



Review Review on Corrosion Inhibitors for Oil and Gas Corrosion Issues

Kausalya Tamalmani and Hazlina Husin *🗈

Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar 32610, Perak, Malaysia; kausalya_18003374@utp.edu.my

* Correspondence: hazlina.husin@utp.edu.my

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Abstract: The pipeline system in the oil and gas industry is the heart for transportation of crude and refined petroleum. Nevertheless, continuous exposure of the pipeline surfaces to impurities and sources of corrosion such as sulfur and chromate is totally unavoidable. Vast employment of commercial corrosion inhibitors to minimize the corrosion is being restrained due to toxicity towards the environment. The emergence of "green" chemistry has led to the use of plant extracts and fruit wastes which have proven to be good corrosion inhibitors. This paper aims to provide insight into carrying out further investigation under this research theme for accurate inhibition efficiency measurement.

Keywords: corrosion; mechanism of corrosion; sources of corrosion; commercial corrosion inhibitor; green-based corrosion inhibitor

1. Introduction

In oil and gas industries, the corrosion issue has always been of great importance, with consequences similar result to those of natural disaster. Corrosion normally occurs in oil and gas pipelines. Since the pipelines play the role of transporting oil and gas from the wellheads to the processing facilities, they are exposed to the continuous threat of corrosion, from the date of commissioning up to decommissioning or abandonment. According to [1], the rough estimation of the aggregate yearly cost of corrosion is \$1.372 billion, which is the total of surface pipeline and facility costs (\$589 million), down-hole tubing costs (\$463 million), as well as capital expenses (\$320 million).

Corrosion inhibitors are one of the mediums applied to minimize corrosion in petroleum industries. For an optimum inhibition to be achieved, the inhibitors must be added above a certain minimum concentration. There are plenty of techniques, e.g., cathodic protection [2,3], organic coatings [4–6], and application of first-rate corrosion-resistant alloys [7], that can be implemented to fight against corrosion, yet film-forming inhibitors are still known to be the unrivalled method of defense for mild steel in an acidic environment [8,9]. The film-forming inhibitors are used in industries to create a molecular layer right on the surface of the steel and aliphatic tail as a second layer in hydrocarbon to prevent the water from contacting the steel surface and causing corrosion [10].

Recently, the rise of the "green" chemistry concept in the fields of science, technology and engineering [11,12] is restraining the application of commercial corrosion inhibitors by implementing certain theories or ideas to reduce the contamination [13] from being discharged into the environment as well as coming up with the eco-friendly chemicals [14–16]. As a movement to support this concept, the use of green-based corrosion inhibitors like plant extracts [17], chemical drugs [18], and ionic liquids [19,20] are being practiced. These green inhibitors are organic compounds that function through the adsorption on the surface of the metal to prevent the occurrence of corrosion. Moreover, fruit-based corrosion inhibitors are also one of the natural elements utilized due to their richness in vitamins,

minerals, and phenolic compounds. Nevertheless, the corrosion inhibitors adhere to certain factors like concentration, rate of dispersion, velocity, temperature, film persistency, pH, flow regime, and fluid composition, as well as the presence of instabilities able to perturbate the flow in minimizing corrosion.

This review paper assesses the trilateral view of corrosion: mechanism of corrosion, sources of corrosion, commercial and green-based corrosion inhibitors. Hence, this paper is anticipated to serve as the foundation for future research on green corrosion inhibitors. Note that comprehensive discussions or analysis regarding the current state and the future of green-based inhibitors will not be covered.

2. Corrosion

Corrosion is observed as one of the main reasons for the failures of oil and gas infrastructure. The existence of corrosion is the consequence of chemicals such as naphthenic acid (NA) reacting with iron particles or developing a surface film; this occurs with sulfur particles (S) in the hydrocarbon industries. As the foremost drivers of corrosion, sulfur and naphthenic acid exist as organic acids in various crude oils. However, the rate of corrosion is also dependent on the quality of the crude oil, its acidic constituents, and the environment of the transport [21]. It is crucial to study the nature of these acids and the amount of sulfur and naphthenic acid components present in the crude oil to understand the performance and the root of corrosion. Despite the defects in oil and gas infrastructure (e.g., pipelines), the nature of crude oil itself promotes corrosion due to its harmful impurities like naphthenic acid and sulfur [22].

