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An overview of green corrosion inhibitors for sustainable and environment friendly industrial development

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ABSTRACT

Corrosion wreaks havoc on our properties, our lives, and environment. So, prevention of corrosion is of the utmost importance. Inorganic inhibitors are used to prevent corrosion, but these are toxic. Therefore, environment-friendly inhibitor is necessary. Green corrosion inhibitors are a probable solution to this. Their demand both environmentally and economically, is increasing. This review article briefly deals with different types of corrosion prevention methods, various green inhibitors with their source and methods of their efficient applications. The working principle of green inhibitors in different media is also explained. Corrosion determination methods are briefly discussed. Of course, the economic significance of these inhibitors has been debated. In the end, considering the current research gaps, future research directions are put forward.

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Corrosion; green inhibitor; organic; inorganic; sustainability

1. Introduction

Pure metals and their alloys are corroded by chemical and/or electrochemical reactions with the surrounding environment. Different factors like surface impurities, pressure, and temperature, and solution activity make corrosion [1]. The stable forms include oxides, hydroxides, and sulfides [2]. In the rapid development of industrial technology, corrosion has become a global problem [3]. Damaging of assets like industrial machinery, households, buildings, traffic, and railway bridges is enormous because of corrosion [4]. Due to corrosion, one-third of steel is lost every year and the global economic loss is around 3% of GDP [5]. To save from this loss, industries have developed various corrosion protection methods [6]. Corrosion inhibitors being among them are widely

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used in different sectors because of their low cost, strong adaptability, simple process, and economic efficiency [7].

At extremely low concentration, the corrosion inhibitor can protect metal from destruction [8]. The corrosion inhibitors have several advantages including quick response, high efficiency, simple operation, low cost and can be applied without changing the process and equipment [9]. Moreover, corrosion inhibitors can be sourced from plants such as flowers, seeds, leaves, roots, and stems containing organic compounds such as alkaloids, flavonoids, heteroatoms, tannins and nitrogen-based compounds [10]. Among them, organic compounds containing heteroatom are an effective corrosion inhibitor [11]. The extracts of these plant parts show good inhibition properties in acidic media [12]. Besides, they are safe, nontoxic, and good for the environment.

Traditional inhibitors are expensive, toxic and have negative impacts on the environment. That is why environmentally friendly, cost-effective, highly effective corrosion inhibitors have attracted the attention of researchers [13]. The concept of green corrosion inhibitors has gained popularity. Green corrosion inhibitors include drugs, roots, chitosan, oil, flour, yeast, natural honey, leaves, herbs and so on [14]. According to the report, some natural and biodegradable materials are highly effective inhibitors [15]. Polar compounds containing oxygen and nitrogen and nonpolar compounds having aromatic rings, aliphatic chains, heterocyclic rings, and functional moieties are abundant in plant extracts. These compounds can get effectively absorbed on the metal surface and thus protect it from corrosion without harming the environment like inorganic compounds [16].

In this review, current problems of corrosion industry, green inhibitor mechanism for corrosion prevention, various corrosion test methods, and economic impact of corrosion are reviewed. Besides, suggestions have been given about the future research directions.

2. Potential challenges of corrosion in industry

Traditionally corrosion is prevented by coatings, inhibitors, and cathodic protection [17]. Corrosion inhibitors are basically two: inorganic and organic [18]. Inorganic inhibitors include nitrite, nitrate, chromate, dichromate, and phosphate [18]. On the other hand, the organic inhibitor contains one or more polar groups; those have O, N, P, S atoms, and π electrons. In between inorganic and organic inhibitors, organic inhibitors are more effective to prevent corrosion [19–21].

The underground and undersea metallic substrates such as oil and gas pipelines, utility pipelines, cables, and structural foundations are protected from corrosion by the cathodic protection system. They are also applied to protect oil drilling platforms, dockyards, jetties, ships, submarines, condenser tubes in heat exchangers, bridges and decks, civil and military aircraft and ground transportation systems from corrosion [22]. However, the cathodic protection system is harmful for the marine environment [23].

