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Azardicha indica (Neem) as a Green Corrosion Inhibitor for Protection of Metals and Alloys-A Review

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Abstract: Corrosion is the deterioration of a metal by a chemical attack or reaction with its environment. *Azardicha indica* (Neem) can control the corrosion of various metals and alloys, such as aluminum, brass, carbon steel, mild steel, stainless steel and zinc. Various techniques like the weight loss (WL) method and electrochemical methods such as potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS), have been used to evaluate the corrosion inhibition efficiency (I.E.) of *Azardicha indica*. The protective film has been analyzed by Fourier-transform infrared spectroscopy (FT-IR), Gas chromatography mass spectroscopy (GC-MS), UV-visible spectroscopy (UV-Vis.), X-ray diffraction (XRD), Energy dispersive spectroscopy (EDS) and scanning electron microscopy (SEM) methods. Adsorption of *Azardicha indica* on metal surfaces obeys the Langmuir, Frumkin, Temkin, Flory-Huggins and Freundlich isotherm depending on the nature of metal and the corrosive environment. A polarization study reveals that *Azardicha indica* (Neem) can function as anodic or mixed type of inhibitor.

1. Introduction

Corrosion is a naturally occurring phenomenon commonly defined as the deterioration of metal surfaces caused by chemical or electrochemical reaction with its environment. Recent study indicates that corrosion causes economic losses of approximately $ 2.5 trillion per year, constituting nearly 3.4% of the worldwide GDP (Verma *et al*., 2018). Corrosion can cause disastrous damage to metal and alloy structures, including repair and replacement costs, safety issues, and environmental pollution. Due to these harmful effects, corrosion is an undesirable phenomenon that ought to be prevented (Buchweishaija, 2009). It is a constant and continuous problem and it is impossible to eliminate it entirely (Uhlig, 1971). There are several ways of preventing corrosion and the rates at which it can propagate with a view of improving the lifetime of metallic and alloy materials. The use of inhibitors for the control of corrosion of metals and alloys which are in contact with aggressive environment is one among the acceptable practices used to reduce and/or prevent corrosion (Kumar and Navaratnam, 2013; Nagalakshmi and Sivasakthi, 2019; Nwosu *et al*., 2014).

A corrosion inhibitor is a substance which when added in small concentration to an environment, effectively reduces the corrosion rate of a metal exposed to that environment (James *et al*.,2007; Tebbji *et al*., 2007). It would be more feasible to avoid corrosion rather than strive to eliminate it entirely. The traditional inhibitors in use over the years have been inorganic and synthesized organic compounds. Unfortunately, most of these compounds are harmful for both human being and environments (Bouklah *et.al.,* 2006; Zarrok *et.al.,* 2012). The known hazardous effect of most synthetic corrosion inhibitors is the motivation for the use of some natural products. Nowadays there is growing attention towards eco-friendly corrosion inhibitions "green corrosion inhibitors". Such inhibitors are biodegradable, cheap, eco-friendly, readily available and renewable sources of materials, and ecologically acceptable (Deepa Rani & Selvaraj, 2010; Abdel-Gaber *et.al.,* 2006; Umoren & Eduok, 2016; Dakhil *et al*., 2018)

Metals are widely used in human activities due to their excellent mechanical and electrical properties (Verma *et al*., 2018; Loto and Olowoyo, 2019; Arrousse *et al*., 2020a). In order to preserve the desired state of these metals, their preventive maintenance is a priority. Corrosion is probably the most common undesired phenomenon that leads metals to become weaker (Elayyachy *et al*., 2005; Mai *et al*., 2016). Aluminium and its alloys are finding wide applications in various industries such as automotive, aerospace, construction, and electrical power generation because of their excellent mechanical properties: ductility, weldability, and low cost due to high energy density. Brass is an alloy made of copper and zinc. Copper is a naturally occurring metal that is soft, malleable, ductile. Copper and its alloys are widely used in industry because of their excellent electrical and thermal conductivity and are often used in heating and cooling systems (Dafali *et al*., 2002; Deepa Rani and Selvaraj, 2010; Stupnisek-Lisac *et al*., 1998). Carbon steels are extensively utilized in petroleum refineries, fertilizer processing, mining of minerals, building materials, etc. (Fouda and Hamdy, 2013). Mild steel, referred to as low carbon steel, has an enormous number of applications in the Engineering field due to its specific characteristics such as its versatility, cost-effectiveness, weldability, good ductility, recyclability, strength, availability, machinability, malleability, and high impact and tensile strength (Ekeke *et al*., 2019; Merimi *et al*., 2021). Mild steel is widely used in the industries, especially in the construction, mining, cleaning of boilers, oil well tubes, and metal processing equipment. Zinc is an important metal with numerous industrial applications and is mainly used for the corrosion protection of steel (Rajappa *et al*., 2008; Shylesha *et al*., 2010). The Mild steel corrosion has gained importance in recent past due to increased industrial applications of mild steel especially in acid solutions such as pickling, industrial acid cleaning, acid descaling and oil well acidizing (Finsgar and Jackson, 2014).

The inhibition effect can be anodic, cathodic, or mixed. It is also worth specifying that some inhibitors are strictly specific to the metal or alloy and environment, and might not show any inhibition phenomenon with others. Anodic inhibitors usually act by forming a protective oxide film on the surface of the metal, cathodic inhibitors act by either slowing the cathodic reaction itself or selectively precipitating on cathodic areas to limit the diffusion of reducing species to the surface. Most of the green corrosion inhibitors belong to the mixed class. Mixed-type inhibitors can accomplish a cathodic and anodic action at the same time by decreasing both their electrochemical rates (Okpala *et al*., 2022). Plant extracts contain many organic compounds, having polar atoms such as O, P, S and N. These are adsorbed on the metal surface by these polar atoms, and protective films are formed, and various adsorption isotherms are obeyed. Several adsorption isotherm models have been proposed to describe the adsorption mechanism of organic inhibitors on the metal surface. The most appropriate model is the one that best fits the experimental values. Effect temperature has an important influence on the phenomenon of corrosion in metal surfaces. Some extracts exhibit an increasing inhibition efficiency tendency towards higher temperatures (Bahlakeh *et al*., 2019). However, other extracts show different behaviors. Thus, evaluating the inhibition efficiency as a function of temperature is important, as every extract may perform differently (Anupama *et al*., 2015; Mourya *et al*., 2014). Similarly, the immersion time is another factor that could modify the inhibition efficiency, and consequently some authors have evaluated it as well (Kumar *et al.*, 2011).

Azadirachta indica (AZI, common name "Neem") is a member of mahogany family, Meliaceae (Yanpallewar *et. al*., 2003, Von Maydell, 1986). It is commonly called 'Indian lilac' or 'Margosa'. The Latin name for neem is *Azadirachta indica*. It is one of two species in the genus of *Azadirachta*. Neem plants grow in various countries in the world, including Asia, Africa, America, and Australia (Hegde, 1995; Sidhu, 1995; Ghosh *et al.*, 2016; Prajapati *et al.*, 2019). It is native to India, Bangladesh, Thailand, Nepal, Cambodia, Laos, Myanmar and Pakistan (Prashanth and Krishnaiah, 2014). It grows well in tropical and sub-tropical regions. It has been used in Ayurvedic medicine for more than 4000 years due to its medicinal properties. The Sanskrit name of the Neem tree is ''Arishtha'' meaning ''reliever of sickness'' and hence is considered as ''Sarbarogani barini'' (Biswas *et al*., 2002). In India, this tree is called "Divine tree", "Wonder tree", "heal all", "Materia Medica", "Free tree of India", Nature's drugstore", "Village Pharmacy", "Panacea for all diseases" (Tiwari *et al.*, 2014; Ghimeray *et al.*, 2009; Shah *et al.*, 2010). In India, other names for this tree like "Heavenly Tree", "Life time enhancing tree", "Environment's Dispensary", "Community Apothecary" (Chattopadhyay, 1999; Negi *et al.*, 2002). The plant is extraordinary, and it is referred to as "21st-century trees" by the United Nations. Neem is also referred to as "a tree for solving global problems" because it offers numerous benefits, and it can treat various diseases (Kumar and Navaratnam, 2013).

Description of the Neem plant

Azadirachta indica (Neem) is a fast-growing tree that can reach a height of 15–20 metres (49–66 ft), and rarely 35–40 m (115–131 ft). It is evergreen, shedding many of its leaves during the dry winter months. The branches are wide and spreading. The fairly dense crown is roundish and may reach a diameter of 20–25 m (66–82 ft). The opposite, pinnate leaves are 20–40 cm (8–16 in) long, with 20 to 30 medium to dark green leaflets about 3–8 cm (1+¼–3+¼ in) long. White and fragrant flowers are arranged in more-or-less drooping axillary panicles which are up to 25 cm (10 in) long. An individual flower is 5–6 mm long and 8–11 mm wide. The fruit is a smooth (glabrous), olive-like drupe which varies in shape from elongate oval to nearly roundish, and when ripe is 14–28 mm by 10–15 mm. The fruit skin (exocarp) is thin and the bitter-sweet pulp (mesocarp) is yellowish-white and very fibrous. The white, hard inner shell (endocarp) of the fruit encloses one, rarely two, or three, elongated seeds (kernels) having a brown seed coat. Its fruits and seeds are the source of neem oil (Naveed *et al.*, 2014). Leaves alternate, crowded near the end of branches, simply pinnate, 20-40 cm long, estipulate, light green, with 2 pairs of glands at the base. Neem gum is naturally extracted from neem tree by induced or natural injury. Neem Gum is clear, bright and amber-colored material non-bitter in taste and is soluble in cold water. It is a byproduct obtained as a result of metabolic mechanism of plants and trees (Dalhatu *et al*., 2018).

