Journal of Oil Palm Research
DOI: https://doi.org/10.21894/jopr.2024.0033

ENHANCING CORROSION RESISTANCE IN BIODIESEL DISTRIBUTION AND TERMINAL OPERATIONS: A COMPREHENSIVE MATERIALS COMPATIBILITY REVIEW

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ABSTRACT

The viability of integrating biodiesel as a renewable energy source in land and maritime transport systems is promising, given its compatibility with extant fossil fuel infrastructures. However, the corrosivity of biodiesel towards metallic components in fuel distribution and storage facilities has emerged as a critical concern. This study conducts a comprehensive evaluation of the corrosion behaviour of metals in contact with biodiesel, elucidating the underlying mechanisms driving this phenomenon from the perspective of biodiesel processing and storage facilities. It further assesses methodologies for corrosion quantification and investigates the comparative corrosiveness of biodiesel relative to traditional diesel. Contributing factors such as biodiesel's affinity for moisture, the presence of oxygen, the potential for microbial proliferation, and the production of corrosive by-products through auto-oxidation are critically analysed. This article aims to provide a comprehensive overview of the current state of research concerning the compatibility of biodiesel with its processing and storage infrastructure, emphasising the role of fibre-reinforced polymer (FRP) as both a corrosion barrier and a means of mechanical reinforcement.

Keywords: biofuel, biodiesel corrosion, fuel distribution, polymeric materials, terminal operations.

Received: 9 November 2023; **Accepted:** 7 March 2024; **Published online:** 27 May 2024.

INTRODUCTION

The rapid depletion of fossil fuel reserves, driven by population growth, poses a significant challenge to the transportation and utility sectors, impacting energy demand. This situation, coupled with the fact that the transportation industry alone contributes 20% of global energy supply in the form of greenhouse gas (GHG) emissions (Chandran, 2020), presents a grave environmental threat. Stricter emission standards have been implemented, but their effectiveness is offset by the growing global vehicle traffic. Moreover, the refining of fossil fuels contributes to air quality degradation. As industrialisation and population growth continue, the energy demand will escalate, further deteriorating air quality. Considering these pressing concerns, researchers have explored alternative fuels that can coexist with sustainable development, energy conversion, efficiency, and environmental preservation. Among the viable options, biodiesel stands out as a promising fuel that fulfils all the requirements. The Malaysian government, represented by the Malaysian Palm Oil Board (MPOB), has reaffirmed its dedication to achieving carbon neutrality by 2050. A crucial aspect of this effort will be the prominent role played by biodiesel. In a study conducted by Parveez *et al.* (2021), it was revealed that in 2020, Malaysia boasted a total of 20 operational oleochemical plants and 19 biodiesel plants. These facilities showcased impressive processing capacities, with the oleochemical plants capable of handling 2.63 million tonnes, and the biodiesel plants with a capacity of 2.23 million tonnes. To provide an overview, *Table 1* presents a

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comparison of biofuel implementation, future targets, and the relevant standards. Additionally, *Table 2* highlights conventional fuel and its biofuel counterparts.

The EURO emissions standards, implemented to reduce harmful pollutants from vehicles, particularly diesel engines in the transportation industry, have set limits for nitrogen oxides (NO_x), particulate matter (PM), and hydrocarbons (HC) emissions to reduce PM emissions, diesel particulate filters (DPF) were also required. EURO 6, which became mandatory for new vehicles in September 2014, is an even stricter standard that limits NO_x and PM emissions even further. Furthermore, EURO 6 mandated real-world emission testing to better reflect the actual emissions of vehicles on the road. These emissions standards have been implemented globally, with many countries requiring new vehicles sold within their borders to meet these standards. The implementation of EURO 5 and EURO 6 has resulted in significant improvements in air quality in many cities, particularly those with high levels of diesel engine usage. The standards, however, have been criticised, with some claiming that they do not go far enough to address the issue of air pollution. Concerns have also been expressed about the accuracy of real-world testing and manufacturers' ability to manipulate test results. *Figure 1* depicts the changes in sulphur content requirements over time because of different implementations of EURO standards. The comparison of biofuel implementation, its future goal, and the implementation standard is presented in *Table 1*. Biodiesel can be derived from various feedstocks, including vegetable oils and animal fats, and is typically categorised as mono-alkyl esters of long-chain fatty acids. These mono-alkyl esters endow biodiesel with diesel-like properties. Biodiesel has the potential to be utilised in contemporary diesel engines, either in its undiluted state as B100 or in combination with petroleum diesel, thereby creating a blend known as a diesel-biodiesel mixture (Fazal *et al*., 2011). The transesterification process, converting vegetable or animal oil into biodiesel, has emerged as a viable renewable fuel option for diesel-powered vehicles. Numerous studies have proposed physical models to optimise the biodiesel transesterification process. The distinct advantages of biodiesel over conventional diesel, including its seamless adoption without significant engine modifications and its versatility in utilising a wide range of feedstocks, have positioned biodiesel as an appealing alternative. Corrosion and degradation issues continue to plague biodiesel utilisation. Biodiesel has a lower storage stability due to its sensitivity to oxygen. Several derivatives are formed during biodiesel oxidation due to degradation, which may be emitted (Fazal *et al*., 2011).

Biodiesel is widely recognised for its higher corrosiveness compared to fossil-based automotive diesel fuel. While studies have been conducted to investigate biodiesel corrosion and degradation in automotive diesel engine parts, research exploring biodiesel's corrosion behaviour in fuel distribution and terminal operations (DTO) remains limited. Additionally, the potential use of nonmetallic materials, whether fully nonmetallic or metallic structures with nonmetallic coatings or linings, to enhance corrosion resistance and serve as reinforcement layers in these structures and components has not been thoroughly explored. The objective of this paper is to conduct a literature review on the compatibility of various metallic and nonmetallic materials in biodiesel distribution and terminal operations, emphasising their potential to improve corrosion resistance.

Extensive research has been conducted on the utilisation of biodiesel as a substitute for traditional diesel fuel, resulting in a thorough comprehension of its merits and drawbacks (Aatola *et al*., 2009; Fazal *et al*., 2012; Gunstone, 2009; Marketing, 2007; Samuel and Gulum, 2019). Biodiesel offers the potential to reduce crude oil imports, and its use can lead to sulphur deficiency and lower CO_2 emissions throughout its life cycle. Biodiesel offers several superior properties compared to diesel fuel, including a higher cetane number, flash point, lubricity, and oxygen content, facilitating cleaner combustion. Furthermore, it is biodegradable, non-toxic, and environmentally friendly when combined with petroleum diesel fuel. However, biodiesel's degradation-prone nature renders it more corrosive than traditional diesel, leading to material failure and the formation of sludge and microbial growth. Despite these benefits, challenges hinder the widespread adoption of biodiesel. The high cost, concerns regarding food competition, deforestation for oil crop plantations, and issues such as clogged fuel filters and injector fouling pose significant obstacles. Additionally, biodiesel exhibits lower oxidative stability, resulting in increased vulnerability to fuel oxidation. Its lower heating value translates to reduced torque and power, while oxidative instability, poor low-temperature properties, and solvent-like characteristics further contribute to its unfavourable properties. This paper aims to conduct a comprehensive literature review on the compatibility of metallic and nonmetallic materials in biodiesel distribution and terminal operations, with a focus on improving corrosion resistance. The urgency of sustainable energy solutions is discussed in the light of fossil fuel depletion and greenhouse gas emissions. The focus is placed on biodiesel as a viable alternative. Its production, properties, and the challenges associated with its use, particularly regarding material compatibility and corrosion, are examined. The aim of this paper is to provide a comprehensive review of the literature on the suitability of various materials in biodiesel environments. This review encompasses both metallic and nonmetallic materials, emphasising the enhancement of corrosion resistance and sustainability in biodiesel-powered systems.

OVERVIEW OF THE FUEL DISTRIBUTION AND TERMINAL OPERATIONS

Biodiesel fuel is transported from production facilities to end-users through various means, including trucks, marine vessels, and pipelines. The transportation of biodiesel fuel presents unique challenges due to the potential for contamination, especially when transporting higher blends of biodiesel. Biodiesel is hygroscopic, enabling water absorption from the air, which, in turn, creates an environment for microorganisms to thrive and cause biodiesel degradation. In fuel DTO, biodiesel encounters a wide array of materials, categorised as metallic and nonmetallic. Metallic materials can corrode when exposed to biodiesel due to chemical and electrochemical factors. The primary objective of this research paper is to investigate the corrosion and degradation phenomena of nonmetallic materials in biodiesel blending systems. Among the various nonmetallic materials, polymers have been frequently utilised and have been observed to undergo degradation when exposed to biodiesel. The paper provides a comprehensive review of corrosion and degradation mechanisms involving various materials in biodiesel blending systems. The study also examines the effectiveness of various protective measures aimed at mitigating corrosion and degradation in biodiesel blending systems. Through a detailed analysis of the available literature, this paper aims to provide valuable insights into the challenges associated with the use of nonmetallic materials in biodiesel blending systems and to inform future research aimed at enhancing the compatibility of nonmetallic materials with biodiesel. *Figure 2* illustrate the overall ADO and PME distribution and terminal operation from the feedstock until the fueling station.

During storage, biodiesel fuel must be kept in tanks that are free of water, which can lead to the development of microbial growth and the formation of corrosive byproducts. The microbiologically induced corrosion (MIC) of storage tanks and associated equipment is a serious issue in the biodiesel industry that can lead to equipment failure, product loss, and safety hazards. Effective corrosion mitigation strategies are critical for ensuring the safe and reliable storage and distribution of biodiesel fuel. These strategies can include the use of corrosion-resistant materials, protective coatings, and biocides. The use of fibreglass reinforced plastic (FRP) materials has emerged as a promising solution to mitigate corrosion in biodiesel storage tanks. Among the various FRP materials, glass fibre reinforced

TABLE 1. THE COMPARISON OF BIOFUEL IMPLEMENTATION, FUTURE TARGET AND THE STANDARD USED IN THE IMPLEMENTATION

Nations	Main source	Current utilisation	Future target	Standard
United States	Corn, Soybean	E10, B5-B20	E20	Renewable Fuel Standard (RFS)
Brazil	Sugarcane	E27, B8	B10	National Program for the Production and Use of Biodiesel (PNPB)
Indonesia	Palm oil	B30	B40	National Energy Policy (NEP)
India	Sugarcane	E10	E20	National Biofuel Policy (NBP)
European Union	Rapeseed	E10, B5.75	B10	EN16709
China		E10		Blended Gasoline: GB 18351-2017 and Bioethanol: GB/T 22030-2008
Malaysia	Palm oil	B7, B10	B20	Blended Gasoil: MS 123-5:2020 and Biodiesel: MS 2008:2014

Source: Chandran (2020).

