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Prediction of copper corrosion by machine learning and conventional methods in neem biodiesel with ecofriendly black pepper extract

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Copper is extensively utilized across many industries due to its outstanding attributes, nonetheless, undergoes corrosion in biodiesel. In view of this menace, eco-friendly black pepper extract was investigated as a corrosion inhibitor for copper in neem biodiesel. Weight loss measurement of copper in neem biodiesel was performed and the resulting values were utilized to calculate inhibition efficiency, corrosion rate, and thermodynamic parameters. A quadratic regression machine learning algorithm was employed to analyze copper corrosion at the operational temperature of the engine. Additionally, FTIR and SEM analyses were performed to identify the functional groups of the inhibitor responsible for corrosion inhibition through adsorption and to examine the surface morphology of the metal respectively. A corrosion inhibition efficiency of 98.0% for copper in neem biodiesel was achieved at room temperature, and the inhibitor demonstrated significant effectiveness at the operating temperature of engine nozzles. Carbonyl and amine groups of the inhibitor adsorbed on the metal formed a barrier against biodiesel enabling corrosion protection. This value-added biodiesel presents a viable alternative fuel option that protects engine components and storage tanks from corrosion.

Keywords: Copper corrosion, Machine learning, Natural inhibitor, Neem biodiesel, Quadratic regression

Introduction

The forecast for the depletion of mineral oils has triggered scientists for the exploration of novel alternative energy sources. Moreover, with the population surge and the continuous enhancement of modern lifestyles, the sustainability of current energy sources is unfeasible[1-4]. One of the most practical ways to meet this requirement is by utilizing ecofriendly biodiesel due to its significant efficiency[5,6]. Trans-esterification process, involving vegetable/animal oils and ethanol or methanol can create esters of long-chain fatty acids, termed as biodiesel. The resulting biodiesel can be effectively used in diesel engines including vehicles as an alternative fuel. Although biodiesel functions as a substitute fuel, it induces corrosive responses in copper, aluminium, and their corresponding alloys that are used for biodiesel transportation and the manufacturing of engines[7]. The ester group's hydrolysis of biodiesel results in the formation of organic acids[8,9], leading to an increase in acid values of biodiesel that trigger an escalation in the corrosion of metals in contact. Copper that is vastly used in many industries due to its malleability, ductility and excellent conductivity is not an exception when used in biodiesel and other adverse environments.

Organic compounds containing elements such as N, O, and S have the ability to adhere to metals forming a barrier in between metal surface and corrosive medium, functioning effectively as corrosion inhibitors. The plant-derived environmentally friendly inhibitors, often referred to as green inhibitors, present a combination of advantages including cost-effectiveness, biodegradability, and non-toxicity to combat metal corrosion[10,11]. Considering these advantages, experiments involving acid extracts from Citrus *aumahonia* leaves[12], *Solanum nigrum*[13] and*pomegranate* leaves[14] have demonstrated their efficacy in inhibiting mild steel corrosion in acidic environments. The effectiveness of carbon quantum dot prepared from discarded acorn caps as corrosion inhibitors for copper in a 0.5 mol/L sulphuric acid solution was evaluated, demonstrating outstanding inhibition efficiencies of 98.89%, 98.71%, and 98.42% at temperatures of 298 K, 308 K, and 318 K, respectively, when applied at a concentration of

200 mg/L[15]. *Nepeta cataria L.* leaf extract as inhibitor for copper corrosion protection in 0.5 M H_2SO_4 medium was examined that produced good efficiency above 90%[16].

In the realm of biodiesel, plant extracts have emerged as eco-friendly alternatives, capable of safeguarding metals from corrosion. Studies have highlighted various extracts like *Ricinus communis* seed[7], *Vitex negundo* leaves[17], *Tinospora cordifolia*[18], Rosemary[19], and *Terminaliacatappa* leaf[20] as effective green inhibitors.

Neem seed biodiesel is an environmentally friendly fuel, but its corrosive effects on copper engine components necessitate use of inhibitors. The ethyl acetate extracts of *Syzygium aromaticum* flowers and *Myristica fragrans* mace flowers were tested, achieving inhibition efficiencies of 97.96% and 98.04%, respectively, as estimated[21,22].

The extract of *Pyracantha fortuneana* and *Passiflora edulis* leaves acted as inhibitors for copper in H_2SO_4 solution, achieving corrosion inhibition efficiencies of 95% and 96%, respectively[23,24].

The corrosion inhibition potential of black pepper extract named here as black pepper inhibitor (BPI) was explored as an eco-friendly substance for protecting mild steel in a sulphuric acid environment, yielding an impressive corrosion inhibition efficiency of 98.9%[25,13]. Hence, black pepper has piqued interest as a corrosion inhibitor for copper in neem seed biodiesel. The objective of this research is to examine how the presence of black pepper isolate of ethyl acetate influences the corrosion inhibition properties of copper in neem oil-based biodiesel at various temperatures and acid values of biodiesel. This investigation employs immersion studies, FT-IR spectroscopy, and Scanning Electron Microscopy (SEM). A Machine Learning (ML) quadratic regression algorithm is employed to predict copper corrosion in neem biodiesel at high temperatures[21]. In this work, additionally a comparison of copper corrosion at high temperatures is made in the presence and absence of inhibitor in neem biodiesel.