Pipelines, as one of the common tools of the oil and gas industries, have seen an increased demand in infrastructure due to the augmentation of the Canadian oil and gas industry to create improved operational and management conditions. It is vital to maintain the integrity of this pipeline infrastructure from being affected by the environment in ways that will have consequences of economic loss [23,24]. Moreover, internal corrosion of the pipelines turns out to be a key threat to the initial stage of production [25]. In accordance with this, more than 9000 failures due to internal corrosion were reported from 1990 to 2012 [26], which accounted for 54.8% of all spills. The United States' (US) oil and gas companies disburse 1.052 billion dollars annually to prevent internal corrosion [25]. Considering these issues, there is an urge to come up with an effective corrosion prevention approach within the given budget of the companies.

2.1. Mechanism of Corrosion

Anodes and cathodes are the two cells of corrosion generally used to demonstrate the transfer of charges between the iron and electrolyte as well as within the iron itself. The presence of charged ions in the electrolyte causes the electrolyte to transform into an electrically conductive solution. During the corrosion process, the metal ions shift from the active site (anode) into the solution and pass the electrons from the metal at the lower active site (cathode) to an acceptor. Electron acceptors like oxygen, oxidizing agents, or hydrogen ions are required for the cathodic process to take place. Equation (1) represents the general chemical corrosion reaction in the presence of oxygen in moist air. Figure 1 signifies the basic electrochemical cell built using the anode and cathode cells partially immersed into an electrolyte.

The anode cell experiences rusting during the oxidation process, whereas the cathode cell reduces but does not rust. In the production of oil and gas, the Fe²⁺ ions are produced at the anode when the iron from steel is driven into the solution. These ions act in response with oxygen, hydrogen sulfide, or carbon dioxide to form decay yields as presented below. The additional electrons change from the anode to the cathode where hydroxyl ions are produced by reducing water. The hydrogen ions are broken into hydrogen gas by the electrons if the oxygen does not exist at the cathode. The anodic and cathodic positions are regions on the outer surface of the metal that vary in electric potential. Due to the occurrence of salts, the electrolyte is normally transformed from water into being conductive. The chemical reaction of corrosion is given as follows:

$$4Fe + 3O_2 = 2Fe_2O_3 \tag{1}$$



Figure 1. Electrochemical cell [27].

2.2. Sources of Corrosion

Mostly, corrosion is thought to occur in the water phase, except when the water is restricted in the middle of the stream or surrounded by oil, in which there will be no occurrence of corrosion. The major sources of corrosion in the oil industries are hydrochloric acid and its aqueous solutions, hydrogen sulfide, corrosion of steel at hydrocarbon–electrolyte interfaces and in emulsified two-phase environments, oxygen, naphthenic acids, carbon dioxide, as well as water cut. The sources and respective roles are described below:

a. Hydrogen Sulfide

Hydrogen sulfide is known to be very harmful in the corrosion of metals or alloys, regardless of its application in oil and gas. In a matter of fact, hydrogen sulfide can be the root of sulfide stress corrosion cracking (SSCC) failure in pipelines. However, hydrogen sulfide is only corrosive when it is dissolved in water, where its solubility is relatively higher than that of carbon dioxide and oxygen. Moreover, hydrogen sulfide can cause danger in sour oil and gas fields due to its abundance in oil and production processes. The issues associated with the corrosion by the hydrogen sulfide acid are becoming more significant, as the sulfur availability in crude oil is growing proportionally with the reduction of existing sweet oil [28].