TABLE 2. THE CONVENTIONAL FUEL AND ITS BIOFUEL COUNTERPARTS

Conventional Fuel	Biofuel	Main source	Maximum utilisation
Petrol	Bioethanol	Corn, Soybean	E20
Diesel	Biodiesel	Sugarcane, Palm oil	B30
Kerosene	Sustainable Aviation Fuel (SAF)	Palm oil	SAF50

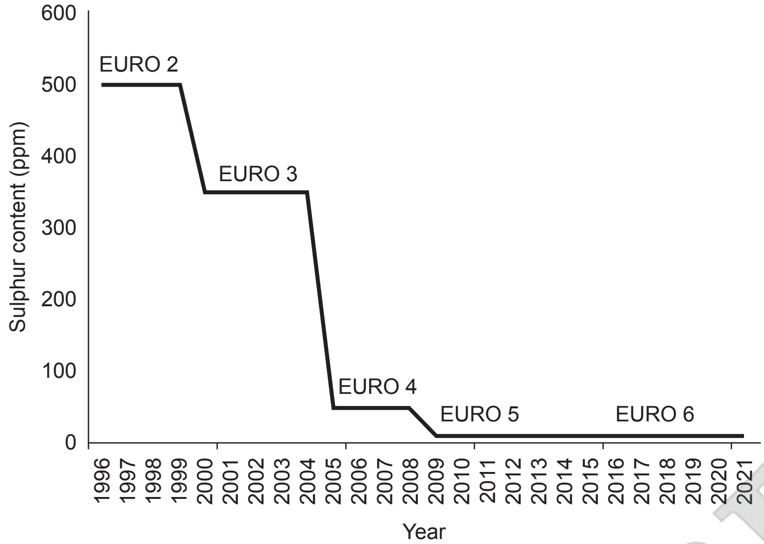


Figure 1. Requirement of sulphur content for diesel – Euro.

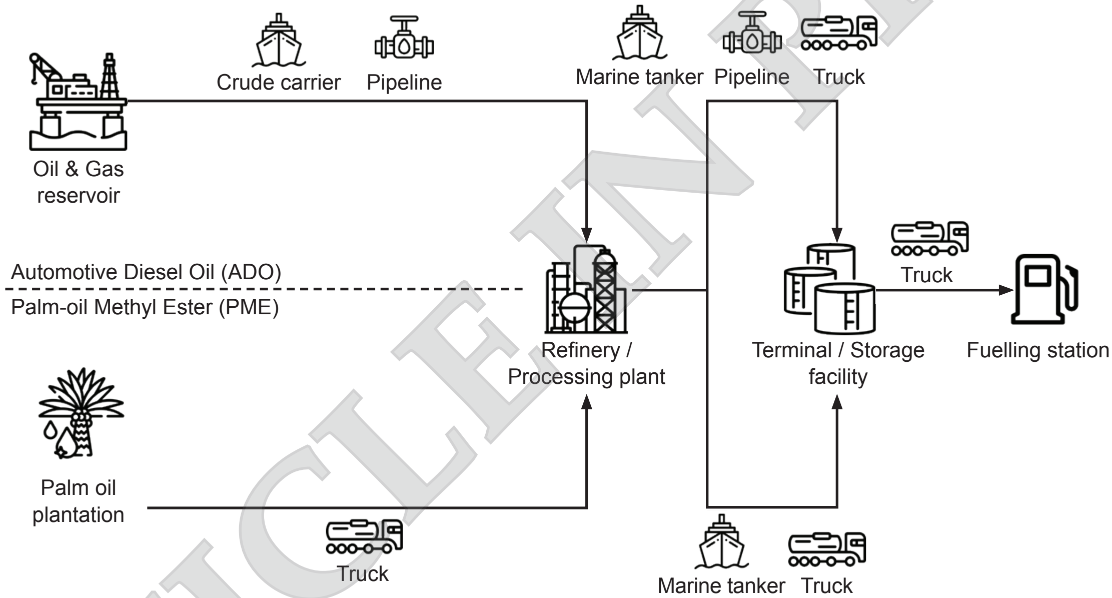


Figure 2. The overview of ADO and PME distribution and terminal operations.

polymer (GFRP) has gained widespread popularity due to its excellent mechanical strength and resistance to corrosion. GFRP has been shown to be particularly effective in resisting the aggressive corrosion mechanisms prevalent in biodiesel storage systems, which can cause significant damage and failure of conventional metallic materials. In addition to the challenges associated with transportation and storage, blending biodiesel with petroleum diesel also presents unique challenges due to differences in physical and chemical properties. Biodiesel blends can be used in conventional diesel engines without modification, but higher blends may require engine modifications or the use of special fuel systems. Overall, the distribution of biodiesel fuel involves several stages, including transportation, storage, blending, and terminal operations. Effective corrosion mitigation strategies are critical for ensuring the safety of reliable storage and distribution of biodiesel fuel and for addressing the challenges associated with microbiologically induced corrosion.

FUEL CHEMISTRY

Biodiesel fuel serves as a renewable alternative to petroleum diesel, produced from diverse feedstocks like vegetable oils, animal fats, and used cooking oils. Palm oil is a commonly used feedstock, undergoing transesterification to convert it into a chemical compound known as methyl ester.

Methyl esters consist of a glycerol backbone and three fatty acid chains, including saturated and unsaturated fatty acids such as palmitic acid, oleic acid and linoleic acid. The chemical structure of palm oil methyl ester (PME) closely resembles that of petroleum diesel, with both molecules having long carbon chains typically ranging from 12 to 18 carbon atoms. The distinction lies in the ester structure of biodiesel. It is referred to as “fatty acid methyl ester” or FAME, denoting the methyl ester’s presence beyond the oxygen atom. Biodiesel exhibits reduced viscosity and burns efficiently in diesel engines. Its ester-bound oxygen renders it less toxic and more biodegradable. Notably, the corrosion, oxidation, and polymerisation characteristics of biodiesel are influenced by the ester-bound oxygen molecule.

Different feedstock oils may exhibit varying properties. Biodiesel differs from diesel in terms of raw materials and production processes (Fazal *et al*., 2012), as biodiesel is derived from renewable resources such as vegetable oils, waste cooking oil, and animal fats, whereas diesel is derived from crude oil. The production process of diesel involves three processes: Separation, upgrading, and conversion, while biodiesel is produced through a single process called transesterification. The products and compositions of diesel and biodiesel are different (Gunstone and Hamilton, 2004). Diesel is mainly composed of carbon and hydrogen, with 81.0% saturated (paraffin and naphthenic) and 18.9% unsaturated (aromatics). On the other hand, biodiesel contains carbon, hydrogen, and oxygen, with varying compositions depending on the feedstock used. For instance, palm biodiesel comprises 81.0% saturated (palmitic and stearic) and 18.9% unsaturated (oleic, linoleic, and linolenic) fatty acids, whereas rapeseed and soy biodiesel have a higher percentage of unsaturated fatty acids. These compositional differences between diesel and biodiesel can impact engine performance and emissions. Biodiesel typically exhibits a higher cetane number, flash point, and lubricity compared to diesel, resulting in cleaner combustion and reduced emissions of hydrocarbons and carbon monoxide. However, biodiesel’s lower heating value can lead to decreased torque and power. Regarding environmental impact, biodiesel presents both advantages and disadvantages compared to diesel (Fazal *et al*., 2018). It utilises renewable resources, potentially lowering CO_2 emissions over its life cycle and reducing dependence on imported crude oil. It is also biodegradable, non-toxic, and environmental-friendly when used with petroleum diesel fuel. Additionally, biodiesel is more prone to degradation, making it more corrosive than conventional diesel, which can lead to material failure, sludge formation, microbial growth, and clogging of fuel filters and injectors. *Figure 3* demonstrates the molecular comparison between typical biodiesel and diesel molecules.

Despite the aforementioned benefits, important chemical composition disparities exist between biodiesel fuel and petroleum diesel. Biodiesel boasts a higher oxygen content and a lower carbon-to-hydrogen ratio, influencing combustion properties and emissions. It also exhibits a higher flash point, signifying the temperature at which the fuel ignites in the presence of an ignition source, compared to petroleum diesel. The production of palm oil biodiesel typically involves transesterification, wherein triglycerides in the oil react with an alcohol (*e.g*., methanol) in the presence of a catalyst (*e.g*., sodium hydroxide or potassium hydroxide). This reaction generates glycerol and FAME which are subsequently separated and purified. The process flowchart for PME production is outlined in the European Standard EN 14214:2012, which stipulates specifications for biodiesel fuel quality,

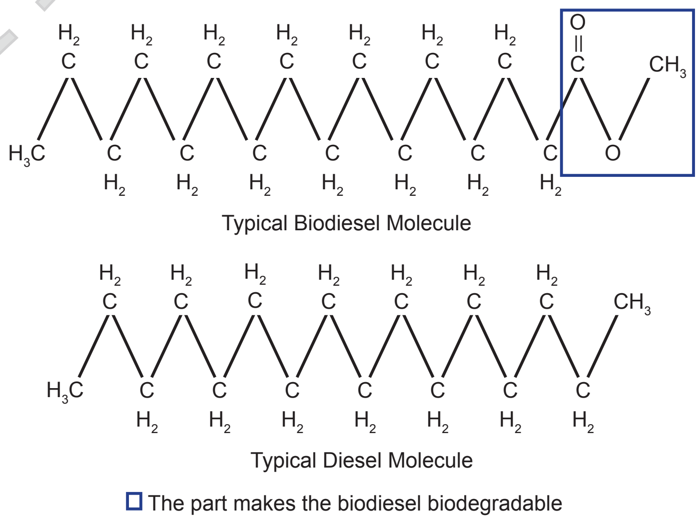


Figure 3. The molecular comparison between typical biodiesel and diesel molecules.

encompassing chemical composition, physical properties, and performance characteristics such as flash point, viscosity, and acid value. Biodiesel possesses advantages and disadvantages compared to petroleum diesel in terms of properties and processes. While biodiesel offers a renewable fuel source capable of reducing greenhouse gas emissions and diminishing reliance on petroleum-based fuels, it may entail higher costs and necessitate engine modifications or specialized fuel systems to accommodate its distinct properties.