Experimental Section

Neem seed biodiesel was produced using neem oil sourced from neem seeds. The trans-esterification method was employed, utilizing methanol at a temperature of 70°C and KOH as the catalyst[26]. Biodiesel samples with 0.4, 0.8, and 1.2 mg KOH/g acid values were obtained by storing them for extended period of days. Analytical reagent grade chemicals such as methanol, sulphuric acid, potassium hydroxide, toluene, sodium hydroxide and acetone were utilized. Titration was conducted three times to accurately determine the acid number following GB/T264 that is also adopted in literature[27], a crucial factor in assessing biodiesel corrosion. The fire point and flash point were determined using the Cleveland open cup method. The cloud point and pour point were assessed following IP-15/16 and IS 1448 methods. Carbon residue was measured using the ASTM D189-IP13 method. Kinetic viscosity and density were evaluated using the IP-70 method with a Redwood viscometer No. 1 cup at 40°C.

The composition of the copper sample was analyzed using a BOWMAN - XRF spectrometer and EDX method using Oxford Instruments Nano Analysis INCA Energy 250 Microanalysis System (EDS). Specimens measuring 7.5 cm x 1.25 cm x 0.15 cm were fabricated for weight loss testing by immersion studies. Prior to testing, the specimens was cleaned using trichloroethylene to remove any grease, and then they were polished using emery papers of varying grades to achieve a smooth and polished copper surface texture.

Approximately fifty grams of dried and powdered black pepper were immersed in ethyl acetate and left to soak overnight. Subsequently, the mixture was filtered and subjected to vacuum drying for 3 h. The resulting paste-like extract was employed as a corrosion inhibitor for biodiesel medium. Five separate volumes of 100 mL each of biodiesel with concentrations of the said inhibitor ranging from 0.5 ppm to 2.5 ppm, with an incremental increase of 0.5 ppm for each subsequent dose were taken.

Copper specimens, which had been previously degreased and polished, were placed in 100 mL of biodiesel both without and with inhibitors at varying concentrations. Corrosion experiments were also conducted at different acid values and temperatures, 303 K, 323 K, 343 K, and 363 K, over a 24 h period. The copper specimens were washed with trichloroethylene, followed by thorough washing with double distilled water and subsequently dried. The weight of these specimens before and after the immersion experiment was measured using a SCHIMADZU AUX220 balance. The inhibition efficiency (IE) was determined using the formula given in the literature. θ is the fraction of the surface area covered by the inhibitor on the metal surface, calculated using the equation given below.

$$\theta = \frac{\text{Inhibitor Efficiency}}{100} \quad ...(1)$$

Corrosion Rate (CR) in millimetres per year (mmpy), was calculated adopting the following formula.

$$CR = \frac{(m_2 - m_1) \times 24 \times 365}{\rho TS \times 100} \quad ...(2)$$

where m_1 and m_2 are weight of copper specimens before and after experiment, ρ: metal density (g/cm^3), T: corrosion time (h), S: metal area of corrosion (cm^2).

Activation energy (E) was calculated by the equation

$$\text{Log}\frac{CR_2}{CR_1} = \frac{E}{2.303R} \times \frac{1}{T_1} - \frac{1}{T_2} \quad ...(3)$$

Where, CR_1 and CR_2 denote the corrosion rates at temperatures T_1 and T_2, respectively.

Free energy change was calculated using the Eq. (4)[10,28-30]

$$\Delta G = - 2.303 \text{ RT log } 55.5 \text{ K} \quad ...(4)$$

Where, $K = = \frac{\frac{\theta}{1-\theta}}{C}$.

To predict the weight loss of copper in neem biodiesel at higher temperatures, regression algorithms in machine learning, including linear and polynomial regressions up to third degree, were employed. Weight loss experimental investigation covered a temperature range from 303 K to 383 K in 10K intervals and considered inhibitor concentrations of 0 and 2.5 ppm. To verify the results, three replicate tests were performed. Using the weight loss data obtained, machine learning analysis to predict copper corrosion up to 1000°C was carried out using Python 3 with the Jupyter Notebook IDE on a system equipped with an i7 processor and 16GB of RAM.

FT-IR spectroscopy and Scanning Electron Microscopy (SEM) were recorded using Shimadzu, IRTracer-100 FTIR spectrometer and TESCAN VEGA3 SBU model scanning electron microscope, respectively. To record the IR spectra of (a) BPI and (b) copper in biodiesel with the BPI, the former was obtained using dried black pepper extract (recorded using KBr pellet method), while the latter was recorded for biodiesel treated with 2.5 ppm inhibitor and powdered copper for 24 h.

Results and Discussion

Fire point, flash point, cloud point and pour point of neem biodiesel prepared are found to be 102°C, 93°C, 10.2°C and 6.6°C, respectively. Carbon residue, kinetic viscosity and density of neem biodiesel are estimated as 0.746%, 8.70 mm²/s and 0.839 g/cm³, respectively.

