*Nishant Kumar*[*1], *Ikhwan Syafiq Mohd Noor*[2], *Muhd Zu Azhan Yahya*[3], *Satya Prakash*[1]

[1]*Department of Civil Engineering, Sharda University, Greater Noida, India; 2Physics Division, Centre of Foundation Studies for Agricultural Sciences, Universiti Putra Malaysia, UPM Serdang, Selangor Darul Ehsan, Malaysia;* [3]*Faculty of Defence Science and Technology, Universiti Pertahanan Nasional Malaysia (UPNM), Kuala Lumpur, Malaysia.*

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# Botanical Corrosion Inhibitors in Reinforced Concrete: Material Sustainability Assessment and Analysis - A Review

## ABSTRACT

*Various methodologies have emerged over the past few decades aimed at controlling and mitigating corrosion. A new field has emerged in controlling corrosion through the use of plant-based corrosion inhibitors. The exploration of botanical extracts' efficacy marks a significant shift in corrosion science, tapping into the potential and utility offered by green plants. This comprehensive study serves as a review encompassing the spectrum of botanical extracts and their applications in diverse contexts concerning reinforced structures. This research critically assesses the correlation between phytochemical compositions, the methodologies employed in solvent extraction, and the adsorption mechanisms pivotal for enhancing the efficacy of plant extracts in corrosion inhibition. The primary objective lies in uncovering the role of inhibitors in safeguarding embedded steel within concrete structures while aiming to curtail corrosion rates. A focal point of this investigation revolves around the transition from employing toxic inhibitors to environmentally friendly botanical extracts for corrosion mitigation. Furthermore, this study accentuates the range of botanical extracts used as corrosion inhibitors shedding light on the specific phytochemical components responsible for driving the corrosion inhibition process. Notably, it expounds upon the future prospects of corrosion inhibitors, outlining the inherent challenges that must be addressed to facilitate their scalability for widespread commercial utilization.*

***Keywords:*** *Corrosion Inhibitors, performance evaluation, corrosion protection, botanical inhibitors, concrete deterioration.*

## 1. INTRODUCTION

Corrosion is the process of a material eroding attributable to chemical or electrochemical interaction of the environments, leading to material mass loss over some time [1]. Concrete and reinforcing bars are constituents of Reinforced Cement Concrete (RCC) where concrete withstands the compressive strength and the reinforcing bars govern the tensile strength. Presence of corrosion affects the durability of the concrete structures leading to failure of structures in adverse situations. Most of the structures today are made of reinforced bars. The reinforcing bars used in RCC structures should be good enough to bear tensile strength. When the corrosion starts on one region of the bars the chances of getting corrosion on the other side of the bars gets increase [1]. Due to the rapid deterioration process involved, serviceability criteria design using reinforced bars gets compromised. The corrosion of steel bars induces the concrete to swell, and triggers scaling and fissures in the concrete, resulting in catastrophic events due to compromised performances through structural deterioration [1]. The tendency of a metal to corrode is governed by its microstructures, its composition as generated during alloying, or the temperature developed during manufacturing for the deformation of a single metal surface. It would be more pragmatic to prevent corrosion instead of endeavouring to eliminate it. Corrosion mechanisms can be as diversified as the environments to which

* Corresponding author: Nishant Kumar
E-mail: Nishant.kumar4@sharda.ac.in
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a substance is exposed, which makes them harder to comprehend [1]. However, it can be controlled simply by understanding the mechanisms of a reaction involved in the process. As per the study conducted by CORCON Institute of Corrosion in 2023, the corrosion-related damage and deterioration of structures is responsible for an economic impact of around 4% of the world's GDP annually. In India, this figure can even surpass an estimated 5% of the GDP per year. This is a clear indication about the lack study on protection of concrete structures against corrosion related damages which ultimately leads to reduction in the design life of the structures. The study also revealed that the saving costs can be increased between 15% to 35% of total cost if different corrosion management and controlling practices are followed [2-4]. The cost of corrosion becomes a burden due to its impacts on the economy, the safety of human life, and material resources and energy. Furthermore, the direct and indirect corrosion costs are increased due to ignoring corrosion which adds up to the economic loss for any country. The cost of corrosion as shown in Figure 1 comprises the economic loss and safety of human life [5].

