JURNAL TEKNIK
Volume 23, No. 2, Desember 2025
P-ISSN : 1693-6191 E-ISSN : 2715-7660 DOI : https://doi.org/10.37031/jt.v23i2.650

ENHANCING HEAT TREATMENT LEARNING FOR MECHANICAL ENGINEERING STUDENTS: A COMPARATIVE STUDY OF CORROSION INHIBITOR EFFECTIVENESS ON ALUMINIUM PROTECTION

[1]Saifuddin Karim, [2]Yayi Febdia Pradani, [3]Danang Yugo Pratomo, [4]Imam Muhtarom, [5]Tamara Rahma Widowati [6]Dian Julianto Wahyudi [7]Amelia Dini Wulandari [8]Prido Subekhi
[1,2,3,4,5,6,7,8] Department of Mechanical and Industrial Engineering, Universitas Negeri Malang, Indonesia.
e-mail: saifuddin.karim.ft@um.ac.id (correspondence email)

Abstract

Corrosion still remains a serious problem in the application of aluminum alloys, such as Aluminum 6061, which is one of the most widely used aluminum alloys in industries because of its high strength-to-weight ratio. However, the material degrades when exposed to aggressive environments, such as acidic, alkaline, or salty solutions, and the control of corrosion has been achieved with the use of synthetic chemical inhibitors, but the increasing concern of environmental and health risks has shifted attention to more eco-friendly alternatives. The present study aimed at evaluating the efficacy of three vegetable oils (coconut oil, palm oil, and soybean oil) as environmentally friendly corrosion inhibitors for Aluminum 6061, and the alloy coupons were subjected to three different corrosive solutions (hydrochloric acid, sodium hydroxide, and sodium chloride). A quantitative experimental procedure was employed to determine the corrosion rate through the measurement of the weight loss of aluminum coupons prior to and after the immersion, and the results showed that all three oils were able to reduce the corrosion rate when compared to the samples without any inhibitor. Among them, coconut oil gave the best protection, followed by soybean oil and palm oil, because the adsorption of the organic compounds and fatty acids in the oils onto the aluminum surface formed a thin layer that separated the metal and the corrosive environment. Consequently, the results also showed that the use of bio-based oils can be a promising alternative to synthetic corrosion inhibitors in industries that use aluminumbased materials.

***Keywords**: Aluminum 6061, Corrosion Inhibitor, Coconut Oil, Palm Oil, Soybean Oil*

Diterima : Oktober 2025
Disetujui : November 2025
Dipublikasi : Desember 2025

Introduction

Corrosion of metallic materials is still a major concern in several industrial applications, especially aluminum alloys such as Aluminum 6061, which is widely used in various applications due to its low density, high mechanical strength, good machinability, and other favorable properties. However, it still undergoes degradation in the presence of aggressive environments such as acidic, alkaline, and saline media (Iroha & Maduelosi, 2021; Rajimol dkk., 2023), and therefore, corrosion problem shortens the lifetime of materials and their structural integrity, especially in the automotive, aerospace, and construction industries. Consequently, the need for effective corrosion control methods cannot be overemphasized, and besides, there is a growing need for sustainable and environmentally friendly methods to inhibit corrosion.

Corrosion control is one of the essential practices in industries, and chemical inhibitors are widely used, however, the chemical inhibitors are harmful to the environment and human health because of their toxic and nonbiodegradable nature. Therefore, in recent years, the focus is on green corrosion inhibitors, which are obtained from natural renewable sources, and among these sources, coconut oil is the most attractive due to its biodegradable nature, low cost, and easy availability. It is reported in the literature that the vegetable oils (including coconut oil) are effective corrosion inhibitors because they adsorb on the metal surface to form a film which prevents the direct contact of metal with the corrosive environment, and this results in the decrease in the corrosion current density (icorr) and the shift in the corrosion potential (Ecorr) to more noble values, both of which lead to a decrease in the corrosion rate (Al-Otaibi dkk., 2014; Deshpande & Jyothi, 2022; Galleguillos Madrid dkk., 2024; Njoku dkk., 2016; Shwethambika & Ishwara Bhat, 2021).