3. Mechanism of corrosion and inhibition

The term green chemistry represents an attempt to develop a holistic approach to managing chemical risk. This idea designs products that eliminate or minimize the



Figure 1. Various sources for natural green corrosion inhibitors [26].

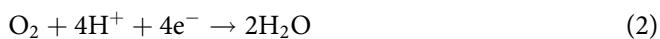
chemical pollution and waste management problems after they occur. The idea of sustainability, minimizing environmental impacts, and ensuring natural resources for future generations is the fundamental concept of green chemistry [24]. Besides, green corrosion inhibitors are biodegradable and do not contain heavy metals or other toxic compounds. They have the potentiality to inhibit corrosion of metals in acidic and alkaline environment [25].

Green corrosion inhibitors can be found from various natural sources (Figure 1). They are rich in organic compounds and they have multiple polar atoms and electron-rich bonds [27,28]. In the inhibition process, their molecules get absorbed on the metal or alloy surface and form a protective layer [29]. In the process, they may donate an electron to the vacant d-orbital-s of iron or metal atoms leading to coordinate bonds [30]. During corrosion, metal ions move into the solution at the anode and transfer electrons to the cathode from the metal. Oxygen, oxidizing agents or hydrogen ions act as electron acceptors and they are required by the cathodic process. By stopping or retarding anodic or cathodic reactions, corrosion can be minimized. On the metal surface, inhibitors are adsorbed and form a protective barrier. Then they interact with anodic reaction or cathodic reaction or both sites and decrease the oxidation or reduction or both corrosive reactions [31].

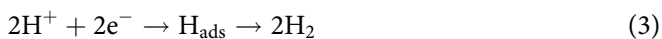
Table 1. Different green inhibitor processes.

Name of the processes	Process methodology	Applications	References
<i>Lemon Balm</i> (LB) extract	At 65 °C, 20 g dried and ground <i>Lemon Balm</i> powder was mixed with 1000 mL deionized water. The obtained solution was dried in an oven at 60 °C. Later, the <i>Lemon Balm</i> was added to 1M HCl solution.	Mild steel	[34]
<i>Chinese gooseberry</i> fruit shell extract	Collected <i>Chinese gooseberry</i> fruit shell was dried under shadow condition and finally ground to obtain powder. For the extraction of the inhibitor Water, ethanol, methanol and cyclohexane have been utilized as proper solvent from the dried plant leaves.	Mild steel	[35]
<i>Rosa canina</i> fruit extract	At first the <i>R. canina</i> fruit was dried and powdered. Then, 25 g of the powder was mixed with 500 ml distilled water at 70 °C for 24 h. finally, the mixture was filtered and dried at 60 °C	Mild steel	[36]
<i>Saraca ashoka</i> seeds extract	<i>Saraca ashoka</i> seeds were cleaned with tap water after collecting from market. It is dried at 60 °C and finally powder is obtained.	Mild steel	[37]
Rabeprazole, domperidone, benfotiamine drug	0.5 mg drug was taken from each sample as powder form and mixed with 3.5% NaCl solution.	Mild steel	[38]
<i>Tithonia Diversifolia</i> flower Extract	25 g <i>T. diversifolia</i> flower Extract was refluxed with 500 ml HCl for 3 hours kept overnight for cooling. To get the inhibitor the cooled extract was filtered.	Mild steel	[39]
Sunflower seed hull extract	After drying the sunflower seed hull extract the dried skin extracted and mixed with water and ethanol for 6 h.	Mild steel	[40]
<i>Sida cordifolia</i> Extract	After cleaning <i>S. cordifolia</i> leaves were dried at 60 °C for 2 days ground to powder.	Mild steel	[41]
Amino acids modified konjac glucomannan	0.1 g p-toluenesulfonic acid, 1.0 g KGM and 2.0 g amino acid were mixed together with 100 mL dimethyl sulfoxide. Then the mixture was heated at 120 °C. Residue was obtained after filtration.	Mild steel	[42]

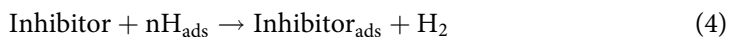
In the corrosive media, the cathodic reactions are given by [Equations \(1\) and \(2\)](#).