Iron sulfide and hydrogen are the products of the corrosion by sulfide. The hydrogen crack is created by the internal stresses that are caused by the molecular hydrogen. The outcomes of hydrogen cracking are unexpected and disastrous most of the time, since there are not any visible signs shown during the early phase [29]. Therefore, it is vital to select the optimal material for well completions, particularly in fields containing sour oil and gas, as the presence of hydrogen sulfide and tensile strength can possibly be the root of sulfide stress cracking (SSC) that might result in equipment loss.

b. Chloride

Chloride, which can be found in the mineralized water at the well bottom is known as another vital substance that causes severe corrosion at high temperatures. This can lead to failure that results from intergranular corrosion and chloride stress corrosion cracking (CSCC). Both the existence of sulfide and chloride have been detected in deep sour gas production that consists mainly of methane without liquid hydrocarbons under high pressure [30].

c. Carbon dioxide

Normally, the corrosion that results from carbon dioxide is labelled as "sweet corrosion". The carbon dioxide that is produced along with oil and gas dissolves in water to procedure carbonic

acid, ensuing a decrease in pH. Moreover, using an injection method for enhanced oil recovery can lead to further corrosion that is caused by CO₂. This will eventually lead to downhole and surface equipment corrosion. One of the characteristics of CO₂-based corrosion is pitting, which is imaged as deep, sharp-edged pits.

In the oil and gas industries, one of the most acidic surroundings found is the aqueous system that has higher concentrations of carbon dioxide. The partial pressure, temperature, speed, and pH are the examples of factors that contribute to corrosion in the existence of carbon dioxide [31,32].

d. Oxygen

Oxygen plays a vital role as the corrosive agent in the secondary recovery by water flooding. The corrosion caused by the dissolved oxygen causes pits in the drill pipe, where propagated fatigue cracks occur due to the stress. Additionally, oxygen can be detrimental to water injection equipment like pumps, piping, and water storage tanks, and the byproduct of corrosion might plug the formation.

Figure 2 shows a comparison of the rusting rates of oxygen, hydrogen sulfide, and carbon dioxide on carbon steel in a water solution containing 2 to 5 g/L sodium chloride at the temperature of 25 °C. From this, it can be derived that oxygen ought to be the source for higher rusting rates at much lesser concentrations than carbon dioxide and hydrogen sulfide. It should be considered that the rusting rates in pits can be a few times larger and that the carbon dioxide rusting rate is inconsistent at low temperatures. Mixtures of oxygen with carbon dioxide or hydrogen sulfide prompt immediate-corrosion environments with smaller oxygen concentrations such as 0.1 ppm [33].



Figure 2. Comparison of rusting rates of three gases [27].

a. Bacteria

Microorganism activity is the root of bacterial corrosion, which can be damaging, especially in enhanced recovery processes. Sulphate-reducing and iron bacteria are known to be the most common bacteria that promote corrosion. Microbiologically-influenced corrosion (MIC) was thoroughly examined from the industrial practice perspective, in order to attain profitable solutions in observing large water injection systems [34].

b. Water Cut

The presence of oil is considered advantageous as it employs a kind of inhibition effect by forming a film on a steel surface to prevent water wetting. On the other hand, gas and condensates do not employ any useful effect due to its non-inhibition characteristic. As for the vertical tubing, an oil film produced on the surface of the steel is steady up to about 20%–40% water cuts. Using the de Waard and Milliams method, the corrosion rate for higher water quantities can be predicted, as the steel can be considered water-wet. Besides, the volume of water is not a significant factor for the horizontal pipes.

Commonly, water is heavier compared to oil, gas and condensed products, thus it may segregate on the lowest surfaces at the 6 o'clock position for stratified flow. As for this case, the corrosion is anticipated to occur only on the water-wet surfaces. For the stratified flow, corrosion is probable to happen in the highest point of the line because of the condensation of water droplets from the wet gas. In this case, the inhibition effect is said to be poor and the corrosion rate in the highest point of the line can be expected to be 10% of the projected rate in a completely immersed condition, regardless of the carbon dioxide content.

c. Strong Acids

In the oil and gas industries, the acid stimulation method is widely applied to enhance production by improving the formation permeability. The commonly used fluids for this method are hydrofluoric acid and hydrochloric or acetic acids for sandstone and carbonates, respectively, which can cause corrosion of production tubing, downhole tools and casing in the absence of corrosion inhibitors [27].

d. Brines

Usually, brines are utilized during the completion stage of oil and gas wells to aid the final operations before the fluid production begins. This is because brines consist of zinc chlorides or calcium bromides and have the capability to regulate the well without damaging the formation. However, they can be harmful to the downhole equipment of the well, since there is the presence of dissolved oxygen.

