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Biodiesel production from *Pongamia pinnata* – A versatile resource for bioenergy production in Indian scenario for carbon neutrality

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In this study the versatility of Pongamia pinnata fruit as a sustainable resource for biodiesel production has been highlighted as a reliable substitute to the diminishing and polluting diesel fuel. Botanical features of Pongamia have been studied and its relevance in Indian context as an excellent non-edible resource for biodiesel production with an oil potential of 55000-135000 tonnes per annum has been analysed. Base-catalysed (single stage) transesterification process is adopted for the production of biodiesel and the parameters affecting the process have been outlined. The physicochemical properties of the produced biodiesel such as acid value (0.436 mg KOH/g), density (872 kg/m^3), kinematic viscosity (5.3 cSt), calorific value (38.2 MJ/kg) were experimentally evaluated. Gas chromatography analysis was conducted to identify the fatty acid methyl ester composition of the biodiesel produced. Properties such as cetane number, saponification number, iodine value, cloud point and pour point have been empirically evaluated. All the investigated properties successfully complied with the ASTM standards indicating the satisfactory quality of biodiesel and the aptness of Pongamia oil as a feedstock. Further, the carbon neutrality aspects of Pongamia as a bioenergy source are highlighted.

Keywords: Biodiesel, Bioenergy, Pongamia pinnata, Transesterification, Carbon neutrality

1 Introduction

Diminishing supply and increasing cost of diesel fuel has led to exploration of renewable sources of energy. Diesel is currently a major energy source, as it is widely used in agricultural operations, electricity generation and transportation systems.

India has to import a substantial fraction of the crude oil that is utilized in the country. In 2021–2022, India imported 212.4 MMT of crude oil valued at Rs. 9,01,262 crore (~USD 108.5 Billion) [1]. While the domestic production of crude oil in India was only 26.69 MMT in 2021–22. The consumption of diesel in India in in 2021–22 was 76.69 MT for high-speed diesel oil and 1.02 MT for low-speed diesel oil, around 90% of which was imported[1]. Therefore, it is imperative to explore locally produced, sustainable and environment-friendly fuel that can provide clean energy transition, reduce import costs and greenhouse gas emissions [2,3]. To this end, Biodiesel produced from biomass is seen as a non-toxic, sustainable and environmentally beneficial substitute to diesel [4,5]. It exhibitsnumerous advantages over diesel such as relatively less hazardous to environment, greater cetane number and oxygen content, sulphur free, higher flash point enabling easy storage and lesser HC and CO emissions, making it an environmentally benign fuel [6].

Biodiesel is derived from natural resources like vegetable oils, fats etc. [7]. When diesel engines came into existence, they were primarily fuelled by vegetable oils, but oils posed difficulty in operation because of their high viscosity. Direct utilization of vegetable oil in engine leads to problems of formation of engine deposits, injector choking causing poor atomization of fuel and inefficient combustion[8].This mandates decreasing the viscosity of vegetable oils for their usage as alternative fuels in engines. Currently, a large proportion of biodiesel is being made from edible oils such as palm, sunflower, rapeseed, soybean etc. [3,9]. However, using edible oils for the production of biodiesel has propelled the 'food versus fuel' debate as there is a demand supply gap between the current availability of edible oils for human consumption. Nonedible oils derived from species such as Pongamia, Jatropha, Shorea robusta, Azadirachta indica and

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Simarouba glauca are sustainable and promising substrates for biodiesel production amidst food security concerns, cost factor and their capability to grow on marginal lands[10].

The present study focusses on the importance of Pongamia in India as a versatile resource for energy and particularly biodiesel. It explores Pongamia species by presenting its botanical profile, and underlining its relevance in Indian context. The paper further discusses biodiesel production process using Pongamia oil and its characterisation based on experimental and empirical analysis. This will promote complete use of Pongamia fruit for bioenergy generation and enhance its value as an energy resource, thus, leading to a reduction in the imports of conventional diesel fuel. The paper also highlights the carbon neutrality aspects of Pongamia.