Several investigations have been carried out on the application of green inhibitors for reduction of aluminum corrosion under different conditions. (Iroha & Maduelosi, 2021) reported that Justicia secunda leaf extract effectively inhibits aluminum corrosion in acidic media, and (Wickramasinghe dkk., 2021) also reported that coconut oil improves corrosion resistance of Aluminum 6061 when used as a cutting fluid. Although these works revealed the inhibition potency of green inhibitors, most works on green inhibition have been based on single inhibitor systems and narrow environmental conditions, hence, comparative analysis of the inhibition performance of different vegetable oils under different corrosive conditions, such as acidic, alkaline, and saline media, are still limited, as noted by (El-Etre, 2003; Verma dkk., 2019).

Hence, the aim of the present study is to investigate and compare the corrosion inhibition performance of coconut oil, palm oil, and soybean oil on Aluminum 6061 in three corrosive environments: acidic, alkaline, and saline solutions. This study is conducted because the weight loss technique was adopted to study the corrosion behavior of the samples by measuring the change in mass of the samples before and after immersion in the test medium, and therefore, it aims to answer two important questions: how effective is each vegetable oil as corrosion inhibitor in comparison with the other two, and in which corrosive medium does each of the oils give the best protection for Aluminum 6061.

Since there is no such comparative study reported in the literature, there is a research gap regarding the comparative investigation of different vegetable oils, especially coconut oil, palm oil, and soybean oil, as corrosion inhibitors for Aluminum 6061 in various corrosive environments. Therefore, this study aims to bridge this research gap by presenting a comprehensive experimental dataset that provides insight into the relative performance of these oils in acidic, alkaline, and saline media, and the outcomes of the current study are expected to assist in the formulation of green corrosion protection strategies and to provide evidence-based data that supports the growing adoption of green technology concepts in materials engineering and allied industries.

Method

The present investigation is to study corrosion inhibition characteristics of coconut oil, palm oil, and soybean oil on Aluminium 6061 using the weight loss method in a controlled laboratory environment and a quantitative experimental design. The weight-loss method is considered a reliable and accurate method of material degradation in a corrosive environment because it provides a precise measurement of corrosion (Kazeem dkk., 2022; Negm dkk., 2014; Popoola dkk., 2013; Raja & Sethuraman, 2008). In this study, all the test parameters were kept constant, including properties of the aluminum specimens, properties of the corrosive solution, such as acidic, alkaline, and saline solutions (1:1 HCl, 1:3 M NaOH, and 1:1 NaCl, respectively), immersion time (24 h), heat treatment of specimens (quenching), temperature of the test (150 °C), and volume of the solution used (250 ml), in order to ensure consistent results. Every test condition was performed in triplicate to improve the repeatability and strengthen the statistical reliability of the results, thus increasing the validity of the findings.