Ecology of Neem

Neem plants grow a lot in areas with rainfall from 450 to 1200 mm, temperatures from 0 to 49 °C and pH varies from and 4-10. Neem can also grow in areas with very low rainfall of 150-200 mm (Saleem *et al.*, 2018). Neem plants can adapt to climate, geographical, and topographic conditions. It does not require much sunlight and water for growth. Neem plants grow in almost all types of soil, including alkaline, clay, and saline soils (Ghosh *et al.*, 2016). It is one of the most studied medicinal plants and is used for health. This plant is widely cultivated throughout the world due to its adaptive to various climate conditions (Ashafa *et al.*, 2012). *Azadirachta indica* (Neem) leaves is shown in **Figure 1**.

Figure 1. Leaves of *Azadirachta indica* (Neem) (Nandini *et al*., 2018)

Traditional uses of Neem

Azadirachta Indica (Neem) is more useful for its medicinal, chemical and biological activities (Schaaf *et al*., 2000). Apart from medicine and other health benefits, neem is a very promising plant as it could be used to reduce the rate of population growth (Seriana *et al*., 2019). Neem fruits, seeds, oil, leaves, bark, and roots have such uses as general antiseptics, anti-microbials, treatment of urinary disorders, diarrhea, fever and bronchitis, skin diseases, septic sores, infected burns, hypertensions, and inflammatory diseases (Sharma *et al*., 2010a). Neem leaves serve as antibacterial, antifungal, anti-inflammatory, immunomodulatory, antihyperglycemic, antiulcer, antifungal, antibacterial, antimutagenic, anticancer, antimalarial, antiviral, antioxidant (Gupta *et al*., 2017; Subapriya and Nagini, 2005; Kumar *et al*., 2016; Deepa Rani and Selvaraj, 2011; Dasgupta *et al*., 2004; Biswas *et al*., 2002; Saleem *et al*., 2018). The tree is popular for its pharmacological attributes such as hypolipidemic, microbicidal, antidiabetic, hepatoprotective, insecticidal, nematicidal, neuroprotective, cardioprotective, and antileishmaniasis properties (Saleem *et al*., 2018). Besides these uses, there are several other reports on the biological and pharmacological actions such as antipyretic, antiseptic and antiparalitic (Prieto *et al*., 1999; Eshrat and Ali, 2002; Britto and Sheeba, 2011). The *Azadirachta indica* leaves are greatly used among the quite a lot of tribes of India to remedy cuts, wounds and different minor dermis illnesses (Jain *et al*., 2010; Padal *et al*., 2013). Neem leaves are useful for chickenpox, increase immunity of the body, reduce fever caused by malaria, treating various foot fungi, useful against termites, used in curing neuromuscular pains. Bathing with Neem leaves is beneficial for itching and other skin diseases. Leaf juice is used as nasal drop to treat worm infestation in nose (Hashmat *et al*., 2012). Various active compounds contained in the neem leaf have an antifertility effect (Hashmat *et al*., 2012; Saleem *et al*., 2018; Despande *et al*, 1980). Women in the northwest Madagascar village consume neem leaves to prevent pregnancy. In Gambia and Ghana, neem leaves are made as tea drink to stop pregnancy at the age of the first 2-3 (Ketkar *et al*., 2005). The leaves are sometimes used for emergency livestock feed. They are also extensively used for dressing unhealthy wounds and ulcers, and also as a febrifuge. Their insect repellent properties for preservation of woolens, etc. are well known (Eddy and Mamza, 2009). Various other important therapeutic effects have been associated to Neem extract like treating diabetes mellitus, improving liver functions, neuroprotective effects, stress and ulcer reduction, treatment of sexually transmitted diseases, skin diseases and malaria (Naveed *et al.*, 2014). Neem may be helpful in prevention and cure of acquired immune deficiency syndrome (AIDS). World Health Organization reported the investigation of Neem with emboldening results on the therapeutic treatment of HIV and cancer (Das *et al.*, 2017). Therapeutically, its crude extracts from bark and leaves have been used in folk medicine to control diseases such as leprosy, intestinal helminthiasis and respiratory system (Prieto *et al.*, 1999). Neem bark is used as an active ingredient in a number of tooth pastes and tooth powders because of its antibacterial properties. Seed oil is used in leprosy, syphilis, eczema, chronic ulcer. Neem kernels contain 30–50% of oil and many active ingredients having antifeedant, growth-inhibiting, anti-oviposition and insecticidal activities (Schmutterer, 1995). Neem oil extracted from the seed goes into soaps, waxes and lubricants, as well as into fuels for lighting and heating. Neem oil and powdered neem leaves are employed in various cosmetic preparations such as face creams, nail polish, nail oils, shampoos, conditioners (Jattan *et al.*, 1995). In addition, wood from the trees is valued for construction, cabinetry and fuel (Eddy and Mamza, 2009). Neem cake as a byproduct of neem oil industry is used as livestock feed, fertilizer and natural pesticide. Neem seed pulp is used as a rich source of carbohydrate in fermentation industries and for methane gas production (Jattan *et al.*, 1995).

2. Methodology

Corrosion inhibition of different metals and alloys in various medium by *Azadirachta indica* (Neem) as an inhibitor was shown in **Table1**.

Table 1. Corrosion inhibition of metals and alloys in different media by *Azadirachta indica* (Neem) as an inhibitor.

Metal / Alloy	**Medium + Additive**	**Techniques used**	**Findings**	**I.E. max. (in %)**	**Reference**
Aluminium	0.5 M HCl + 0.01 M NaI.	PDP, EIS , SEM, SE.	Mixed-type of inhibitor. Freundlich adsorption isotherm	45.07 PDP, 70.13 EIS.	Arab *et al.*, 2008
Aluminium	0.5 N HCl	WL with time and temperature, FT-IR.	Langmuir adsorption isotherm.	92.37 WL	Sharma *et al.*, 2013
Aluminium	1.85 M HCl	GM, SEM.	Langmuir adsorption isotherm.	99.70 GM	Ajanaku *et al.*, 2015
Aluminium	0.5 M HCl	TM , PDP, FT-IR.	Mixed-type of inhibitor.	88.68 TM, 86.36 PDP.	Ekeke *et al.*, 2020
Aluminium (AA 1060)	0.5 M and 2 M HCl	WL with time and temperature.	Langmuir adsorption isotherm.	69.14 WL	Abakedi *et al.*, 2016
Aluminium	0.5 M HCl	WL with temperature.	Langmuir, Freundlich and Termkin adsorption isotherms.	84.96 WL	Desai *et al.*, 2017
Aluminium	0.75 M HCl	WL with temperature.	Langmuir adsorption isotherm.	96.41 WL	Prajapati *et al.*, 2019
Aluminium	0.75, 1.0 & 1.25 M HCl	WL, PDP, EIS.	Mixed-type of inhibitor.	96.41 WL, 91.41 PDP.	Vashi *et al.*, 2019
Aluminium Alloy (AI-3102)	MB & MC Bacteria media	PDP, EIS, SEM, XPS, GC-MS.	Efficient inhibitor.	83.8 PDP for MB & 98.5 PDP for MC	Selvam *et al.*, 2023
Brass	HNO_3	WL with time and temperature, PDP, EIS and SEM.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	98.37 WL, 97.26 PDP, 97.26 EIS.	Patel *et al.*, 2017

Brass	Natural Sea Water	WL with time and temperature, UV Vis. and FTIR.	Langmuir and Temkin isotherms.	87.50 WL	Deepa Rani *et al.*, 2011
Carbon Steel	1 N HCl	WL with time and temperature. PDP, EIS, SEM.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	86.15 WL, 69.33 PDP, 88.05 EIS.	Malarvizhi *et al.*, 2018a
Carbon Steel	0.5 & 1.0 M HCl, 3.74 & 5.61 M NH_4Cl	WL with time, CVF.	Efficient inhibitor.	97.55 WL in 1.0 M HCl, 78.52 WL in 5.61 M NH_4Cl.	Loto and Akpanyung *et al.*, 2025
Carbon Steel	1 N H_2SO_4	WL with time and temperature, PDP, EIS, FT-IR and SEM.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	85.20 WL, 55.60 PDP, 60.35 EIS.	Malarvizhi *et al.*, 2018b
Carbon Steel & Aluminium	3.5 % NaCl and Na_2SO_4	WL with time.	Langmuir adsorption isotherm.	78.06 WL for CS & 90.62 WL for Al.	Meza-Castellar *et al.*, 2018
Carbon Steel (C-1345)	1 M H_2SO_4	WL with time.	Efficient inhibitor.	86.0 WL	Okpala *et al.*, 2022
Carbon Steel	1 M HCl	WL with temperature, PDP.	Mixed type of inhibitor.Termkin adsorption isotherm.	80.0 WL, 86.84 PDP.	Nahl´e *et al.*, 2010
High Carbon Steel	1 M H_2SO_4	WL with time.	Efficient inhibitor.	89.0 WL	Waidi *et al.*, 2022a
Medium Carbon Steel (C-1345)	1 M H_2SO_4	PDP	Mixed-type of inhibitor.	90.0 PDP	Waidi *et al.*, 2022b
Copper	1, 2 and 3 N HNO_3	WL with time.	Mixed-type of inhibitor.	95.69 WL in 1 N HNO_3	Sangeetha *et al.*, 2011
Copper	0.1, 0.25, 0.5 & 1.0 N HNO_3	WL, PDP, EIS.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	94.45 WL, 98.06 PDP, 99.00 EIS.	Patel *et al.*, 2015
Copper	0.5 N HCl	WL with time, SEM and FT-IR.	Langmuir adsorption isotherm.	97.72 WL	Yadav *et al.*, 2014
Copper	0.5 N H_2SO_4	WL, PDP.	Anodic type of inhibitor. Frumkin adsorption isotherm.	92.7 WL, 86.40 PDP	Valek *et al.*, 2007
Copper	1 M HNO_3	WL with temperature.	Langmuir adsorption isotherm.	99.83 WL	Mitu *et al.*, 2019
Copper	0.5 M H_2SO_4	WL, PDP.	Frumkin adsorption isotherm.	92.7 WL	Zulj *et al.*, 2007
Mild Steel	2.36 M HCl	WL with time and temperature.	Efficient inhibitor.	84.85 WL	Chime *et al.*, 2018
Mild Steel	0.01 M & 1 M HCl	WL	Efficient inhibitor.	90.0 WL	Ade *et al.*, 2022
Mild Steel	1 N HCl, H_2SO_4 , HNO_3	WL with time and temperature, SEM, GC-MS.	Langmuir adsorption isotherm.	70.2 WL in 1 N HCl, 65.6 WL in 1N H_2SO_4 & 52.6 WL in 1N HNO_3	Peter *et al.*, 2017