1.1 Pongamia pinnata as a biodiesel feedstock and its relevance in Indian context

Pongamia pinnata investigated in the present study is a prominent, native, nonedible oil producing feedstock in India for the production of biodiesel due to its high productivity, short maturity cycle and wide availability in different parts of the country[10]. Several studies have estimated the Pongamia oil potential in India in the range of 55000-135000 tonnes/year [2,11,12]. Oil content in seeds reported by different authors is in the range of 25 to 40% [13–16]. The Pongamia oil yield is estimated as 2.0-4.0 tonnes per hectare per year [2].

For generation of 1GJ energy approximately 26.18 kg of Pongamia biodiesel would be required based on the investigated calorific value of biodiesel in this study, i.e., 38.2 MJ. Therefore, with a Pongamia oil generation potential of 55,000-1,35,000 tonnes per annum, India can generate around 21,01,000 GJ/year - 51,57,000 GJ/year bioenergy from Pongamia as a feedstock. Considering a calorific value of 44 MJ/kg for diesel, based on author's assessment, this may result in an annual saving of around 47,750 – 1,17,204.5 tonnes of fossil diesel.

Additionally, its capability to grow on marginal lands which can't be used for farming of food crops and its utilization being greenhouse gas neutral, with a possible decrease in engine emissions enhances its viability in the Indian context[17]. These advantages have made Pongamia an extensively researched material [11,18–21]. Further, a unique aspect of Pongamia which makes it even more attractive species is the prospect of its various fruit parts being used for bioenergy generation through appropriate technologies.

1.2 Versatility of Pongamia Pinnata

Pongamia seeds till now have been focused for oil extraction to produce biodiesel which leads to partial utilisation of Pongamia fruit as a bioenergy resource. However, to make biodiesel an economically feasible substitute to diesel, consuming only the oil for biodiesel production and rendering huge amount of unutilized biomass in the form of Pongamia de-oiled seedcake and shells of the fruit does not suffice.

It is estimated that the current approach uses only 17.5% of the Pongamia fruit (on mass basis) in the form of its oil and the remaining fruit parts namely the shell and de-oiled seed cake remain unutilised. This is because the shell occupies approximately 50% of the total fruit mass and remaining 50% is the seed. Considering 35% of oil extraction from seed, remaining de-oiled seed cake will occupy the rest 32.5% of the total fruit mass. Energy value of the ignored biomass i.e., Pongamia shells (15 MJ/kg) and de-oiled seed cake (19 MJ/kg) indicates that only 30% of the energy embodied in the Pongamia fruit is being derived in the form of biodiesel (38 MJ/kg) showing that the energy value of the ignored biomass (i.e. 82.5% by mass) is significantly high at 70%. Thus, the potential utilization of the shells and de-oiled seedcake when Pongamia is being considered for bioenergy makes it a versatile resource. Pongamia de-oiled seed cake has been investigated for biogas production. Its average specific biogas yield was found to be 0.738 Nm^3/kg VS with 62.5% methane content for a retention period of 30 days [22].

2 Materials and Methods

2.1 Botanical profile of the selected feedstock material - Pongamia pinnata

Pongamia pinnata (Linn) Pierre, selected in the present study is a member of the subfamily Fabaceae (Papilionaceae) of family Leguminaceae[23,24]. It is native to humid subtropical climates of the Indian sub-continent and has been introduced to the humid tropical regions of New Zealand, Australia, Indonesia, Malaysia, China and the USA[11]. It grows widely in more than 15 Indian states and is abundantly found in the states of Maharashtra, Andhra Pradesh, Gujarat, Karnataka, Chhattisgarh and Uttar Pradesh [25].

Fig. 1 — Visuals of Pongamia pinnata tree, pods and seeds, respectively.

Pongamia is a fast-growing, medium-sized (15 - 25 meters tall), drought resistant and nitrogen-fixing leguminous tree [26]. It grows well in areas having a temperature range of 27 - 38°C, annual rainfall of 500 - 2500 mm and altitudes ranging from 0-1,200 m [16]. Its natural distribution occurs along coasts and riverbanks and is also planted along road sides, open farm lands and canal banks.

