Research Article

Effect of Flow and Dissolved Oxygen on the Compatibility of *Pongamia pinnata* Biodiesel with Common Construction Materials Used in Storage and Transportation

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The compatibility of *Pongamia pinnata* biodiesel (PBD) and its NaCl blends on aluminium, brass, copper, carbon steel, and mild steel has been studied by static mass loss and rotating cage methods. The effects of dissolved oxygen and flow on the metal corrosion in PBD were also observed. This study confirmed that the copper strip test alone is not enough to determine the fuel property since the corrosion of ferrous metal was found to be high in PBD compared to other metals. The least corrosion rate of aluminium was confirmed by surface morphology and elemental analysis.

1. Introduction

Vegetable oils have become more attractive as substitute for traditional fossil fuels because of their environmental benefits and the fact that they are made from renewable resources. The consumption of edible oil is very high in the country and still the indigenous production does not meet the demand and considerable amount of edible oil is imported and it is therefore not advisable to divert these sources for biodiesel production. On the other hand, the nonedible oil resources can be a solution for biodiesel production [1–3]. *Pongamia pinnata*, *Jatropha curcas*, and other trees of nonedible grade native to humid and subtropical environments can be grown on degraded and marginal land. Among these, *Pongamia pinnata* is an untapped resource for the biodiesel [4]. It is anticipated that by planting *Pongamia* on roadsides, on riverbanks, and on the two sides of irrigation canals, India will be able to produce several million tons of biodiesel in near future.

Biodiesel is produced by reacting vegetable oil or animal fat with an alcohol, usually methanol by the transesterification

reaction [5–7]. This process brings the properties of the raw materials closer to those of conventional petroleum diesel. Fatty acid methyl ester (FAME) can be used neat as a fuel but is more commonly blended with petroleum diesel for use in diesel engines [8–10]. Various metals are used to handle biodiesel during the storage, transportation, combustion, and automobile operational conditions [11–13]. Regardless of how well the infrastructure is maintained, biodiesel may be contaminated with water at various stages. In general, biodiesel attracts water more than petroleum diesel. The corrosive effect of biodiesel is mainly caused by the presence of water. Water in biodiesel can promote unwanted microbiological growth, which may lead to filter blocking and corrosion [14–16]. Water can support hydrolytic reactions, breaking down the FAME to form free fatty acids. Such species are corrosive and may attack exposed metal surfaces. A number of different effects may be involved (changes in TAN value, increased water content, oxidation product, presence of metals species, changes in structural features of biodiesel component, etc.) in making the situation more complicated [17–19]. Therefore

FIGURE 1: Corrosion types and locations.

it is important to understand the biodiesel-materials interaction in various stages (production, storage, transportation, and usage). Figure 1 presents the corrosion types and their locations in storage and transportation of biodiesel.

The corrosivity of water in the presence of biodiesel depends on the composition of the fuel. In general, depending on how well it affects corrosivity of the water phase, the biodiesel may broadly be classified into (a) protective, (b) inhibitive, (c) neutral, and (d) corrosive ones. This classification is based on the evaluation of wettability, emulsion tendency, and corrosion rate [20]. It should be understood that emulsion and wettability are two different properties. Biodiesel may hold a lot of water, but as soon as the inversion point occurs, the surface may become water-wet immediately. On the other hand, an inversion point may occur at a very low water cut, but the surface may not become water-wet until a very high water cut is reached. The difference in behavior is due to the fact that the emulsion depends on liquid-liquid (oil-water) interaction whereas wettability depends on the balance between two solid-liquid (metal-oil and metal-water) interactions. Corrosivity of water phase becomes significant only in the presence of either oil in water emulsion or free water and on a water-wet or mixed-wet surface. The factor responsible for one property may or may not influence other properties. For this reason, all three properties (emulsion, wettability, and corrosivity) should be determined independently.