The reduction reaction of hydrogen gas is given by [Equation \(3\)](#).



On the metal surface, hydrogen ions are adsorbed and in combination with other hydrogen ions they are catalyzed. Then, they evolve hydrogen gas on the cathode surface holding them hidden. The action of inhibitor molecules occurs in the form of neutral molecules because of the adsorption on an exposed metal surface instead of hydrogen ions adsorbed from the metal surface given by [Equation \(4\)](#).



According to [Equation \(2\)](#), by displacement of water molecules on the metal surface as site blocking elements, green inhibitors have adsorption properties [32,33] ([Table 1](#)).

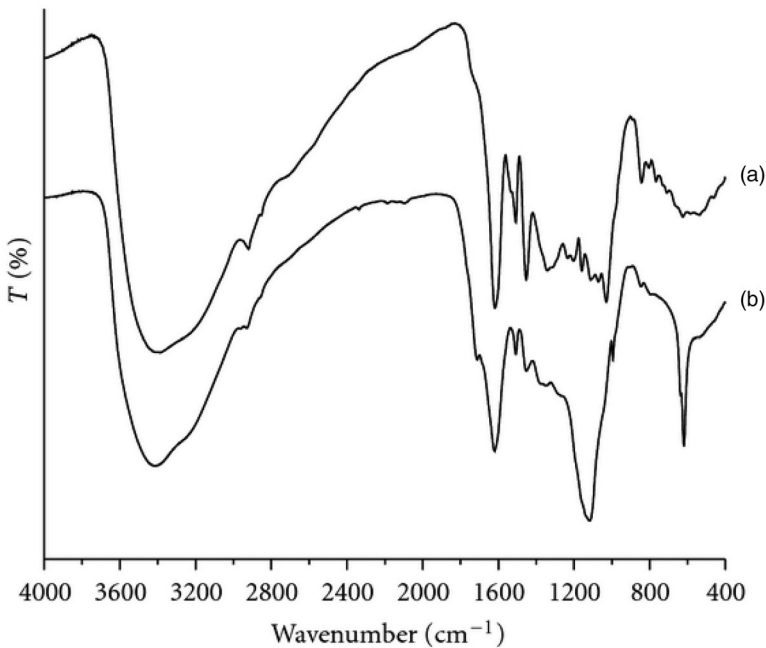


Figure 2. FTIR spectra of (a) the black wattle tannin and the blue-black precipitate formed in the bulk of the electrolyte after one hour of immersion of steel in aerated $0.1 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_4$ solution (pH 6.0) in the presence of acacia tannin [43].

4. Characterization of corrosion improvement

The most conventional and reliable way to measure corrosion is weight loss measurement, kinetics of corrosion and electrochemical measurement. FTIR analysis is done to see the chemical bonds (Figure 2). Figure 2 shows the FTIR spectrum of the black wattle tannin. Because of the presence of hydroxyl groups' broad absorption band with a maximum absorbance at 3413 cm^{-1} is observed [44]. Between 1600 and 1450 cm^{-1} peaks are formed which are characteristic of aromatic compounds [44]. In the 600 – 1300 cm^{-1} various peaks correspond to substituted benzene rings [44]. The reduction of free OH group's intensity of the broad peak is seen at around 3413 cm^{-1} [45]. The tannins to form ferric-tannate complexes are enabled by these hydroxyl groups in aromatic rings. The peaks occurring at 1110 cm^{-1} and 619 cm^{-1} are characteristic of sulphate groups (electrolyte solution) [43,46–56].