Piper nigrum, commonly known as 'black pepper' belongs to the Piperaceae family. Vietnam is recognized as the leading pepper producer and exporter. The compound piperine found in black pepper possesses antioxidant attributes, effectively mitigating oxidative damage by neutralizing reactive species accountable for oxidation[31]. Given that corrosion is essentially an oxidation process, the antioxidant attributes of black pepper can serve as an effective inhibitor.

BOWMAN - X-ray fluorescence, MODEL: GOLD SCOPE SDD, SERIAL NO- XI18120024SDD estimated that the test specimen has 100% copper as illustrated in Fig. 1. EDX method has

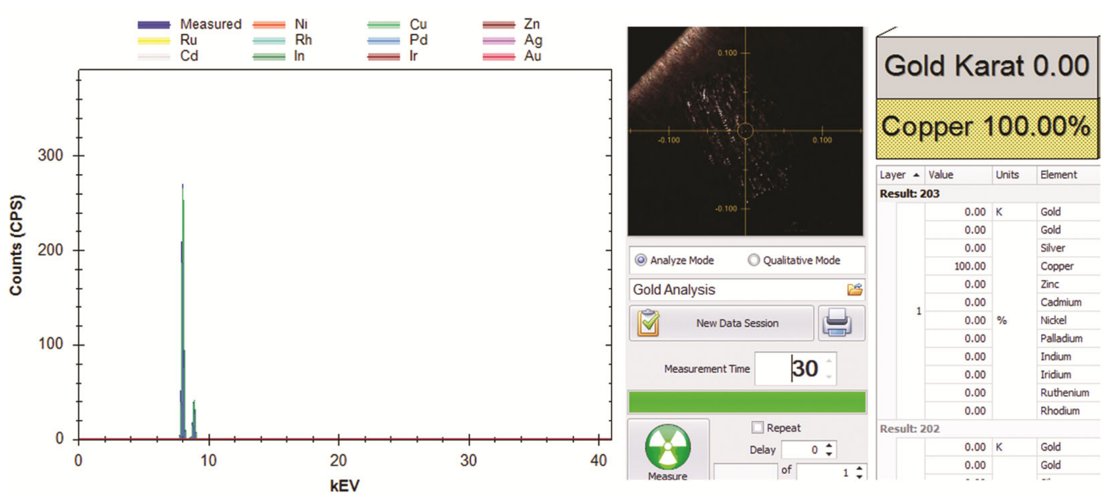

Fig. 1 — XRF image of copper specimen

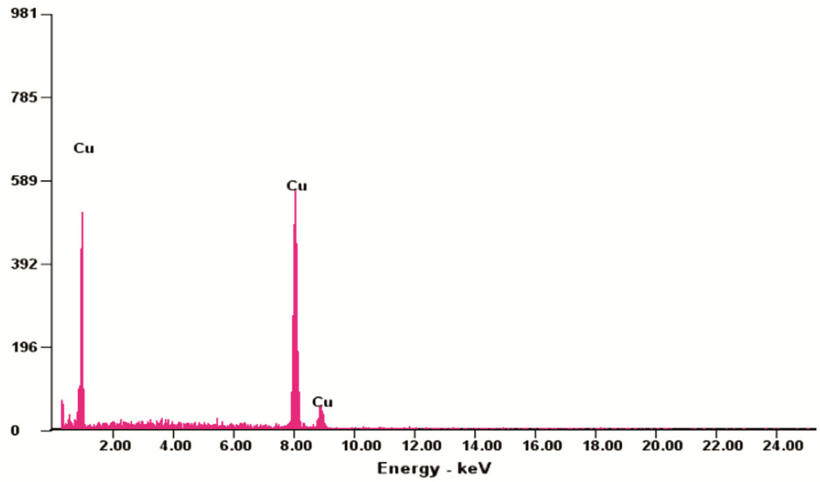

Fig. 2 — EDX image of copper specimen

also revealed 100% copper purity that is illustrated in the Fig. 2.

An increase in the acid value of biodiesel was observed during storage over several days. Consequently, investigating corrosion characteristics under higher acid values is very crucial[32,33]. Weight loss evaluations were performed for all the three acid values of biodiesel.

Weight loss evaluations

During corrosion, copper metals undergo oxidation and dissolves in biodiesel medium as copper ions, resulting in the weight loss of copper metal specimen submerged in biodiesel. The weight loss behaviour of copper, both in the presence and absence of a corrosion inhibitor within biodiesel media, was systematically evaluated and is presented in Figs 2-5. The analysis clearly indicated that the weight loss of copper samples increased progressively with rising temperatures. This trend is consistent with the well-known principle that higher temperatures typically accelerate the kinetics of corrosion reactions, leading to greater material degradation. As temperature rises, the energy available for chemical reactions also increases, thereby facilitating faster oxidation processes on the copper surface. Despite the intensified corrosive conditions at elevated temperatures, the application of the corrosion inhibitor proved to be highly effective. Even under challenging high-temperature environments, the inhibitor maintained significant corrosion protection, drastically reducing the extent of copper weight loss compared to uninhibited samples. This highlights the strong temperature-resistant performance of the inhibitor, suggesting its potential suitability for real-