Any part of the biodiesel supply system needs to be assessed for materials compatibility and may need to be refitted with materials that are resistant to the effects of biodiesel. Currently used indicators of corrosiveness of biodiesel, for example, copper strip corrosion and TAN value that are prescribed by different standards, are not effective enough and corrosive nature of biodiesel under wide spectrum of compositional, environmental, and operating variables should be investigated. Hence in this investigation the corrosion rates of five metals (aluminium, brass, copper, carbon steel, and mild steel) in PBD were studied by static mass loss and rotating cage methods. Static mass loss is used to depict storage condition and rotating cage is used to simulate pipeline flow under laboratory conditions by rotating the specimens at speeds up to 1500 rpm [21]. The corrosivity of

TABLE 1: Composition, density, and equivalent weight of the materials.

Element	% composition		
	Aluminium	Carbon steel	Mild steel
Zn	0.009	—	—
Al	98.66	—	0.023
Sn	—	—	<0.005
Pb	0.002	—	<0.010
Si	0.47	0.011	0.018
Ni	<0.005	0.008	0.014
Fe	0.69	99.6	99.56
Mn	0.092	0.222	0.27
P	—	0.030	0.009
S	—	0.026	0.005
Bi	<0.010	—	—
Sb	—	—	—
Cu	0.023	—	0.030
Cr	0.007	0.003	0.019
C	—	0.120	0.049
Mo	—	0.035	0.002
Density (g/cm ³)	2.73	7.87	7.87
Equivalent weight	9.09	27.92	27.92

PBD for different metals is analyzed by rotating cage method in the presence and absence of oxygen to study the effect of dissolved oxygen.

2. Materials and Methods

2.1. Biodiesel Procurement and Characterization. PBD was collected from a commercial company in Coimbatore, India, and characterized by FT-IR using a Bio-Rad Excalibur Model FTS3000MX in the range 4000–600 cm⁻¹. Biodiesel can be used in neat form or blended with petroleum diesel for use in compression ignition (diesel) engines. Its physical and chemical properties as it relates to operation of diesel engines are similar to petroleum based diesel fuel. Therefore PBD used for the present investigation was examined for various physicochemical characteristics as per American Standards for Testing and Materials (ASTM D6751) in a testing laboratory.

2.2. Selection of Metals. The most common construction metals used for tankers, storage tanks, pipes, and pumping equipment are carbon steel, stainless steel, aluminum, and copper alloys. Hence aluminium, copper, brass, carbon steel, and mild steel were chosen for the present investigation. Commercially available metal sheets machined into coupons of area 33.9 cm² (ASTM G184) were used for the entire study. The elemental compositions of brass and copper are given elsewhere [22]; aluminium and ferrous metals are presented in Table 1.

The following test media were used for the present investigation:

- (i) B100 $\rightarrow$ 100% biodiesel (pure biodiesel),
- (ii) NaCl $\rightarrow$ 3% (w/v) sodium chloride,
- (iii) B99 $\rightarrow$ 1 mL of 3 (w/v)% NaCl + 99% biodiesel (99 mL biodiesel) to prepare 100 mL solution.

The 3% NaCl is considered to represent water contamination, because at this concentration highest corrosion rate of carbon steel has been observed [23].

2.3. Wettability. The presence of free water or of o/w emulsion does not necessarily lead to corrosion. Under this condition, wettability of the biodiesel on the metal determines corrosivity. The wettability of PBD on various metals was studied by contact angle method and detailed discussion has been given in previous publication [24], the significance of which is detailed elsewhere [20].

2.4. Emulsion Inversion Point. Emulsion inversion point (EIP) was determined by measuring the conductivity of the solution. Test solution was placed in an electromagnetic stirrer and continuously stirred for 20 minutes to obtain standard emulsion. The conductivity was measured at 2-minute interval and data were averaged. These steps were repeated for different biodiesel/NaCl ratios, starting with 100% of biodiesel (B100) and progressively increasing the water content (3% NaCl) in steps (90 mL B100 + 10 mL of 3% NaCl, 80 mL B100 + 20 mL of 3% NaCl until 0 mL B100 + 100 mL of 3% NaCl was reached). From the plot of conductance versus biodiesel/NaCl ratio, EIP was determined for PBD.