Various parts of Pongamia tree have been conventionally used for green manure, animal fodder, medicine, timber, fish poison and fuel for lighting lamps[27]. It is a preferred species as a shade and ornamental tree with the ability to control soil erosion.

Pods are brown in colour as shown in Fig. 1, generally elliptical (3-7 cm long) and usually containing a single seed. Annual yield of seeds has been stated to be in the range of 10-50 kg/tree [14]. Pongamia seeds oil content lies between 30-40 % and the oil is yellowish-orange to reddish-brown in colour[15]It is used as a pesticide, lubricant, in tanning and soap making industries and it also has therapeutic value for the healing of rheumatism and other skin diseases [28]. Crude Pongamia oil tastes bitter and is reported to contain furanoflavonols, furanoflavones, flavones, chromenoflavones, and furanodiketones which makes the oil non-edible [29]. Pongamia seeds can be stored easily for a year in air-tight containers [30].

2.2. Transesterification process for biodiesel production

Biodiesel consists of mono-alkyl esters of long-chain fatty acids and can be produced from transesterification process [12].Transesterification is the reaction between triglycerides and alcohol (methanol, ethanol etc.) in the presence of a catalyst (bases: NaOH, KOH, etc.; Acids: H_2SO_4, HCl etc.) to yield biodiesel and valuable by-product glycerol [31]as shown in Fig. 2. Transesterification greatly decreases oil's viscosity and other main parameters such as acid value enabling successful engine operation [32]. Molar ratio of alcohol to oil, type and amount of catalyst and alcohol, time and temperature of reaction are the major factors affecting transesterification [33,34]. Oils with less than 5% free fatty acids (FFA) content can undergo base-catalysed transesterification without any need of pre-treatment [23]. For higher FFA content, acid-catalysed transesterification needs to be adopted, else the FFA's in oil will react with basic catalyst forming soap and inhibiting the production of methyl esters [35]. However, it is a time taking process and demands greater use of alcohol and catalyst, making it less preferable. Therefore, base-catalysed transesterification is awidely adopted commercial procedure for biodiesel production worldwide [36].

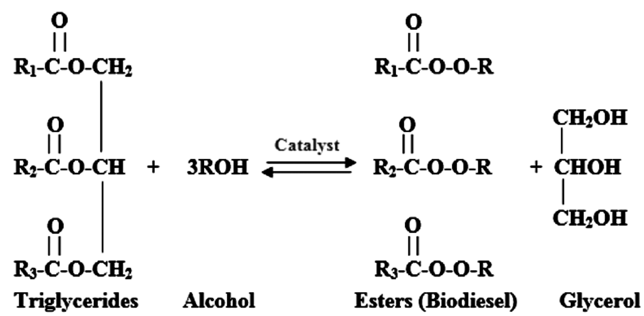

Fig. 2 — Transesterification reaction of a triglyceride.

2.3 Biodiesel production from Pongamia oil using Transesterification process

2.3.1 Experimental procedure for biodiesel production from Pongamia oil

The experiments were conducted in a 500 mL capacity round-bottomed flask kept on a magnetic stirrer with temperature and stirring speed control. The apparatus and chemicals required in the process are listed in Table 1.

The reactor setup consisted of a reflux condenser, inlet and outlet ports, stirrer and a digital temperature controller cum indicator, as shown in Fig. 3. The flask was submerged in a water bath having temperature control. In one of the side necks, a reflux condenser was installed and on the other side neck, a thermometer was inserted to check the temperature inside the reactor. Agitation in the reaction mixture was carried through a stirrer, passing from the central neck and connected to a motor having speed regulator to control the stirrer speed.

Transesterification is a reversible reaction and stoichiometrically a molar ratio of 3:1 of alcohol to triglycerides is needed, but to shift reaction equilibrium towards product side excess of alcohol, in a ratio of 6:1 is generally used [12,37,38]. A strong catalyst (base/acid) is required in transesterification to accelerate its rate of reaction. The concentration of oil, alcohol and catalyst and the time of reaction for the experimentation were adopted as described in the literature [38,39]. 250 mL oil was poured into the round-bottomed flask. 2.5 g NaOH (catalyst) was added at 1% (w/w of oil). 70 mL methanol (alcohol) was used at a concentration of 28% (v/v of oil). NaOH was premixed with methanol in a beaker. The beaker was heated to 40°C and left for some time to settle so that the NaOH could dissolve in methanol forming sodium methoxide. Contents of the beaker were then moved to the flask having Pongamia oil.