Mild Steel	0.1 to 2.0 M HCl, H_2SO_4 and HNO_3	WL with temperature.	Langmuir adsorption isotherm.	93.37 WL in HCl, 96.59 WL in H_2SO_4 & 90.50 WL in HNO_3	Dalhataru *et al.*, 2018
Mild Steel	HCl and HNO_3	WL with temperature.	Flory-Huggins adsorption isotherm.	74.0 WL in HCl & 85.0 WL in HNO_3	Agu *et al.*, 2010
Mild Steel	0.5 , 1.0 & 2.0 N HCl	WL with time.	Efficient inhibitor.	91.42 WL	Abass *et al.*, 2021
Mild Steel	0.5 M HCl and 0.5 M H_2SO_4	WL with temperature, OCP.	Efficient inhibitor.	27.37 WL in 0.5 M HCl & 24.08 WL in 0.5 M H_2SO_4	Loto *et al.*, 2011
Mild Steel	1 and 2 M H_2SO_4	WL with time.	Efficient inhibitor.	75.49 WL in 2 M H_2SO_4	Ugwuoke *et al.*, 2017
Mild Steel	1 M H_2SO_4	WL with time, SEM, FT-IR.	Efficient inhibitor.	69.69 WL	Chukwueze *et al.*, 2019
Mild Steel	1 M H_2SO_4	WL with time and temperature, SEM, FT-IR.	Efficient inhibitor.	85.1 WL	Chukwueze *et al.*, 2020
Mild Steel & HYSD Bars	0.5 M H_2SO_4	WL with time.	Efficient inhibitor.	98.56 WL for MS & 88.61 WL for HYSD Bars	Nandini *et al.*, 2018
Mild Steel	0.5 M H_2SO_4	WL with temperature.	Efficient inhibitor.	75.95 WL	Ebenso *et al.*, 1998
Mild Steel	2 M H_2SO_4	WL with time and temperature, HE.	Efficient inhibitor.	60.4 WL for leaves, 66.8 WL for root & 81.8 WL for Seeds.	Okafor *et al.*, 2010
Mild Steel	0.5, 1.0 & 2.0 N HNO_3	WL with temperature.	Frumkin adsorption isotherm.	82.50 WL	Sharma *et al.*, 2010a
Mild Steel	0.5 N HNO_3	WL with temperature.	Langmuir adsorption isotherm.	63.15 WL	Meena 2023
Mild Steel	0.1 M H_2SO_4	WL, HE, FT-IR.	Flory-Huggins adsorption isotherm.	94.24 WL, 92.34 HE	Eddy *et al.*, 2009
Mild Steel	1 M H_2SO_4 & 2 M HCl	WL with temperature, HE, PDP.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	--	Oguzie *et al.*, 2006
Mild Steel	1 M H_2SO_4 & 1 M HCl	WL with time, PDP, EIS.	Mixed-type of inhibitor. Temkin adsorption isotherm.	89.0 WL for 1 M HCl & 80.0 WL for 1 M H_2SO_4	Alberts *et al.*, 2023
Mild Steel	1 M H_2SO_4 & 2 M HCl	WL with temperature, HE.	Langmuir adsorption isotherm.	93.8 WL in 1 M H_2SO_4 & 95.6 WL in 2 M HCl	Oguzie *et al.*, 2008
Mild Steel and Copper	0.5, 1.0 & 1.5 M H_2SO_4	GM.	Efficient inhibitor.	----	Ekeke *et al.*, 2019
Mild Steel	1M H_2SO_4	WL with time.	Efficient inhibitor.	86.0 WL	Waidi *et al.*, 2022c

Mild Steel	1.5 M H_2SO_4	WL with time, PDP, FT-IR, OM.	Cathodic-type of inhibitor. Langmuir and Temkin adsorption isotherms.	72.03 WL	Nwigwe *et al.*, 2023
Mild Steel	0.5 M HCl	WL with time.	Efficient inhibitor.	65.1 WL	Sadiq *et al.*, 2015
Mild Steel	1 M HCl	WL with time and temperature, PDP, EIS, FT-IR.	Mixed- type of inhibitor. Langmuir adsorption isotherm.	92.11 WL, 81.7 PDP, 67.1 EIS.	Malarvizhi *et al.*, 2016
Mild Steel	0.5 M HCl	WL with time.	Efficient inhibitor.	48.56 WL	Elachi *et al.*, 2021
Mild Steel	1 M HCl	WL with temperature, PDP.	Mixed-type of inhibitor. Langmuir, Freundlich and Termkin adsorption isotherms.	94.11 WL, 99.63 PDP.	Desai *et al.*, 2015
Mild Steel	0.1 M HCl	WL with time, GC-MS, FT-IR, PDP.	Mixed-type of inhibitor. Langmuir, Freundlich and Termkin adsorption isotherms.	93.24 WL	Okewale *et al.*, 2018
Mild Steel	1 M HCl	WL with time, PDP, EIS, SEM, EDS.	Efficient inhibitor.	97.0 WL	Abro *et al.*, 2020
Mild Steel	5 M HCl	WL, PDP, EIS, SEM, MDS, DFT.	Langmuir and Freundlich adsorption isotherms.	89.25 WL	Kumar *et al.*, 2022
Mild Steel	1 M HCl	WL with temperature, PDP, EIS, FT-IR.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	73.2 WL, 57.9 PDP, 51.2 EIS.	Brindha and Mallika, 2015a
Mild Steel	1 M HCl + Zn^{+2} & Ni $^{+2}$ ions.	WL with time and temperature, PDP, EIS, FT-IR.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	76.88 WL with Zn^{+2} & 81.2 WL with Ni $^{+2}$	Brindha and Mallika *et al.*, 2015b
Mild Steel	1 M HCl + Piperidin-4-one derivatives.	WL, SE, PDP, EIS, FT-IR.	Mixed-type of inhibitor.	91.8 WL, 97.8 PDP, 76.1 EIS.	Brindha and Mallika, 2016
Mild Steel	0.25 M HCl	WL with time.	Langmuir adsorption isotherm.	94.22 WL for leaves, 86.27 WL for Stem & 83.22 WL for Seed.	Ogundana *et al.*, 2022
Mild Steel	1 M HCl & 1 M H_2SO_4	WL	Langmuir and Temkin adsorption isotherms.	97.0 WL in 1 M HCl & 86.0 WL in 1M H_2SO_4	Ndukwe *et al.*, 2023
Mild Steel	1 Wt.% $Ca(OH)_2$ + 0.5 Wt% NaCl	WL with temperature, PDP.	Efficient inhibitor.	86.0 WL	Baitule *et al.*, 2020

Mild Steel	1 Wt.% $Ca(OH)_2$ + 0.5 Wt% NaCl	WL with temperature, EIS, FT-IR, XPS, XRD.	Frumkin adsorption isotherm.	78.0 WL	Baitule *et al.*, 2025
Mild Steel	0.5 M H_2SO_4	WL with temperature. UV-Vis., FT-IR, SEM, GC-MS.	Freundlich, Langmuir and Dubinin - Raduskevich adsorption isotherms.	46.88 WL for leaves 31.16 WL for complex & 59.69 WL for the ratio 1:1 blend	Itodo *et al.*, 2018
Mild Steel	HCl and HNO_3	WL with temperature, PDP.	Efficient inhibitor.	---	Jain *et al.*, 2014
Mild Steel	Sea Water	WL, PDP, EIS, FT-IR, UV-Vis., FS.	Mixed-type of inhibitor predominately anodic in nature.	98.0 WL	Sribharti *et al.*, 2018
Mild Steel	Salt Water	WL with time.	Efficient inhibitor.	80.0 WL	Tuaweri *et al.*, 2015
Mild Steel	2.5 M Citric acid.	OCP, PDP, OM, FT-IR.	Anodic -type of inhibitor.	99.55 WL, 88.88 PDP	Loto *et al.*, 2019
Mild Steel	0.5 & 1.0 M Saline + Enzyme	WL with time.	Efficient inhibitor.	85.0 WL	Udoh *et al.*, 2022
Stainless Steel	HCl, H_2SO_4 and HNO_3	WL with time.	Efficient inhibitor.	85.0 WL	Obiukwu *et al.*, 2013
304 Stainless Steel	1 M H_2SO_4	WL with teperature, SEM.	Efficient inhibitor.	88.9 WL	Singh *et al.*, 2022
Steel (TMT Rebars)	1 M HCl and 1 M NaCl	WL with time and temperature, PDP, EIS, EDS, UV-Vis., FT-IR, GC-MS, SEM, AFM, ANN, AAS.	Mixed-type of inhibitor. Langmuir adsorption isotherm.	**In 1M HCl** 93.25 WL, 85.06 PDP, 83.79 EIS. **In 1M NaCl** 81.16 WL, 59.75 PDP.	Junaid Ahmed *and Mohan Ganesh*, 2024
Reinforcement Steels (TMT,CRC ,TMX)	1 M HCl	PDP, EIS, CV, QCC, ANN, OM.	Mixed-type of inhibitor predominately anodic in nature, Langmuir adsorption isotherm.	85.1 PDP, 75.74 EIS for TMT Steel	Junaid Ahmed *and Mohan Ganesh*, 2025
Zinc	0.2 N HCl	WL with temperature, PDP, EIS, SEM.	Mixed-type of inhibitor predominately cathodic in nature. Temkin adsorption isotherm.	70.0 WL, 70.0 PDP, 69.0 EIS	Prabhu *et al.*, 2014