Table 3 presents a comprehensive comparison of key properties between ultra-low sulphur diesel and soy biodiesel, following the standards set by the American Society for Testing and Materials (ASTM) (Fazal *et al*., 2012). *Table 4* illustrates the comparison of limit and codes quality tests of conventional ADO and the B100 PME. These properties play a crucial role in determining the performance of these fuels in various applications. Oxidation stability, for instance, influences the fuel's resistance to degradation over time. The higher heating value is a vital factor that determines the fuel's energy content, thereby affecting its efficiency in engines. Flash point, on the other hand, indicates the lowest temperature at which the fuel can vaporise and ignite in the presence of an ignition source, making it essential for safety considerations. Density at 15°C and viscosity at 40°C determine the fluidity of the fuel and its suitability for different applications. Sulphur content is a critical property, as it contributes to the formation of sulphur oxides during combustion, which have adverse effects on the environment and human health. Ultra-low sulphur diesel adheres to the ASTM D975 specification, containing less than 15 parts per million (ppm) of sulphur, while soy biodiesel complies with the ASTM D6751 specification, containing less than 10 ppm of sulphur. The cetane number, which measures the fuel's ignition quality and ability to start and run smoothly in diesel engines, is also provided. This table serves as a valuable resource, offering insightful information on the essential properties of ultra-low sulphur diesel and soy biodiesel, aiding researchers and industry professionals in making informed decisions regarding fuel choices and applications. *Figure 4* illustrates the typical process flowchart of PME in accordance with EN 14214:2012.

The quality of biodiesel stored in tanks made of carbon steel may be significantly impacted by corrosion of this material. As carbon steel corrodes, it can release iron oxide particles into the biodiesel, which can lead to the formation of insoluble sediments. These sediments can cause filter blockages, reduce fuel flow, and lead to engine problems (Milano *et al*., 2021). Furthermore, corrosion can also promote the growth of microorganisms such as bacteria and fungi, which can degrade the quality of the biodiesel by breaking down the fatty acid chains that make up the fuel. Microbial-mediated hydrolysis of fatty acid chains has been identified as a significant process leading to the liberation of free fatty acids (FFA) within the biodiesel matrix. The present

TABLE 3. TYPICAL PROPERTIES OF ULTRA-LOW SULPHUR DIESEL (ASTM D975) AND SOY BIODIESEL (ASTM D6751)

Property	Ultra-low sulphur diesel (ASTM D975)	Soy biodiesel (ASTM D6751)
Oxidation stability (hr)	>40	<10
Higher heating value (kJ/kg)	42.7	40.6
Flash point (°C)	60	130
Density at 15°C (kg/m^3)	0.85	0.88
Viscosity at 40°C (mm^2/s)	2.6	6
Sulphur content	<15	<15
Cetane number	44	55

Source: Marketing (2007).

TABLE 4. THE COMPARISON OF LIMIT AND CODES QUALITY TESTS OF ADO AND PME

Test	ADO	PME
Total acid number (mg KOH/g)	Max 0.25 ASTM D974	Max 0.5 EN 14104
Sulphated ash content (%)	Max 0.01 ASTM D482	Max 0.02 ISO 3987
Viscosity @ 40 mm^2/s	2.0-4.5 ASTM D445	3.5-5.0 ISO 3104
Flash point (ºC)	Min 60 ASTM D93	Min 120 ISO 3679
Sulphur content (ppm)	Max 10 ASTM D5453	Max 10 ISO 20846
Water content (ppm)	Max 500 ASTM D95	Max 400 ISO 12937
Cetane number	Min 49 ASTM D4737	Min 51 ISO 5165
Copper corrosion	Max 1 3H @ 100 ASTM D130	Min 1 3H @ 50 ISO 2160
Density @ 15 kg/m^3	810-845 ASTM D4052	860-900 ISO 12185

study examines the potential reactivity of FFA with water, leading to the formation of carboxylic acids, thereby elucidating the consequent impact on the acidity levels of biodiesel. Additionally, the presence of iron oxide particles released by corroding carbon steel can also catalyse this reaction and further increase the acidity of the biodiesel. This can lead to increase acidity, viscosity, and oxidation, which can negatively impact engine performance and lifespan (Borugadda and Goud, 2012).

The detrimental effects of corrosion extend beyond the degradation of biodiesel quality, encompassing the potential for consequential harm to storage tanks and associated equipment. Such corrosion-induced damage can result in the occurrence of leaks and spills, posing significant risks to both the environment and human well-being. Therefore, effective corrosion mitigation strategies are necessary to ensure the quality and safety of biodiesel fuel in storage and distribution. Overall, the chemistry and production of biodiesel fuel, including PME, involves a complex series of chemical reactions and purification steps. Understanding the chemical properties and production processes of biodiesel is important for developing effective strategies for its distribution, storage, and use as an alternative fuel source. *Figure 5* illustrates the research flowchart to characterise the biodiesel corrosion behaviour.

BIODIESEL CORROSION BEHAVIOUR ON METALLIC STRUCTURES

As previously mentioned, biodiesel comprising FAME can provide a source of nutrients for microorganisms such as bacteria, fungi, and algae. These microorganisms can grow in fuel storage systems and can form biofilms, which are communities of microorganisms that adhere to surfaces and produce a protective slime layer. Biofilms can promote the corrosion of carbon steel and other metals by producing acidic and corrosive metabolic byproducts, such as hydrogen sulphide, acetic acid and carbon dioxide. The presence of

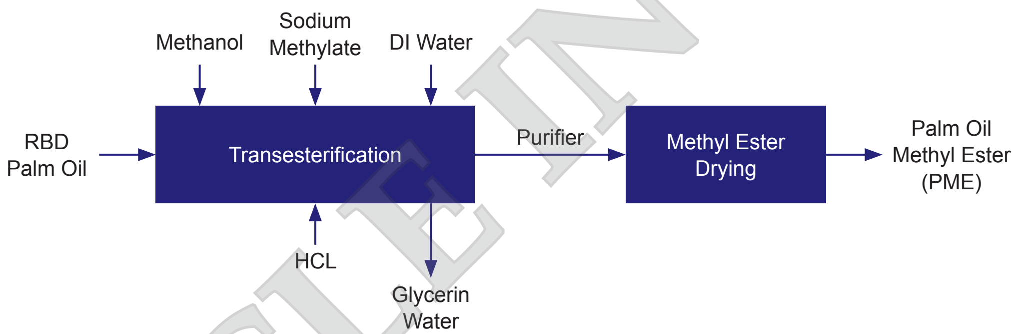


Figure 4. Process flowchart of Palm-oil Methyl Ester (PME) in accordance with EN 14214:2012.

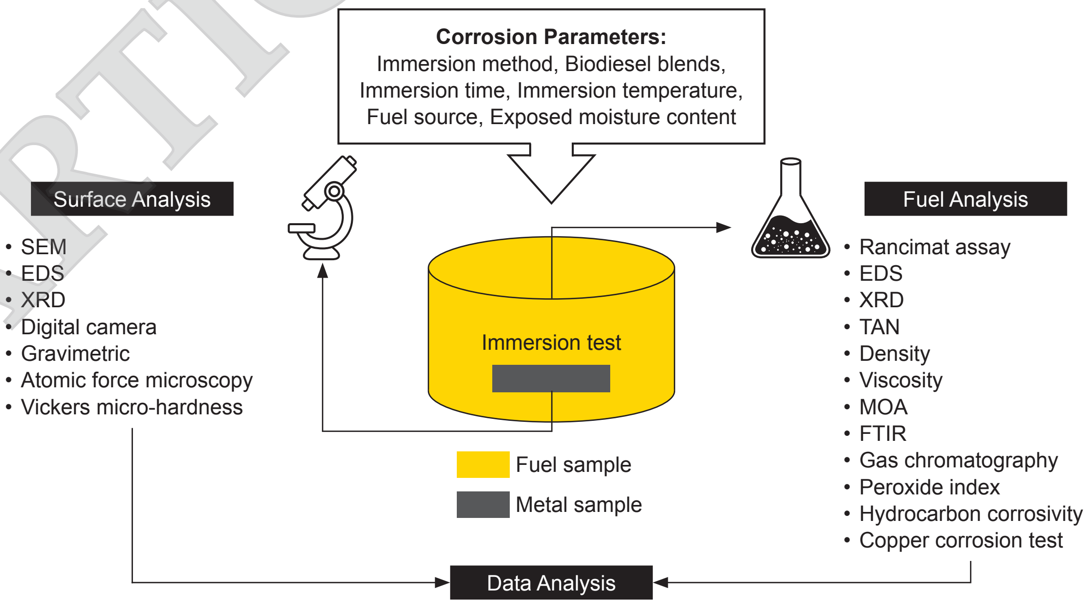


Figure 5. The research flowchart to characterise the biodiesel corrosion behaviour.

water in fuel storage systems, which can result from condensation or leaks, can also increase the growth of microorganisms and promote MIC. Several studies have investigated the corrosive effects of biodiesel on various metals commonly used in processing plants and storage facilities. It is imperative to acknowledge that the corrosive impacts of biodiesel may exhibit variability contingent upon the precise composition of the fuel, alongside the circumstances governing its storage and utilisation. Additionally, if the biodiesel is stored at high temperatures or exposed to air, this can also increase its corrosiveness. Several methods have been proposed to reduce the corrosive effects of biodiesel on processing plants and storage facilities. One method is to use corrosion-resistant materials in the construction of these facilities. Another method is to implement proper storage and handling practices, such as keeping the fuel dry and at cool temperatures. Additionally, using additives to the fuel can also reduce the corrosive effects. Understanding the general corrosion behaviour of biodiesel on metals leads us to examine more closely the interaction between biodiesel and specific metals, such as copper and its alloys, carbon steel, stainless steel, aluminum and its alloys and terne steel which play a crucial role in biodiesel processing. *Table 5* offers a comprehensive summary of research studies investigating the impact of biodiesel on metal corrosion.