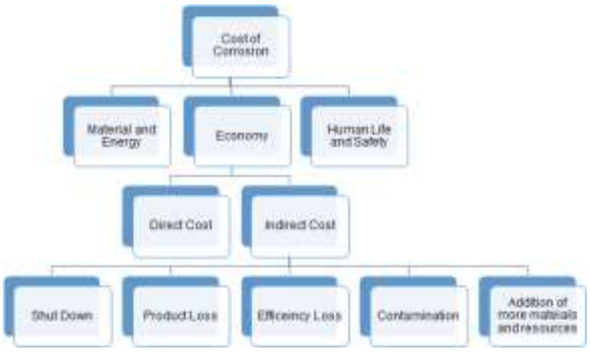


*Figure 1. Cost incurred due to corrosion [5]*

In Reinforced structures, trillions of dollars have been invested to control the corrosion. Research are going on in finding the best implementable corrosion protection methods [5]. The concept of green corrosion always has better scopes due to its multiple advantages.  Furthermore, the efficiency of the green corrosion inhibitors is higher than the toxic organic and inorganic inhibitors. Thousands of green corrosion inhibitors are available that can be used in the form of solutions and paste in the reinforcing bars. The coating can be very effective in different environments ranging from acidic to basic to saline environments. The inhibition efficiency of those natural extracts and eco-friendly materials used in different concentrations is efficacious for use in RC structures [5].

Reinforced Concrete have flaws due to the possibility of corrosion seen in a reinforced bar, this process cannot be reversed rather it can be controlled. The phenomenon of the corrosion process is unpredictable and incalculable. Due to the influence of numerous factors including pH and temperatures, the exact calculation and prediction become difficult [6]. The corrosion behaviour shows contrast in every testing specimen too. So, the tasks become more challenging to find accurate results. The influence of the performances of the materials, and reaction on the environment show a direct impact on the corrosion process. Different preventive techniques have been introduced for a few decades. With the recent advancement in technology, numerous inorganic commercial corrosion inhibitors are available, affirming having the highest efficiency of protection of rebars. Some studies have proved that the use of arsenates, chromates, phosphates molybdates etc. inhibits corrosion in a different medium [7-9]. However, these inhibitors are expensive, non-eco-friendly, and sometimes toxic. Different standards have banned such inhibitors due to their impact on human lives. So, the need for natural inhibitors is seen in more demand due to their multiple advantages over conventional inhibitors. this review attempts to study corrosion and its mechanism in RC structures. In addition, it explains some of the major constituents of different plant-based extracts corrosion inhibitors, their mechanisms of inhibitions, and some plant-based extracts in different environments. Furthermore, this study outlook at using corrosion inhibitors for different applications, including RC structures. The phenomenon involved in corrosion initiation to corrosion inhibition process with different adsorption processes on metal surfaces.

## 2. LITERATURE OVERVIEW

For a better understanding of the use of corrosion inhibitors in reinforced concrete, an extensive literature review was done and the papers were analysed from 2004 to 2023. As per the database report from Google Scholar, the number of articles published on the use of corrosion inhibitors in reinforced concrete vis-à-vis year is as,

2004-2009: 9,380

2010-2014: 13,200

2015-2019: 16,500 and

2020-2023: 20,100

As evident through the increasing trend in the number of articles published on the use of corrosion inhibitors in concrete, it highlights the ongoing potential for further research in this field. The online database used to search the relevant literature on the use of corrosion inhibitors in reinforced concrete were, Scopus (www.scopus.com) and Web of Science (www.webofscience.com). The keywords that were used to search the literature were "Corrosion Inhibitors", "corrosion", "corrosion protection", "botanical inhibitors", "durability of concrete" resulted in 203 articles. After scrutinizing and removing the irrelevant and duplicate literature 84 articles were selected for the study. The selected papers were classified according to publication year and publication area.