Table 1 — Apparatus and materials used in experimentation

S. No.	Apparatus	S. No.	Materials Required
1	Round bottom flask	1	Feedstock: Pongamia oil
2	Reflux Condenser	2	Alcohol: Methanol Neutral alcohol: Ethyl alcohol
3	Temperature controller and indicator	3	Catalyst: Sodium hydroxide (NaOH)
4	Stirring system	4	Indicator: Phenolphthalein
5	Separating funnel	5	Anhydrous sodium sulphate (Na_2SO_4)

From here, the system was completely sealed from the atmosphere to avoid any loss of alcohols and absorption of moisture. The reaction was carried out at 60°C, which is close to methanol boiling point i.e. 65°C and at 400 RPM stirrer speed. Mixing is necessary as oil and methanol are immiscible. To avoid loss of methanol due to evaporation a reflux condenser was used. Reaction time was kept as 120 minutes.

2.3.2 Biodiesel and glycerol separation

After reaction completion, a mixture was obtained in the reactor consisting of two main products, biodiesel and glycerol. This mixture was then shifted to a separating funnel and allowed to settle overnight. Two separate layers were formed, upper being the biodiesel and lower being the denser glycerol. The glycerol which settled down due to gravity was taken out from the bottom of the separating funnel. Fig. 4 shows the separated layers of biodiesel and darker glycerol at the top and bottom of the funnel, respectively.

2.3.3 Methyl ester water washing

After separation, to remove any traces of impurities present in biodiesel in the form of residual catalyst, soaps or methanol, it was washed with lukewarm distilled water, gently shaken, and permitted to settle for 15 minutes. This process was reiterated 3 to 4 times until the lower water layer in the separating funnel became transparent showing that the impurities

Fig. 3 — Round bottom flask reactors used for biodiesel production.

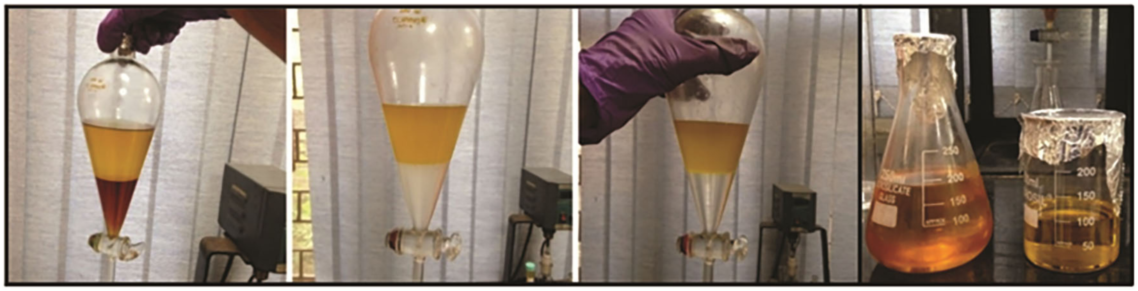

Fig. 4 — Biodiesel separation and washing.

have been removed and the biodiesel was now purified.

2.3.4 Drying of biodiesel

To ensure that the biodiesel does not have any moisture remaining in it as it can be detrimental to engine parts biodiesel was slowly passed over anhydrous sodium sulphate (Na_2SO_4) to remove all the moisture present. The clear yellow liquid gotten was biodiesel, i.e., the methyl ester of Pongamia oil.

2.4 Experimental analysis of the biodiesel produced

After completion of the biodiesel production process, basic properties of purified biodiesel such as viscosity, acid value, calorific value and esters quantification using gas chromatography were experimentally evaluated to govern its quality.