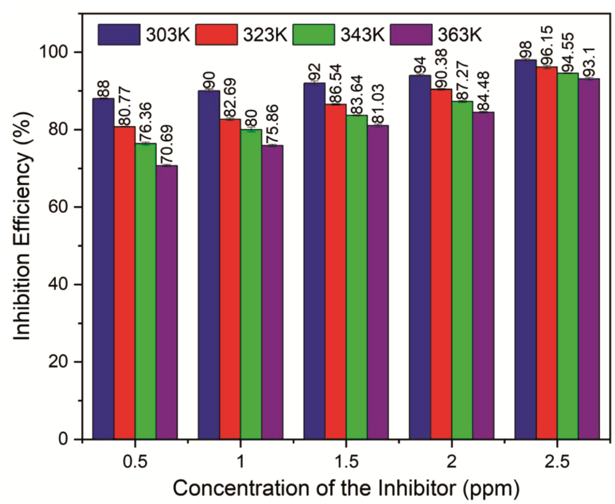

Fig. 3 — Plot with error bars for inhibitor dosages versus IE at different temperatures for biodiesel with an acid value of 0.4 mg KOH/g

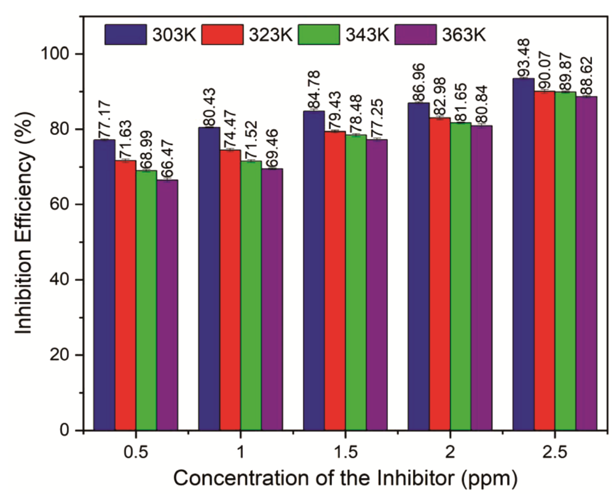

Fig. 4 — Plot with error bars for inhibitor dosages versus IE at different temperatures for biodiesel with an acid value of 0.8 mg KOH/g

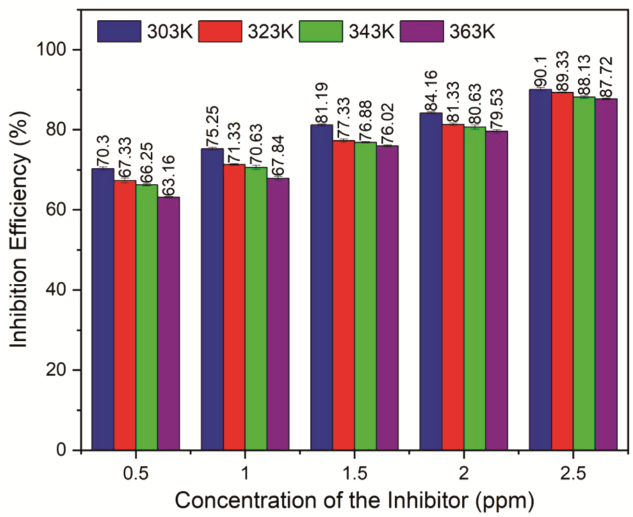

Fig. 5 — Plot with error bars for inhibitor dosages versus IE at different temperatures for biodiesel with an acid value of 1.2 mg KOH/g.

world applications where biodiesel systems are exposed to fluctuating or high thermal conditions. Overall, these results reinforce the critical role of corrosion inhibitors in preserving metal integrity in biodiesel media, particularly under thermal stress, underlining the effectiveness of the specific inhibitor used in mitigating copper corrosion across a broad range of temperatures. Additionally, it was observed that copper corrosion increased only slightly with higher acid values in biodiesel[34]. The corrosion of metals increases with higher acid values in biodiesel. However, the standard ASTM and EU acid value specifications for biodiesel are 0.8 and 0.5 mg KOH/g, respectively[35].

As demonstrated in Figs 3-5, the IE reaches its peak at higher doses of the inhibitor, as indicated by the graphical representation. Notably, for doses of 2 ppm and 2.5 ppm, IE is very close. A maximum IE of 98% was observed for 2.5 ppm using weight loss method[36].

Upon visual examination, copper specimens immersed in biodiesel with an acid value of 0.4 mg KOH/g retained their original colour on the metal alloy surface. Nevertheless, for samples immersed in biodiesel featuring acid values of 0.8 and 1.2 mg KOH/g, the surface changed to bluish-green hue, particularly pronounced in the latter case. Interestingly, the addition of the inhibitor to the biodiesel prevented the development of this bluish-green color on the metal surface. Existing literature notes that the corrosion product of copper exhibits a bluish-green colour. Thus, visual inspection affirms that the investigated natural inhibitor provides protection against biodiesel-induced copper corrosion[37].

