	–	–	54.6	–	37.9	47 (min)
Iodine value	g I/100 g	129.4	–	–	54	–	128–143	120 (max)
Saponification number	–	202.9	–	–	–	–	–	–
Refractive Index (RI) at 25 °C	N/A	1.4583	1.4513	1.4574	1.4468	1.4544	1.4553	–
Transmission at WL 656.1	%T	82.0	90.3	87.7	89.1	91.1	92	–
Absorbance at WL 656.1	Abs	0.086	0.045	0.057	0.05	0.041	0.037	–

[a] Data taken from Ref. [12].

Table 8
Physicochemical properties of diesel, APME and APME-diesel blends.

Property	Unit	Diesel	B5	B10	B20	B40	B60	B80	B100	ASTM D7467
Kinematic viscosity at 40 °C	mm^2/s	3.3920	3.4673	3.5357	3.656	3.9602	4.1599	4.4139	4.7177	1.9–4.1
Kinematic viscosity at 100 °C	mm^2/s	1.3240	1.3479	1.368	1.4029	1.511	1.6066	1.712	1.8239	N/A
Dynamic viscosity at 40 °C	mPa.s	2.8148	2.8851	2.9501	3.0663	3.3577	3.5632	3.8185	4.121	N/A
Density at 40 °C	kg/m^3	829.8	832.1	834.4	838.7	847.9	856.6	865.1	873.5	N/A
Density at 15 °C	kg/m^3	847.1	849.4	852.1	856	865.3	874.2	883	893	N/A
Specific gravity at 15 °C	N/A	0.8479	0.8502	0.8529	0.8568	0.8661	0.875	0.8838	0.8938	N/A
Viscosity Index (VI)	N/A	116.9	122.8	132.2	138.4	150.4	184.8	208.7	220.7	N/A
Cloud point (CP)	°C	−4	−4	−3	−3	0	2	5	8	Report
Pour Point (PP)	°C	−4	−3	−3	−2	1	3	4	8	Report
Cold filter plugging point	°C	−7	−4	−3	−3	−3	−1	2	5	Report
Flash point	°C	84.5	84.5	85.5	86.5	91.5	98.5	118.5	188.5	52 min
Calorific value	kJ/kg	45,389	44,995	44,702	43,252	42,892	41,739	40,656	39,960	N/A
Oxidation stability	h at 110 °C	N/D	–	–	–	3.4	2.43	0.4	0.16	6 (min)
Acid value	mgKOH/g oil	0.1120	0.1611	0.2242	0.2804	0.2804	0.3366	0.3916	0.448	0.3 (max)

with substantial amounts of oxygen in their structure [16]. *A. polystachya* oil contains mostly long chain unsaturated fatty acids, presence of which leads to a high density, kinematic viscosity and CN [17]. On the other hand the oxygen content of biodiesel results in a reduced calorific value i.e. the energy content of the fuel. Thus, due to these inherent attributes, APME has a significant effect on engine performance as well as emissions. Engine tests were carried out to enumerate the effects of APME blends on brake torque, BP, and BSFC etc.

3.4.1. Brake torque

Fig. 4 shows the variation of the engine torque at full load condition and different engine speeds when fueled by diesel, APME5, and APME10. It has been observed that the torque for blends APME5 and APME10 was lower than that for diesel. These results are in agreement with the earlier literature [18,19]. It can be observed that, the trends for both biodiesel blends are almost similar to neat diesel fuel. Initially, engine torque increases as the engine speed increases until it reaches a maximum value and then starts decreasing with further increasing engine speed. At low speeds of the engine, because of lower vacuum of the cylinder and because of lower vaporization, the air-fuel ratio remain richer and resulting incomplete combustion which results in lower brake torque [20]. At higher speeds. the decrease can be attributed to two main factors; firstly, lower volumetric efficiency of the engine due to the increase in engine speed, and secondly, the augmentation in the mechanical losses [21]. Over the whole speed range, the average torque values for diesel, APME5, and APME10 were found to be 146 Nm, 144.50 Nm, and 143 Nm, respectively. Thus, for the same amount of fuel injected, APME5 and APME10 gave an average reduction in torque of 0.9% and 1.81%, respectively, compared to pure diesel. These changes were significant at $p < 0.02$. This torque loss can be attributed to the lower heating value and higher density and kinematic viscosity compared to diesel fuel [22,23]. Higher kinematic viscosity and density of blends thereby lower volatility of blends and hence result in a poor mixture formation and lower brake torque output.

3.4.2. Brake power (BP)

Fig. 5 shows the variation of BP of diesel, APME5, and APME10 at full load condition and different engine speeds. In general, biodiesel blends produce lower brake power compared to pure diesel fuel. Among the two biodiesel blends, it was found that APME5 had the highest and lowest BP values overall; a maximum BP value of 55.16 kW at 4000 rpm, and a minimum BP value of 12.91 kW at 1000 rpm. APME10 had a maximum BP value of 54.28 kW at 4000 rpm, and a minimum BP value of 12.97 kW at 1000 rpm. It was also observed that the BP gradually increased with increasing engine speed up to 4000 rpm and then decreased. In addition, the BP decreased with an increasing percentage of biodiesel in the blend. Over the entire speed range, the average BP for diesel, APME5, and APME10 were 40.5 kW, 40 kW, and 39.5 kW, respectively. The average reduction of BP compared to diesel for APME5 and APME10 was 0.9% and 2.1%, respectively. These changes were significant at $p < 0.04$. This reduction can be attributed to their lower calorific value and higher viscosity compared to diesel fuel [20]. Higher viscosity results in higher resistance in the fuel line

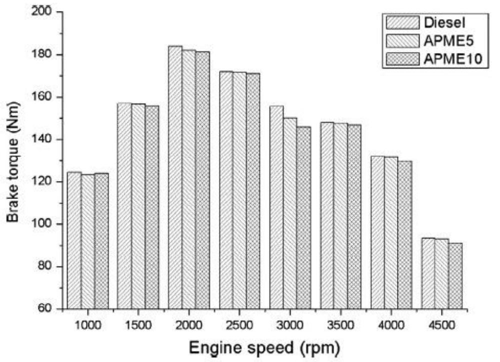


Fig. 4. Variation of torque at different engine speeds and full load condition.

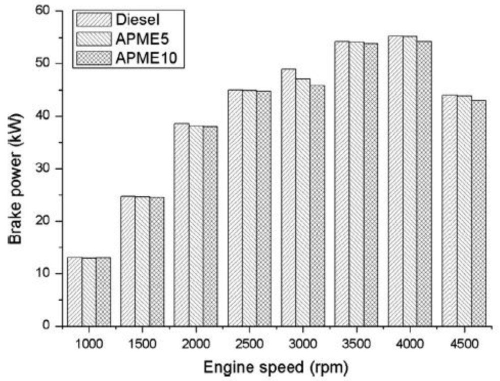


Fig. 5. Variation of brake power at different engine speeds and full load condition.

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