Copper and Its Alloy

In biodiesel processing, copper is commonly used as a material in several pieces of equipment due to its high thermal and electrical conductivity, strength, and resistance to corrosion. Some of the equipment that require copper in biodiesel processing include heat exchangers, pipelines, pumps, valves and electrical components. Copper is also used in catalysts for chemical reactions during the biodiesel production process. The specific use of copper in each piece of equipment will depend on the specific requirements of the equipment, such as temperature, pressure and chemical resistance. Nevertheless, it is crucial to consider the potential ramifications of biodiesel on copper corrosion and select the suitable grade and form of copper to guarantee its enduring efficacy and sustainability in the process of biodiesel production. *Figure 6* shows the reported studies on copper corrosion in B100 biodiesel while *Table 6* compares the studies on copper corrosion in various biodiesel blends. Samuel and Gulum (2019) investigated the effects of waste sunflower oil biodiesel-diesel fuel blends on the mechanical and corrosion properties of brass. The study found that the exposure of brass to the fuel blend resulted in a decrease in the mechanical properties of the brass, but also improved its corrosion resistance. The use of waste sunflower oil biodiesel-diesel fuel blends had a detrimental effect on the mechanical properties of brass, but the improvement in its corrosion resistance could be utilised in certain applications where corrosion resistance was more important than mechanical strength. The statement is supported by the research conducted by Fazal *et al.* (2012) which examined the degradation of automotive materials, copper, brass, aluminum and cast iron, in palm biodiesel. This study presented a comprehensive investigation of the impact of palm biodiesel on the degradation of automotive materials. The results demonstrated that the selection of the appropriate material for vehicle components was critical to ensure the long-term reliability and performance of vehicles powered by biodiesel. The findings revealed that copper, brass, aluminum, and cast iron were susceptible to degradation when exposed to palm biodiesel. The order of degradation for different metals followed the sequence of copper > brass > aluminum > cast iron. The variation in the degradation behaviour of different materials can be attributed to their differing total surface energy. The higher the total surface energy, the greater the affinity for biodiesel, and therefore, the more significant the degradation. These results highlighted the importance of considering material properties, including total surface energy, when selecting materials for use in vehicles that operate on biodiesel. The degradation of automotive materials in palm biodiesel highlighted the importance of careful consideration of the materials used in vehicles powered by biodiesel-based fuels to ensure their long-term performance and sustainability.

In a study conducted by Haseeb *et al*. (2010) copper corrosion was investigated under various fuel conditions, including pure diesel fuel (B0), a blend of 50% biodiesel and 50% diesel (B50), and pure palm biodiesel (B100). The corrosion tests were performed at room temperature for 2640 hr at 60°C without stirring for 840 hr. The authors observed that the corrosion rate of copper in B100 at room temperature was 0.042 mpy, which increased to 0.053 mpy at 60°C. However, the use of oxidised B100 resulted in a higher corrosion rate of approximately 0.080 mpy. These findings highlight the importance of using biodiesel within specified quality parameters to mitigate the corrosion of incompatible metallic materials. Fazal *et al.* (2012) conducted a similar investigation on copper corrosion in B100 over a period of 2880 hr at room temperature. The study revealed that copper corrosion rates were higher in contact with palm biodiesel compared to other materials. The authors also noted variations in the degradation of automotive materials in

TABLE 5. REPORTED STUDIES ON THE EFFECTS OF BIODIESEL TOWARDS METAL CORROSION

Metal	Fuel	Experimental conditions	Corrosion rate (mpy)		Observations	Ref.
Copper	B0 (ULSD), B50, B75, B100 (rapeseed)	Immersion, 80°C, 600 hr	B0 B50 B75 B100	0.35 0.62 0.80 0.92	Higher corrosion rate as biodiesel concentration in diesel increases.	Norouzi *et al.* (2012)
Piston metal	B100	Immersion, 26°C, 7200 hr	*Jatropha curcas* *Karanja* *Madhuca indica* *Salvadora oleides*	0.0117 0.0058 0.0058 0.1236	Corrosion rate varies when exposed to biodiesel made from different feedstock.	Kaul *et al.* (2007)
Aluminum Brass Cast iron Copper	B100 (palm)	Immersion, 26°C, 2880 hr	Aluminium Brass Cast iron Copper	0.173055 0.209898 0.112232 0.39278	Different metals have different corrosion rates.	Fazal *et al.* (2012)
Mild steel	B100 (palm)	Immersion, 26°C, 50°C, 80°C, 1200 hr	26°C 50°C 80°C	0.052 0.056 0.059	At higher fuel temperatures, the corrosion rate increases.	Fazal *et al.* (2011)
Copper	B100	Immersion, 26°C, 55°C, 120 hr	26°C 50°C	0.174 0.020	Lower corrosion rate as fuel temperature rises.	Aquino *et al.* (2012)
Copper	B100 (palm)	Immersion, 26°C, 200 hr, 300 hr, 600 hr, 1200 hr and 2880 hr	200 hr 300 hr 600 hr 1 200 hr 2 880 hr	0.295 0.433 0.591 0.709 0.571	Higher corrosion rate with longer immersion time.	Fazal *et al.* (2013)
Low carbon steel	B100 (soy), B100 (soy) with 1% water	Immersion, 2016 hr	B100 B100 +1% water	0.591 0.709	Water encourages corrosion.	Grainawi, (2009)
Copper	B100 (palm), Oxidised B100 (palm)	Immersion, 60°C, 840 hr	B100 Oxidised B100	0.053 0.084	Corrosion rate is higher in oxidised biodiesel than in non-oxidised biodiesel.	Haseeb *et al.* (2010)
Terne steel	B1, B3, B5	Immersion, 80°C, 1000 hr Fuel replaced every 250 hr, supplied fresh air once per day.	Initial TAN (mg KOH/g): B1 0.05 B3 0.06 B5 0.07	Final metal concentration (ppm) Pb / Sn: 8 / 1> 40 / 1> 1 800 / 12	Higher corrosion rate as total acid number increases.	Tsuchiya *et al.* (2006)

TABLE 5. REPORTED STUDIES ON THE EFFECTS OF BIODIESEL TOWARDS METAL CORROSION (continued)

Metal	Fuel	Experimental conditions	Corrosion rate (mpy)			Observations	Ref.
Brass, Carbon steel, Copper	B100 (*Jatropha curcas*)	Immersion, 100 hr Linear polarisation resistance (LPR), measured every 24 hr		Immersion	LPR	Lower instantaneous corrosion rate than duration averaged corrosion rate.	Anand *et al.* (2011)
			Brass	0.4875	0.1346		
			Carbon steel	0.1290	0.1483		
			Copper	1.1206	0.1416		
Copper	B100 (*Pongamia pinnata*)	Immersion, 100 hr Rotating cage, 500 rpm	Immersion	0.219		Fuel flow encourages corrosion.	Parameswaran *et al.* (2013)
			Rotating	2.704			
Carbon steel, Copper	B100 (*Jatropha curcas*) B99 (*Jatropha curcas* +1% NaCl)	Immersion, 100 hr		Carbon steel initial conductivity (μΩ)	Corrosion rate (mpy)	Carbon steel corrodes more quickly in fuel with a higher conductivity value. Lower copper corrosion rate in fuel with higher conductivity value.	(Anand *et al.* (2011)
			B100	0.12	0.762		
			B99	0.32	1.339		
				Copper initial conductivity (μΩ)	Corrosion rate (mpy)		
			B100	0.68	0.243		
			B99	0.68	0.085		

palm biodiesel, with some metals experiencing higher levels of degradation than others. The degradation process in palm biodiesel primarily arises from the formation of FFA and glycerol during oxidation, which accelerates the corrosion of metallic materials. These findings underscore the importance of carefully selecting materials for vehicles powered by biodiesel-based fuels to ensure long-term performance and sustainability. The conductivity value, a crucial quality parameter indicating biodiesel deterioration level, can also expedite the ion exchange process during metal corrosion, particularly when biodiesel feedstocks vary (Chandran *et al*., 2016).

Fazal *et al*. (2018) conducted a study to examine the impact of copper on the stability and corrosiveness of palm biodiesel and its blends. The results revealed that the presence of copper in palm biodiesel and its blends significantly reduced their stability and increased their corrosiveness. The authors noted that the use of contaminated feedstock and storage facilities could lead to the presence of copper in biodiesel and its blends, affecting their stability and performance. The findings of this study emphasised the importance of proper storage and handling practices to maintain the quality and sustainability of biodiesel. Chandran *et al*. (2019) evaluated the sustainability of water in diesel emulsion fuel and its impact on the corrosion of copper. The study found that the presence of water in diesel emulsion fuels could significantly increase the corrosion of copper. The corrosion rate increased with the increasing water content. The authors highlighted that the choice of emulsifiers, fuel-water ratio, and other factors were crucial for ensuring the long-term sustainability and performance of equipment that came in contact with diesel emulsion fuels. Rocha *et al*. (2019) investigated the impact of biodiesel properties on the corrosion of metallic copper. The study found that the composition of FAME in biodiesel, as well as the acid value and water content, could significantly influence the corrosion of copper. The results revealed that higher acid values and water contents in biodiesel could lead to increase corrosion rates of copper, while the composition of FAME could also have a direct impact on the corrosion behaviour of copper. The authors concluded that the study highlighted the importance of considering the properties of biodiesel in the design and operation of equipment that came in contact with biodiesel to ensure the long-term performance and sustainability of copper-based materials. Overall, these studies emphasise the need for proper storage and handling practices and the consideration of fuel properties in the design and operation of equipment that comes in contact with biodiesel to ensure the long-term performance and sustainability of materials.

In summary, the use of copper in biodiesel processing is common due to its properties such as high thermal and electrical conductivity, strength, and resistance to corrosion. Copper is used in equipment such as heat exchangers, pipelines, pumps, valves, and electrical components, and in catalysts for chemical reactions during biodiesel production. Ergo, different grades and forms of copper may be chosen based on the specific requirements of the equipment. The degradation of copper can be influenced by factors such as the type of feedstock used in biodiesel production, the conductivity value, the composition of FAME, the acid value, and the water content. The presence of copper in biodiesel and its blends can negatively impact their stability and sustainability and highlight the need for proper storage and handling practices. The results emphasise the importance of considering the impact of biodiesel on the corrosion of copper and choosing the appropriate materials for biodiesel processing to ensure their long-term performance and sustainability.