Without and with basil loaded halloysite nanotubes extracts, the steel panels were immersed in the saline solutions and over the time the surface changes of the immersed samples were recorded (Figure 3). After 6 h of immersion, the corrosion products are obvious on the surface of the additive-free sample. On the anodic and cathodic region, the Fe^{2+} cations and hydroxyl anions are produced, respectively [48]. After 48 h of immersion, the surface of the steel panels was corrosion-free in visual images with basil loaded halloysite nanotubes (Figure 3(a)). The inhibitor molecules released from the basil-loaded halloysite nanotubes are deposited on the active surface of the steel that reduce the iron dissolution rate [49] (Table 2).

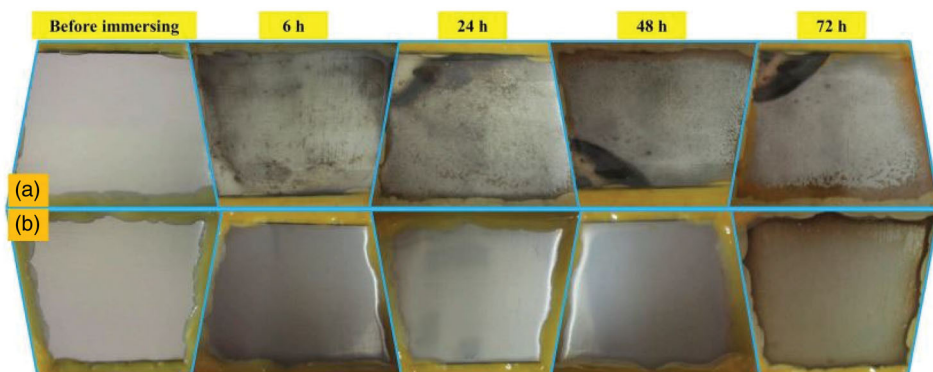


Figure 3. Visual changes of sample surfaces immersed in NaCl solution (3.5 wt %): (a) without additives (Additive-free) and (b) containing basil-loaded halloysite nanotubes (BHN), at different times [49].

5. Applications of green inhibitors

Different green corrosion inhibitors are isolated from different sources that help to minimize corrosion of various metals. Olakolegan et al. [50] obtained green corrosion inhibitors from *Terminalia glaucescens* Planch extracts. The extracts have been added with 0.3 M sulphuric acid and 3.5% sodium chloride and have been applied to aluminum 6063 alloy. The inhibitors successfully reduce the rate of corrosion. Pengcheng Hu et al. [51] used protic ionic liquids as a green corrosion inhibitor. The inhibitor is mixed with nitric acid and applied to brass material. The corrosion rate is reduced successfully. Ali Dehghani et al. [52] formed a corrosion inhibitor from Ziziphora leaves extract. The inhibitor is then mixed with hydrochloric acid and applied to mild steel. The corrosion rate is reduced 93% after 2.5 h. Raziieh Farahati et al. [53] used Cysteine amino acid as a water-soluble green corrosion inhibitor. The inhibitor is applied to mild steel and the corrosion rate is reduced successfully. Ambrish Singh et al. [54] sourced green corrosion inhibitors from pyrimidine derivatives. Then this inhibitor is mixed with 15% hydrochloric acid and applied on N80 steel. 96.4% corrosion is reduced by the application of this corrosion inhibitor. Table 3 shows the green inhibitor source, substrate, acid concentration, acid name, highest inhibition efficiency (%) with reference.

The inhibitor has the ability to form a protective layer that can prevent the ingress of aggressive species like oxygen, carbon-di-oxide, sulfate, chloride, and moisture. In reinforcement corrosion, many researchers have conducted various experimental works so that they can improve the inhibitor's efficiency. Their effectiveness of inhibitors depends on the property of their chemical constituents. The role of inhibitor to extend the service life of steel concrete has shown improvements [109]. Table 4 shows the corrosion protection mechanism of green inhibitors.

6. Green inhibitors in saline environment

Like acidic environments some steel structures are exposed to saline environment. That is why the mitigation of the metals subjected to this environment should be

Table 2. Improvement in characterization of different green inhibitor processes.