3. Commercial Corrosion Inhibitors

As problems related to the corrosion issue have been skyrocketing, especially in the oil and gas industries, corrosion scientists have developed various techniques to mitigate this issue, such as corrosion inhibitors [35], cathodic protection [36], and paint-based corrosion inhibitors [37]. Most of the corrosion inhibitors utilized are mainly organic and inorganic composites, where organic inhibitors reduce corrosion through adsorption techniques, while the inorganic ones prevent corrosion by reacting with the anodic or cathodic parts of the process [38,39].

Organic compounds that consist of nitrogen, oxygen, and/or sulfur are considered as competent industrial corrosion inhibitors [40]. These inhibitors inherit the ability to form a protective layer between the metal surface and corrosive environment [41] through the adsorption process to delay the metal disintegration [42–44]. For instance, azole and pyrimidine byproducts are the most-used inhibitors to minimize the corrosion of metals and alloys by injecting the inhibitors into the system at low treatment concentrations [45,46]. In addition, organic inhibitors have the tendency to work productively in all acid concentrations and do not poison the refinery catalysts.

Nevertheless, the disposal of contaminated industrial corrosion inhibitors results in damaging effects on the ecosystem; thus, the use of green and environmental-friendly inhibitors is on the rise [47,48]. To illustrate, the benzotriazoles that are usually utilized to minimize the corrosion of heat exchangers were proven to poison marine creatures, even at concentrations as low as 3 ppm [49]. However, organic inhibitors chemically reduce as time passes in the presence of acid yet cannot withstand at temperatures above 95 °C; furthermore, their use is expensive.

Next, inorganic corrosion inhibitors contain the salts of zinc, copper, nickel, arsenic, and additional metals, with the arsenic compounds being the ones that are most commonly used. When these arsenic compounds are mixed with the corrosive solution, they scrape at the cathode cell of the unprotected metal surfaces. The plating reduces the percentage of hydrogen ion interchange due to the formation of iron sulfide amid the steel and acids that act as an obstacle. The reaction of acid with iron sulfide is known as a dynamic process. There are advantages as well as disadvantages when using the inorganic inhibitors. The advantages are they work excellently at high temperatures for longer periods and are less expensive than organic inhibitors. As for the shortcomings, inorganic inhibitors are more likely

to lose their grip in acid solutions that are stronger than 17% hydrochloric acid, tougher to combine, and might release toxic arsine gas as the product of corrosion.

Although these inhibitors are potent at high concentrations, they are unarguably damaging to the environment. In conjunction with this problem, new inhibitors concentrating on polymers [50–52] and plant-based [53,54] substances were studied. However, polymers were defined as moderate inhibitors, needing secondary refinement that will only result in higher cost [55,56]. Thus, extensive research is being undertaken on plant parts, as they are easily accessible in an inexpensive way.

4. Green-Based Corrosion Inhibitors

Green-based inhibitors that are nontoxic in nature, such as plant extracts, have higher demand compared to commercial inhibitors [57–59]. This is because plant extracts are observed to be green and sustainable materials due to their natural and biological properties and will be able to inhibit the metals and alloys from corroding [60]. The leaf, out of all parts of the plant, has the utmost preference for its abundance of phytochemicals (active components) produced through synthesis, that act similarly to commercial inhibitors. It is also vital to acknowledge that the extract of other parts of a plant such as root, bark, flower, fruit, wood, seed and peel have contributed to the inhibition efficiency [61–63]. Furthermore, the phytochemical synthesis uses carbon dioxide, which is known as the highly poisonous greenhouse gas, to undergo the photosynthesis, contributing to the green chemistry theory as well.