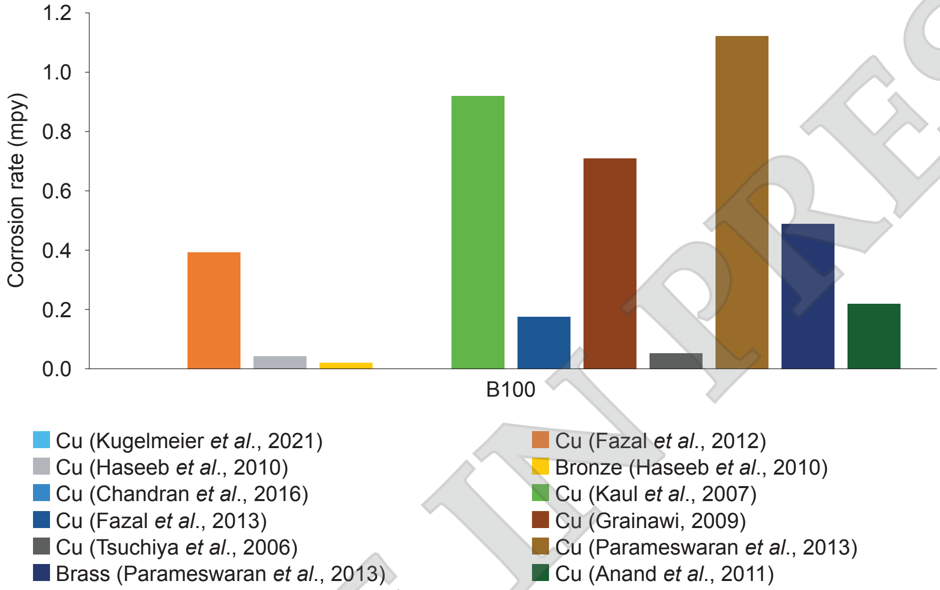
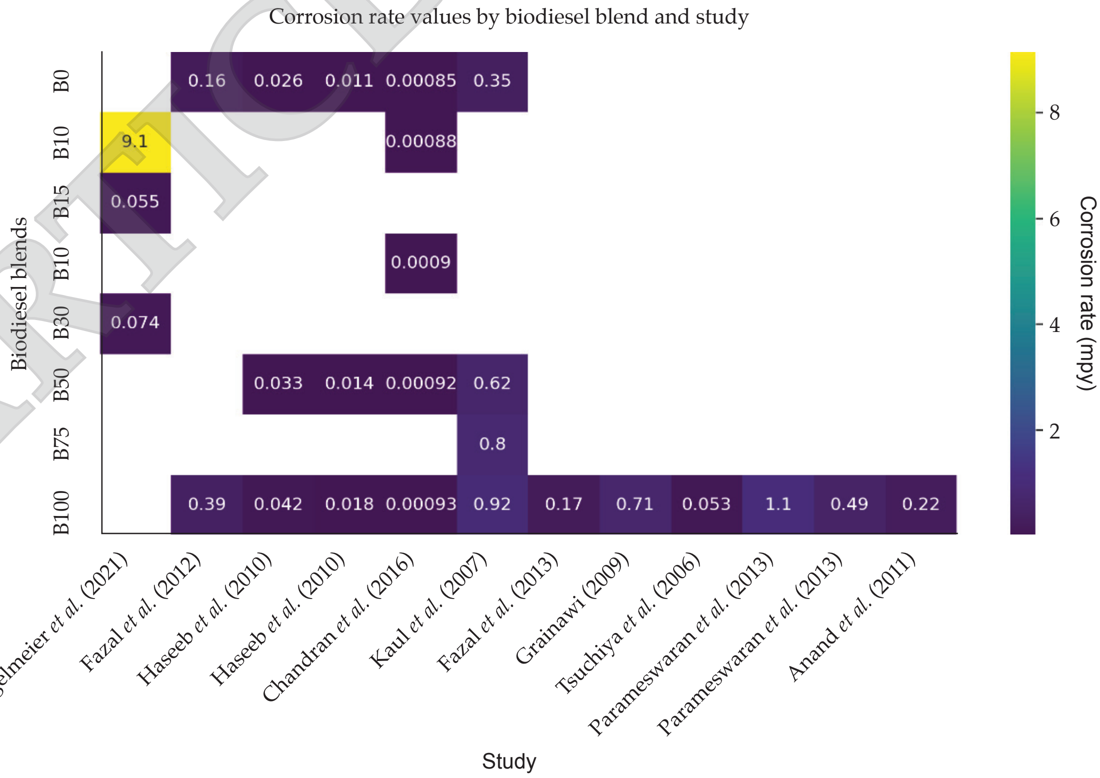


Figure 6. The reported studies on copper corrosion in B100 biodiesel.

TABLE 6. THE REPORTED STUDIES ON COPPER CORROSION IN VARYING BIODIESEL BLENDS



Carbon Steel

As copper is common to high thermal and electrical conductivity applications, carbon steel is a common material used for structures, pipelines, valves, pressure vessel and storage tanks, as it is relatively cheap, strong, and durable. However, biodiesel can be corrosive to carbon steel and cause significant damage to the equipment, leading to increased maintenance costs and reduced operational efficiency. The corrosion phenomenon under consideration is attributed to a confluence of multiple factors, encompassing the intricate interplay between the chemical characteristics inherent to biodiesel, the existence of water, and the proliferation of microorganisms. The presence of elevated concentrations of FFA in biodiesel has been identified as a potential catalyst for corrosion upon interaction with carbon steel. The presence of FFA in the vicinity of metal surfaces can initiate a chemical reaction resulting in the formation of a corrosive layer. This layer, upon accumulation, can induce the degradation of the underlying steel material, ultimately leading to structural failure. Moreover, it is noteworthy to mention that biodiesel exhibits hygroscopic properties, indicating its propensity to readily assimilate moisture from the surrounding environment. The potential impact of water content on corrosion in biodiesel is a subject of concern due to its role as a conducive environment for the proliferation of microorganisms, including bacteria and fungi.

Pusparizkita *et al*. (2020) examined the effect of *Bacillus megaterium* on carbon steel corrosion in biodiesel and diesel oil mixtures. The results showed that the presence of *B. megaterium* led to higher rates of corrosion in the carbon steel. The study concluded that the bacterial strain had a significant impact on the corrosion of carbon steel in biodiesel and diesel oil mixtures. Similar finding was found by Fernandes *et al*. (2019) that presented the carbon steel corrosion behaviour when exposed to *Moringa oleifera* Lam biodiesel. Among the two carbon steels (CS1015 and CS4140), the CS4140 was more compatible with the biodiesel type as there was no iron detected while 8 μg/g of iron was detected in biodiesel exposed with CS1015. CS4140 having higher carbon content and better mechanical properties than CS1015. Subsequent investigations into the effects of MIC, specifically caused by *B. licheniformis*, on ST-37 carbon steel in diesel tanks with varying biodiesel blends, revealed that the microbial activity of *B. licheniformis* notably exacerbated corrosion rates in the B15 biodiesel mixture. However, it was observed that in blends with biodiesel concentrations of B20 or higher, the corrosion rates were reduced, likely due to the formation of a thicker and more uniform biofilm by the bacteria (Pusparizkita *et al*., 2023). The authors found that the biodiesel had a corrosive effect on the carbon steel and concluded that further research is needed to understand the mechanisms involved and determine appropriate measures to prevent corrosion in biodiesel storage systems. In their study, Deshpande *et al*. (2019) investigated the corrosion behaviour of nodular cast iron when exposed to biodiesel blends. The researchers employed a suitable heat treatment technique and immersed the cast iron samples in various biodiesel blends to gain a deeper understanding of the underlying mechanisms at play. The present study investigates the influence of microstructural modifications on the corrosion resistance of metals, specifically in the context of biodiesel applications. The authors have observed that alterations in the fundamental microstructure of metal can lead to an enhanced resistance against corrosion. This phenomenon is attributed to the alteration in the metal phase, which subsequently affects the long-term performance and sustainability of materials utilised in biodiesel applications. In a study conducted by Cursaru *et al*. (2018), an additional factor contributing to biodiesel corrosion was examined. In this study, the researchers examined the influence of moisture on the corrosion behaviour of copper and mild carbon steel when exposed to corn biodiesel. The findings indicated that the corrosion behaviour of both metals in corn biodiesel was notably influenced by moisture content. The experimental investigation conducted herein examines the influence of moisture on the corrosion rates of two distinct metals, namely mild carbon steel and copper. The objective of this study was to ascertain the relative corrosion rates of these metals when exposed to a moist environment. The findings of this investigation revealed that both metals exhibited an increase in corrosion rates in the presence of moisture. Notably, the corrosion rate of mild carbon steel was observed to be higher than that of copper under these conditions. According to the findings above, proper storage conditions and the use of corrosion inhibitors were required to reduce corrosion in biodiesel processing and storage facilities. Batista *et al*. (2019) investigated the ester composition of biodiesel made from Macauba kernel oil in direct contact with carbon steel and galvanised carbon steel. The goal was to track changes in ester composition caused by potential corrosion from contact with metal materials. The results revealed that the composition of esters changed when they came into contact with both types of metal materials, with the changes being more pronounced when they came into contact with carbon steel. The study emphasises the importance of taking metal corrosion into account in biodiesel processing and storage facilities.

In a study by Serqueira *et al.* (2021) the authors proposed the consideration of antioxidants to improve the oxidative stability and corrosivity of biodiesel, thereby enhancing carbon steel corrosion resistance. The oxidative stability and corrosivity of biodiesel, derived from residual cooking oil, were evaluated under simulated storage conditions while exposed to copper and carbon steel. The results demonstrated that antioxidants effectively reduced the corrosivity of biodiesel, thereby improving the long-term performance and sustainability of materials utilised in biodiesel applications. This finding emphasised the significance of considering biodiesel properties and their impact on material corrosion during the design and operation of biodiesel equipment. The study investigated the dual effect of antioxidants on biodiesel stability and corrosivity. The results showed that adding antioxidants to biodiesel affected its oxidative stability and corrosivity, The impact varies depending on the type of antioxidant and the metal to which it was exposed. Martins *et al*. (2020) presented a promising study focusing on the synthesis of a new phenolic-Schiff base molecule as an antioxidant in soybean biodiesel and as a corrosion inhibitor in AISI 1020 carbon steel. The study demonstrated that the new molecule enhanced the oxidative stability of soybean biodiesel and reduced the corrosion rate of AISI 1020 carbon steel. These findings highlighted the potential for reducing biodiesel corrosion through the utilisation of innovative corrosion inhibitors and antioxidants. In summary, preventing biodiesel corrosion necessitates careful consideration of factors such as bacteria-induced corrosion, carbon content, metal phase, biodiesel type, environmental moisture and ester composition. Further research is needed to fully comprehend the effects of biodiesel on non-metal materials and to develop effective strategies for mitigating corrosion. It is advisable to implement proper storage and handling procedures which includes maintaining proper temperature and humidity levels, using appropriate materials for biodiesel processing and storage equipment, and regularly monitoring and cleaning the equipment.