Green inhibitor processes	Surface morphology improvement	FTIR	UV rest	Inhibition efficiency	Inhibitor concentration	Time of immersion	References
Lemon Balm (LB) extract	The surface damage considerably decreased by addition of LBE	At 3457, 2939, 1746, 1633 and 1439 cm^{-1} are related to O-H, C-H, C=O, C=C and COOH stretching vibrations, respectively, the absorption peaks observed	At around 234 nm Intensive absorption peak is observed, which is assigned to the $\pi-\pi$ electronic transition of conjugated C=C bonds of aromatic ring.	95%	1 M (HCl)	0.5, 2, 4, 6, 12 and 24 h	[34]
Chinese gooseberry fruit shell extract	The steel surface became smoother and a less corroded due to the presence of inhibitor	An intensive and broad absorption peak at 3460 cm^{-1} , reveals the presence of many O-H functional groups in the chemical structure	Over the steel surface it forms a protective film	94%	1 M (HCl)	2.5 and 5 h	[35]
Rosa canina fruit extract	Less surface damage are seen solutions containing R. canina fruit extract.	The organic compounds of <i>R. canina</i> fruit extract include many aromatic rings with polar functional groups like hydroxyl, carbonyl and carboxylic	The intensity of the mentioned peaks declined after immersion of steel panel in the 1M HCl solution containing inhibitor	86%	1 M (HCl)	2, 4, 6, 24 and 48 h	[36]
Saraca ashoka seeds extract	Less surface damage of the specimen is seen due to the presence of <i>S. ashoka</i> .	The anti-corrosion property of <i>S. ashoka</i> atoms and aromatic rings in the compounds.	A few molecules from the solution have been adsorbed on the metal surface when the mild steel specimen was immersed into the acidic solution of <i>S. ashoka</i> extract.	93.09%	0.5 M (H_2SO_4)	24 h	[37]
Rabeprazole, domperidone, benfotamine drug	Because of the presence of inhibitor molecules the MS surface is pit free.	In 3.5 wt% NaCl medium the expiry drug molecules act as an excellent barrier film	Due to the deposition of the inhibitor molecule spectrums are increased from 300 nm to 450 nm	98.92%		5 days	[38]
<i>Tithonia diversifolia</i> flower Extract	Because of the presence of the inhibitor there is much less damage.	The strong N-H Stretch of primary and secondary amides and very strong C-H stretch of alkanes are observed in inhibitor present FTIR.		94.55%	1 M (HCl)	24 h	[39]
Sunflower seed hull extract	Sunflower seed hulls extract contain long chain fatty acid, carbohydrates like xylose, and furfural and phenolic compounds like phenolic acid, amino acid, and anthocyanin.		By adding inhibitor the corrosion resistance increases.	98.46%	1 M (HCl)	72 h	[40]
<i>Sida cordifolia</i> Extract	Less surface damage is seen in the presence of <i>S. cordifolia</i> extract.	Due to the presence of O atoms and aromatic rings in the compounds the anti-corrosion property of <i>S. cordifolia</i> extract is present.	Molecules are adsorbed on the metal surface due to the presence of inhibitor.	98.96%	0.5 M (H_2SO_4)	24 h	[41]
Amino acids modified konjac glucomannan	Much smoother surfaces without obvious corrosion pits obtained in the presence of inhibitor	The esterification reaction between KGM and selected amino acids is confirmed by the FTIR spectra.	Formation of metal-inhibitor complex is confirmed by UV-visible spectra.	92.4 %	0.5 M (HCl)	8 h	[42]

Table 3. The green inhibitor source, substrate, acid concentration, acid name, highest inhibition efficiency (%) with reference.