2.4.1 Acid value

Acid value (AV), is the mass of potassium hydroxide (KOH) in mg needed to neutralize the free fatty acids present in one gram of the chemical substance (oil/biodiesel) and is denoted in mg KOH/g. To calculate the acid value, ethyl alcohol was used as neutral alcohol and phenolphthalein was used as an indicator. AV was estimated using the following equations:

$$AV = \frac{V * N * 56.1}{W} \quad \text{... (1)}$$

$$FFA = 0.503\, AV \quad \text{... (2)}$$

Where,

V= volume of KOH used, mL; N= Normality of KOH, value; W= weight of the sample, g,

FFA = Free fatty acid content, %

2.4.2 Kinematic viscosity of biodiesel

The resistance to flow of a fluid under gravity is known as kinematic viscosity. The viscosity of biodiesel was analysed using an Anton Paar make viscometer having a temperature range of 0^oC to 180^oC for measuring viscosity. The viscosity value was obtained from the viscometer and knowing the density the kinematic viscosity of biodiesel was calculated.

$$\nu = \frac{\mu}{\rho} \times 10^6 \quad \text{... (3)}$$

Where,

ν = kinematic viscosity of sample, cSt; μ = Viscosity of the sample, cP ;ρ = Density of the sample, kg/m^3

2.4.3 Determination of density

Density indicates the compactness of the matter within a substance and is denoted in kg/m^3. An electronic weighing balance was used for mass measurement and a 100 mL measuring cylinder was used for volume measurement of the sample. To evaluate the density of the sample (oil/biodiesel) following formula was used:

$$\rho = \frac{W_1 - W_2}{V} * 1000 \quad \text{... (4)}$$

Where,

ρ = Density of the sample, kg/m^3; W_1 = Mass of the cylinder and the sample, g; W_2 = Mass of the empty cylinder, g; V = Volume of the sample, mL

2.4.4 Determination of calorific value

Calorific value is the amount of heat released on complete combustion of a quantified mass of fuel sample in a calorimeter under specified conditions. It is indicated in kJ/kg or kJ/m^3. Bomb Calorimeter was used to combust the biodiesel sample at a constant volume in a completely closed container in the presence of oxygen at high pressure. Calorific value of the produced biodiesel was evaluated using Eq. 5:

$$H_{comb} = \left[\frac{W_{eq} \times \Delta T}{M_{samp}}\right] \quad \text{... (5)}$$

Where,

H_{comb} = Heat of combustion of the selected seed samples, MJ/kg; W_{eq}= Water equivalent of the calorimeter assembly, MJ/ °C; ΔT = Increase in temperature, °C; M_{samp}= Mass of biodiesel combusted, kg.

2.5 Empirical analysis of the biodiesel produced

Properties such as pour point, cloud point, iodine value, saponification number and cetane number were assessed empirically to analyse the quality of biodiesel.

2.5.1 Determination of saponification number of biodiesel

Saponification number (SN) or value is the indication of the nature (molecular weight) of fatty acids present in the biodiesel. It corresponds to the number of milligrams of KOH needed to neutralize the FFAs and saponify the esters present in 1 gram of material. It can be estimated using the following relation [9]:

$$SN = \Sigma \frac{(560 \times Pi)}{MWi} \quad \ldots (6)$$

Where,

Pi is the fatty acid percentage composition; MWi is the molecular mass and i represents the respective fatty acid in biodiesel.

2.5.2 Determination of iodine value of biodiesel

Iodine Value (IV) is the measure of unsaturation of oils and their fatty acid derivatives. It mainly depends upon the percentage composition of the unsaturated fatty acid constituents and the number of double bonds existing in the molecular structure. It can be estimated using Eq. 7 [9].

$$IV = \Sigma \frac{(254 \times B \times Pi)}{MWi} \quad \ldots (7)$$

Where,

B is the number of double bonds and the other notations are as defined in section 2.5.1.