The year-wise distribution of the articles (Figure 2) shows an increase in the number of papers published with each passing year since 2017. However, a decrease in the numbers of papers was observed in the years 2017 and 2015. Also the point to focus is from the year 2019, almost 61% of the total papers used in the study were published in the last 5 years which shows the tremendous potential of the research in this field.

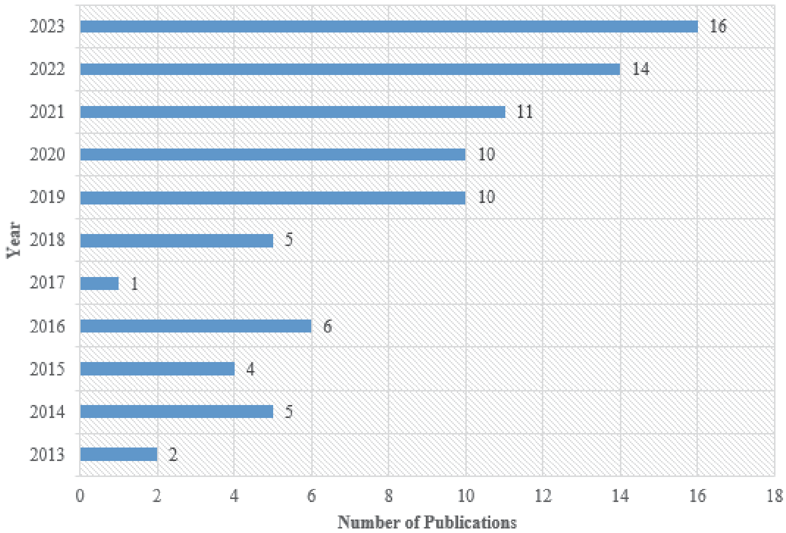


*Figure 2. Papers published in last 10 years*

The spatial spread of the publications revealed that almost 43% of the research was carried out by India and China, followed by Nigeria, Iran and Morocco as depicted in Figure 3. Latin America, North America, UK and South East Asia contributed very less to the research.


*Figure 3. Spatial spread of the literature survey*

## 3. CORROSION MECHANISM OF EMBEDDED REINFORCEMENT BAR

Corrosion is the inevitable degradation of steel influenced by numerous environmental parameters such as acid, moisture, etc. making it phenomenon more complex. The reactivity of the metal, the presence of inclusions, the availability of oxygen, humidity, gases such as Sulphur dioxide and carbon dioxide, and the availability of electrolytes are all factors that induce corrosion. While interlinked capillary porosity makes it very difficult for chloride ions, oxygen, and moisture to permeate concrete fractures and gives a more direct route to react with reinforced bar thus increasing the probability of corrosion [10-12]. Figure 4 explains the corrosion mechanism of reinforced concrete structures.