2.5. Corrosion Rate Measurement

2.5.1. Static Mass Loss Method. As per ASTM G1 the metal coupons were immersed in triplicate in 200 mL of various test media for a period of 100 h. Specimens were removed after the set intervals of time and wiped with trichloroethylene for the removal of the excess fuel. Then aluminum coupons were dipped in concentrated nitric acid for 5 min and steel coupons in solution containing 500 mL con.HCl and 3.5 g hexamethylenetetramine for 10 min as per ASTM G1-90. The coupons were then washed with distilled water, dried, and reweighed. The loss in mass was determined. From the mass loss the corrosion rates were calculated and average results from three specimens are reported.

2.5.2. Rotating Cage. Rotating cage used for the experiments has been fabricated as per ASTM G184. The acrylic vessel was filled with 4 litres of test solution. The metal samples were held between two Teflon holders, which have been designed to hold eight coupons. Experiments were conducted for a period of 100 h at the rotation speed of 500 rpm. The description of rotating cage and experimental procedure was explained elsewhere [22]. The corrosion rate was calculated from the difference in mass of the coupons. To study the effect of dissolved oxygen at the emulsion inversion point, rotating cage experiments were carried out at deaerated condition.

This condition was achieved by purging nitrogen to the solution at the rate of four bubbles per second for a period of four hours and maintained the blanket throughout the experiment. The following formula has been used to calculate the corrosion rate in Mills per year (mpy):

Corrosion Rate (mpy)

$$= \frac{3.45 \times 10^6 \times \text{Mass loss (grams)}}{\text{Density (g/cm}^3) \times \text{Area (cm}^2) \times \text{Time (hours)}} \quad (1)$$

2.6. Scanning Electron Microscopy. The surface morphology and the elemental composition of the corrosion products were determined by JEOL, JSM-6390 Scanning Electron Microscope (SEM) equipped with a light element energy-dispersive X-ray detector (EDX) for composition analysis in and away from the corrosion pits. Secondary electron images were collected along with EDX spectra.

3. Results and Discussion

3.1. Characterization of Pongamia pinnata Biodiesel

3.1.1. FT-IR Analysis. The FT-IR spectra in the midinfrared region are used to identify the functional groups and the bands corresponding to various stretching and bending vibrations in PBD and the spectra are given in Figure 2. Biodiesel kinds are basically esters which have two characteristically strong absorption bands arising from carbonyl (ν C=O) around 1750–1730 cm^{-1} and that of C–O (antisymmetric axial stretching and asymmetric axial stretching) at 1300–1000 cm^{-1} [25, 26]. The position of carbonyl group in FT-IR is sensitive to substituent effects and to the structure of the molecule. The possible structures obtained from FT-IR spectrum search are the alkyl group, a carboxylic acid ester, long chain aliphatic esters, and carbonyl compounds. In the spectra, peaks in the 1000–900 cm^{-1} region are assigned to symmetric angular deformation (out of plane) of the C–H bonds of olefins, peaks around 1200 cm^{-1} are assigned to the asymmetric stretching band of C–C (O)–O bonds of the ester group, and peaks 1180–1200 cm^{-1} are assigned to the asymmetric stretching band of O–C–C bonds. Since biodiesel is mainly monoalkyl ester, the intense C=O stretching band of methyl ester appears at 1743 cm^{-1} for Pongamia biodiesel.

3.1.2. Physicochemical Characteristics. The Biodiesel Association of Canada defines biodiesel as follows: “The monoalkyl esters of long-chain fatty acids that are derived from fats and oils that meets the specification of ASTM D6751 and EN 14214 or any legal successor thereto” [27]. The ASTM standards for diesel, biodiesel, and measured parameters for PBD as per ASTM D6751 are presented in Table 2. The observation of each fuel property of PBD is explained in detail.

Flash Point. The flash point is the minimum temperature at which the fuel will ignite on application of an ignition source under specified conditions. The flash point of biodiesel should be at least 130°C, and in general it is higher than that of diesel fuels having a flash point of at least 52°C. The

TABLE 2: ASTM standards for diesel, biodiesel, and fuel properties of PBD.