Green inhibitor source	Substrate	Acid concentration	Acid name	Highest inhibition efficiency (%)	Reference
<i>Tabernaemont-ana divaricata</i>	Iron	1 M	HCl	95	[55]
<i>Punica granatum</i>	Q235A steel	1 M	HCl	95	[56]
<i>Citrus peel</i>	Mild steel	1 M	HCl	94.2	[57]
<i>Thyme</i>	Mild steel	2 M	HCl	84	[58]
<i>Musa paradisiaca</i>	Mild Steel	1 M	HCl	90	[59]
<i>Citrus peel</i>	Aluminum	0.5 to 2 M	HCl	91	[60]
<i>Morusalba pendula</i>	Steel	1 M	HCl	93	[61]
<i>Silybum marianum</i>	304 stainless steel	1 M	HCl	96.4	[62]
Pectin from apples	X60 steel	0.5 M	HCl	78.7	[63]
<i>Ficus hispida</i>	Mild steel	1 M	HCl	90	[64]
<i>Aloe vera gel</i>	Mild steel	1 M	HCl	92.6	[65]
Leaves of henna	Mild Steel	1 M	HCl	90.34	[66]
<i>Solanam xanthocarpum</i>	Carbon steel	1 M	HCl	83.2	[67]
<i>Thymus vulgaris</i>	304 stainless steel	1 M	HCl	62.2	[68]
<i>Justicia gendarussa</i>	Mild steel	1 M	HCl	91.6	[69]
<i>Rosemarinus officinalis</i>	Mild steel	0.1M	HCl	98.33	[70]
Longan	Mild Steel	0.5 M	HCl	92.4	[71]
<i>Peganum harmala</i>	6063 Aluminum alloy	1 M	HCl	91.78	[72]
<i>Murraya koenigii</i>	Mild Steel	1 M	HCl	84.6	[73]
Lychee	Mild Steel	0.5 M	HCl	98	[74]
<i>Schinopsis lorentzii</i>	Low carbon steel	1 M	HCl	66	[75]
<i>Emblica officinalis</i>	Mild Steel	1 M	HCl	88	[76]
<i>Euphorbia falcata</i>	Carbon steel	1 M	HCl	93.2	[77]
Ascorbic acid	Mild steel		H ₂ SO ₄	71.5	[78]
<i>Sesbania sesban</i>	Carbon steel	1 M	HCl	91.08	[79]
<i>Tagetes erecta</i>	Mild steel	0.5 M	H ₂ SO ₄	96.1	[80]
<i>Piper guineense</i>	Mild steel	0.5 M	H ₂ SO ₄	97.7	[81]
<i>Bryophyllum pinnatum</i>	Mild Steel	0.5 M	HCl	94.27	[82]
Coconut	Mild steel	0.5	H ₂ SO ₄	94.3	[83]
Streptomycin	Mild steel	1 M	HCl	88.5	[84]
<i>Azadirachta excelsa</i>	Mild steel	1 M	HCl	78.55	[85]
<i>Aloe vera</i>	Stainless steel	1 M	H ₂ SO ₄	98	[86]
<i>Aspidosperma album</i>	C38 steel	1 M	HCl	90	[87]
<i>Acalypha indica</i>	Mild steel	1 M	HCl	93.26	[88]
<i>Cryptostegia grandiflora</i>	Mild steel	1 M	H ₂ SO ₄	87.5	[89]
<i>Geissospermum leave</i>	C38 steel	1 M	HCl	90	[90]
<i>Phoenix dactylifera</i>	Carbon steel	1 M	HCl	97.7	[91]
<i>Aster koraiensis</i>	Mild steel	1 M	H ₂ SO ₄	90.5	[92]
<i>Retama monosperma</i>	Carbon steel	1 M	HCl	83	[93]
<i>Ruta graveolens</i>	Mild steel	1 M	HCl	98.25	[94]
<i>Sida acuta</i>	Mild steel	1 M	H ₂ SO ₄	85	[95]
<i>Neolamarckia cadamba</i>	Mild steel	1 M	HCl	91	[96]
<i>Michelia alba</i>	Carbon steel	1 M	HCl	98.4	[97]
<i>Nauclea latifolia</i>	Mild steel	1 M	H ₂ SO ₄	91.6	[98]
<i>Palicourea guianensis</i>	C38 steel	1 M	HCl	89	[99]
<i>Anthocleista djalonensis</i>	Mild steel	1 M	HCl	97.23	[100,101]
<i>Lannea coromandelica</i>	Mild steel	1 M	H ₂ SO ₄	93.8	[102]
Olive leaves	Carbon steel	2 M	HCl	93	[103]
<i>Vitex negundo</i>	Carbon steel	1 M	HCl	79.2	[104]
<i>Litchi chinensis</i>	Mild steel	0.5 M	H ₂ SO ₄	97.4	[105]
<i>Cryptostegia grandiflora</i>	Mild steel	1 M	H ₂ SO ₄	83.54	[89]
Adenine-L-alanine ramifcation	Steel	0.1 M	HCl	91.26%	[106]
<i>Curcuma longa</i>	Mild steel	1 M	HCl	92%	[107]
Glycine derivative N-benzylidene-2	Mild steel	1 M	HCl	95.55	[108]