2.5.3 Determination of cetane number of biodiesel

Cetane number of a fuel indicates the time delay between the start of injection and the point of fuel injection. It is affected by the molecular composition and structure in terms of the degree of unsaturation, chain length, and the position of double bond. Most of the biodiesel fuels from different oils usually have a higher cetane number than the diesel fuel. In the present study cetane number has been estimated using the following correlation [13]:

$$CN = 46.3 + \frac{5458}{SN} - (0.225 \times IV) \quad \ldots (8)$$

Where,

CN is the cetane number the other notations are as defined in section 2.5.1 and 2.5.2.

2.5.4 Determination of cloud point and Pour Point of biodiesel

Cloud point (CP) of a fuel is defined as the temperature at which the first crystal is detected and starts forming a hazy or cloudy suspension. Pour point (PP) is the temperature at which the fuel ceases to flow. The existence of higher amount of saturated fatty acid components in biodiesel increases its cloud point and pour point. CP and PP of biodiesel can be assessed by using the following relation [40].

$$CP = -0.576 \times U + 48.255 \quad \ldots (9)$$

$$PP = -0.626 \times U + 45.594 \quad \ldots (10)$$

Where, U is the content of total unsaturated fatty acid methyl esters in biodiesel.

3 Results and Discussions

The commonly reported molar ratio of 6:1 for methanol-to-oil and catalyst (NaOH) amount of 1%, were used in our experiments with a reaction time of two hours at 60°C, and it lead to the successful conversion of Pongamia oil into biodiesel as evident from the values achieved which were within the specified range of ASTM D6751.

3.1 Experimental analysis

Table 2 shows the results from experimental and empirical analysis of the biodiesel produced from Pongamia in this study. Density which is an important

Table 2 — Properties of tested biodiesel sample

Biodiesel property	Unit	Experimental Value	ASTM D6751/ EN14214*
Density of oil @ 15°C	kg/m³	924	-
Density of biodiesel @ 15°C	kg/m³	872	860-900
Acid value of oil	mg KOH/g	6.89	-
FFA content of oil	%	3.44	-
Acid value of biodiesel	mg KOH/g	0.436	0.80
Kinematic viscosity @ 40 °C	cSt	5.3	1.9 – 6.0
Calorific value	MJ/kg	38.2	-
Saponification number	Value	174.04	-
Iodine value	Value	78.14	120 Max.*
Cetane number	Value	60.08	47 Min.
Cloud point	°C	10.65	-
Pour point	°C	4.73	-

fuel parameter was found to be 924 kg/m^3 for Pongamia oil and the density of biodiesel upon conversion was obtained as 872 kg/m^3. Several authors have studied the densities of Pongamia oil and its biodiesel and found them to be in the range of 912-991 kg/m^3 and 860-894 kg/m^3, respectively[6,25,41].

Acid value of the Pongamia oil was determined to be 6.89 mg KOH/g. Similarly, acid value of biodiesel was evaluated as 0.436 mg KOH/g. Previous studies have investigated the acid values of Pongamia and found them to be in the range of 5.06 to 12.27 mg KOH/g for oil and 0.4 to 0.46 mg KOH/g for biodiesel [11,20,42]. Since the FFA content in the analysed Pongamia oil was close to 3%, single step base-catalysed transesterification process was followed for biodiesel production in the present study. Acid value is used to quantify the total acidity of fuel and indicates its tendency to corrode metals. It is a basic parameter for deciding the mode of transesterification method to be adopted for biodiesel preparation and for higher acid value oils a two-step acid-catalysed transesterification procedure is generally followed.

Kinematic viscosity of the produced biodiesel was experimentally found to be 5.3 cSt. Several studies have evaluated the kinematic viscosity of Pongamia biodiesel and found it to be in the range of 3.64 to 7.53 cSt[11,43]. Viscosity is the measure of resistance to flow and a critical parameter for biodiesel utilization in engines because of its influence on the fuel injection system at lower temperatures. The viscosity of biodiesel increases with the increase in length of carbon chain, the presence of free fatty acids, degree of saturation of the fatty acids and their esters. It is to be noted that a high viscosity value of the fuel has negative effects as it lowers the vaporisation and the atomization characteristics of the fuel thus increasing the time required for fuel to mix with air.