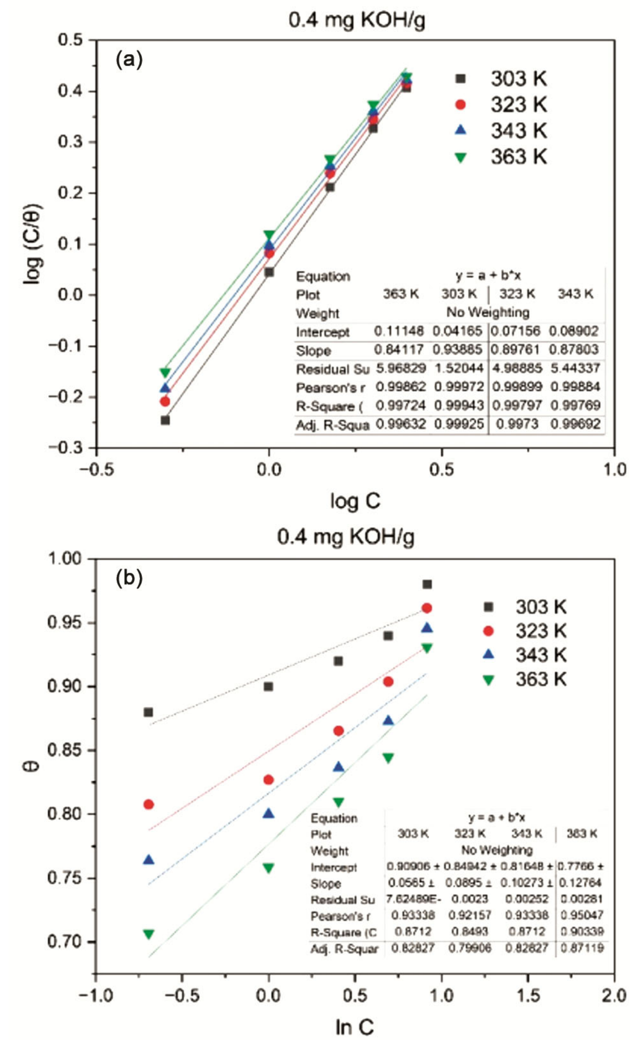

Fig. 6 — Isotherm plots for (a) Langmuir and (b) Temkin's Adsorption

Adsorption isotherm

Langmuir and Temkin adsorption isotherms were constructed and are illustrated in Fig. 6. Upon analysis, it is clear that the correlation coefficient (R^2) for the Langmuir isotherm is closer to unity compared to that of the Temkin isotherm. This stronger linearity suggests that the adsorption of inhibitor molecules from the extract onto the copper surface predominantly followed the Langmuir model. Such behaviour implies that the adsorption process involved a uniform monolayer formation, where each active site on the copper surface was occupied by a single inhibitor molecule without any significant interaction between adsorbed species. This finding supports the hypothesis of molecular-level interactions between the inhibitor components and the copper substrate, resulting in effective surface coverage and protection. The close adherence to the Langmuir model revealed the efficiency of the inhibitors in forming a compact and stable monolayer, which is crucial for minimizing corrosion processes[38,39,40].

Evaluation of Thermodynamics of Corrosion Inhibition

Negative values were obtained for the heat of adsorption, indicating that the inhibitor's adsorption onto the copper metal surface occurred spontaneously. Through adsorption of the said inhibitor on the copper metal surface a barrier was formed that avoided direct contact of the biodiesel with the said metal. Evidently, the adsorption mechanism of the inhibitor ceased the corrosion reactions[41].

Negative entropy values manifest the adsorption of the inhibitor onto the copper surface. Initially, the inhibitor circulated freely within the entire biodiesel medium. However, upon introducing the metal surface into the medium, the inhibitor molecules were attracted and adsorbed onto the copper. This reduced the inhibitor's randomness within the biodiesel medium, consequently mitigating corrosion, while reducing entropy. The free energy change values for the adsorption process of the inhibitor onto the metal surface were approximately -20 kJ/mol. This indicates that the adsorption of the BPI on copper surface is a physical adsorption phenomenon. If chemisorption had taken place, Gibbs free energy values should have been within the range of -49 to -58 kJ/mol. The negative free energy values also signify the spontaneous nature of the adsorption process of the inhibitor on the copper surface[42].

The activation energy (E) and corrosion rate (CR) for different inhibitor concentrations in the biodiesel medium, applied to copper corrosion reactions at various temperatures and acid values, were calculated using Eqs (1) and (2), respectively.

Notably, an increase in the inhibitor concentration corresponds to a decrease in the corrosion rate at the respective temperature. It is worth highlighting that across various inhibitor concentrations, the activation energy for the corrosion reaction consistently surpasses the value obtained in the absence of an inhibitor[13]. This underscores the heightened energy requirement for the corrosion reaction to take place at different inhibitor doses. Hence, it is very clear that the presence of BPI in biodiesel substantially impedes copper corrosion across diverse temperatures and acid values.