Parameters	ASTM D975	ASTM D6751	PBD	Unit
Flash point	52 min	130.0 min	126	°C
Water content and sediment	0.050 max	0.050 max	0.0322	% vol
Kinematic viscosity 40°C	1.9–4.1	1.9–6.0	6.06	mm ² /sec
Sulfated ash	0.01 max	0.020 max	0.01	% mass
Sulfur (grade number 2, low sulfur/S 500 grade)	0.05 max	0.05 max	0.0013	% mass
Copper strip corrosion	Number 3 max	Number 3 max	2	—
Cetane	40 min	47 min	62.0	—
Carbon residue	0.35 max	0.050 max	0.02	% mass
Acid number	—	0.80 max	0.3	Mg KOH/g
Free glycerin	—	0.020 max	0.01	% mass
Total glycerin	—	0.240 max	0.12	% mass
Phosphorous contents	—	0.001 max	0.0001	% mass
Distillation temperature, atmospheric equivalent temperature, 90% recovered	282–338	360 max	242	°C
Aromaticity	35 max	—	—	% vol.

FIGURE 2: FT-IR spectra of *Pongamia pinnata* biodiesel.

flash point of PBD is reported as 126°C, higher than that of the conventional diesel. Hence storing biodiesel is safe as compared to storing diesel [28].

Water Content and Sediment. The presence of water and sediment generally indicates poor fuel handling practices. Water in the sample can promote microbial growth, lead to tank corrosion, participate in the formation of emulsions, and cause hydrolysis or hydrolytic oxidation [29]. It is evident from Table 2 that water and sediment content of PBD (0.0322%) is well within limits specified by standard.

Kinematic Viscosity. Higher viscosity of a fuel causes poor fuel atomization during spray, increases the engine deposits, needs more energy to pump the fuel, and wears fuel pump elements and injectors. This also causes more problems in cold weather, because viscosity increases with decreasing temperatures. The ASTM has prescribed an acceptable kinematic viscosity at 40°C for biodiesel to be 1.9–6.0 mm²/sec. The viscosity of PBD is 6.06 mm²/sec, which is very close to the ASTM D6751 standard value.

Sulfated Ash. Sulfated ash content describes the amount of inorganic contaminants. ASTM D6751 mentions that the biodiesel samples can have a maximum 0.02% sulfated ash. As evident in table, the sulfated ash of PBD is found to be 0.01%, which is well within the limits of ASTM specification.

Sulfur Content. Presence of sulfur in the fuel will lead to the formation of SO₂ and SO₃, which are corrosive gases that might corrode the engine parts. The ASTM standard approved maximum sulfur content for biodiesel of 0.05% which was fulfilled by PBD (0.013%).

Copper Strip Corrosion. The copper strip corrosion test consists of dipping a strip of copper into the fuel for a specified time and defined temperature to observe the corrosive action of the fuel. The degree of tarnish on the corroded strip correlates with the overall corrosiveness of the fuel sample. ASTM certifies copper strip corrosion value for biodiesel to be 3 maximum. The copper strip corrosion property of the investigated biodiesel was found to be 2, well within the specifications of ASTM D6751.

Cetane Number. The cetane number is a dimensionless descriptor of the ignition quality of a fuel. Generally, higher cetane number causes significant reductions in the NO_x emissions due to shorter ignition delay times and the resulting lower average combustion temperatures. In the present analysis the cetane index was found to be 62 for PBD. The higher cetane number is due to the increase in carbon chain length.

Carbon Residue. In fuels, the carbon residue is the part remaining after a sample is subjected to thermal decomposition and it indicates coking tendency. The maximum limit for carbon residue in biodiesel is 0.050% by mass. A carbon residue value of *Pongamia* biodiesel was 0.02% mass and successfully meets the ASTM standards.

Acid Number. The acid number is a measure of acidic substance in the biodiesel. It is used as a guide in the quality control as well as monitoring biodiesel degradation during storage. The lowest acid number was obtained for PBD (0.3 mg KOH/g). Acid number of biodiesel is 0.5 mg KOH/g specified as the maximum value according to ASTM D6751 which was fulfilled by *Pongamia* biodiesel. The acid number can become a serious issue, when feed stocks with high free fatty acids are used to produce biodiesel.