Zinc	0.25 M HNO_3	WL with temperature, FT-IR, SEM.	Freundlich adsorption isotherm.	58.54 WL	Muhammad *et al.*, 2022
Zinc	2 N H_2SO_4	WL with temperature.	Efficient inhibitor.	83.58 WL	Sharma *et al.*, 2009
Zinc	2 N H_2SO_4	WL with temperature.	Efficient inhibitor.	83.58 WL	Tokala *et al.*, 2017
Zinc	2 N HCl	WL with temperature.	Efficient inhibitor.	78.33 WL	Sharma *et al.*, 2010b
Zinc	1 M HCl	WL with time and temperature, FT-IR, SEM.	Langmuir adsorption isotherm.	98.45 WL	Ibrahim *et al.*, 2024
Zinc	0.1M HCl and 0.1 M NaOH	WL with time.	Efficient inhibitor.	84.0 WL in 0.1M HCl & 95.0 WL in 0.1M NaOH	Ameh *et al.*, 2025

Abbrevations: AFM: atomic force microscope, **AZI:** azadirachta indica**, ANN**: artificial neural network , **DFT**: density function theory, **AAS**: Atomic absorption spectroscopy, **CV**: cyclic voltametry, **CVF**: computational validity factor, **EDS**: energy dispersive spectroscopy, **EIS**: electrochemical impedance spectroscopy**, FS:** fluorescence spectrophotometer, **FT-IR**: fourier-transform infrared spectroscope, **GC-MS:** gas chromatography mass spectrometry, **GM**: gasometric method, **HE**: hydrogen evolution, **HPLC:** high pressure liquid chromatography, **MDS**: molecular dynamics simulation, **PDP:** potentiodynamic polarization **, SE**: synergistic effect, **SEM**: scanning electron microscopy **TM**: thermometric method**, OCP:** open circuit potential**, OM:** optical microscope**, QCC:** quantum chemical calculation, **UV-Vis**.: ultraviolet-visible spectrophotometry, **XRD**: X-ray diffraction, **XPS**: X-ray photoelectron spectroscopy, **WL:** weight loss.

Gas chromatography mass spectrometry (GC-MS) study

Peter and Sharma (Peter and Sharma, 2017) studied of corrosion inhibition of Mild steel in 1 M HCl solution by *Azadirachta indica* as an corrosion inhibitor. They carried out GC-MS spectra of the Banana Peel extracts shown in **Figure 2** which indicates various levels of peaks. The chromatogram of compounds which were reported in GC-MS of *Azardiracta indica* are following: Phenol, 2-methoxy-4-propyl-; Digitoxin; Cyclohexanol, 4-[(trimethylsilyl)oxy]-,*cis*-; Hexadecanoic acid, 1,1-dimethylethyl ester; Cyclononasiloxane, octadecamethyl-; Cyclopentanol, 2-cyclopentylidene-; Octadecanoic acid, butyl ester; Cyclononasiloxane, octadecamethyl-; 2,6-Dimethyl-4-nitro-3-phenyl-cyclohexanone; 1,2-Propanediol, 3- benzyloxy-1,2-diacetyl-;Heptasiloxane, hexadecamethyl-;2-(3-Hydroxy-2-nitro-1-phenylbutyl) cyclohexane, Succinic acid,3,7-dimethyloct-6-en-1-yl isobutyl; Butyl myristate; Stearic acid, 3-(octadecyloxy)propyl esters; 1-Penten-3-one, 4,4-dimethyl-1-phenyl-; *beta*-Tocopherol; Retinol, acetate; Andrographolide; *trans*-Dehydroandrosterone, methyl ether. The spectrum of the unfamiliar constituent was paralleled with the spectrum of the known constituent compounds deposited in the NIST library. From the GC-MS spectrum of AZI, it is evident that the spectrum of AZI consisted of 33 peaks with various values of retention time (RT) and fragmentation peaks. Because the area below a chromatogram is proportional to the concentration of the analyte, area normalization was carried out in categorize to calculate the percentage constituent of molecules identified in each peak. Long carbon chain or aromatic compounds have reported in GC-MS analysis.

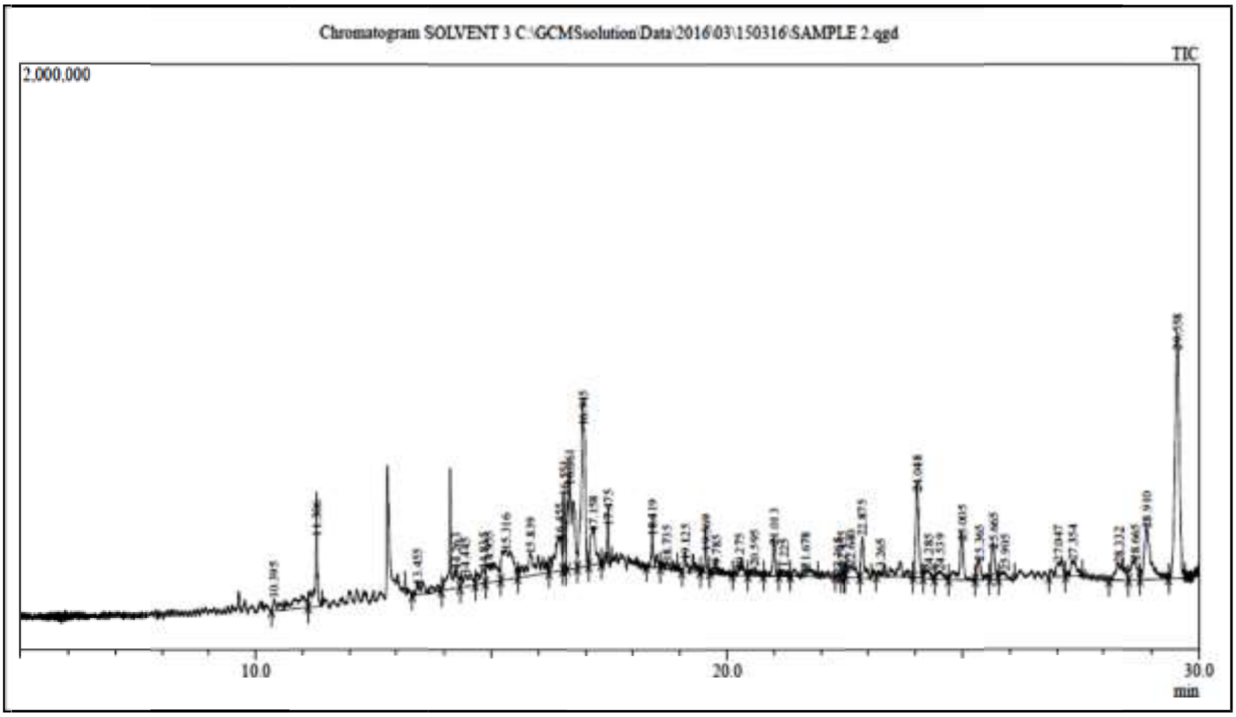


Figure 2. GC-MS spectrum of *Azardirachta indica* (Peter and Sharma, 2017)

Potentiodynamic polarization (PDP) Study

Malarvizhi and Mallika et al. (Malarvizhi and Mallika *et al.*, 2018a) studied the polarization curves for carbon steel in 1 N HCl in the absence and presence of different concentrations of Azadirachta Indica (Neem) for a 4 h immersion period, as shown in **Figure 3.** A decrease in the I_{corr} value shows the retardation of electrochemical reactions. The corrosion potential (E_{corr}) reflects the balance between anodic and cathodic reactions (Muralidharan *et al.*, 1995).