Fig. 7 shows the FTIR spectra of (a) BPI as an inhibitor and (b) copper in biodiesel with the same extract. Black pepper's chemical composition includes terpenes and nitrogen-containing compounds such as α- and β-pipene, myrcene, α-phellandrene, limonene, linalool, methyl propanal, 2- and 3-methylbutanal, butyric acid, 3-methylbutyric acid, 2,3-diethyl-5-methylpyrazine, piperine, and 2-isopropyl-3-methoxypyrazine[28,29]. The shift in the carbonyl group's absorption band from 1738.53 cm^{-1} to 1732.14 cm^{-1} indicates its involvement in adsorption onto the metal surface. Additionally, shift in the aldehydic carbon-hydrogen bond from 2920.79 cm^{-1} to 2931.79 cm^{-1} was observed[31]. The change in the absorption band from 1438.56 cm^{-1} to 1445.15 cm^{-1} suggests adsorption of the amine group onto the metal. The reduction in absorption frequency of various functional groups during adsorption on the copper surface can be attributed to a weakening of bond strength. This weakening occurs due to the interaction between the bond and the metal surface. Overall, the FTIR spectral absorption frequency differences between (a) and (b) underline the adsorption of inhibitors on to the metal surface creating a protective barrier against biodiesel inhibiting corrosion.

SEM analysis

Scanning Electron Microscope (SEM) analysis with the corresponding images was presented in Figs. 8a-c.

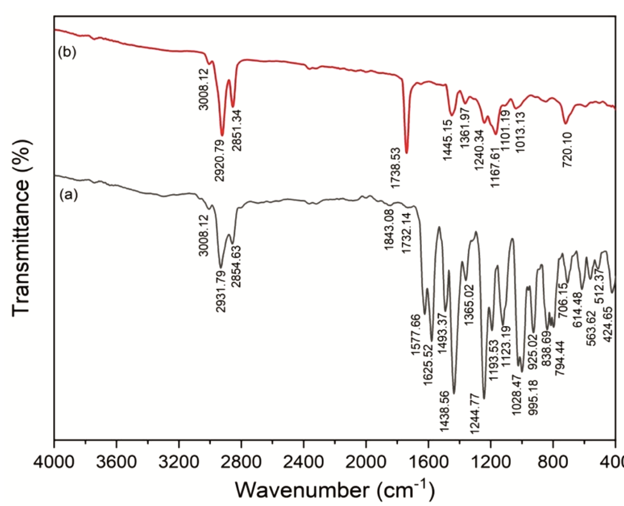

Fig. 7 — Amalgamated FTIR image (a) black pepper inhibitor and (b) Copper in biodiesel with BPI

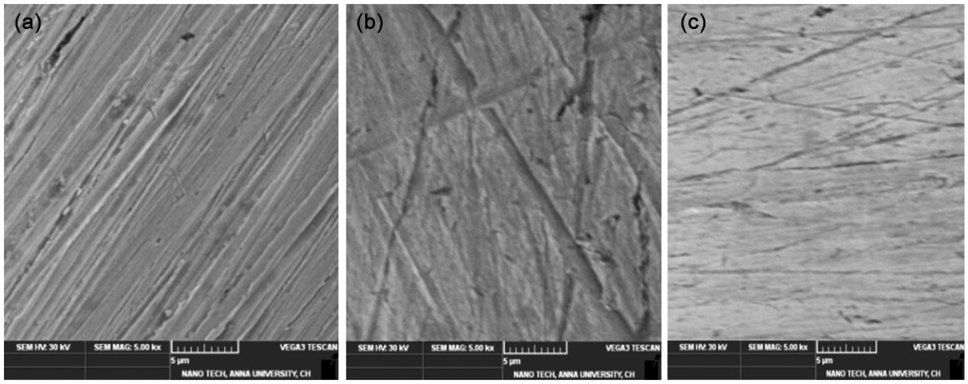

Fig. 8 — SEM of copper specimens: (a) after polishing, (b) exposed to biodiesel without inhibitor (c) 2.5 ppm inhibitor in biodiesel

The copper specimen subjected to biodiesel without the inhibitor demonstrated more evident external damage, including colour alteration as well as minor pits and cracks, visibly discernible in the SEM micrograph (Fig. 8b). Conversely, upon the application of the inhibitor, the SEM analysis of the copper samples displayed no changes in surface morphology, such as the presence of pits or cracks. This observation underscores the protective attributes of the BPI having heterogeneous compounds that function against copper corrosion in the said natural fuel.

High temperature corrosion prediction with machine learning

Neem biodiesel exhibits flash and fire points of 446 K and 478 K, respectively. Any biodiesel undergoes spontaneous combustion above its fire point, consequently, corrosion experiments cannot be conducted under such conditions. Biodiesel remains in liquid form as it flows through the nozzle into the combustion chamber of diesel engines, where temperatures reach 575 K, emphasizing the importance of evaluating corrosion effects at this elevated thermal condition. Therefore, high-temperature corrosion prediction was performed to evaluate its effect on copper corrosion under engine nozzle operating temperatures[43,44]. This prediction was made by machine learning quadratic regression. The schematic diagram of the quadratic regression algorithm is given in Fig. 9.