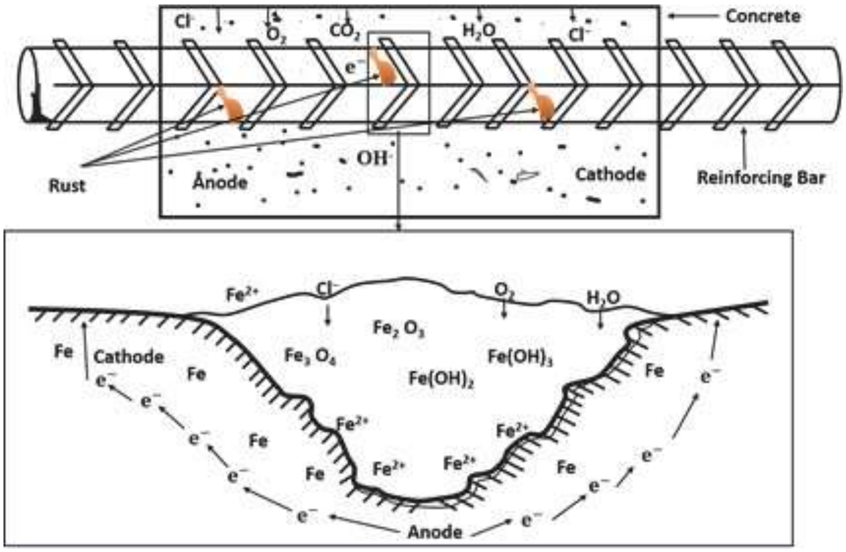


*Figure 4. Corrosion mechanism in Reinforced concrete [12]*

Figure 5 explains the various stages of deterioration in concrete due to corrosion of reinforcement. Initially concrete has a pH value of 11-13 which indicates high alkalinity due to the presence of $Ca(OH)_2$ which protects the reinforcement from corrosion. Carbonation is a process of chemical reaction of alkaline components in concrete (i.e. Ca $(OH)_2$) with atmospheric carbon dioxide which enters inside concrete through the surface cracks developed and causes a reduction of pH below 11 [12].

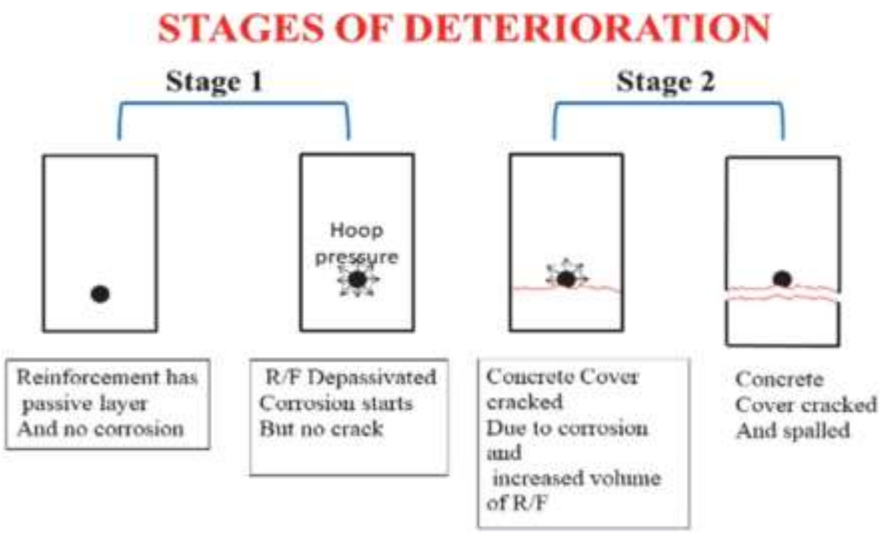


*Figure 5. Stages of Deterioration due to corrosion in Reinforced concrete*

During the Carbonation process, $CO_2$ reacts with water or moisture available near structures, since concrete is a permeable material, this gas penetrates concrete cover and reduces alkalinity to 10 or 9, and the passivating layer is damaged and once the passivating layer is damaged, corrosion starts. Once the corrosion starts, rust is formed on the surface of the steel bar which exerts hoop pressure on the surrounding concrete. Due to this continuous hoop pressure, the concrete cracks and eventually spalling of concrete occurs.

The performance of RC structures diminishes as concrete structures deteriorate due to adverse climatic conditions, and the untimely disintegration of structures before the periodic maintenance life is a primary issue for engineers and researchers. The rate at which structures degrade is influenced by the conditions of exposure and the intensity of maintenance. Corrosion, which is triggered by chemical or electrochemical responses, seems to be the most prevalent cause of RC structure deterioration. It is primarily governed by chloride ingress and RC structure carbonation depth. Carbonation and infiltration of chloride ions are the two most common causes of rebar corrosion in concrete constructions. Corrosion of RC structures begins when chloride ions pierce concrete beyond the predefined threshold or when carbonation depth surpasses concrete cover.