The green corrosion inhibitors function when used in a very low concentration to inhibit the metal surface from a corrosive medium. The rate of corrosion by adsorption process on the metal surface is affected by plant extracts via influencing either the anodic or cathodic reaction kinetics and then affecting the rate of diffusion of aggressive ions from interacting with the metal surface. Consecutively, a layer of film can be established by increasing the electrical resistance of the metal surface [64]. Besides, green corrosion inhibitors are well known for their adsorptive properties (site-blocking elements), enabling the active molecules from the plant extract to adsorb on exposed metal surfaces [65]. Equation (2) shows the working mechanism of the inhibitor molecules in the form of neutral molecules adsorbing on the metal surface instead of the hydrogen ions [66]:

Inhibitor +
$$nH_{ads} \rightarrow Inhibitor_{ads} + H_2$$
 (2)

where nH_{ads} is adsorbed hydrogen ions sourced from water and Inhibitor_{ads} is adsorbed neutral molecules sourced from plant extract.

In conjunction with this, there are a few limitations that must be examined during the preparation of plant extracts. Normally, the solvents used for extraction will diffuse into plant tissue, solubilize, and extract the available phytochemicals [67,68]. Hence, it is essential to select the right solvent for better results. One of the solvents that is readily available, cheap, and safe is water [69,70], yet ethanol and methanol are still in demand for selective plant extracts [71,72]. Next, the temperature creates a noticeable result when it comes to extract preparation. The solubility of the phytochemicals result in decomposition. The recommended temperature for an ideal extraction falls between the range of 60–80 °C [73,74]. As for the drying temperature, oven drying is advisable, since drying at room temperature can take up to months to accomplish.

Green-based corrosion inhibitors can be divided into two classes: organic and inorganic [75–77]. The organic class of green-based corrosion inhibitors consist of synthetic substances that are nontoxic for the environment. Flavonoids, alkaloids, and byproducts of plants are example of organic inhibitors [78]. The inorganic class of inhibitors are vastly utilized in aqueous systems due to their high productivity [79]. The chromates exhibit a toxic nature in which the employment of this inorganic inhibitor for industrial use is limited. Concerning this issue, lanthanide salts were studied as an eco-friendly inhibitor substitute [80].

Correspondingly, the fruit wastes, e.g., seeds and peels, have gained noticeable attention for their natural antioxidant properties. For instance, mango, orange, passionfruit, and cashew peels are known to contain ample amounts of antioxidants like polyphenols, carotenoids, and vitamins C and E. Emphasizing on the phenolic compounds, specifically flavonoids, the efficiency of the antioxidant activity depends on their structural characteristics like figure and location of phenolic hydroxyls. On the other hand, mango, orange and passion fruits are said to have ample sources of pectin, which belongs to the polysaccharide group [81].

Recently, a study on banana peel extracts was conducted for mild steel in an acidic environment, and another study was performed simultaneously, utilizing mango and orange peel to combat corrosion of mild steel, aluminum, zinc, and copper in acid solutions (HCl and H_2SO_4) [82]. In conjunction with this, it can be derived that the industrial waste and aqueous fruit peel extracts can be used as green-based corrosion inhibitors, as they fulfil the criteria of green chemistry. Tables 1 and 2 show the gap analysis from the previous case studies of inhibitors from plant- and fruit-based origin from 2010 to 2019. Remarks listed under the gap column give insight towards carrying out further investigation under this research theme for accurate inhibition efficiency measurement.