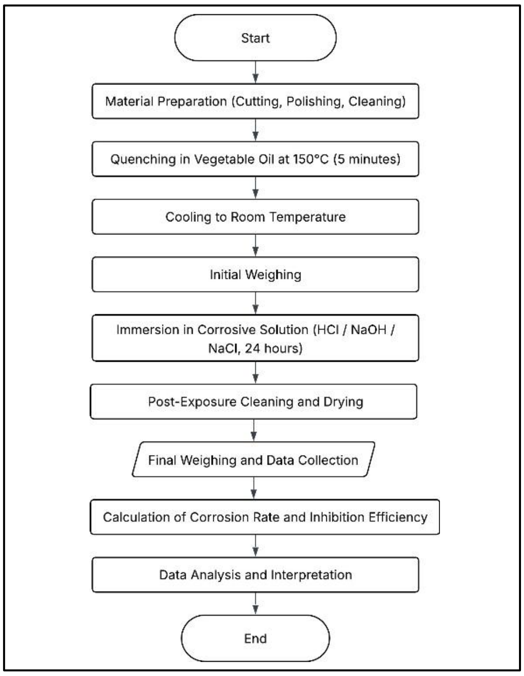


Figure 1. Experimental Procedure Flowchart for Corrosion

The main data produced by this study include the mass loss of Aluminum 6061 before and after immersion, the corrosion rates and inhibition efficiencies calculated, because masses were measured using a precision analytical balance with a resolution of 0.1 g. Before immersion, the samples were washed in an ultrasonic cleaner to remove surface contaminants and ensure that each sample is exposed uniformly to the corrosive media. The study is both exploratory and comparative, as it seeks to investigate the potential of coconut, palm, and soybean oils as natural corrosion inhibitors and compare their inhibitive performance in different corrosive media.

The present study proposes to develop a multivariate analytical method for understanding the cumulative influences of critical factors (solution concentration and exposure time) on the corrosion behavior of Aluminum 6061, and alongside the technical aspects, the study is also directed towards sustainable developments through assessment of environmentally friendly alternatives to conventional synthetic corrosion inhibitors. In agreement with the recent directions in green chemistry and sustainable materials engineering (El-Lateef dkk., 2022), the proposed study is expected to produce findings that can be useful for designing novel, eco-friendly corrosion protection technologies.

Corrosion rate is a quantitative measure of the rate of deterioration of a material, and it is often converted from mass change per unit area per unit time. The units of corrosion rate are often millimeters per year (mm/yr) or milligrams per square decimeter per day (mdd), because in laboratory weight-loss experiments, the corrosion rate is usually determined by mass change of the specimen using the following equation:

$$\boldsymbol{C.R}\left(\frac{\boldsymbol{mm}}{\boldsymbol{year}}\right) = \frac{(\mathbf{w0} - \mathbf{w1})\ \mathbf{x}\ \boldsymbol{K}}{\boldsymbol{a}\,.\,\boldsymbol{t}\,.\,\boldsymbol{d}}$$

w0 = Initial Weight Before Corrosion (grams)
w1 = Final Weight After Corrosion (grams)
a = Surface Area (cm²)
t = Exposure Time (Hours)
d = Metal Density (2.70 grams/cm3)
K = Constant To Convert The Units To The Desired Corrosion Rate Unit

A conversion constant (K) is used to keep the units constant in the corrosion rate equation when the corrosion rate is calculated in mm/year, and in this study, the K value of 87,600 was used for weight loss in milligrams, exposed surface area in cm², exposure time in hours, and material density in g/cm³. This constant includes the units conversion for the time of exposure (from hours to years) and the mass loss in thickness loss. The aluminum specimens were machined to 8.2 × 5.152 × 5 cm³, and before the tests, the surface of the samples was polished progressively with emery paper to a final polish of 1200 grit to a uniform finish. After this, the specimens were washed with distilled water and dried, and after immersion in the corrosive medium, each specimen was washed, ultrasonically cleaned in ethanol to remove the products of corrosion, and dried before the final weighing. This procedure was used to minimize the effect of post-immersion oxidation and to obtain a more accurate measure of mass loss.

Result and Discussion

Result

The incorporation of coconut oil, palm oil, and soybean oil as corrosion inhibitors promoted a reduction of the corrosion rate of the Aluminum 6061 when compared to samples exposed to the corrosive media without inhibitor, and this result is in agreement with the literature, which says that the organic compounds present in the vegetable oils can adsorb on the surface of the metal, forming a protective film, thereby avoiding the direct contact of the metal with the aggressive ions of the environment.