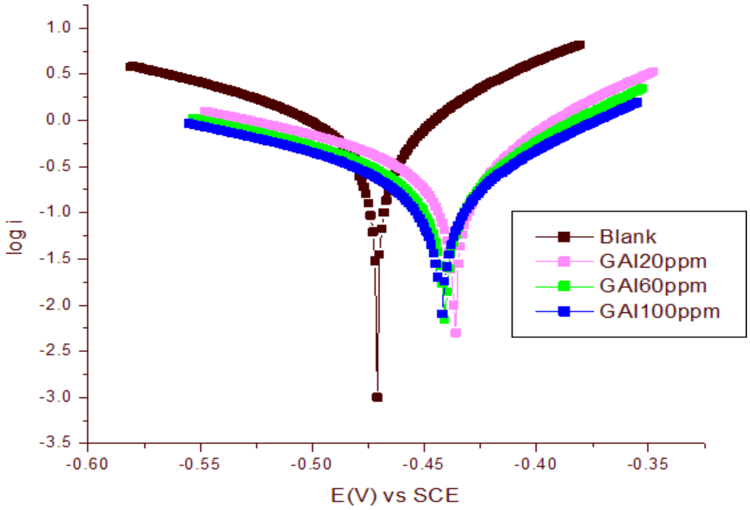


Figure 3. Potentiodynamic polarization curves for Carbon steel in 1 N HCl in absence and presence of different concentrations *Azadirachta Indica* (Malarvizhi and Mallika et al., 2018a).

When an inhibitor is added and E_{corr} shows no significant shift (typically within ±85 mV), it indicates that the inhibitor affects both reactions similarly. This behavior characterizes a mixed-type inhibitor, which reduces both metal dissolution and cathodic processes without favoring one. Thus, the absence of significant E_{corr} change suggests a mixed-mode inhibition mechanism (Arrousse et al., 2020b; Salim *et al.*, 2024). From **Figure 3**, it was clear that corrosion rate decreases in the presence of GAI as a consequence of production of lower current densities by both anionic dissolution of metals and cationic hydrogen evolution reaction. Change in the Tafel constants prove that GAI affects both anodic and cathodic reaction. This shows Nyquist plots increasing in diameter of semi-circles with GAI concentration which is indicative of the fact that GAI adsorption on to the metal hinders the corrosion process.

Electrochemical impedance spectroscopy (EIS) study

Malarvizhi and Mallika et al. (Malarvizhi and Mallika et al., 2018a) studied EIS diagrams for Carbon steel in 1 N HCl after 4 h immersion for free acid and inhibited test solutions and Nyquist plots were shown in **Figure 4**. This shows Nyquist plots increasing in diameter of semi-circles with GAI concentrations which is indicative of the fact that GAI adsorption on to the metal hinders the corrosion process. Difference in the shape of the semi-circles can be explained with reference to non-homogeneity of the surface and roughness of the metal (Malarvizhi and Mallika *et al.*, 2018a; Hajjaji *et al.*, 2019).

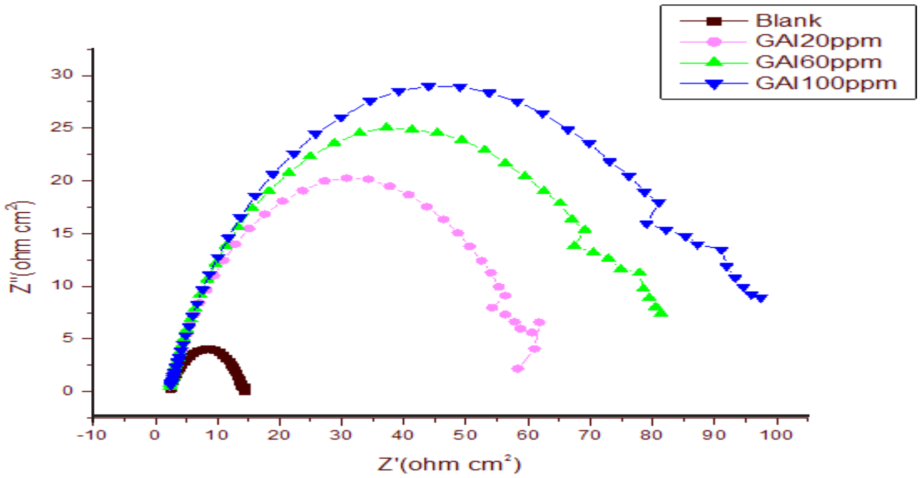


Figure 4. Nyquist plots of CS in 1N HCl (Malarvizhi and Mallika *et al.*, 2018a).

Ultra violet visible spectroscopy (UV-Vis.) study

Junaid Ahmed and Mohan Ganesh (Junaid Ahmed and Mohan Ganesh, 2024) studied UV-Vis. spectra for steel in 1 M HCl and 1M NaCl solutions with and without Neem powder are shown in **Figure 5**. UV–Vis analysis was done to detect specific functional groups present in the samples before and after corrosion. They were identified through the absorption peaks obtained near UV (200–400 cm^{-1}) and visible regions (400–800 cm^{-1}). The type of compound from the high peaks can be determined by correlating it with standardized data. The first sample was a pure neem extract solution and the other two samples were the solutions obtained after steel corrosion. The later were prepared by immersing steel samples of 0.5 cm length for 5h at 40 °C in exposure mediums containing 10g/500 mL neem powder. The samples were rinsed, soaked in distilled water for 30 min, followed by scraping the surface (Ji *et al.*, 2015) and the solution was subjected for analysis.

For the pure neem sample in **Figure 5(a)**, multiple peaks of absorbance were detected, indicating the presence of ample phytochemicals. The entire region of UV and visible spectra showed multiple peaks because the extract was a colored solution (Tiwari *et al.*, 2018). In **Figure 5(b),** the neem peaks fall in the UV region, because the solution is colorless. Furthermore, the UV–Visible spectrum between 200–400 nm can reveal important structural features of organic compounds. Intense peaks in this range are usually due to $\boldsymbol{\pi \rightarrow \pi^*}$ transitions, common in conjugated systems like alkenes, aromatics, and azo compounds. Weaker peaks often correspond to **n** → ***π**** transitions, typical of compounds with lone pair electrons such as carbonyls or nitro groups. The presence of both transitions indicates the existence of conjugated or polar functional groups in the molecule (Saleem *et al*., 2018).

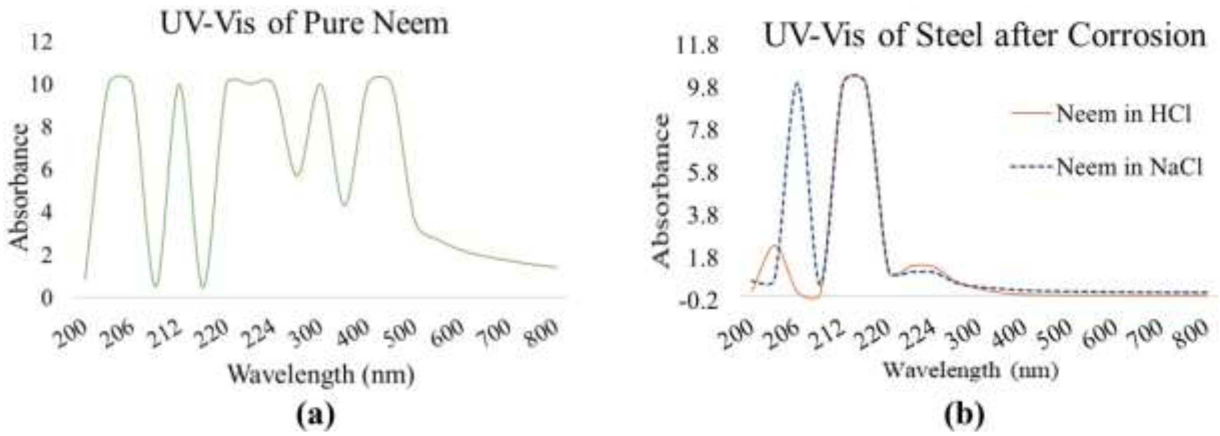


Figure 5. UV–Vis spectra of samples before (a) and after (b) corrosion (Junaid A & Mohan Ganesh, 2024).

Fourier transform infrared spectroscopy (FT-IR) study

Muhammad and Ibrahim (Muhammad and Ibrahim, 2022) studied the inhibitive effect of *Azadirachta indica* bark on the corrosion of Zinc in 0.25 M HNO_3 with 0.80 g/L inhibitor concentration are presented in **Figure 6a** and **6b** respectively. The FT-IR analysis was employed to investigate the functional groups present in the adsorption film that emerge during the adsorption process of inhibitor molecules on metal surface. The analysis was conducted to investigate the structural organization of the extract and corrosion product, as well as to identify the carbon-based and inorganic functional groups present (Okewale and Omoruwuo, 2018; Ayuba and Abdullateef, 2020).