Details	Gap	Reference/Year
 (a) Borage flower (b) Experiments: Weight loss, EIS, surface analysis (c) Parameters: Concentration (200, 400, 600, 800 ppm) and immersion time (0.5, 2.5, 5.0 h) (d) Results: 800 ppm; 2.5 h; 91% IE 	Limitation: Constant temperature (25 $^{\circ}$ C) Remark: Vary the temperature from 25 up to 90 $^{\circ}$	[83]/2019
 (a) Rice straw extract (b) Experiments: Weight loss, surface and morphology analysis, and electrochemical test (c) Parameters: Immersion time (7, 14, 21, 28, 35, 42 days) at room temperature (25 °C) (d) Results: Immersion time of 7 to 14 days and 85% IE 	Limitation: Constant temperature (25 °C) used throughout 42 days Remark: Vary the temperature from 25 up to 90 °C	[84]/2019
 (a) <i>Glycyrrhiza glabra</i> (Pea and bean family) leaves (b) Experiments: EIS, surface characterization (c) Parameters: Concentration of inhibitor (200, 400, 600, 800 ppm) (d) Results: 800 ppm gave 88% IE 	Limitation:Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[85]/2018
 (a) Lemon balm extracts (b) Experiments: Characterization technique (LBE, EIS, surface analysis) (c) Parameters: Inhibitor concentration (200, 400, 600, 800 ppm) and immersion time (0.5, 2, 4, 6, 12, 24 h) (d) Result: 800 ppm with immersion time of 24 h and 94.6% IE 	Limitation: Constant temperature (25 °C) Remark: Vary the temperature from 25 up to 90 °C	[86]/2018
 (a) <i>Ficus religiose</i> (leaf, bodhi tree) (b) Experiments: EIS, gravimetric measurements, quantum chemical study, SEM (c) Parameters: Temperature (25, 35, 45 °C), inhibitor concentration (100–500 ppm) (d) Results: 50 ppm gave 88.29% IE at 25 °C 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[87]/2018
 (a) Myristica fragrans (nutmeg fruit) (b) Experiments: Weight loss, UV-vis spectroscopy, FT-IR spectroscopy, NMR analysis, quantum chemical studies, SEM (c) Parameter: Inhibitor concentration (100, 200, 300, 400, 500 ppm) D) Results: 500 ppm gave 87.81% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[88]/2018

Table 1. Summary of research gaps for plant-based green corrosion inhibitors from 2010 to 2019.-Note: EIS-Electrochemical impedance spectroscopy; IE- inhibition efficiency; FTIR- fourier transformed infrared spectroscopy

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Details	Gap	Reference/Year
 (a) Sunflower seed hull (flower) (b) Experiments: FT-IR, UV-vis (c) Parameters: Inhibitor concentration (50, 100, 200, 300, 400 ppm) and temperatures (25, 40, 50, 60 °C) (d) Result: 400 ppm gave 98.46% IE at 60 °C 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[89]/2018
 (a) <i>Gongronema latifolium</i> (utazi, herb) (b) Experiments: Gasometric method (c) Parameters: Inhibitor concentration (50, 100, 250, 500, 1000ppm) and temperature (30, 40, 50, 60 °C) (d) Results i. EEGL: 1000 ppm gave 93.7% IE at 30 °C ii. SEGL: 1000 ppm gave 96.5% IE at 50 °C 	Limitation: Immersion time was not stated in this article, and only one major experiment was carried out Remark: Immersion time should be tested from 3 up to 30 days	[90]/2018
 (a) Zizyphus lotuse (lotus) (b) Active ingredients: Vitamin C (ascorbic acid), linoleic acid, oleanolic acid, flavonoid compound, triterpenoic acid, jujuboside (c) Experiments: Electrochemical methods, potentiodynamic polarization, SEM and EDS analysis (d) Parameters: Concentration of inhibitors (0.05–2 g L⁻¹) and Temperatures (25, 35, 45, 55 °C) (e) Results: Concentration effect: 1000 ppm gave 93% IE Temperature effect at 1000 ppm: 25 °C; 93.16% IE 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[91]/2018
 (a) <i>Xanthium strumarium</i> (cocklebur) leaf extract (b) Experiments: SEM, FTIR, weight loss (c) Parameters: Inhibitor concentration (200, 400, 600, 800, 1000 ppm) and temperature (30, 40, 50, 60 °C) (d) Results: 1000 ppm gave 94.82% IE at 60 °C 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[92]/2018
 (a) <i>Cuscuta reflexa</i> (morning glory family, fruit extract) (b) Experiments: Weight loss, electrochemical measurement, UV-visible spectroscopy, FT-IR spectroscopy, surface analyses, quantum chemical studies (c) Parameter: Inhibitor concentration (100, 200, 300, 400, 500 ppm) (d) Results: 500 ppm gave 95.47% IE 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[93]/2018
 (a) <i>Taraxacum officinale</i> (dandelion, flower) (b) Experiments: Weight loss, Thermometric measurements, Electrochemical measurements, Gravimetric (c) Parameters: Type of crude (saponins—SETOL; flavonoids—FETOL; alkaloids—AETOL) and inhibitor concentration (10, 30, 70, 150, 300 ppm) and temperature (25, 40, 60 °C) (d) Results Gravimetric (a) Gravimetric (b) AETOL (c) Parameters: Type of crude (saponins—SETOL; flavonoids—FETOL; alkaloids—AETOL) and inhibitor (c) Concentration (10, 30, 70, 150, 300 ppm) and temperature (25, 40, 60 °C) (d) Results Gravimetric (c) AETOL (c) Solo ppm; 25 °C; 98.2% IE (c) EIS (c) AETOL; 79.0% IE 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[94]/2018
 (a) <i>Tridax procumbens</i> (daisy flower) and Chromolaena odorata (Christmas bush-leaf) (b) Experiments: EIS and adsorption isotherm (c) Parameters: Inhibitor concentration (100, 200, 300, 400 ppm) (d) Results: 100 ppm gave 95.06% IE 	Limitation: Constant temperature (40 °C) and immersion time Remark: Vary the temperature from 25 up to 90 °C and the immersion time from 3 up to 30 days	[95]/2018