Table 4. Corrosion protection mechanism of green inhibitors with source of extraction solvents, applied materials, and references.

Plants extracts	Protection mechanism	Solutions	Metals	References
<i>G. mangostana</i>	Adsorption on the metal surface is due to the heteroatoms present in the organic constituents of the extract of <i>G. mangostana</i>	HCl	Mild steel	[25]
<i>E. crassipes</i>	Physically adsorbed	HCl	Mild steel	[110]
<i>allium cepa</i>	Adsorption site on the surface of the metal	Waste water	Aluminum	[111]
<i>Artemisia pallens</i>	Adsorption due to Fe-inhibitor complex at iron oxide layer	HCl	Mild Steel	[112]
<i>H. rosasinensis</i>	Langmuir, Flory-Huggins and Freundlich adsorption	HCl	Mild steel	[113]
Caffeic acid	Adsorption of organic molecules by blocking the cathodic site of electrode surface	H ₂ SO ₄	Mild steel	[114]
Orange peel	Adsorption site on the surface of the metal	HCl	Mild steel	[115]
<i>I. paraguariensis</i>	Langmuir adsorption isotherm	HCl	Carbon steel	[116]
2-((5-Mercapto 1,3,4-thiadiazol-2-ylimino) methyl) phenol	Chemisorption	HCl	Mild steel	[117]
<i>Murraya koenigii</i>	Adsorption of inhibitor molecules on surface due to protonation of amino group	H ₂ SO ₄	Mild steel	[118]
<i>Musa sapientum</i>	Physical adsorption	H ₂ SO ₄	Mild steel	[119]
<i>Osmanthus fragran</i>	Physical Adsorption	HCl	Carbon steel	[120]
Black pepper extract	Adsorption of phytoconstituents of black peppers forming a protective layer on surface	H ₂ SO ₄	Mild steel	[121]
<i>fenugreek leaves</i>	Langmuir in HCl solution, Temkin in H ₂ SO ₄ solution	HCl and H ₂ SO ₄	Mild steel	[122]
Alkaloid extracts	Adsorption of extract and aniline onto the steel surface blocking its active sites	HCl	Mild steel	[123]
Carboxymethyl cellulose	Physical adsorption mechanism by blocking the surface	H ₂ SO ₄	Mild steel	[124]
<i>Theobroma cacao</i>	Langmuir adsorption isotherm	HCl	Mild steel	[103]
Fast green dyes	Adsorption of large and flat inhibitor molecules by blocking the surface area of mild steel and adsorbed electrostatically	HCl	Mild steel	[98]
<i>Nauclea latifolia</i>	Physical adsorption of the extracts on the surface by simply blocking the active corrosion site	H ₂ SO ₄	Mild steel	[125]
<i>Combretum bracteosum</i>	Frumkin adsorption isotherm	H ₂ SO ₄	Mild steel	[123]
<i>Ananas sativum</i>	Chemisorption of phytochemical constituents of the extract	HCl	Aluminum	[126]
Cyproconazole (CPA)	Absorption on solid surface as a result of physical/chemical adsorption	H ₂ SO ₄	Copper	[127]