If corrosion commences in concrete structures, it proceeds and diminishes the structures' service life, and the pace of corrosion has an impact on the remaining serviceability of RC structures [13]. Nevertheless, these extreme environments promote reinforcement corrosion unless the requisite concentrations of oxidative degradation are accessible at the rebar level in concrete structures. Corrosion can significantly impair the strength and life of structures, and contaminants from the atmosphere can permeate through the concrete cover and induce corrosion of steel in humid situations. As explained in Figure 6 the cathode and anode are formed in various locations of the same reinforcing bar. Whenever the corrosive process is initiated, the section is degraded in the anodic region. The iron gets transformed into ferrous ionic species, which also are transferred from the anode to the cathode. These regions on the reinforcement bar exhibiting positive electrochemical potential serve as cathode material using moisture, reducing oxygen, and devouring electrons from the anode to form hydroxyl ions. Inside the electrochemical system, the steel bars act as conducting materials, whereas the concrete solution functions as the electrolytic medium whereby the ions migrate [14].

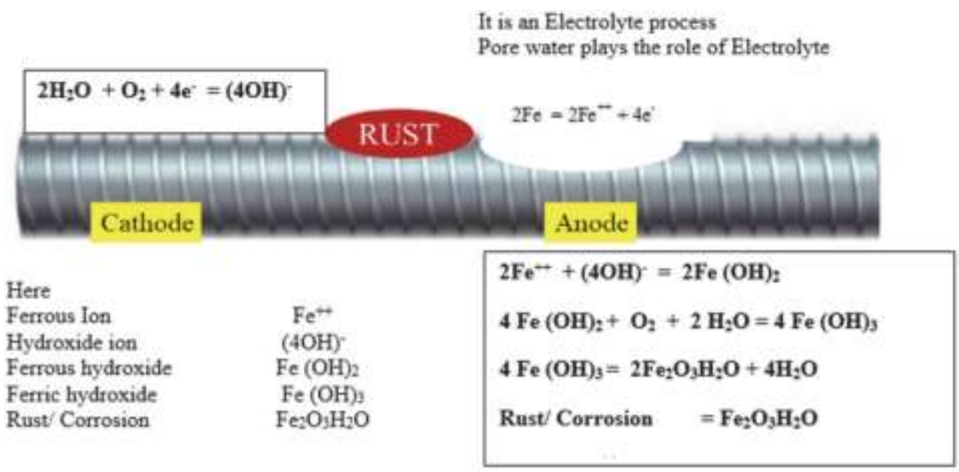


*Figure 6. Anode-Cathode formation on steel reinforcement bar [14]*

## 4. CORROSION INHIBITORS

Corrosion inhibitors are additives to concrete that are used to minimize or delay the start of corrosion in reinforced concrete structures. Corrosion inhibitors are substances that, when introduced in minute doses to corrosive environments, avoid or minimize the metal from interacting with it [15]. The majority of inhibitors stabilize steel by generating a protective layer on its surface; nevertheless, certain inhibitors react with concrete complexes to restrict the concrete's permeability. Corrosion inhibitors are typically incorporated into the normal concrete mixture in modern constructions, but they can also be sprayed on the concrete surface during repairs. Corrosion inhibitors help in reducing the ion's movements within the surfaces which results in slowing down of corrosion process. Furthermore, inhibitors are known to increase the reinforcing bar's cathodic and anodic polarization behavior. The implementation of relevant and effective inhibitors is one of the most appropriate strategies for preserving metals against severe corrosion breakdown [16]. In recent decades, researchers have been looking into the inhibitory capabilities of bioactive antioxidants derived from plants, and they have revealed that they are potent inhibitors. Natural products have the advantage of becoming environmentally friendly and ecologically accepted. Different synthetic inhibitors have serious health consequences, consequently, natural products that seem to be affordable, non-toxic, and environmentally preferable must be used instead [16].