- Control (Without Corrosion Inhibitors)

The corrosion behavior of Aluminum 6061 in uninhibited condition was evaluated in three corrosive environments of 1:1 HCl, 1:3 NaOH and 1:1 NaCl for 24 h, and the specimen underwent zero treatment and was ultrasonically degreased for 10 min before and after immersion. The corrosion rate of the Aluminum 6061 specimens with a surface area of 42.2464 cm², as summarized in Table 1, varied with the three corrosive media, because the highest corrosion rate of 0.435 mm/year was recorded in 1:3 NaOH, followed by 1:1 HCl with a corrosion rate of 0.230 mm/year, and the lowest corrosion rate of 0.022 mm/year was recorded in 1:1 NaCl. The alkaline solution of NaOH is the most aggressive medium for the corrosion of Aluminum 6061 in the absence of an inhibitor, whereas the saline solution of NaCl is less corrosive; therefore, these results in the absence of an inhibitor serve as the baseline in evaluating the effectiveness of the vegetable oil–based corrosion inhibitor treatments in the following experiments.


Figure 2. Result HCL

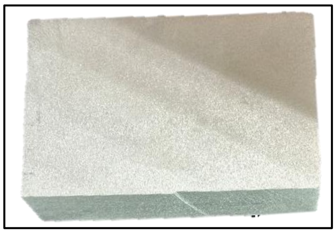


Figure 3. Result NaOH


Figure 4. Result NaCL

Table 1. Corrosion control results table

No	Initial and Final Degreasing	Treatment Time and Temperature	Surface Area (cm²)	Solvent	Initial Weight (grams)	Final Weight (grams)	Corrosion Rate (mm/year)
1	Ultrasonic 10 Minutes	0	42.2464	HCL 1:1	298.2	291	0.230394385

2			42.2464	NaOH 1:3	311.4	297.8	0.435189393
3			42.2464	NaCL 1:1	301.9	301.2	0.022399454

- Coconut Oil

Coconut oil is a good corrosion inhibitor of aluminium in HCl solution, and it reduced the corrosion rate considerably, with an inhibition efficiency of about 84% reported in a previous study at higher inhibitor concentration. The protective action was mainly attributed to the physical adsorption of coconut oil molecules onto the aluminium surface to form a barrier that reduces the access of corrosive species to the metal. The results in Table 2 show that the aluminium 6061 specimens of total exposed surface area of 42.2454 cm² had different corrosion rates in the corrosive media, with the highest corrosion rate of 0.371 mm/year obtained in the 1:3 NaOH solution, while the 1:1 HCl solution had 0.208 mm/year and the 1:1 NaCl solution had the lowest corrosion rate of 0.019 mm/year. This means that the alkaline medium of NaOH is more aggressive than NaCl towards Aluminium 6061, and the saline medium of NaCl is less aggressive; hence, the uninhibited condition is considered as a control to enable the comparison and assessment of the relative effectiveness of the corrosion inhibitor treatment.

Figure 5. Result HCL

Figure 6. Result NaOH

Figure 7. Result NaCL

Table 2. Corrosion Quenching Coconut Oil results table

No	Initial and Final Degreasing	Treatment Time and Temperature	Surface Area (cm²)	Solven t	Initial Weight (grams)	Final Weight (grams)	Corrosion Rate (mm/year)
1	Ultrasonic 10 Minutes	5 minute in 150°C	42.2464	HCL 1:1	298.7	292.2	0.207994931
2			42.2464	NaOH 1:3	303.7	292.1	0.371190953
3			42.2464	NaCL 1:1	311.2	310.6	0.019199532

- Palm Oil

The palm oil has been shown to be an excellent corrosion inhibitor, particularly in the acid environment, and the reaction product from palm fatty acids and monoethanolamine has been reported to reduce the corrosion rate up to 80% at certain concentrations. The inhibition mechanism was found to follow the Langmuir adsorption isotherm, which means that the inhibitor molecules of palm oil are adsorbed on the surface of metal, forming a stable and protective layer preventing the corrosive species from reaching the aluminum. In this study, the corrosion performance of palm oil treated Aluminum 6061 was determined using specimens with exposed surface area of 42.2464 cm² in three corrosive media as shown in Table 3. The highest corrosion rate was obtained in 1:3 NaOH solution, which was 0.419 mm/year, and the second highest was 1:1 HCl solution, which was 0.1344 mm/year, while the lowest corrosion rate was in the 1:1 NaCl solution, which was 0.0032 mm/year. These results show that the palm oil treated specimens still exhibited the most aggressive corrosion behaviour in the alkaline environment of NaOH, and the least corrosion behaviour in the saline NaCl solution, even in the presence of palm oil. Therefore, the NaCl solution serves as a reference medium to assess the corrosion behaviour of palm oil treated specimens in the different corrosive media.