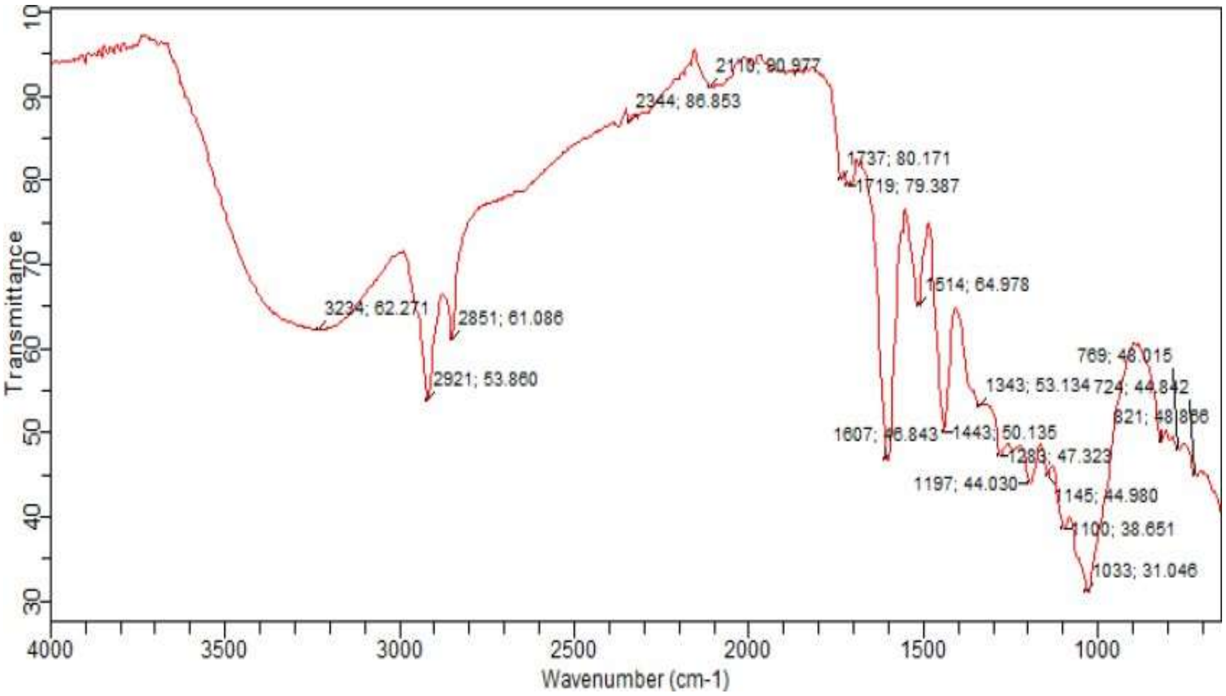


Figure 6a. FT-IR Spectrum of the neem (AI) bark extract (Muhammad and Ibrahim, 2022).

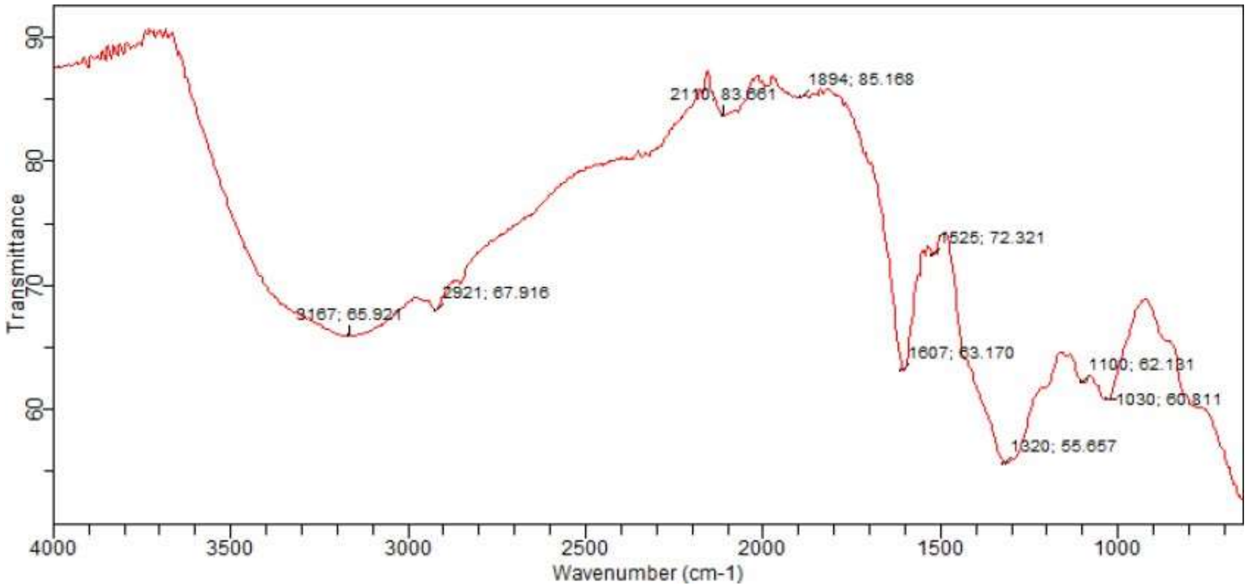


Figure 6b: FT-IR Spectrum of zinc corrosion product immersed in inhibited nitric acid (Muhammad and Ibrahim, 2022).

It can be observed from **Figure 6a** that adsorption band at 3234 cm^{-1} corresponding to –OH stretching vibration, peak at 2921 cm^{-1} is assign to C-H Stretch vibration, peak at 2344 cm^{-1} is assign to C≡N Stretching vibration, and absorption band at 2110 cm^{-1} is assign to C=C stretching vibration. The peak at 1607 cm^{-1} correspond to N-H bending vibration, and adsorption band at 1514 cm^{-1}, 1343 cm^{-1}, and 1033 cm^{-1} correspond to C-H bending vibration, C-O bending vibration, and C=O bending vibration respectively. Subsequently, in **Figure 6b** –OH stretching vibration appear at 3167 cm^{-1}, C≡N Stretching vibration at 2110 cm^{-1}, C=C stretching vibration at 1894 cm^{-1}, C-H bending vibration at 1525 cm^{-1}, C-O bending vibration at 1320 cm^{-1}, and C=O bending vibration at 1030 cm^{-1}. This indicated that there is slight shift in absorption band of the corrosion product when compared to that of the plant extract which suggestion the possible adsorption of inhibitor molecules on zinc surface by physical adsorption mechanism. It is evident from FT-IR result the extract possesses the inhibitive effect (Sivakumar and Srikanth, 2020).

Atomic force microscopy (AFM) studies

AFM studies offer both qualitative and quantitative information on many physical properties, including size, morphology, surface texture, and roughness. The AFM technique supplies photos with atomic or near-atomic-resolution surface topography, which gives the surface roughness of coupons by the angstrom scale. Junaid Ahmed and Mohan Ganesh (Junaid Ahmed and Mohan Ganesh, 2024) studied steel in 1M HCl and 1M NaCl solutions with and without Neem powder was shown in **Figure 7.** The pictograph of the sample surfaces showed various levels of heterogeneity and greater height variations in the blank, **Figure7(a)** as compared to the inhibitor **Figure7(b).** This heterogeneity is due to the dissolution of the metal in the corrosive medium, leading to the formation of scratches and pit development on the surface. The addition of the inhibitor greatly reduced the surface heterogeneity and decreased the level of height variation through a protective layer formation against chloride ions, indicating the suppression of metal loss with lower levels of roughness as seen in **Figure7(b).**

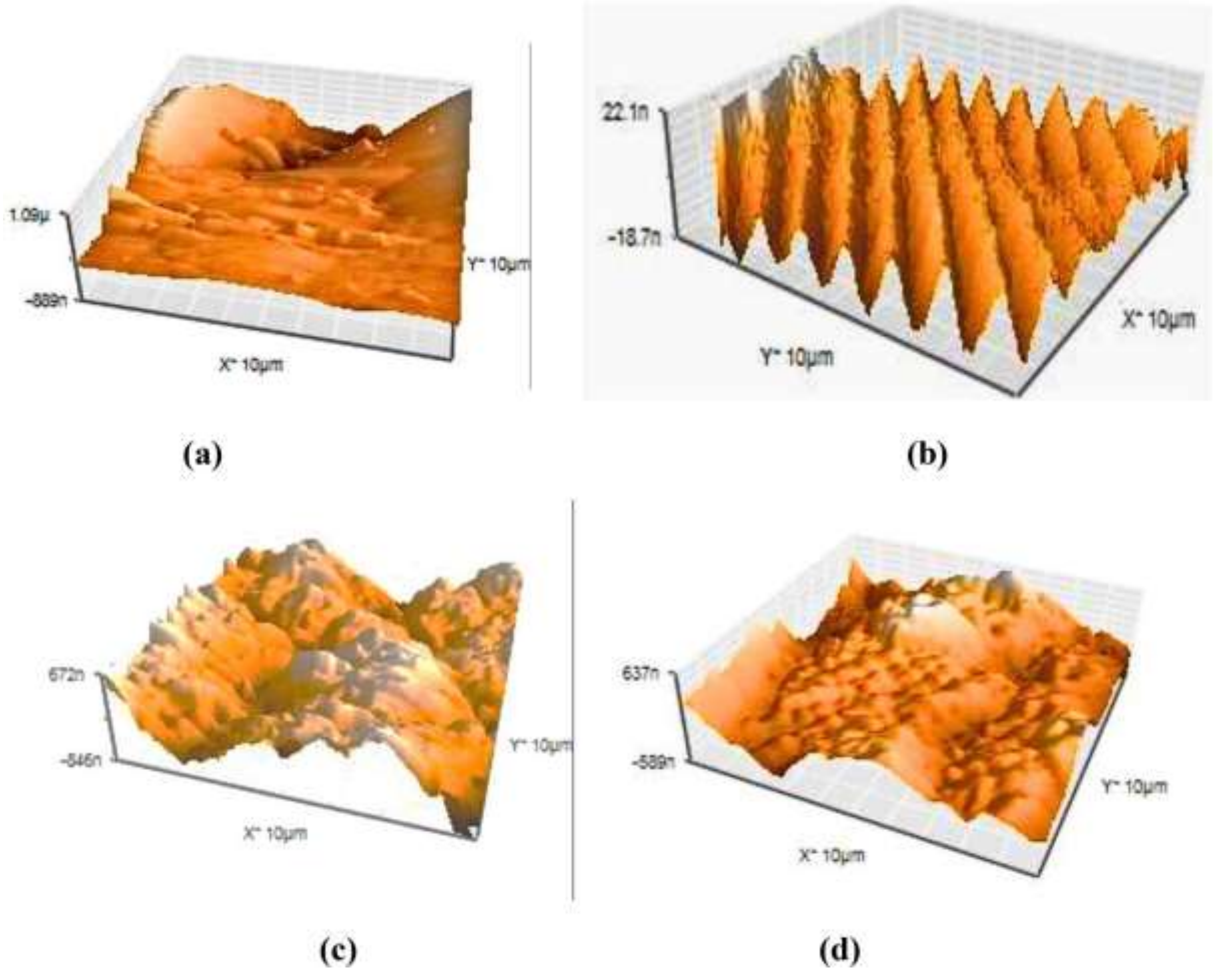
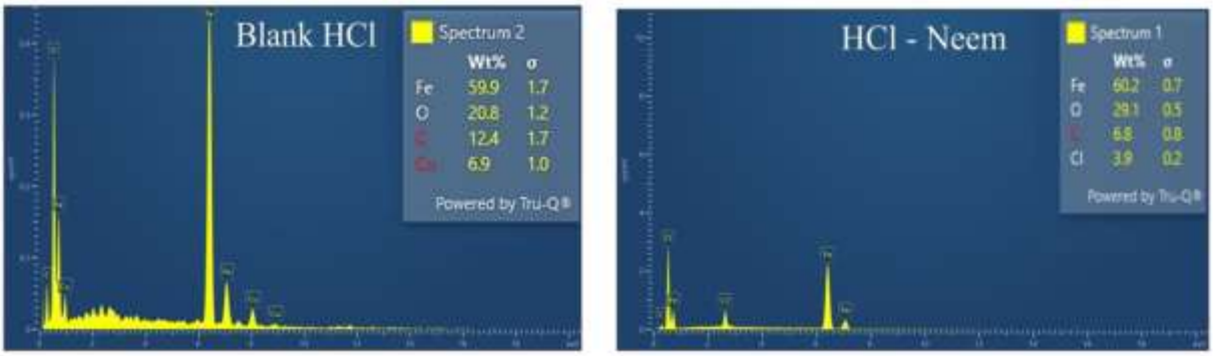