Organic and inorganic inhibitors have shown promising potential in inhibiting efficiency. Different green materials have been studied to understand the nature of the inhibiting action it can bestow for the corrosion-reducing process [17]. The inhibitors inhibit corrosion by increasing anodic or cathodic polarizing behavior, reducing ion mobility on the metallic surface, and raising the metallic surface's electrical resistance [17]. Corrosion inhibitors in concrete have become immensely popular in recent years due to their low cost and accessibility of use in today's scenario, concrete and reinforcing bars have been used worldwide [18].

### *4.1. Botanical Corrosion Inhibitors*

Green Corrosion inhibitors are such inhibitors that serve the purpose of inhibiting corrosion mechanisms without harming human health and environment as they are non-toxic. Botanical corrosion inhibitors are called plant-based extract inhibitors. Due to their abundant availability and being environmentally friendly, the use of corrosion inhibitors has been used widely in different applications [19]. The use of such corrosion inhibitors can add to up structure's life from early deterioration. Using botanical extracts is pertinent for corrosion protection as potential botanical extracts have wide areas of applications. Leaf, roots, fruits, flowers, oil, whole plants, wooden parts including stem, branch, bark, waste, etc. all comprises the parts of plants. All parts of plants have different inhibiting compounds. Different studies on the materials and the methodology were carried out to understand the potential plant-based extract material.

It showed that the plant has an incredible corrosion inhibition potential. Similarly, the use of curcumin properties of turmeric powder had an inhibiting efficacy of 90% in 0.5M $H_2SO_4$ on the carbon steel [19]. A similar study was carried out on the use of Xanthan gum in a 15% HCl environment to see the insights of inhibiting efficiency. Experimental data from the lab on mild steel and Density functional theory (DFT) were used for correlation which resulted in better inhibition performances [20]. Furthermore, the use of Xanthan gum as a corrosion inhibitor in aluminium in 0.5 M HCl was also studied and it was observed that the inhibition efficiency was increased while increasing the concentration of gum extract and decreased with an increase in the temperatures [20]. Numeral studies were carried out on plant-based extracts which suggests that the corrosion mechanisms are inhibited when using corrosion inhibitors and are influenced by the substrates. These all-potential plant-based extracts have shown the influence of different adsorption mechanisms in inhibiting efficiency [21-24].

### *4.2. Phytochemicals in Botanical Extracts*

The study of phytochemicals present in the plant-based extract is very important to understand the concentration required for corrosion inhibition for the intended applications [25-28]. Along with this, the study of different phytochemicals helps in understanding which extracts to be used from the plants. The reactivity and the adsorption types involved in the metal substrate help to identify the efficiency of botanical extract corrosion inhibitors. The phenolic acids compounds, terpenoids, carbohydrates, lipids, and alkaloids-based compounds have been proven to be effective in slowing down the corrosion process [26-28]. Figure 7 illustrates the composition of the phytochemicals present in plant-based extracts which are absorbed into the surface of metal following the process of physisorption and chemisorption. Alkaloids and phenolic acids are the most commonly seen phytochemicals in botanical extracts. The combination of different plants-based extracts and their compatibility the similar kinds of phytochemicals can be effective for increasing efficiency [29].


*Figure 7. Phytochemicals present in botanical extract [25-29]*

### *4.3. Solvent Extraction Methods of Botanical Extracts*

The identification of phytochemicals with characterizations and quantification of plant-based extraction are done using different types of methodological approaches [30]. Figure 8 comprises both conventional and advanced solving extraction methods which are more commonly used for corrosion inhibitors solvent extractions. Maceration, percolation, decoction, etc. come under the conventional extraction methods. These methods require a higher volume of solvents with a considerably longer time for extraction. To overcome such problems, greener and advanced extraction methods were introduced like supercritical fluid (SFC), Pressurized Liquid Extraction (PLE), microwave-assisted extraction (MAE), etc. the advantages of using such methods can be as the consumption of organic solvents is lesser and has a very shorter extraction [31-32]. Such advanced methods are very effective in possessing and without losing any of those phytochemical compounds.