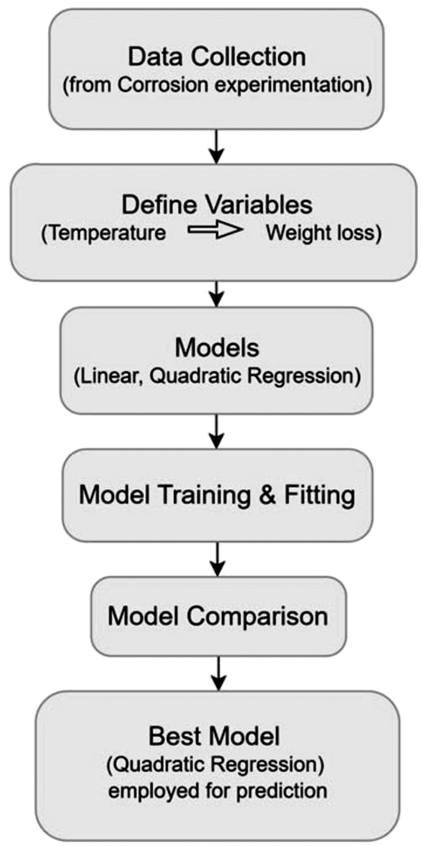

Fig. 9 — Schematic diagram of the quadratic regression algorithm

Fig.10 illustrates the scatter plots depicting the relationship between weight loss and temperature, while Table 1 presents the regression parameters, including data skewness, kurtosis, R^2, and adjusted R^2 values. The scatter plots suggest that the quadratic (degree 2) regression model provides the best fit for this relationship, as the cubic polynomial model shows a lower adjusted R^2 value. The ordinary least squares regression analysis shows similar skewness values for weight loss data at both 0 ppm and 2.5 ppm concentrations under linear regression. However, in quadratic regression, skewness values differ due to the data transformation involving power terms. The linear regression data approximates a normal distribution, whereas quadratic regression data shows greater dispersion from the mean, as indicated by higher kurtosis values. This dispersion is attributed to the inclusion of power terms in the quadratic model.

The coefficient of determination, R^2, represents the proportion of weight loss variation with respect to

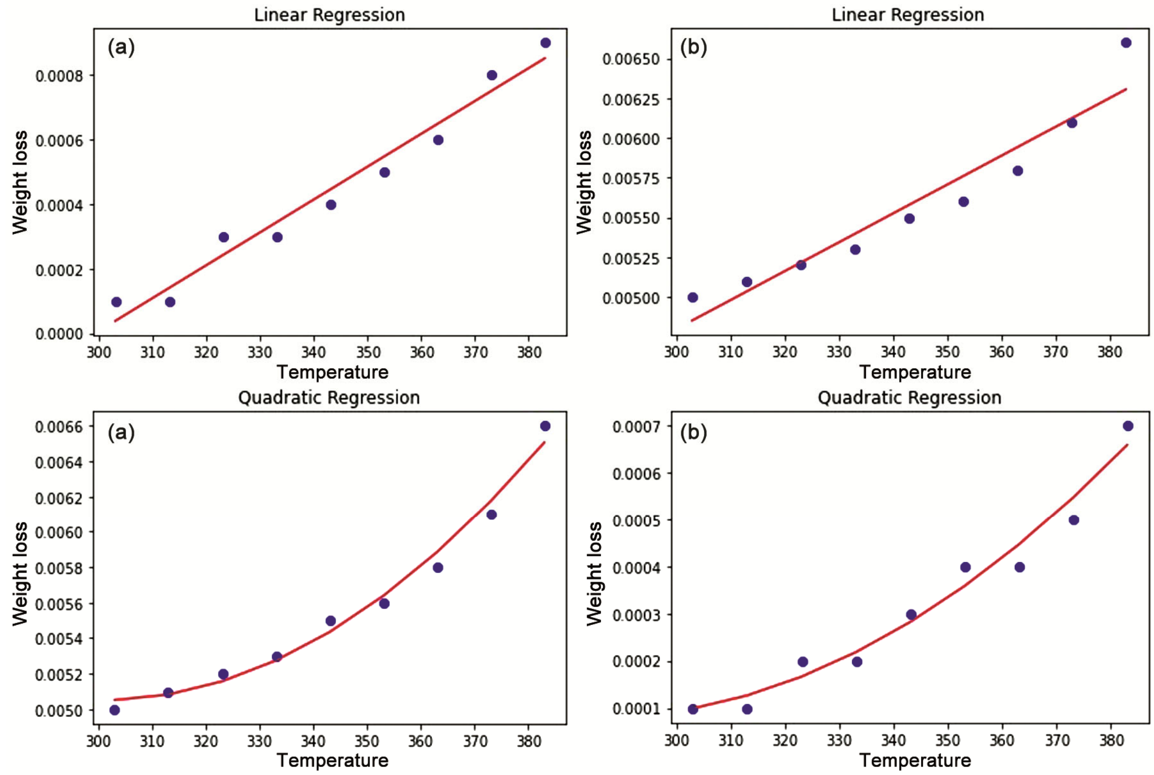

Fig. 10 — Scattered plots for weight loss against temperature (a) 0PPM and (b) 2.5 ppm inhibitor dosage in neem biodiesel