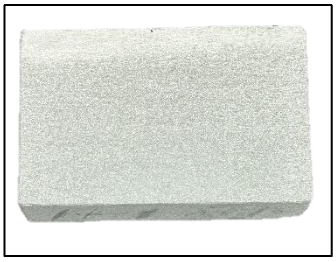


Figure 8. Result HCL

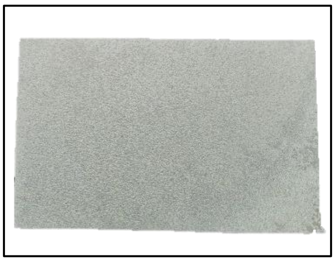


Figure 9. Result NaOH

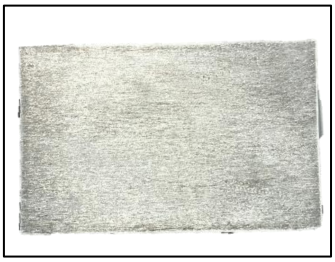


Figure 10. Result NaCL

Table 3. Corrosion Quenching Palm Oil results table

No	Initial and Final Degreasing	Treatment Time and Temperature	Surface Area (cm²)	Solvent	Initial Weight (grams)	Final Weight (grams)	Corrosion Rate (mm/year)
1	Ultrasonic 10 Minutes	5 minute in 150°C	42.2464	HCL 1:1	297.2	293	0.134396724
2			42.2464	NaOH 1:3	297	283.9	0.419189783
3			42.2464	NaCL 1:1	298.6	298.5	0.003199922

- Soybean Oil

Although few experimental works can be found regarding the use of soybean oil as corrosion inhibitor for aluminum, it is a consensus in the literature that vegetable oils rich in unsaturated fatty acids are able to inhibit corrosion through surface adsorption, because fatty-acid compounds in these oils tend to form adherent and protective films on metal surfaces that prevent the direct contact between the metal and aggressive species in the environment, which leads to a reduction in the corrosion rate. In this work, the behavior of Aluminum 6061 treated with soybean oil was evaluated in three different corrosive media, and the results are shown in Table 4, which indicates that all specimens treated with soybean oil presented different corrosion responses depending on the solution. The highest corrosion rate was observed in 1:3 NaOH solution (0.2496 mm/year), followed by 1:1 HCl solution (0.1376 mm/year), while the lowest corrosion rate occurred in 1:1 NaCl solution (0.0096 mm/year). These results confirm that the alkaline medium of NaOH is the most aggressive medium for Aluminum 6061 among the media investigated in this work, even when treated with soybean oil, and the saline medium of NaCl has the mildest corrosive effect; therefore, the NaCl condition is used as the baseline for comparison of the performance of soybean oil with other inhibitors used in this work.