Stainless Steel

Unlike carbon steel, stainless steel is often preferred for specialty services, such as food-grade feedstock storage, transesterification process, methanol recover, glycerol separation and purification in biodiesel service due to its resistance to corrosion caused by the chemical properties of biodiesel. Regular carbon steel is susceptible to corrosion when in contact with biodiesel, which can lead to leaks and failure of the system. On the other hand, stainless steel, specifically type 316 or type 304, has a higher resistance to corrosion and can better withstand the corrosive effects of biodiesel. Additionally, stainless steel has a longer service life, which results in lower maintenance costs and a reduced need for replacement of parts. Stainless steel is more corrosion-resistant and may be a better choice for long-term storage, especially in environments where the biodiesel blend is highly corrosive. Ultimately, the choice of material depends on the specific requirements and conditions of the biodiesel production process.

Alves *et al*. (2019) conducted an investigation on the effect of stainless-steel corrosion on biodiesel oxidation during storage. The study involved immersing samples in a controlled environment of low air turnover and darkness. The results showed that the presence of metal ions released during stainless steel corrosion promoted oxidation of the biodiesel, leading to changes in its composition, quality, and a decrease in its overall oxidative stability. Interestingly, the study found that the type of ester used (methyl or ethyl) had little effect on metal degradation, indicating that both routes had a low corrosion rate despite the presence of surface micro-pitting. Kugelmeier *et al*. (2021) conducted a study on the corrosion behaviour of different materials (carbon steel, stainless steel, aluminum, and copper) when exposed to a biodiesel/ petrodiesel blend. The results indicated that stainless steel exhibited the highest corrosion resistance among the materials tested, outperforming the others. Chandran *et al*. (2023) assessed the corrosion effects on stainless steel and galvanised steel when exposed to water-emulsified diesel, diesel, and palm biodiesel, revealing that stainless steel's corrosion rate was 1.1 times higher in emulsified diesel than in diesel, and 0.5 times lower than in biodiesel, while galvanised steel's corrosion rate was 8.5 times higher in emulsified diesel than in diesel, and 3.5 times higher than in biodiesel. Additionally, Komariah *et al*. (2021) investigated the corrosion behaviour of different tank materials (stainless steel, galvanised steel, and carbon steel) after contact with palm-based biodiesel, focusing on corrosion type and behaviour in different zones within the fuel tank made of various coating elements. The results revealed that different protective layers exhibited diverse corrosion types, with localised corrosion observed in stainless steel tanks but widespread corrosion in galvanised and carbon steel tanks. The contamination level of oil in stainless steel tanks was lower compared to galvanized and carbon steel tanks, and the corrosion type varied across different zones within the tank's interior. Leaks were more likely to occur at the base of the tank than on the walls and roof (Komariah *et al*., 2023). In their study, Yung *et al.* (2018) explored the compatibility of palm biodiesel blends, specifically B7, B10 and

B15, with automotive fuel tank materials, with a particular emphasis on terne sheet. Their research uncovered that when utilising high-quality fuels, the palm biodiesel blends did not induce corrosion or present compatibility concerns with terne sheet. This conclusion was substantiated by scanning electron microscopy analysis and the absence of heavy metal leaching, as documented in the study. These studies provide valuable insights into the corrosion behaviour of different materials when exposed to biodiesel blends, highlighting the importance of considering the type of material and its protective coatings to ensure the long-term sustainability and performance of biodiesel storage and handling equipment.

Aluminum and Its Alloy

In contrast to the above metals, aluminum and its alloys are relatively less common in the biodiesel processing and storage facilities. Aluminum is typically used in the biodiesel equipment that require human handling for ergonomic reason such as transfer hose, drip tray, sampling can, and loading arms. However, they are common in the automotive parts due to their lightweight and corrosion-resistant properties, focusing on improving alloy resistance to biodiesel's acidity to ensure component durability and system efficiency, especially for piston material. Kaul *et al*. (2007) performed a long-duration static immersion assessment on piston metals and liners over a consistent ambient temperature span of 15°C to 40°C for nearly a full year. The research revealed that Mahua and Karanja biodiesel fuels did not cause corrosion in the piston metals and liners, whereas Salvadora biodiesel did, likely owing to its elevated sulphur levels of 1200 ppm. Jatropha biodiesel had a minor impact on the piston liner. Following the testing period, all biodiesel variants experienced substantial degradation. The acid number (AN) showed a significant increase for Jatropha, Mahua, and Karanja biodiesels, rising from 0.40 mg of KOH/g to a range of 11.00 to 19.00 mg of KOH/g. In the case of Salvadora biodiesel, the AN also rose, from 0.45 mg KOH/g to between 2.30 and 2.50 mg KOH/g. Aside from comparing the different biodiesel sources, Fazal *et al*. (2012) assessed the corrosion resistance of aluminum when exposed to pure palm methyl ester biodiesel (B100) at a temperature of 26°C over a span of 2880 hr, juxtaposing its performance against other metals. The findings revealed that aluminum's corrosion rate stood at 0.17 mils per year (mpy), which outperformed brass and copper. However, it did not surpass cast iron in corrosion resistance. Nonetheless, the reduced weight of aluminum offers a significant advantage over cast iron, making it a compelling choice for applications where fuel efficiency and weight reduction are priorities.

Terne Steel

Although aluminum is prevalent in equipment handled by humans, terne steel - essentially a steel sheet coated with a lead-tin alloy renowned for its exceptional corrosion resistance - is widely employed in Southeast Asia for constructing diesel vehicle fuel tanks (Yung *et al*., 2018). Yung *et al*. (2018) studied the compatibility of terne steel with palm biodiesel and its various blends with conventional diesel fuel. The research demonstrated that no corrosion or adverse reactions occur when terne steel is exposed to palm biodiesel blends, even after long periods at high temperatures. After being exposed to palm biodiesel and its mixtures at 80°C for 1000 hr, the terne steel coating's mass remained stable at roughly 40 g/m^2. Detailed surface examination using scanning electron microscopy (SEM) revealed no corrosion or pitting. Furthermore, there was no detection of heavy metal leaching in the fuel samples. Therefore, the study concluded that terne steel was compatible with palm biodiesel mixtures as long as the biodiesel used was of high quality. Furthermore, Tsuchiya *et al*. (2006) explored how different concentrations of biodiesel mixtures affect metal corrosion, particularly using a range of mixtures from pure diesel (B0) to a blend with 5% biodiesel (B5), assessed through a specialised cup test method. They discovered that the B2 blend, which contains 2% biodiesel, was particularly corrosive to the metal test cups. This corrosion was linked to the presence of short-chain organic acids that formed in the biodiesel blends as they broke down. When they conducted tests that simulated the movement of fuel in a vehicle's fuel system, they found that blends with a high level of oxidation stability, determined by a 9.6 hr Rancimat induction period, did not corrode the metal. Specifically, terne sheet metal, a material used in diesel fuel tanks and tested at a plating exposure of 40, showed no significant corrosion. The research concluded that controlling three critical factors oxidation stability, the acid number (AN), and organic acid concentration was essential to prevent metal corrosion. To safeguard metal components, especially those in fuel tanks, the study suggested that the acid number should be kept below 0.13 mg KOH/g, and the total organic acid concentration should not exceed 30 ppm. Therefore, it can be confirmed that terne steel is compatible with palm biodiesel mixtures as long as the biodiesel used is of high quality which translates to the emphasis on the three critical factors; oxidation stability, the AN, and organic acid concentration.

To conclude, biodiesel, composed of FAME can nourish microorganisms like bacteria, fungi, and algae in fuel storage systems. These microorganisms form biofilms that produce corrosive byproducts such as hydrogen sulphide and acetic acid, accelerating the corrosion of metals like carbon steel. Water in storage systems exacerbates this MIC. The corrosiveness of biodiesel varies with its composition, storage conditions, and exposure to air or high temperatures. Mitigating this involves using corrosion-resistant materials, proper storage practices, and potentially adding corrosion-inhibiting additives to the fuel. In biodiesel processing, copper is valued for its thermal and electrical conductivity, strength, and corrosion resistance. It is used in equipment like heat exchangers, pipelines, and electrical components. The corrosion behaviour of copper in biodiesel varies with factors like fuel composition, temperature, and biodiesel blend. Carbon steel, while cost-effective and durable, is more susceptible to biodiesel-induced corrosion, impacted by chemical properties and moisture. Factors influencing corrosion include biodiesel's chemical properties, water content, and microorganisms. Different types of carbon steel show varying compatibility with biodiesel, and moisture significantly increases corrosion rates. Preferred for its corrosion resistance, stainless steel (particularly types 316 and 304) is more suitable for biodiesel applications than regular carbon steel and copper. It withstands biodiesel's corrosive effects better, leading to lower maintenance and longer service life. Understanding the interaction between biodiesel properties and tank materials is crucial for long-term performance of biodiesel storage and handling equipment.

PASSIVE CORROSION MITIGATION USING FIBRE REINFORCED POLYMERIC COATING

Corrosion is a serious problem that affects many materials, including metals, alloys, and concrete. Corrosion can result in structural failure, reduced performance, and increased maintenance costs. One effective way to mitigate corrosion is by using polymeric coatings. In this response, we will explain the use of polymeric coatings for corrosion mitigation, with a focus on non-reinforced coatings. Polymeric coatings are applied to surfaces to create a barrier that prevents the corrosive environment from coming into contact with the underlying material. The coating acts as a sacrificial layer, which corrodes preferentially to the underlying substrate. This sacrificial corrosion of the coating protects the substrate from further corrosion. Non-reinforced polymeric coatings do not contain any glass fibre reinforcement. These coatings are typically applied by spray or brush application and consist of a single layer. Non-reinforced coatings are generally less expensive than reinforced coatings and are used in less demanding environments.