Table 1 — Regression Parameters

Regression algorithms	Skew		Kurtosis		R^2 values		Adj. R^2 values	
	0 ppm	2.5 ppm	0 ppm	2.5 ppm	0 ppm	2.5 ppm	0 ppm	2.5 ppm
Linear regression	0.865	0.668	2.723	2.449	0.932	0.966	0.922	0.961
Quadratic regression	0.032	-0.091	1.611	1.474	0.968	0.983	0.957	0.977
Degree-3 regression	0.880	0.120	2.888	1.590	0.955	0.983	0.972	0.973

changes in temperature. A higher R^2 value, approaching the maximum of 1, indicates a better fit of the model. Comparing the linear and quadratic regression models for both 0 ppm and 2.5 ppm inhibitor concentrations, the quadratic model demonstrates superior fit over the linear model. The cubic polynomial regression shows a lower R^2 value, confirming that the quadratic model, more accurately predicts copper weight loss in biodiesel across varying temperatures[42].

The confidence interval for the intercept ranges from -0.003 to 0.011, and similar non-zero values are observed for other coefficients. The quadratic regression coefficients for copper corrosion in neem biodiesel, with 2.5 ppm inhibitor dosage, are $-3.067e^{-05}$ and $5.952e^{-08}$, which are also non-zero for the 0 ppm dosage, indicating the impact of temperature on copper corrosion. This confirms the validity of the alternative hypothesis and leads to the rejection of the null hypothesis. The quadratic equations for weight loss in neem biodiesel with 0 ppm and 2.5 ppm inhibitor are $154e^{-07}T^2 - 1.001e^{-05}T + 0.0025$ and $5.952e^{-08}T^2 - 3.067e^{-05}T + 0.0039$, respectively.

Table 2 presents predictions of copper weight loss in neem biodiesel at various temperatures using both linear and quadratic regression models. It is evident from Table 2 that irrespective of the presence or absence of the corrosion inhibitor in neem biodiesel, corrosion is very high for copper around 600K, the operating temperature of copper nozzles. Copper experiences greater weight loss in neem biodiesel without an inhibitor, both at ambient temperatures and at higher temperatures typical of engine operation, compared to when 2.5 ppm of inhibitor is used. Notably, the quadratic regression model predicts a reduction in weight loss of 0.006 g at 400K and 0.0174 g at 600K with the 2.5 ppm inhibitor. Given

Table 2 — Weight loss predictions for copper in neem biodiesel at different temperatures

Temperature	Weight loss Predictions for copper in neem biodiesel in grams			
	Linear model for 0 ppm inhibitor in biodiesel	Linear model for 2.5 ppm inhibitor in biodiesel	Quadratic model for 0 ppm inhibitor in biodiesel	Quadratic model for 2.5 ppm inhibitor in biodiesel
400	0.0066	0.0010	0.0072	0.0012
450	0.0075	0.0015	0.0098	0.0022
500	0.0084	0.0020	0.0136	0.0035
550	0.0093	0.0025	0.0184	0.0051
600	0.0102	0.0031	0.0243	0.0069
650	0.0112	0.0036	0.0313	0.0091
700	0.0121	0.0041	0.0394	0.0116
750	0.0130	0.0046	0.0485	0.0144
800	0.0139	0.0051	0.0587	0.0175
850	0.0149	0.0056	0.0700	0.0209
900	0.0157	0.0061	0.0824	0.0245
950	0.0166	0.0066	0.0958	0.0285
1000	0.0175	0.0071	0.1103	0.0328

the higher accuracy of the quadratic regression model over the linear model, the values from the quadratic model are preferred.

Conclusion

XRF and EDX analyses confirmed that the copper test specimen was composed entirely of copper. The weight loss assessments indicated a clear positive correlation between acid values and corrosion rates. Nonetheless, the inclusion of BPI in neem biodiesel significantly reduced corrosion, achieving an inhibition IE of 98%.Elevated temperatures above room temperature resulted in larger weight loss of copper in neem biodiesel; however, the incorporation of BPI significantly reduced the extent of corrosion.

The adsorption of the BPI was found to be spontaneous, as evidenced by negative free energy change values. This leads to higher activation energy for the corrosion reaction of copper in inhibitor added biodiesel than without it. The negative heat of adsorption suggests an exothermic reaction. The inhibitor's adsorption onto the copper surface followed the monolayer Langmuir adsorption isotherm.

FTIR spectra indicated the formation of a protective layer by the said inhibitor on the copper surface in neem biodiesel environment, contributing to corrosion prevention. Scanning Electron Microscopy (SEM) images provided clear evidence of the protective effects of the BPI on the copper surface in biodiesel, preventing the formation of cracks and indentations.

Quadratic regression models predicted a reduction in weight loss by approximately 0.0174 g at the operational temperature of copper nozzles (600K) with 2.5 ppm inhibitor in the biodiesel than the blank.

Overall, the findings demonstrate that value added biodiesel with black pepper corrosion inhibitor can serve as an effective, non-corrosive, and environmentally friendly fuel without compromising its performance characteristics.

Conflict of interest

The authors declare no conflict of interest.

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