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Details	Gap	Reference/Year
 (a) <i>Diospyros kaki</i> (persimmon) (b) Experiments: EIS and polarization, weight loss, surface analysis (c) Results: 225 ppm gave 83.45% IE at immersion time of 6 h 	Limitation: Constant temperature (25 °C) and short immersion time (3–6 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[96]/2016
 (a) <i>Sida acuta leaves and stem</i> (wireweed) (b) Experiments: Weight loss, hydrogen evaluation measurement, spectrophotometric analysis (c) Parameters: Temperature (30–60 °C) (d) Results: 500 ppm gave 85% (leaves) and 52% (stem) IE at 30 °C 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[97]/2016
 (a) Bamboo leaf extract (b) Experiments: Weight loss measurements, electrochemical measurements and atomic force microscope (c) Parameters: Acid concentration (1 M HCl and 0.5 M H₂SO₄), temperatures (20, 30, 40, 50 °C), immersion time (6–160 h) (d) Results: i. 1 M HCl 40 °C temperature 91.2% IE ii. 0.5 M H₂SO₄ 50 °C temperature 86.5% IE iii. Immersion time 36 to 160 h 95% IE; 1 M HCl 86% IE; 0.5 M H₂SO₄ 	Limitation: Constant inhibitor concentration was used Remark: Vary the concentration from 50 to 250 ppm	[98]/2012
 (a) Murraya koenigii (curry leaves) (b) Experiments: Weight loss method, EIS (c) Parameters: Inhibitor concentration, acid concentration (d) Results i. Concentration: 600 ppm 96.66% and 94.66% IE in HCl and H₂SO₄ ii. Acid concentration 1 M HCl; 97.54% IE 	Limitation: Small temperature range (35–65 °C) and short immersion time (2 to 8 h) used Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[99]/2010

Table 2. Summary of research gap for fruit-based green corrosion inhibitors from 2010 to 2019.

Details	Gap	References/Year
 (a) Rosa canina fruit (b) Experiments: Characterization, quantum chemical and EIS (c) Parameters: Inhibitor concentration (200, 400, 600, 800 ppm) and immersion time (2, 4, 6, 24, 48 h) (d) Result: 600 ppm gave 85.7% IE at immersion time of 6 h 	Limitation: Constant temperature (25 °C) Remark: Vary the temperature from 25 up to 90 °C	[100]/2019
 (a) Lychee waste (b) Experiments: Weight loss, EIS, FTIR and SEM, and computational studies (c) Parameters: Extraction process (blank, etoh-U, etoh-R, H₂O-U), immersion time (1.5, 3.0, 4.5 h) and inhibitor concentration (300, 400, 500, 600, 700 ppm) (d) Results Etoh-U: 97.95% IE 1.5 h: 97.95% IE 600 ppm: 97.95% IE 	Limitation: Constant temperature (25 °C) Remark: Vary the temperature from 25 up to 90 °C	[101]/2018

Table 2. Cont.