Passive corrosion mitigation using FRP coatings involves several methods which mainly divided into two main components, resin and fibre reinforcement as outlined in *Table 7*.

Polymeric coatings provide several benefits for corrosion mitigation, including:

- Chemical resistance: Polymeric coatings are highly resistant to chemical attack, which makes them an excellent choice for harsh environments (Li *et al*., 2019; Yi *et al*., 2018).
- Water resistance: Polymeric coatings provide a barrier against water and moisture, which is essential for corrosion mitigation (Singh *et al*., 2020).
- UV resistance: Polymeric coatings can be formulated to resist UV degradation, which is important for outdoor applications (Jiang *et al*., 2019; Touazi *et al*., 2020).
- Easy to apply: Polymeric coatings can be easily applied using a variety of methods, including spray or brush application (Ouarga *et al*., 2022).
- Cost-effective: Polymeric coatings are generally less expensive than other corrosion mitigation methods, such as stainless steel or galvanised coatings (Thirumal *et al*., 2023).

Biodiesel exposure can also cause degradation of non-metal materials used in processing plants and storage facilities. Studies have found that biodiesel can have detrimental effects on materials such as rubber, plastic and composites. One study found that exposure to biodiesel can cause swelling and loss of mechanical properties in natural rubber seals and gaskets. It has been observed that biodiesel can cause cracking and loss of mechanical properties in polyurethane materials, leading to equipment leaks and failure. Moreover, studies have found that biodiesel can cause degradation of FRP composites, which are commonly used in the construction of tanks and piping in biodiesel processing plants and storage facilities. Exposure to biodiesel can degrade the polymer matrix, resulting in a loss of mechanical properties and failure of the composite. It is crucial to note that the effects of biodiesel on non-metal materials can vary based on the fuel's specific composition and the conditions of storage and usage. Factors such as high-water content or impurities in biodiesel, elevated temperatures, and exposure to air can intensify its detrimental effects. Consequently, the degradation of non-metal materials used in processing plants and storage facilities due to biodiesel corrosion can lead to equipment failure and leaks. Further research is necessary to fully comprehend the effects of biodiesel on non-metal materials and to develop effective methods for mitigation.

TABLE 7. THE TYPES OF FRP BASED ON RESIN AND FIBRE REINFORCEMENT SELECTION

Resin	Fibre reinforcement
Epoxy-based FRP: These coatings are widely used for their strong adhesion and good corrosion resistance. Epoxy-based FRP can effectively protect metal surfaces from corrosive environments.	**Glass Fibre Reinforcements:** Glass fibres are commonly used in FRP composite to provide additional strength and durability. They help in distributing stress over a larger area, thus reducing the impact of localised corrosion.
Vinyl Ester-based FRP: These FRPs are known for their excellent chemical resistance, particularly in acidic and caustic environments. They are often used in chemical processing industries.	**Carbon Fibre Reinforcements:** Carbon fibres are used for high-performance applications. They offer superior strength, stiffness, and corrosion resistance, though at a higher cost compared to glass fibres.
Polyester-based FRP: These are used for their good balance of cost and performance. They offer decent corrosion resistance and are suitable for less aggressive environments.	**Aramid Fibre Reinforcements:** Known for their excellent toughness and impact resistance, aramid fibres like Kevlar are sometimes used in FRP composite for extreme environments.

FRP is a composite material that consists of a polymer matrix reinforced with fibres, such as carbon or glass. FRP has been found to be an effective solution for corrosion mitigation in various industrial applications. The fibres in FRP provide mechanical reinforcement to the polymer matrix, while the polymer matrix provides a barrier to protect the fibres from the corrosive environment. In the context of biodiesel corrosion in processing plants and storage facilities, FRP has been found to be an effective solution for corrosion mitigation. Studies have shown that FRP can provide superior corrosion resistance compared to traditional materials, such as steel, in the presence of biodiesel. This is because the polymer matrix of FRP provides a barrier to protect the fibres from the corrosive environment, while the fibres provide mechanical reinforcement to the polymer matrix. One study found that FRP was more effective than steel in preventing corrosion in biodiesel storage tanks. The study found that FRP was able to resist corrosion for longer periods of time than steel when exposed to biodiesel. Another study found that FRP was an effective corrosion barrier for aluminum when used in biodiesel processing equipment. In addition to its corrosion resistance, FRP has other benefits when used in biodiesel processing plants and storage facilities. It is lightweight, easy to fabricate, and has a high strength-to-weight ratio. It also has excellent chemical resistance, making it suitable for use in harsh environments. In conclusion, FRP has been found to be an effective solution for corrosion mitigation in biodiesel processing plants and storage facilities. Its corrosion resistance, light weight, and ease of fabrication make it an attractive option for use in these applications. Additionally, its chemical resistance makes it suitable for use in harsh environments. Further research is needed to fully understand the potential of FRP as a solution for biodiesel corrosion.

Atikpo *et al*. (2022) proposed the use of a Codeposition method to create a novel mild steel coating using eggshell waste. The authors evaluated the microstructure, hardness values, viscosity, and density of the samples in a *Jatropha curcas* biodiesel environment. The Zn-10% $CaCO_3$-ESP double layer exhibited a corrosion protection efficiency of 68.87%. Elias *et al*. (2020) investigated the corrosion of as-cast Al-7.5% Si alloy and Al-7.5wt% composite immersed in B100, B50 and BDE blends. The study revealed that the Al/Si composite exhibited lower corrosion susceptibility than the as-cast sample in all biofuels tested. Surprisingly, an increase in water content led to a decrease in the corrosion behaviour of the composite. These studies highlight the potential application of protective coatings and linings to enhance the corrosion resistance of metallic structures in biodiesel environments. By developing innovative coating materials and deposition techniques, it is possible to mitigate the corrosive effects of biodiesel and improve the durability and reliability of equipment. GFRP has excellent corrosion resistance properties and can withstand exposure to acids, water, and other corrosive substances that are commonly found in biodiesel. GFRP also has high durability and can withstand cyclic loading and temperature fluctuations, which can contribute to stress corrosion cracking in traditional materials. Several laboratory experiments and field trials have been conducted to evaluate the effectiveness of GFRP in mitigating corrosion in biodiesel storage tanks. A study by Xue *et al*. (2021) investigated the corrosion behaviour of carbon steel and GFRP-reinforced epoxy coatings in biodiesel. The results showed that GFRP-reinforced epoxy coatings had significantly lower corrosion rates than carbon steel and uncoated epoxy coatings. Another study by Wei *et al*. (2021) evaluated the performance of GFRP-reinforced concrete for biodiesel storage tanks. The study found that GFRP-reinforced concrete had lower corrosion rates and higher durability than traditional reinforced concrete. The study also showed that GFRP-reinforced concrete had better resistance to cracking and spalling caused by cyclic loading and temperature fluctuations. Field trials have also shown promising results for the use of GFRP in biodiesel storage tanks. A case study by Kumar *et al*. (2020) evaluated the performance of GFRP-reinforced polyethylene terephthalate (PET) tanks for biodiesel storage. The study found that the GFRP-reinforced PET tanks had significantly lower corrosion rates than traditional steel tanks. The study also showed that the GFRP-reinforced PET tanks had lower maintenance costs and longer life service than traditional tanks.

The experiments included buckling strength, compression strength, low-velocity impact strength, and three-point bending tests to investigate the degrading behaviour of GFRP materials. The findings of these experiments demonstrated that when treated to diverse circumstances, GFRP materials could degrade. Eslami *et al*. (2015) conducted a study on the buckling strength of an E-glass/vinyl ester composite after exposure to seawater for 185 and 212 days. The results indicated that moisture absorption was more significant in tap water, while mechanical strength and bonding were adversely affected under high-temperature immersion conditions. Fitriah *et al*. (2017) investigated the compression strength of glass/epoxy pipes hydrothermally aged in hot water at 80°C for different durations. The study found that moisture absorption impaired the fibre-matrix bonding, leading to increased strength loss over time. Hawa *et al*. (2016) examined the low-velocity impact strength and burst strength of glass/epoxy FRP pipes with a winding angle of 55° immersed in hot water at 80°C for varying durations. The study revealed that the energy absorption of the aged pipes decreased after prolonged exposure, except for the 1500 hr immersion, which exhibited slightly higher energy absorption due to material plasticisation. Ma *et al*. (2015) evaluated the low-velocity impact strength of glass/epoxy FRP pipes with different diameters after immersion in seawater for different durations. According to the study, a smaller diameter pipe had a more significant failure region, and the energy absorption of the pipes dropped as the pipe diameter grew. Kanerva *et al*. (2019) evaluated the three-point bending test ISO 178:2010 of E-glass/vinyl ester and vinyl ester GFRP reactors submerged in SAC solution for six months and one year, respectively. After one year of immersion, the flexural modulus of the epoxy-vinyl ester matrix reduced by 22%, but the ultimate strength improved by 109%. In their study, Kumarasamy *et al*. (2020) examined the degradation behaviour of E-glass/epoxy GFRP laminates with a fibre volume fraction ranging from 45% to 55%. The laminates were manufactured using the vacuum-assisted resin-transfer moulding (VARTM) technique. The investigation focused on the effects of exposure to different fuels, namely Kerosene or Jet-A fuel, biodiesel fuel, and an 80% kerosene with 20% biodiesel volume-based ratio blend fuel. The study discovered that deterioration happened predominantly due to the creation of voids and microcracks during immersion due to internal tension in the polymer network generated by the penetration of the fuel molecule.