Total and Free Glycerin. Fuel with excessive free glycerol can result in material incompatibility, engine deposits, and combustion problems in the engine. The free glycerol content of a biodiesel should not exceed 0.020% by mass and the maximum amount of total glycerol should be 0.240% by mass. Free and total glycerol contents are within the standard requirement (0.01 and 0.12), respectively, for PBD.

Phosphorous Content. The influence of phosphorous is cumulative; therefore even very low levels of its contamination may lead to unexpected deterioration of the system. For *Pongamia* biodiesel, the amount of phosphorous is found to be 0.0005% by mass, which is below the standard allowable limit of 0.001% by mass.

Distillation Temperature. This provides a measure range over which a fuel volatilizes to a vapor. For petrodiesel, the distillation curve is associated with properties such as viscosity, vapor pressure, heating value, and average molecular weight. Petrodiesel is composed of hundreds of compounds boiling at different temperatures. Biodiesel does not exhibit a distillation curve since the fatty esters comprising it have very similar boiling point under the reduced pressure conditions. The atmospheric boiling point of biodiesel is generally 360°C maximum. The distillation temperature of PBD was found to be 242°C.

The measured fuel properties of PBD were within prescribed ASTM D6751 specifications, thus indicating that PBD is acceptable as a substitute for petrodiesel fuel for diesel engines.

3.2. Emulsion Tendency. Water enters into storage tanks and pipelines from various sources. Whatever the source of water is, whenever it comes in contact with the surface of metal, the surface becomes susceptible to corrosion. Biodiesel plays an important role in determining whether the water will come in contact with the surface and in determining the corrosivity of the water. Due to nonionic nature of biodiesel, it cannot dissolve ionic water. However at low concentrations of water, biodiesel can form an emulsion with the water. The type of emulsion and its stability depends on the type of biodiesel, the ionic content of the water, and the pressure, temperature, and flow rate. Therefore determining the inversion point (w/o becomes o/w) under pipeline operating conditions is necessary. Typical inversion point results of PBD and PO are presented in Figure 3.

From the perspective of corrosion, two types (water in oil [w/o] or oil in water [o/w]) of emulsion are important. In w/o emulsion, oil is the continuous phase, and hence it

FIGURE 3: Emulsion inversion point of *Pongamia* biodiesel.

is noncorrosive. In o/w emulsion, water is the continuous phase, and hence it is corrosive. As long as w/o emulsion is present in the pipeline other properties (e.g., wettability and corrosivity) are not important because the water is trapped inside the oil phase. On the other hand, in the presence of o/w emulsion, other properties become relevant. The EIPs occurred at 50% water cut. Corrosive nature of biodiesel seems to be attributed to its free fatty acid components and impurities remaining after processing. In addition, biodiesel is hygroscopic in nature and can absorb moisture from air and thereby can increase the water content [30]. In the presence of free water or o/w emulsion and on a water-wet surface, oil can influence the incidence of corrosion in the water phase. Since EIP for *Pongamia* biodiesel occurred at 50% water cut, it is necessary to measure the corrosion rates of various metals in PBD and its blends with NaCl.

3.3. Corrosion Rate Measurement

3.3.1. Static Mass Loss Method. Most corrosion issues of biodiesel have been observed during storage. As the fuel tank is emptied, air enters through the vent pipes to displace the fuel in the tank. Under stagnant conditions, the water drop will form a separate phase at the bottom of the biodiesel container. Therefore the formation of the water drop on the metal surface may push the majority of biodiesel away but leave a thin layer of water biodiesel mixture on the metal surface. This may facilitate the anodic metal oxidation and cathodic reduction of water and dissolved oxygen as well. Hence corrosion rates of the chosen metals in B100, B99, and NaCl by static mass loss method were determined and presented in Table 3.

Higher corrosion rates were observed in NaCl for all metals. An addition of 1% of 3% (w/v) NaCl solution has increased their corrosion rate when compared to B100. As received fuels are virtually water-free but during storage or use, due to the hygroscopic nature, biodiesel can absorb moisture from atmosphere. Upon exposure of metals into biodiesel, water may condense on metal surface and thereby enhance the corrosion process. The order of corrosion rate for studied metals in B100 was found to be carbon steel > mild steel > brass > copper > aluminium.