Calorific value of biodiesel was obtained as 38.2 MJ/kg. Previous pongamia biodiesel studies have found it to be in the range of 35.9 MJ/kg to 39.7 MJ/kg [18,31,41,44]. Calorific value is an key parameter for any fuel as it is ameasure of the amount of heat produced during complete combustion of a unit mass of fuel. Higher the calorific value of a fuel, higher will be the efficiency of the engine.

Analysis of the results obtained upon testing of biodiesel sample revealed that the outcomes were in the range as laid down by ASTM D6751 standard and also the values reported in literature [11,31]. It is reported that high acid value and viscosity of oil are the major factors due to which vegetable oils are not directly utilized as fuels in engines. Their values decreased significantly upon conversion to biodiesel indicating that the transesterification process happened successfully and it can be used to convert oil into engine friendly fuel i.e. biodiesel.

Biodiesel was also tested using a Nucon 5765 Gas Chromatograph to identify the methyl ester composition in it. The column was kept at 40°C. Hexane was used as a carrier solvent with a flow rate of 1ml/min. The sample injection volume was 20 µl. Peaks were identified upon comparison with the standards of methyl esters, monoglycerides, diglycerides and triglycerides.

It was observed that methyl esters of oleic acid (C18:1, 44.10 %) were the major component present in the analyzed biodiesel sample followed by that of linoleic acid (C18:2, 21.17 %). Oleic acid is a mono-unsaturated fatty acid having a single double bond in the fatty acid chain and linoleic acid is a poly-unsaturated fatty acid having two double bonds. Oleic acid is known to have excellent biodiesel features with respect to ignition quality, fuel stability and nitrogen oxides (NOx) emissions. Other major methyl esters were found to be of stearic acid (C18:0, 15.91 %) and palmitic acid (C16:0; 5.82 %) both of which are saturated fatty acids. The yield of methyl esters was 87 %. The molecular weight of the palmitic acid is 270 g, stearic acid is 298 g, oleic acid is 296 g and linoleic acid is 294 g. The composition of the fatty acids obtained conform with the range of fatty acids reported in previous studies carried out for Pongamia biodiesel indicating that the product was of desired quality.

3.2 Empirical analysis

The important characteristics of biodiesel such as saponification number, iodine value, cetane number, cloud point and pour point were calculated as shown in Table 2, from the empirical relations available for these in literature.

Saponification number (SN) is dependent on the molecular weight and the percentage composition of fatty acid constituents existing in the fatty acid methyl esters. SN is used for the determination of the average relative molecular mass of oils and fats. Saponification number of the biodiesel was analysed using the correlation as discussed in section 2.5.1 and was found to be 174.04. Previous investigations have reported SN in the range of 169.2 to 202.6 for biodiesel from different oils [9,45]. It is reported that high SN requires greater methanol, and produces more glycerol and less biodiesel. Oils having high SN also impart high foamability.

Iodine value refers to the degree of unsaturation found in vegetable oil. It is the mass of iodine which reacts with the double bonds in a given vegetable oil. More are the unsaturated fatty acids (having double bonds) present in biodiesel, higher is the iodine value. In the present study the IV was calculated from the empirical relation as described in section 2.5.2 and was found to be 78.14. Several studies have presented the iodine value of biodiesel produced from different oils in the range of 59-132 [9,45]. EN 14214 has set the limit for IV as max. 120. Higher IV of biodiesel can lead to the formation of different degradation products which can adversely affect the engine operation and can also decrease the lubrication quality.

Cetane number is the capability of a fuel to ignite quickly after getting injected. Cetane number of the biodiesel was calculated from the evaluated saponification number and the iodine value. The cetane number for the produced biodiesel was evaluated to be 60.08. It falls in the range of cetane number obtained in different studies as well as the value specified in ASTM D6751 i.e., 47 min. Previous investigations have reported CN in the range of 45 to 67 for biodiesel from different oils and between 40 and 49 for diesel fuel [9,45,46]. It is reported that the long straight chain hydrocarbons exhibit higher cetane number which is more favourable for diesel engines, whereas higher unsaturation level (double bonds) results in lower CN. Higher CN leads to shorter ignition delay period for a fuel as lower activation energy is needed to ignite the fuel. This can result in lower NOx emissions due to shorter pre-mixed combustion phase as there will be a drop in peak temperature and pressure in the combustion chamber.