Figure 7. AFM analysis of steel samples exposed to (a) 1 M Blank HCl solution; (b) 1 M HCl acid + inhibitor; (c) 1 M NaCl Blank solution; (d) 1 M NaCl base + inhibitor (Junaid Ahmed and Mohan Ganesh, 2024).

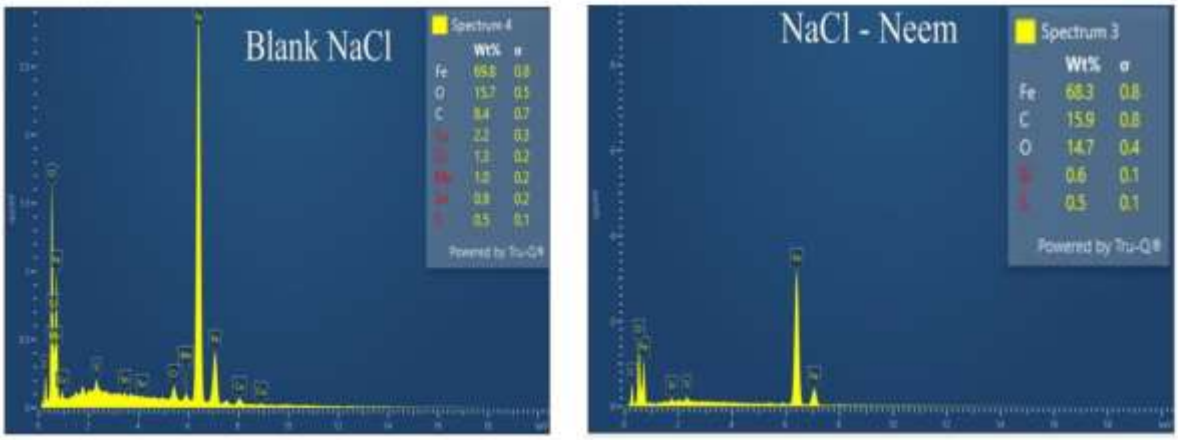
The visual appearance of the pictographs **Figure7(c)** and **(d)** showed higher levels of heterogeneity in the blank sample, indicating deep surface indicating deep surface aggression owing to the surface agglomeration of corrosion deposits ((Junaid Ahmed and Mohan Ganesh, 2024). The presence of the inhibitor reduced the roughness and pit formations significantly by decreasing the steel dissolution and depleting the intensity of O_2 and H_2O on the Steel (Palaniappan *et al*., 2020).

Energy dispersive spectroscopy (EDS) study

Junaid Ahmed and Mohan Ganesh (Junaid Ahmed and Mohan Ganesh, 2024) studied the EDS spectra of surface of the steel specimens in 1M HCl and 1M NaCl solutions in absence and presence of Neem extract are shown in **Figure 8**. Comparing **Figure 8(a)** and **(b)**, with the addition of neem, the weight percentage of Fe (60.2) in the steel was higher than that of the blank HCl solution. Thus, the addition of neem prevents metal degradation to some extent because of the higher weight percentage of oxygen atoms, which clearly indicates that additional oxygen atoms present in the inhibitor are adsorbed, and form a protective layer. It is evident from **Figure 8(c)** and **(d)** that with the addition of neem, the weight percentages of both Fe (68.3) and O (14.7) are reduced when compared to the blank sample – Fe (69.8) and O (15.7). This provides two important understandings: – higher anodic dissolution of the substrate and the formation of iron oxides on its surface (Tabatabaei Majd *et al.*, 2019; Ettahiri *et al.*, 2023).



(a) 1 M HCl Blank (b) 1 M HCl + Neem Powder



(c) 1 M NaCl Blank (d) 1 M NaCl + Neem Powder

Figure 8. EDS of steel samples absence and presence of Neem extract in 1M HCl and 1M NaCl at 40 °C for 5 h (Junaid Ahmed and Mohan Ganesh, 2024).

Scanning Electron Microscopy (SEM) Study

Arab et al. (Arab et al. 2008) studied the SEM images of Aluminium surface before and after corrosion in 0.5 M HCl solutions and in presence of 4% v/v and 24% v/v of AZI extract were shown in **Figure 9(a-d)**. **Figure 9(a)** illustrates the clean surface of Al sample before immersion in the test solution, while **Figure 9(b)** illustrates the effect of 0.5 M HCl solution on Al specimen at 30 °C after 90 min. immersion. Inspection of these figures it is clear that: The presence of general corrosion and localized corrosion on Al surface. **Figure 9(c)** illustrates the effect of 4% v/v of AZI extract at 30°C. It appears that the attacked of acid on Al surface become less and apparently an adsorbed porous layer on Al surface may found. **Figure 9(d)** illustrates the Al surface after immersion in 0.5 M HCl in presence of 24% v/v of AZI extract, it appears that the surface of Al sample almost free from pits and mostly covers by a protection layer consist of the adsorbed of AZI components on the Al surface. The formed layer nearly compact and thick due to the presence of plenty of molecules of AZI which leads to cover almost all the surface of the sample at this concentration.

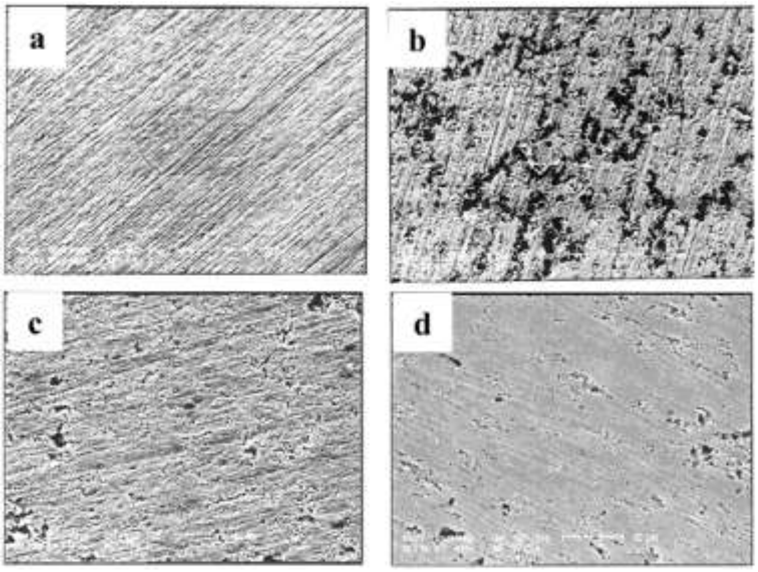


Figure 9. SEM photographs of Aluminium sample, (a) before immersion, (b) after corrosion, (c) in presence of 4% v/v AZI (low concentration) and (d) in presence of 24% v/v of AZI extract (high concentration) in 0.5 M HCl solution at 30 °C (Arab *et al.*, 2008).