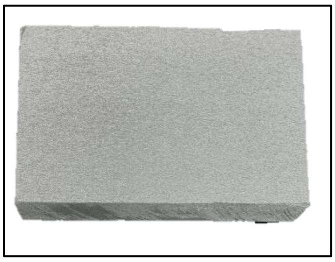


Figure 11. Result HCL

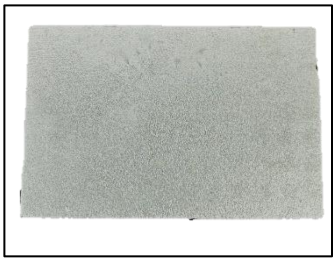


Figure 12. Result NaOH

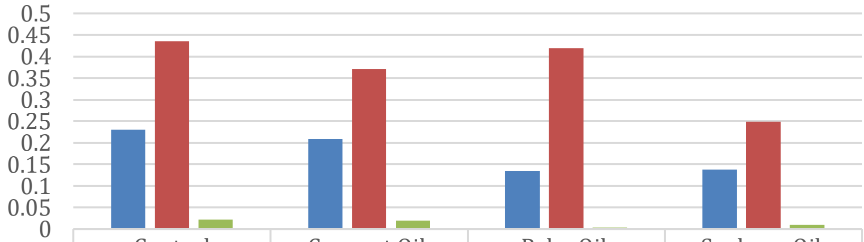
Figure 13. Result NaCL

Table 4. Corrosion Quenching Soyabean Oil results table

No	Initial and Final Degreasing	Treatment Time and Temperature	Surface Area (cm²)	Solvent	Initial Weight (grams)	Final Weight (grams)	Corrosion Rate (mm/year)
1	Ultrasonic 10 Minutes	5 minute in 150°C	42.2464	HCL 1:1	296.6	292.3	0.137596646
2			42.2464	NaOH 1:3	304.3	296.5	0.249593917
3			42.2464	NaCL 1:1	301.5	301.2	0.009599766

Based on the data Graph 1, corrosion rates of Aluminum 6061 with different corrosive mediums and vegetable oils as inhibitors. The corrosion rate of the aluminum 6061 in the different corrosive mediums is strongly influenced by the type of corrosive medium and type of vegetable oil as inhibitor. The least corrosion rate of the aluminum 6061 in the 1:3 NaOH solution was obtained with palm oil with a corrosion rate of 0.1344 mm/year, hence it can be deduced that palm oil provides the most effective protection for the aluminum 6061 in an alkaline environment. The least corrosion rate of the aluminum 6061 in the 1:1 HCl solution was obtained with coconut oil with a corrosion rate of 0.208 mm/year, hence it can be deduced that coconut oil is the most effective vegetable oil among the oils used in the acidic medium. The least corrosion rate of the aluminum 6061 in the 1:1 NaCl solution was obtained with soybean oil with a corrosion rate of 0.0032 mm/year, hence it can be deduced that soybean oil is the most effective vegetable oil among the oils used in the saline medium. Hence, it can be concluded that the inhibition efficiency of the vegetable oil is dependent on the type of corrosive environment, and each oil gave the best protection in a specific corrosive environment.

Graph 1. Corrosion Rate Graph



	Control	Coconut Oil	Palm Oil	Soybean Oil
HCL 1:1	0.230394385	0.207994931	0.134396724	0.137596646
NaOH 1:3	0.435189393	0.371190953	0.419189783	0.249593917
NaCL 1:1	0.022399454	0.019199532	0.003199922	0.009599766

HCL 1:1 NaOH 1:3 NaCL 1:1

Discussion

Corrosion is an electrochemical process of gradual degradation of material, in this case metal, by its interaction with the environment. Aluminum 6061, mainly consisting of aluminum with magnesium and silicon as main alloying elements, is a corrosion-resistant material in neutral environments, but it shows poor corrosion resistance in more aggressive conditions, and when exposed to acidic (HCl), alkaline (NaOH), or saline (NaCl) environments without any protective surface treatment or corrosion inhibitor, it will show high degradation and fast degradation of the material.

The experimental results indicated that the untreated control specimens had a relatively high corrosion rate in all the media investigated. The most aggressive medium in this case is the alkaline NaOH solution, in which the corrosion rate was 0.4351 mm/year, followed by the acidic HCl solution, in which the corrosion rate was 0.2304 mm/year, and this is in line with the established corrosion mechanism, which states that in alkaline media, aluminum dissolves to form soluble aluminate complexes, which are believed to promote continuous metal dissolution, while in acidic solution, the hydrogen ions are believed to promote the electrochemical reaction at the metal surface, leading to a high corrosion rate (Bierwagen dkk., 2003).