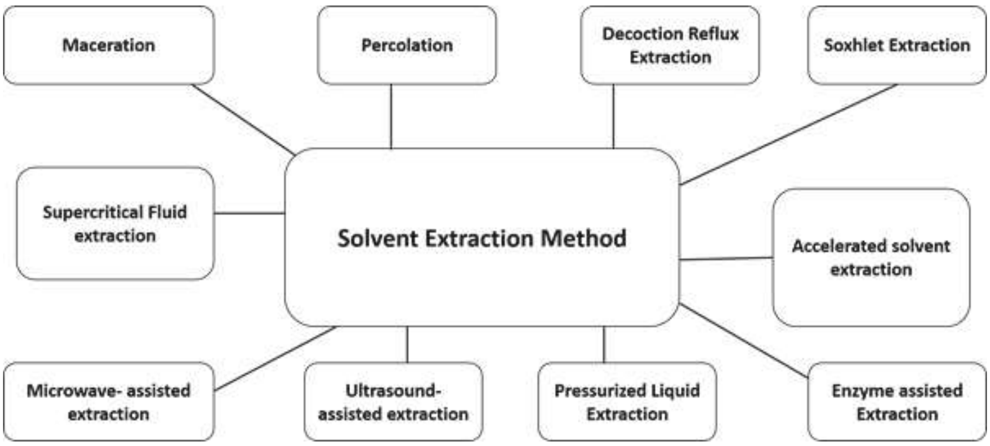


*Figure 8. Solvent extraction methods of botanical extracts [33]*

### *4.4. Performances of Botanical Extracts*

Botanical extracts have been proven to be the best environmental friendly alternative due to their numerous benefits including higher efficiency in different acidic, alkaline, and saline environments [34-44]. Different advanced methods have been employed for corrosion measurement which makes it more efficient [45-61]. The role of inhibitors plays a vital role in the performance of botanical extracts. The parts of plants like leaves, fruit, peel, bark, seed, root, etc. all can have different performances with different efficiency. Studies revealed that leaf extracts are potential parts for corrosion protection [62-78]. These extracts can inhibit the corrosion process more than the other extracts. Table: 1 in acidic, Table: 2 in alkaline, and Table: 3 in saline environments show some of the potential botanical extracts capable of inhibiting the corrosion process with better efficiency.