Details	Gap	References/Year
 (a) Musa paradisica peels (banana) (b) Experiments: EIS, polarization, surface analysis (c) Parameters: Acid solution (1 M HCl and 0.5 M H₂SO₄) and inhibitor concentration (200, 300, 400 ppm) (d) Results: 1 M HCl, 400 ppm gave 90% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[102]/2018
 (a) Longan seed and peel (b) Experiment: EIS, Weight loss, FTIR, SEM and computational studies (c) Parameters: Inhibitor concentration (300, 400, 500, 600 ppm) and temperature (25, 35, 45, 55 °C) (d) Results: 600ppm: 92.93% IE 55 °C: 89.29% IE 	Limitation: Constant immersion time (24 h) Remark: Vary the immersion time from 3 up to 30 days	[103]/2017
 (a) Papaya Seed (b) Experiments: Electrochemical studies, adsorption studies (c) Parameter: Different H₂SO₄ solutions (0.5 M, 1 M, 3 M) (d) Results: 3 M H₂SO₄ gave 90% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[104]/2016
 (a) Capsicum annuum fruit paste (b) Experiments: Weight loss, contact angle measurements, analysis of protective film (c) Parameter: Immersion time (24, 96, 168 h) (d) Results: 96.48% IE at immersion time of 24 h 	Limitation: Constant temperature (25 °C) and concentration Remark: Vary the temperature from 25 up to 90 °C and concentrations from 50 to 250 ppm	[105]/2016
 (a) Gingko biloba fruit (b) Experiments: MS, FTIR, EIS, contact angle measurement and SEM (c) Parameters: Inhibitor concentration (250, 500, 1000 ppm) (d) Results: 1000 ppm gave 97% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[106]/2015
 (a) Litchi fruit (b) Experiments: Weight loss, EIS, surface analysis (c) Parameter: Inhibitor concentration (25, 75, 100, 150, 200, 300 ppm) (d) Results: 300 ppm gave 97.8% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[107]/2015
 (a) Watermelon waste (b) Experiments: EIS, SEM, UV-vis and FTIR (c) Parameters: Watermelon waste (rind, seed, peel) and inhibitor concentration (10, 50, 100, 200 ppm) (d) Results: Rind: 200 ppm, 79.86% IE Seed: 200 ppm, 83.67% IE Peel: 200 ppm, 72.42% IE 	Limitation: Constant temperature (25 °C) and immersion time (24 h) Remark: Vary the temperature from 25 up to 90 °C and extend the immersion time from 3 up to 30 days	[108]/2015
 (a) Apricot juice (b) Experiments: Adsorption study and inhibition mechanism (c) Parameters: Inhibitor concentration (100, 200, 300, 400 ppm) and temperature (30, 40, 50, 60 °C) (d) Results: 400 ppm gave 75% IE at 30 °C 	Limitation: Constant immersion time (24 h) used throughout experiment Remark: Vary the immersion time from 3 up to 30 days	[109]/2013

Details	Gap	References/Year
(a) Fruit peels	No limitation or remarks	[110]/2010
(b) Experiments: EIS, polarization, weight loss, SEM		
(c) Parameters: Type of fruit peels (mango, orange, passion, and		
cashew), inhibitor concentration (100-800 ppm), immersion time (1,		
4, 24 h) and temperature (25, 40, 60 °C)		
(d) Results:		
i. Mango		
600 mg/L: 91% IE		
Orange		
400 mg/L: 95% IE		
Passion		
500 mg/L: 90% IE		
Cashew		
800 mg/L: 80% IE		
ii. Immersion time		
24 h: 96% IE		
iii. Temperature		
25 °C: 92% IE		

Table 2. Cont.

5. Conclusions

The issue is unavoidable for the oil and gas industry, creating a similar impact to those of natural disasters. Hence, completely stopping this issue is not possible, but taking preventative measure to inhibit the metal surface from corroding is more economical. The use of conventional corrosion inhibitors has long been in practice. Nonetheless, employment of commercial inhibitors has been restrained over time. This is due to their toxic properties that contribute to the destruction of the environment. Hence, with the aim of combating this, knowledge concerning the green (plant- and fruit-based) corrosion inhibitors has been consolidated in this paper to aid in mitigating the corrosion of pipelines.

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