On the other hand, the quenching treatment with vegetable oils was responsible for a significant decrease of the corrosion rate, and the oils of coconut, palm and soybean presented an inhibitory behavior, which can be attributed to the organic compounds present in its composition, mainly the saturated and unsaturated fatty acids, such as lauric, oleic and linoleic acids. The polar functional groups of these molecules increased their ability to be adsorbed on the aluminum surface, forming a protective film, which prevents the direct contact between the metal substrate and the corrosive medium, thereby reducing the overall corrosion rate (Deshpande & Jyothi, 2022; Shwethambika & Ishwara Bhat, 2021).

Among the oils tested, palm oil was found to be the most effective corrosion inhibitor, and the corrosion inhibition effect was more pronounced in NaCl medium, and it brought the corrosion rate to 0.0032 mm/year, which is the lowest value obtained in this work. This shows that palm oil adsorbs on the surface of Aluminum 6061 to form a protective layer, which protects it from corrosion, and the result is in agreement with the literature that plant-based organic compounds have been reported to be good inhibitors for aluminium, and they usually act by mixed-type inhibition, i.e., affecting both the anodic metal dissolution and cathodic reduction reaction (Iroha & Maduelosi, 2021).

Soybean oil also performed admirably, and it did so in a manner that was notable. But not quite as admirably as palm oil, because palm oil has certain properties that make it more effective. Why, and the answer is because of the way the fatty acids in soybean oil are constructed. They react with the aluminum, and they adhere to it because of their chemical properties. And they lower the energy required for corrosion, thus corrosion slows (Rajimol dkk., 2023).

The different inhibition behaviours of the vegetable oils could be caused by the viscosity of the oil, the amount and the type of polar compounds and the thermal stability at the quenching temperature of 150 °C, because Palm oil appears to have the optimal combination of saturated and unsaturated compounds under these conditions that form a more stable and long-lasting passive layer on the surface of Aluminum 6061. The results presented above are in line with the fact that vegetable oils can be used as effective, sustainable and environmentally friendly corrosion inhibitors, and the very small mass loss of specimens quenched or treated with vegetable oils indicates that active compounds in the oils adsorb on the aluminum surface and form protective films. Moreover, the untreated specimens lost significant mass, which agrees with their higher corrosion rates and more serious surface damage observed.

Conclusion

The work presented in this paper shows that the use of vegetable oils as quenching media could reduce the corrosion rate of the Aluminum 6061 in aggressive environments like HCl, NaOH and NaCl solutions. All the oils used were good corrosion inhibitors, because they contain organic compounds and fatty acids, which adsorb onto the surface of the aluminum to form a protective film, and therefore, coconut oil had the highest degree of corrosion inhibition, followed by soybean oil and palm oil. The protective film prevents the direct contact between the metal and the corrosive ions in the solution and therefore reduces the corrosion rate.

This result has addressed the objective of the research, which is to show that thermochemical treatment of the locally available bio-based material offers a very effective and environmentally friendly alternative to the conventional synthetic corrosion inhibitors, because most synthetic chemicals are generally associated with some degree of environmental and health hazards. The utilization of vegetable oils as corrosion inhibitor is a viable and sustainable option, and this study has contributed to the advancement of green corrosion inhibition technologies, which are feasible in industrial applications where aluminum alloys are commonly employed.

Reference

Al-Otaibi, M. S., Al-Mayouf, A. M., Khan, M., Mousa, A. A., Al-Mazroa, S. A., & Alkhathlan, H. Z. (2014). Corrosion inhibitory action of some plant extracts on the corrosion of mild steel in acidic media. *Arabian Journal of Chemistry*, *7*(3), 340–346. https://doi.org/10.1016/j.arabjc.2012.01.015

Bierwagen, G., Tallman, D., Li, J., He, L., & Jeffcoate, C. (2003). EIS studies of coated metals in accelerated exposure. *Progress in organic coatings*, *46*(2), 149–158.