Phytochemical constituents of Neem

To date more than 300 natural products have been isolated from different parts of the tree, with new compounds added to the list every year (Schaaf *et al.*, 2000; Morgan and Wilson, 1999). The neem active compound is classified into two main groups, namely isoprenoid and non-isoprenoid groups. The isoprenoid group includes diterpenoid and triterpenoid, namely protomeliasin, limonoid, gedunin, azadiron, and azadiractin derivatives. Some examples of non-isoprenoid are proteins, sulfur, carbohydrates, dihydrochalcone, polyphenols, and glycoside (Saleem et al., 2018). The other examples of non-isoprenoid are coumarin, tannins, aliphatic compound and phenolic acids (Girish and Bhat, 2008). Phytochemical test results show that Neem leaf extract contains phenol compounds (Nahak and Sahu, 2014), flavonoids, saponins, steroids, alkaloids, amino acids, and tannins (Al-Hashemi and Hossain, 2016; Itodo *et al.*, 2018; Das *et al.*, 2017; Ogbuewu *et al.*, 2011; Ibrahim *et al.*, 2024). Furthermore, in the GC-MS analysis shows that neem leaf extract contains hydrocarbon, phenolic, terpenoid, alkaloids, and glycoside (Hossain et al., 2013). The results of phytochemical evaluation using high-performance thin-layer chromatography (HPTLC) shows that the neem leaf extract contains stigmasterol, terpinene-4-ol, sugiol, 4-cymene, nimbiol, α-terpinene, and vitamin E (Nand et al., 2012). Neem leaves also contain isoprenoid, flavanones e (8,3-di isoprenoid-5,7-dihydroxy-‘4'-metoxyflavanone), non-isoprenoid, and meliacin (2',3-dehydrosalannol) (Garg and Bhakuni, 1984; Garg and Bhakuni, 1985). The results of the methanol extract of neem leaves contain triterpenoids, dihydronimocinol, and desfurano-6 α hydroxy azadiradione (Siddiqui et al., 2002). In addition, neem leaves also contain azadiradione (Govindachari et al., 2000).

The chemical constituents found in the leaves of neem as Nimbin, nimbanene, 6-desacetylnimbinene, nimban-diol, nimbolide, ascorbic acid, n-hexacosanol and amino acid, 7-desacetyl-7-benzoylazadiradione, 7- desacetyl-7-benzoylgedbenzoylgedunin, 17-hydroxyazadiradione and nimbiol (Hossain et al., 2011; Obot et al., 2009; Peter and Sharma, 2010). The chemical constituents of *Azadirachta indica* fruit mainly are nimbin, nimbinin, nimbidin, metiantriol (triterpenoid), azadirone, azadiradionolide, meliacinin, limocin and epoxyazadiradione (Okafor *et al.*, 2010; Sharma *et al*., 2010a; Eddy *et al*., 2009; Sangeetha and Fredimoses, 2011; Loto *et al*., 2011). Fresh leaves of Neem tree are also contain following physico-chemical compounds: calcium (510 mg/100 g), phosphorus (80 mg/100 g), iron (17 mg/100 g), thiamine (0.04 mg/100 g), niacin (1.40 mg/100 g), vitamin C (218 mg/100 g), carotene (1,998 µg/100 g), tyrosine (31.50 mg/100 g), alanine (6.40 mg/100 g), proline (4.00 mg/100 g), glutamine (1.00 mg/100 g), glutamic acid (73.30 mg/100 g), aspartic acid (15.50 mg/100 g), carbohydrates (22.9%), minerals (3.4%), proteins (7.1%), fibre (6.25%) moisture (59.4%), and calorific value 1290 Kcal/Kg. In addition to azadirachitin mentioned earlier, there are many other active compounds found in the Neem tree. The other most common are: nimbin, nimbidin, nimbidol, sodium nimbinate, geduin, salanin and quercetin – all which possess significant pharmaceutical applications (Loto *et al*., 2011).

Mechanism of corrosion inhibition by *Azadirachta indica* (Neem)

Azadirachta indica is composed of numerous naturally occurring organic compounds. Over 300 compounds have been isolated and characterised from the plant. Among these: azadirachtin, nimbin, nimbandiol, nimbinene, nimbolide, nimonol, nimbolin, salannin, margolone, melianol, vilasanin, flavanoids and structurally related compounds (Ganguli *et al*., 2002; Siddiqui *et al*., 2001; Suresh *et al*. 1997; Nair *et. al*.,1997; Prajapati *et al*. 2019). Phytochemical constituents of plant extract, such as saponnin, tannin, alkaloid, glycoside, anthraquinone and flavonoid (Arab *et al*. 2008; Eddy *et al*. 2008) are the major factors that determine the inhibition efficiency of the plant extract. The inhibition properties of plant extracts may be due to the presence of nitrogenous compounds in the extract and tannins. They may have been responsible for the formation of an oriented film layer which is essentially blocks the discharge of H^+ and the dissolution of metal ions (Okafor *et al*., 2010). Neem leaves are exceedingly bitter due to the high tannin content as well as the presence of a series of complex triterpene glycosides in their composition (Ugwu *et al*. 1997). The inhibitive properties of tannins result from reaction of the polyphenolic fraction of the tannin molecule with metal ions, thereby forming a highly cross-linked network of metal tannate moieties, which ensures effective protection of the metal surface (Martinez and Stern *et al*. 1999). Tannins are made up of polyphenols and their acidic and heterocyclic derivatives. These constituents were composed mostly of oxygen- containing organic compounds. Furthermore, these compounds also may form complexes with the metallic cations. These complexes can cause blockage of micro anodes and or micro cathodes that are generated on the surface under corrosive conditions, and hence can retard the dissolution of the metal (Arab *et al*. 2008). The structures of the main active chemical compounds present in AZI leaves extract are given below **Figure 10**. In the same way, triterpenes have some functional groups such as (OH, C = O, C = C) that can interact with the metal surface and protect it from the attack of hydronium (H_3O^+) ions (Prajapati *et al*. 2019). Most of these compounds have complicated molecular structures with high molecular weights and significant number of oxygen, sulphur and nitrogen atoms incorporated in this molecular structure. These compounds can adsorb on the metal surface via the lone pair of electrons present on their oxygen, sulphur and nitrogen atoms. The adsorption of such compounds on the metal surface creates a barrier for charge and mass transfer leading to decrease in the interaction between the metal and the corrosive environment (Raja and Sethuraman, 2008; Rani and Selvaraj *et al*. 2011; Mitu *et al*. 2019; Prajapati *et al*. 2019). The various components present in the natural extract contains aromatic rings, double and triple bonds, ketones, heteroatoms… which facilitate the adsorption phenomenon and then authors explained the inhibition process via the synergistic intermolecular effect of all constituents of the natural extract (Emran *et al*. 2014; Boujakhrout *et al*. 2016; Lrhoul *et al*. 2023; Vashi, 2025).

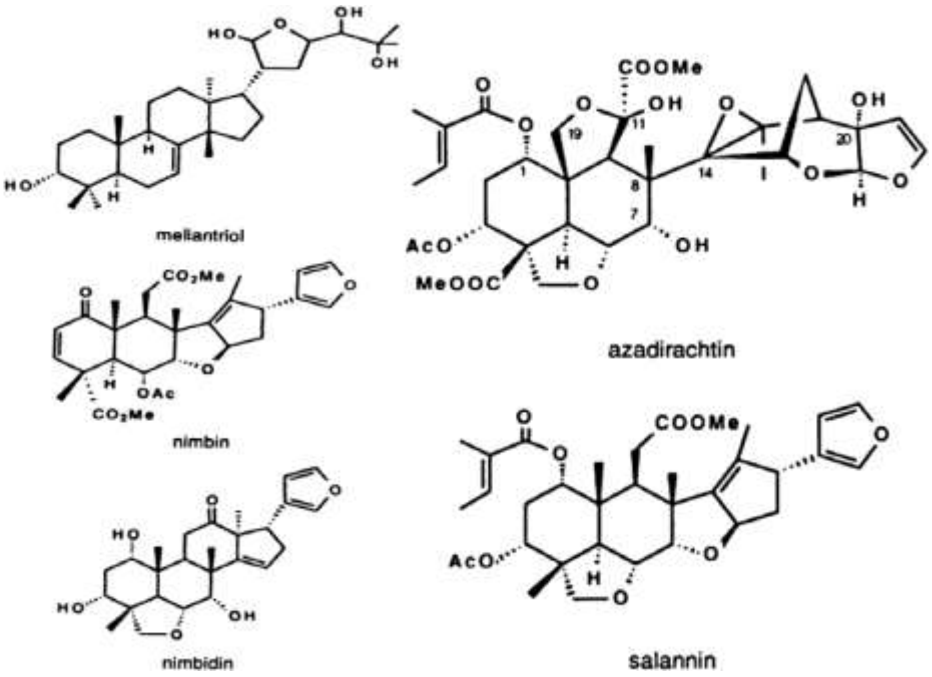


Figure 10. Structure of main constituents of *Azadirachta indica* extract (Prajapati et al. 2019).

As a result, the corrosion rate is decreased considerably. The inhibition efficiency depends on many factors including, number of adsorption sites, functional groups, molecular size and mode of interaction (Khuzhaeu and Aripova, 2000). Plant extracts are viewed as an incredeble rich source of naturally synthesized chemical compounds. These large numbers of different chemical compounds may form adsorbed intermediates (organo-metallic complexes) (Abdel–Gaber *et al*., 2006) which may either inhibit or catalyze further metal dissolution (Mitu *et al*. 2019).

Conclusion

In this review, various research works on the corrosion inhibition of different metals and alloys in different acidic, neutral and seawater media by Azadirachta indica (Neem) as green inhibitor were presented. Langmuir, Frumkin and Temkin adsorption isotherms were observed. Neem extract behaved as a cathodic or mixed-type of inhibitor. The maximum inhibition efficiency for Azadirachta indica (Neem) was found to be 99.83% (WL data). The results obtained from weight loss data were in good agreement with the results obtained from the PDP and EIS methods. Various techniques such as SEM, FT-IR, GC-MS, EDS, MDS, ANN, AAS, XPS, DFT, UV-Vis. etc. were used to study the corrosion mechanism.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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