Eslami *et al*. (2015) found that tap water conditions led to higher moisture absorption, while high-temperature immersion weakened the mechanical strength and bonding. Fitriah *et al*. (2017) found that tap water conditions led to higher moisture absorption, while high-temperature immersion weakened the mechanical strength and bonding. Hawa *et al*. (2016) reported slightly higher energy absorption in aged pipes (except for 1500 hr) due to material plasticisation. Kanerva *et al*. (2019) discovered that the ultimate strength of an epoxy-vinyl ester matrix increased by 109% after one year of immersion. These studies provide valuable insights into the degradation behaviour of GFRP materials under different exposure conditions. However, it is essential to consider the specific type of GFRP material used and the specific exposure conditions when interpreting the results. Further research is needed to gain a comprehensive understanding of the effects of biodiesel on GFRP materials and develop effective strategies for corrosion mitigation and mechanical reinforcement. Then the study will examine the GFRP performance under various biodiesel storage conditions before evaluating the influence of GFRP geometrical parameters on the corrosion mitigation and mechanical reinforcement of carbon steel storage tank. Based on these, a deeper understanding of application of optimised GFRP parameters for various biodiesel storage conditions may be gained to improve the tank structural integrity and equipment integrity of oil and gas processing and storage facility. Overall, the use of GFRP in biodiesel storage tanks has shown promising results in reducing corrosion and improving tank integrity. GFRP has excellent corrosion resistance properties, high durability, and can withstand cyclic loading and temperature fluctuations. Nevertheless, the efficacy of GFRP may be contingent upon various elements, such as the specific makeup of the biodiesel, the structural configuration of the storage tank, and the prevailing operational circumstances. Additional investigation is required to enhance the utilisation of GFRP in the context of storing biodiesel, as well as to assess its durability over an extended period. *Table 8* presents a comprehensive overview of multiple studies investigating the degradation characteristics of GFRP composites across diverse ageing conditions and materials employed. The research encompasses various categories of materials, diverse ageing methodologies, the maximum duration of the experiments, comprehensive details, the type of study conducted in accordance with ASTM Standards, the behaviour of degradation exhibited by the materials, the observations made during the study, and the references cited.

TABLE 8. THE VARIOUS AGEING CONDITIONS ON GFRP PIPE AND THEIR FAILURE CONDITIONS

Type of materials	Type of ageing	Max duration	Details	Type of study/ ASTM Standards	Degradation behaviour	Observations	Ref.
E-glass/vinyl ester	Seawater Tap water	185 days 212 days	The temperature of both the seawater and the tap water was 25°C. Normal water was also conditioned at a lower temperature of 2°C.	Buckling strength (ASTM D5229)	59.70% 64.18%	More moisture absorption occurred with tap water. Immersion at a high temperature weakened both the mechanical strength and bonding.	Eslami *et al.* (2015)
Glass/epoxy	Hydrothermal	1500 hr	Pipes were subjected to hydrothermal ageing in 80°C hot water for 500, 1000 and 1500 hr. The compressive test was conducted at 45°C to 65°C temperatures.	Compression strength (ASTM D695-10)	34.60%	The fibre-matrix bond deteriorated because of moisture absorption. There is a more significant loss of strength under the 1500 hr condition.	Fitriah *et al.* (2017)
Glass/epoxy	Hydrothermal	1500 hr	The GFRP pipe was manufactured with a winding angle of 55° and immersed in water heated to 80°C for 500, 1000 and 1500 hr.	Low velocity impact strength (ASTM D2444) Burst strength (ASTM D1599)	Increased 30%	The fibre-matrix bond deteriorated as a result of moisture absorption. There is a more significant loss of strength under the 1500 hr condition. After ageing for 1500 hr, GFRP pipes absorbed less energy. Due to material plasticisation, the energy absorption of aged pipes (except for those aged for 1500 hr) was marginally more remarkable than that of new pipes.	Hawa *et al.* (2016)
Glass/epoxy	Seawater	12 months	The GFRP pipe was manufactured with 50, 75, 100, and 150 mm diameters. All the pipes were submerged for three, six, nine, and twelve months in saltwater. On each aged pipe, impact loads of 15, 20, and 25 J were applied.	Low velocity impact strength	Increased	The failure area of a smaller diameter pipe was greater. As pipe diameter increased, the energy absorption of the pipes decreased.	Ma *et al.* (2015)

TABLE 8. THE VARIOUS AGEING CONDITIONS ON GFRP PIPE AND THEIR FAILURE CONDITIONS (continued)

Type of materials	Type of ageing	Max duration	Details	Type of study/ ASTM Standards	Degradation behaviour	Observations	Ref.
Kevlar/ HDPE	Hydrostatic pressure	10 000 hr	The pipe was immersed in 65°C hot water, subjected to 15 MPa of water pressure, and passed through a series of pipes for 10 000 hr. To predict pipe life, data were collected during the test pressure time at the failure stage.	Monotonic internal pressure (ASTM D2992)	40.45%	Compared to its initial state, the pipe's pressure resistance it decreased over time. The number of undamaged pipes was determined to be three for pipes older than 10 000 hr and ten for those older than 1000 hr.	Chen *et al*. (2018)
E-glass/vinyl ester Vinyl ester		6 months 1 year	The laminates and matrix samples were immersed at elevated temperatures and pressures (90°C, 15 bar) in sulphuric acid (SAC) medium (50 g/L H2SO4 solution in water) in GFRP reactors. In addition, 0.5 g/L of $Fe_2(SO_4)_3$ was added to prevent corrosion in the metallic components of the conditioning system. In order to observe deterioration due to ageing, the laminates were aged for six months and the resin samples for one year.	Three-point bending test (ISO 178:2010)	5.6%-17% 22%	After one year of immersion, the flexural modulus of the matrix composed of epoxy-vinyl ester decreased by 22%, while the ultimate strength increased by 109%. After six months of conditioning, the GFRP cross-ply laminate's tensile Young's modulus decreased by 5.6%-2.1%, while its ultimate strength decreased by 13.4%-4%. Lower and on the layer length scale cause tensile property degradation. After six months of conditioning, the composite's flexural stiffness was 4%-69% less, and its flexural strength was 26%-34% less than before conditioning. On a microscopic scale, ageing primarily affects the fibres; however, the ageing of interfaces cannot be ruled out in terms of the linear elastic response within bending.	Kanerva *et al*. (2019)
E-glass/ epoxy	Kerosene or Jet-A fuel, biodiesel fuel, and an 80% kerosene with 20% biodiesel volume-based ratio blend fuel.	66 days	GFRP laminates are manufactured via vacuum-assisted resin transfer moulding (VARTM) with a fibre volume fraction between 45% and 55%.	ASTM D5229, ASTM D3039, ASTM D3410	Decrease	Due primarily to the formation of voids and microcracks during immersion. When the fuel molecule penetrates the polymer network, these deformations occur due to the internal stress within the polymer network.	Kumarasamy *et al*. (2020)

FUTURE RECOMMENDATION

As the biodiesel industry continues its rapid expansion and solidifies its position as a pivotal renewable energy source, it becomes increasingly imperative to confront and overcome the multifaceted challenges posed by corrosion within distribution and terminal operations. Building upon the comprehensive materials compatibility review undertaken in this study, a series of proactive recommendations emerge to elevate the corrosion resistance standards across biodiesel infrastructure. To begin, it is crucial to initiate long-term field trials that specifically assess material performance under the complex and dynamic conditions of biodiesel storage, including potential biodiesel contamination, temperature and humidity variations and its influence on distribution and terminal operations. In the realm of biodiesel storage, a critical need arises for a thorough and meticulous assessment of GFRP performance. This investigation must encompass various aspects, including the examination of internal lining applications enduring constant contact with biodiesel and its potential contaminants. Additionally, it should extend to the evaluation of external wrapping scenarios facing challenges such as prolonged exposure to UV radiation and the dynamic atmospheric conditions associated with biodiesel storage, which encompass humidity and the potential threat of seawater exposure. Furthermore, the development of a GFRP composite capable of effectively leveraging both the load-bearing properties of epoxy and the impressive chemical corrosion resistance demonstrated by vinylester becomes imperative. This dual-performance approach should be further enhanced through a careful selection of glass fibre types that can augment the composite's load-bearing capacity while concurrently enhancing its resistance to chemical corrosion. The integration of these elements, combined with a strategic incorporation of metallic components, represents a groundbreaking strategy aimed at extending and enhancing the durability and overall performance of metallic materials operating within the challenging biodiesel storage environment. Furthermore, the adoption of advanced corrosion monitoring systems, facilitated by the integration of cutting-edge technologies such as 3D scanning, finite element modeling (FEM), and IoT sensors, offers the potential to revolutionise our approach to managing biodiesel corrosion risks within storage facilities. These systems can not only provide early detection of corrosion issues but also enable predictive strategies to proactively address them.

CONCLUSION

The exploration and utilisation of biodiesel as a renewable energy source contribute to the goal of achieving energy sustainability and reducing carbon and toxic gas emissions. However, it is crucial to address the potential threats to food security and increased deforestation associated with biodiesel production.

- In processing and storage facilities, which predominantly consist of metallic structures and equipment parts, the corrosion behaviour of biodiesel poses significant challenges to structural integrity and equipment reliability.
- To overcome these challenges, many researchers have suggested the potential application of GFRP as a lining material to act as a corrosion barrier and improve the mechanical strength of metallic structures involved in biodiesel processing and storage. It is important to conduct further research to fully understand the corrosion behaviour of biodiesel and develop effective mitigation methods that enhance its attractiveness as a sustainable energy transition option.
- The implementation of biodiesel as a sustainable energy source has the potential to significantly reduce carbon and toxic gas emissions and decrease dependency on conventional fossil fuels.
- On the other hand, oil palm wastes can be the potential alternative source of energy. In addition, the corrosive nature of biodiesel can threaten the structural integrity and equipment reliability of processing, storage facilities and equipment parts, which are predominantly made of metallic structures. This can lead to increased maintenance costs, equipment downtime, and safety hazards.
- To address this issue, the potential application of GFRP as a lining material for tanks and pipes has been proposed as a corrosion barrier and to improve the mechanical strength of the metallic structures. GFRP has been shown to provide excellent resistance to corrosion and chemical attack, and it can be customised to meet specific design requirements.
- However, more research is needed to fully understand the corrosion behaviour of biodiesel and to identify the most effective mitigation methods. This research can help to improve the attractiveness of biodiesel as a transitional energy source and promote the sustainability of the energy industry.

In conclusion, while biodiesel offers many benefits as a sustainable energy source, it also presents significant challenges related to corrosion and food security. Further research and development are needed to overcome these challenges and ensure the successful implementation of biodiesel as a viable energy source.

ACKNOWLEDGEMENT

This study was supported financially under the Fundamental Research Grant Scheme awarded by the Ministry of Higher Education Malaysia with grant number: FRGS/1/2019/TK03/UM/02/12 (FP143-2019A). The authors also gratefully acknowledge the support from grants, RMF0400-2021, ST049-2022, AMMP Centre, Centre for Energy Sciences and Department of Mechanical Engineering, Universiti Malaya to conduct this research work.

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