Deshpande, V., & Jyothi, P. (2022). A review on sustainable eco-friendly cutting fluids. *Journal of Sustainability and Environmental Management*, *1*(2), 306–320.

El-Etre, A. (2003). Inhibition of aluminum corrosion using Opuntia extract. *Corrosion science*, *45*(11), 2485–2495.

El-Lateef, H. M. A., El-Dabea, T., Khalaf, M. M., & Abu-Dief, A. M. (2022). Innovation of imine metal chelates as corrosion inhibitors at different media: A collective study. *International Journal of Molecular Sciences*, *23*(16), 9360.

Galleguillos Madrid, F. M., Soliz, A., Cáceres, L., Bergendahl, M., Leiva-Guajardo, S., Portillo, C., Olivares, D., Toro, N., Jimenez-Arevalo, V., & Páez, M. (2024). Green Corrosion Inhibitors for Metal and Alloys Protection in Contact with Aqueous Saline. *Materials*, *17*(16), 3996.

Iroha, N. B., & Maduelosi, N. J. (2021). Corrosion inhibitive action and adsorption behaviour of justicia secunda leaves extract as an eco-friendly inhibitor for aluminium in acidic media. *Biointerface Res. Appl. Chem*, *11*, 13019–13030.

Kazeem, R. A., Fadare, D. A., Ikumapayi, O. M., Adediran, A. A., Aliyu, S. J., Akinlabi, S. A., Jen, T.-C., & Akinlabi, E. T. (2022). Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations—A review. *Lubricants*, *10*(4), 69.

Negm, N. A., El-Farargy, A. F., Abdel Halim, E. A., El-Iboudy, S., & Ahmed, A. E.-S. I. (2014). Novel biobased nonionic surfactants: Synthesis, surface activity and corrosion inhibition efficiency against aluminum alloy dissolution in acidic media. *Journal of surfactants and detergents*, *17*, 1203–1211.

Njoku, D. I., Ukaga, I., Ikenna, O. B., Oguzie, E. E., Oguzie, K. L., & Ibisi, N. (2016). Natural products for materials protection: Corrosion protection of aluminium in hydrochloric acid by Kola nitida extract. *Journal of Molecular Liquids*, *219*, 417–424.

Popoola, L. T., Grema, A. S., Latinwo, G. K., Gutti, B., & Balogun, A. S. (2013). Corrosion problems during oil and gas production and its mitigation. *International Journal of Industrial Chemistry*, *4*, 1–15.

Raja, P. B., & Sethuraman, M. G. (2008). Natural products as corrosion inhibitor for metals in corrosive media—A review. *Materials letters*, *62*(1), 113–116.

Rajimol, P., Ulaeto, S. B., Puthiyamadam, A., Sahoo, S. K., Rajan, T., Radhakrishnan, K., & Sukumaran, R. K. (2023). Development of an oxyresveratrol incorporated bio-based smart nanocomposite coating with anti-corrosive, self-healing, and anti-microbial properties. *Green Chemistry*, *25*(18), 7189–7215.

Shwethambika, P., & Ishwara Bhat, J. (2021). Matured Theobroma Cocoa Pod Extracts as Green Inhibitor for Acid Corrosion of Aluminium. *Iranian Journal of Chemistry and Chemical Engineering*, *40*(3), 906–919.

Verma, C., Haque, J., Quraishi, M., & Ebenso, E. E. (2019). Aqueous phase environmental friendly organic corrosion inhibitors derived from one step multicomponent reactions: A review. *Journal of Molecular Liquids*, *275*, 18–40.

Wickramasinghe, K., Sasahara, H., Abd Rahim, E., & Perera, G. (2021). Recent advances on high performance machining of aerospace materials and composites using vegetable oil-based metal working fluids. *Journal of Cleaner Production*, *310*, 127459.