The flow properties of biodiesel at low temperatures are described by the cloud point (CP) and pour point (PP) and these should be measured for compression-ignition (CI) engine operation in cold weather conditions. The presence of higher amount of saturated fatty acid alkyl esters in biodiesel increases its cloud point and pour point leading to poor cold flow properties as the extended exposure of the fuel to temperatures lower than CP results in crystallization. The CP and PP in the current study of Pongamia biodiesel were assessed to be 10.65 and 4.73 ^{o}C, respectively, using the correlations presented in section 2.5.4. As CP and PP are the triggers for the harmful effect on fuel injection, their estimation is important.

3.3. Carbon neutrality aspects of Pongamia Biodiesel

Biodiesel derived from Pongamia pinnata has been recognized for its potential to lower greenhouse gas (GHG) emissions in comparison to fossilized diesel fuel due to its several environmental benefits [3]. Lifecycle analyses studies conducted for biodiesel indicate that it's utilization as a replacement of diesel fuel can lead to GHG emission savings of around 40-86%, considering all stages from cultivation to combustion[3,44]. The specific savings depend upon various factors including the efficiency of cultivation, extraction of oil, processing technologies, biodiesel transport, it's utilization in engines and the lifecycle assessment method used. When compared to other biodiesel sources like palm oil, soybean etc., Pongamia displays a better emission profile on account of its ability to grow in degraded lands, and lower land-use change emissions. It is estimated that the CO_2 emission saving per liter of Pongamia based biodiesel, vis-à-vis diesel, ranges from approximately 1.61 - 2.14 kg CO_2. A study on Life cycle analysis of Pongamia derived biodiesel estimated the GHG emissions for Pongamia as 63.81 g CO_2eq/MJ[47]. As per the study, cultivation (44.7%), oil extraction (25.9%), and biodiesel production (26.%) accounted for the majority contribution towards the total GHG emissions. GHGs emissions for cultivation, Oil extraction, and Biodiesel production were estimated to be 28.5, 16.5, and 17.13 g CO_2 eq, respectively, to produce 1 MJ biodiesel from Pongamia. Cultivation accounts for the highest emission, which is due to the burning of fossil diesel for the production of fertilizers, electricity use,and farming.Further, the CO_2 sequestration potential of Pongamia tree has been found to be much higher than several other tree species during the 10 - 15 years of its growth [16]. Studies indicate that Pongamia can sequester around 45-50 kg of C per tree per annum in comparison to 23-26 kg of *Madhuca latifolia,* 28-35 kg of *Azadirachta indica*, and 11-15 kg of *Diospyros melanoxylon*[48–50].The study also suggests that 200 trees (20 years age) in 1 ha area can sequester approximately 15 tonnes of carbon [16]. Thus, Pongamia is a versatile tree with multiple bioenergy producing options and a high carbon emission reduction potential.

4 Conclusion

Pongamia Pinnata based biodiesel is found to be a suitable native feedstock for substitution of diesel fuel in India due to its high fruit and oil yield, and ability to grow on degraded lands. Experimental observations indicate that the base-catalysed transesterification is a feasible method for biodiesel production of Pongamia oil having a lower FFA content since the process is faster, requiring a simple infrastructure and fewer chemicals making it more economical and safer in comparison to acid catalysed esterification. Reaction conditions, 6:1 molar ratio of alcohol to oil, NaOH catalyst quantity 1% (w/w of oil), time: 2 hours and temperature: 60°C were found to be appropriate for biodiesel production of desired quality such that the analysed physiochemical properties were within the range specified in ASTM standards. It is seen that, Pongamia is a versatile feedstock as its fruit can also provide additional energy through de-oiled seed cake and shells. Pongamia with an estimated bioenergy generation potential of 21,01,000 GJ/year - 51,57,000 GJ/year has a significant potential to contribute to India's energy security and net zero goals.

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