TABLE 3: Mean corrosion rates of various metals under static and flow conditions.

Metal	Mean corrosion rates (mpy)					
	B100		B99		NaCl	
	Static	Flow	Static	Flow	Static	Flow
Aluminium	0.12	1.04	1.31	2.43	2.06	10.08
Brass	0.38	5.85	0.53	8.2	0.87	9.61
Copper	0.16	1.83	1.03	2.31	1.8	2.58
Carbon steel	0.63	1.48	1.48	3.63	2.34	25.76
Mild steel	0.43	0.78	2.36	4.08	3.72	30.31

Aluminium was least corroded (0.12 mpy) in B100, since the water present in the fuel might mitigate the corrosion by contributing to the formation of a protective hydrous oxide surface film such as bayerite ($\text{Al}(\text{OH})_3$) or boehmite (AlOOH) by the following reactions [31]:

ASTM D130 in ASTM D6751 and ISO 2160 in EN14214 (copper strip corrosion test standards) are utilized to evaluate the corrosiveness of biodiesel toward a copper surface. This method consists of dipping a strip of copper into the fuel for a specified time and defined temperature to observe the corrosive action of the fuel. The degree of tarnish on the corroded strip correlates with the overall corrosiveness of the fuel sample. This technique is limited in its ability to qualify and distinguish the extent of attack for low corrosive biodiesel [32]. The present study confirmed that the copper strip test alone is not enough to determine the fuel property since the corrosion of ferrous metal was found to be high in PBD compared to other metals. Hence the corrosivity data of various metals in biodiesel should be established in order to confidently use biodiesel without corrosion problems.

3.3.2. Rotating Cage Studies. Table 3 reveals that the corrosion was severe in NaCl and the least in B100 which can be justified from the fact that the corrosion rate increases with increase in vortex length [19]. The measured vortex lengths for NaCl and B100 are 13.2 and 6.5 cm, respectively. On addition of 1% of 3% (w/v) NaCl solution the corrosion rate increased to a small extent when compared to B100. Measured corrosion rates were higher in flow than in static condition for all studied metals in PBD and its blends with NaCl. It has been found that the order of metal corrosion depends on the condition applied. Higher corrosion in the flow condition may be attributed to the presence of relative motion between metal and the fuel [33]. This is due to increased relative movement between the fluid and the wall of the pipe, resulting in mechanical wear and abrasion. This wear eventually results into erosion corrosion, characterized by pit, grooves on the metal surface. In the presence of air or oxygen biodiesel will

FIGURE 4: Comparison of mean corrosion rates of studied metals in B100 using rotating cage.

be hydrolyzed to alcohol and acid. Presence of alcohol will lead to reduction in flash point and presence of acid will increase total acid number. All of these make methyl ester relatively unstable on storage and cause damage to engine parts. The results obtained for the study carried out under aerated and deaerated conditions using rotating cage are tabulated in Table 4.

Comparison of mean corrosion rates of various metals in B100 under aerated and deaerated conditions has been pictorially represented in Figure 4. A red line at 4 mpy in the figure is the target line for acceptable corrosion rates. It is clear that all metals, except copper under aerated condition, are away below the target lines at all conditions. Dissolved oxygen in biodiesel kinds can ultimately accelerate the corrosion rate. This agreement is supported by the compared corrosion rates of aluminium, brass, copper, carbon steel, and mild steel in B100, B99, and NaCl obtained from rotating cage studies under aerated and deaerated conditions (Table 4). The stability of biodiesel depends on the fatty acid profile of the parent feedstock. Biodiesel kinds contain more or less unsaturated fatty acids in their composition, which are susceptible to oxidation reactions accelerated by exposure to oxygen to yield stable products like aldehydes, shorter chain carboxylic acids, insolubles, gum, and sediments. If biodiesel containing these oxidation products is used in the engine, it impairs the engine performance due to fuel filter plugging, injector fouling, and deposit formation in engine, the combustion chamber, and various components of the fuel system [34].