considered for the research of green inhibitors. Significant numbers of researches have been performed in this field. Different green inhibitors have been experimented as well. The green water extract of *Lemon Balm* has been experimented for steel corrosion retardation. The experiment shows 93% inhibition in the saline environment [128]. Zinc acetylacetonate has been experimented as a green corrosion inhibitor in 3.5% NaCl solution and significant result has been found [129]. Aqueous extract of Esfand seed has been experimented to reduce the corrosion effect of steel. 98.8% efficiency has

been observed after 264 h of experiment [130]. Nettle leaves extract has been experimented in chloride solution as a green corrosion inhibitor on carbon steel. The corrosion rate decreased significantly after the use of inhibitor compared to the immersion without inhibitor [131]. *Juglans regia* green fruit shell extracts have been experimented in seawater on mild steel as a green corrosion inhibitor. The experimental results show that the rate of corrosion decreases around 84% in the presence of inhibitor [132].

7. Economic impact of corrosion

Corrosion causes considerable economic losses around the world. The production of oil and gas and their transportation is highly influenced by it. The industries of manufacture, chemical plants, oil industry, and many more metal-using industries are facing expensive problems because of this. When exposed to electrical components and materials, corroded chemical leakage, oil pipelines breakdown, and even fire can cause most corrosion-related problems [133]. Many industries have realized that the lack of corrosion management can be very costly. This cost-saving can be achieved by proper corrosion management. According to a report, the global market for corrosion inhibitors was \$7.2 billion in 2019 and it is expected to reach \$9.6 billion by 2026 with the growth rate of 3.6% [134]. To prevent corrosion, many methods have been invented including use of corrosion inhibitors. Among them, very few are considered as green corrosion inhibitors. The market of plants extracted and organic green corrosion inhibitors is expected to increase by 7.0% by 2026 for being ecofriendly. There are many effective green inhibitors such as in brief; *Phoenix clactylifera* seeds are used as green corrosion inhibitors for metals [135]. The inhibition efficiency of this inhibitor is around 97% at 50° C. *Azadirachta indica* shows 98% efficiency [136], *Pongamia glabra* and *Annona squamosal* show 89–95% efficiency [137], *Acacia arabica* shows 93–97% efficiency [138], Natural honey shows 82–91% efficiency [139], Vanillin show 93–98% efficiency [140], Reduced saccharide fructose and mannose show 92% efficiency [141]. Besides, every day, a considerable number of leaves fall down around our surroundings and generally they are burnt which creates environmental pollution. If we can convert this waste material into corrosion inhibitor, it will turn into a valuable product with very low production cost [142].

8. Research gaps and future directions

Based on the studies of numerous papers revised here, some gaps have been included here:

- All bioactive molecules present in green extracts do not possess corrosion inhibition properties. Thus, which one is partial and active in this regard is not pointed out.
- The toxicity of the green inhibitors is not examined in most of the literature.
- Whether all bioactive molecules combine together as inhibitor or not has not been addressed.
- Much research has not been done by using bio-nanomaterial.

- Research is not conducted based on green synthesized 2D material.

The following suggestions can be given as future direction:

- From the green extracts, bioactive molecules can be isolated and applied separately for corrosion test.
- Before checking inhibition performance, toxicity test can be done.
- Bio-nanomaterial based corrosion inhibition test can be emphasized.
- Green synthesized 2D material can be employed for green corrosion inhibition performance.

9. Conclusions

Green inhibitors were demonstrated to be the ideal candidate for the replacement of the traditional expensive, toxic, and synthetic organic corrosion inhibitors. The green inhibitors contain several constituents that can absorb and inhibit metallic corrosion. Several constituents that can absorb, inhibit metallic corrosion, and inhibit the chemical reactions are available in green inhibitors. In order to justify as an effective corrosion inhibitor against iron, mild steel, carbon steel, stainless steel, aluminum alloy, copper alloy, and other metals and alloys several types such as plants extraction, fungi, polymers, bio-ingredients, and drugs have been examined in different acidic, basic, and neutral media [143]. The discussed surface morphology also confirms the effectiveness of these new products.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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