Since copper accelerates oxidation of biodiesel, higher corrosion rate was found in copper than in aluminium, brass, and ferrous metals (Figure 4). According to Feng et al., 1996 [35], in the presence of oxygen, copper can lead to the formation of cuprous oxide (Cu_2O). But Cu_2O is unstable and rapidly it turns to the stable species, CuO . The presence of dissolved water, CO_2 , RCOO^- , and so forth in biodiesel causes the formation of carbonate and hydroxyl based copper compounds. Fazal et al., 2013 [36], assumed that the copper compounds such as Cu_2O , CuO , CuCO_3 , and $\text{Cu}(\text{OH})_2$

TABLE 4: Mean corrosion rates of metals in aerated and deaerated conditions.

Metal	Mean corrosion rates (mpy)					
	B100		B99		NaCl	
	Aerated	Deaerated	Aerated	Deaerated	Aerated	Deaerated
Aluminium	1.04	0.16	2.43	1.19	10.08	3.77
Brass	1.83	0.37	2.31	1.08	2.58	1.89
Copper	5.85	0.42	8.2	1.04	9.61	1.76
Carbon steel	1.48	0.19	3.63	1.39	25.76	5.07
Mild steel	0.78	0.52	4.08	2.02	30.31	17.68

FIGURE 5: SEM image and EDS spectra of aluminium sample immersed in PBD.

FIGURE 6: SEM image and EDS spectra of carbon steel sample immersed in PBD.

are the major constituents formed on the copper surface immersed in palm biodiesel. They observed that dissolved O_2 , H_2O , CO_2 , and $RCOO^-$ in biodiesel are associated with the formation of different copper compounds.

3.4. Surface Analysis. The change in surface morphology of aluminium (least corroded) and carbon steel (corroded) after exposure to PBD for 100 h under static condition was characterized by SEM. The SEM micrographs and the corresponding energy dispersive X-ray spectra of the aluminium and carbon steel samples exposed to PBD are presented in Figures 5 and 6, respectively. Visually, these micrographs reveal that there was not much damage on aluminium whereas occasional pits were observed on carbon steel. Formation of pits may be due to the corrosive attack of oxygenated compounds present on steel surfaces which has been proved by EDX. The elemental analyses of metal samples immersed in PBD surfaces show the presence of higher percentage of oxygen in carbon steel than in aluminium with their base metal.

The various observations and results of this study would certainly be of immense help to engineers to have a better idea on the corrosion issues and metal compatibility of the biofuels.

4. Conclusions

- (i) The measured fuel properties of PBD were within prescribed ASTM D6751 specifications, thus indicating

that PBD is acceptable as a substitute for petrodiesel fuel for diesel engines also supported by FT-IR analysis.

- (ii) In the presence of free water or o/w emulsion and on a water-wet surface, oil can influence the incidence of corrosion in the water phase. EIP for *Pongamia* biodiesel occurred at 50% water cut which necessitates measuring the corrosion rates of various metals in PBD and its blends with NaCl.
- (iii) The order of corrosion rate for studied metals in PBD was found to be carbon steel > mild steel > brass > copper > aluminium.
- (iv) The present study confirmed that the copper strip test alone is not enough to determine the fuel property since the corrosion of ferrous metal was found to be high in PBD compared to other metals. Hence the corrosivity data of various metals in biodiesel should be established in order to confidently use biodiesel without corrosion problems.
- (v) Measured corrosion rates were higher in flow than in static condition for all studied metals in PBD and its blends with NaCl. It has been found that the order of metal corrosion depends on the condition applied. Higher corrosion in the flow condition may be attributed to the presence of relative motion between metal and the fuel.

- (vi) Dissolved oxygen in biodiesel kinds can ultimately accelerate the corrosion rate. This agreement is supported by the compared corrosion rates of aluminium, brass, copper, carbon steel, and mild steel in B100, B99, and NaCl obtained from rotating cage studies under aerated and deaerated conditions.
- (vii) Neat surface morphology and minimum percentage of oxygen on the aluminium surface confirm the least corrosion rate of aluminium under static condition.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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