*Table: 1 Botanical extracts in acidic environment*

| S. No. | Plants | Parts used | Concentration | Substrate | Medium | Methodology | Efficiency (%) | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Brassica oleracea | Leaves | 300 mg/l | Q2355 steel | 1 M HCl | XPS, FTIR, UVS, XRD Surface topography | 93.8 | [34] |
| 2 | Neem Leaf | Leaves | 4g/200ml | Mild Steel | HCl | WL. Phytochemical test, FTIR, and GCMS | 93.24 | [35] |
| 3 | Solanum Lasiocarpum | Leaves | 1g/L | A3 steel | HCl | WLM, PDP, EIS, FTIS, SEM | 93.31 | [36] |
| 4 | Triticum aestivum | straw | 4g/L | Stainless Steel (SS-410) | 15% HCl | PDP, AFM, XPS, SEM, XRD | 92.6 | [37] |
| 5 | Lilium Brownii | Leaves | 200 mg/L | X70 Steel | 1M HCl | EIS, FTIR, ECM | 85 | [38] |
| 6 | Green Eucalyptus | Leaves | 800 mg/l | Mild Steel | 1M HCl | EIS and polarization test | 88 | [39] |
| 7 | Citrullus lanatus | fruit | 800 mg/l | Mild steel | 1M HCl | PDP, EIS, SEM, AFM | 91 | [40] |
| 8 | Pomelo Peel | Fruit waste | 8gm/l | Mild steel | 0.1M HCL | PDP, EIS, SEM, FTIR, EDS | 74.64 | [41] |
| 9 | Natural Nutmeg oil | Oil | 500 mg/l | L-52 carbon steel | 1 M HCl | EIS, WL, ECM | 94.73 | [42] |
| 10 | Glycyrrhiza glabra | leaves | 800g/l | Mild Steel | 1 M HCl | ECM, surface Characterizations, MD simulations | 88% | [43] |
| 11 | Cuscuta reflexa | Fruit | 500 mg/L | Mild Steel | 0.5 M $H_2SO_4$ | UV, FTIR, AFM, SEM, DFT | 95.47 | [44] |
| 12 | Peganum Harmala | Leaves | 283.4 g/l | C-Steel | 0.25 M $H_2SO_4$ | FTIR, EIS, SEM, UV-spectroscopy | 98 | [45] |
| 13 | Sunflower | Seed hull | 400 g/l | Mild steel | 1 M HCl | EIS, FTIR, GC analysis and dynamic polarization | 98.5 | [46] |
| 14 | Ginkgo | Leaves | 200 mg/l | X 70 steel | 1 M HCl | Electrochemical measurements, FE-SEM, AFM | 90 | [47] |
| 15 | Locust bean | Gum | 5mM | Q 235 steel | 0.5 M $H_2SO_4$ | OCP, PDP, EIS, MDS, QCC | 89.8 | [48] |
| 16 | Tinospora crispa | leaves | 8 g/l | Mild Steel | 1 M HCl | WLM, PDP, EIS, | 80 | [49] |
| 17 | Punica granatum | leaves | 1g/l | Mild steel | 1 M HCl | FTIR, XRD, WLM, PDP | 94 | [50] |
| 18 | Gantiana olivieri | Fruit | 800mg/l | Mild steel | 0.5 M HCl | EIS, HPLC, SEM/EDX | 93.7 | [51] |
| 19 | Tender arecanut | Seed | 4.5 g/l | Aluminum | 0.5 M HCl | AIS, AFM, electrochemical measurements | 94.4 | [52] |
| 20 | Tagetes erecta | flower | 1 g/l | Mild steel | 0.5 M $H_2SO_4$ | Gravimetric, PDP, EIS | 96.1 | [53] |
| 21 | Luffa Aegyptiaca | leaf | 0.24 g/l | Mild steel | 0.5 M $H_2SO_4$ | PDP, FTIR, EIS | 93.3 | [54] |
| 22 | Borage flower | Flower | 0.8 g/l | Mild Steel | 1 M HCL | WLM, PDP, EIS | 91 | [55] |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 23 | Red apple (malus domestica) | Fruit | 5g/l | Mild steel | 0.5M HCL | WLM, PDP, EIS, SEM | 87.9 | [56] |
| 24 | Ammi visnaga | seed | 1 g/l | Mild steel | 1 M HCl | PDP, EIS | 84 | [57] |
| 25 | Ircinia strobilina | Crude | 2g/l | Mild steel | 1 M HCl | WLM, PDP, LPR, EIS LC-MS | 82 | [58] |
| 26 | Kappaphycus alvarezii | Thallus | 0.5g/l | Mild steel | 1 M $H_2SO_4$ | WLM, PDP, EIS, SEM, AFM | 79.44 | [59] |
| 27 | Myristica fragrans | Fruit | 0.5g/l | Mild steel | 0.5 M $H_2SO_4$ | WLM, EIS, UV, SEM, AFM | 87.81 | [60] |
| 28 | Phyllanthus amarus | Leaves | 4% (V/V) | Mild steel | 1 M HCl | WLM, Gasometric technique | 96.1 | [61] |
| 29 | Coffea canephora | Seed | 1g/l | Carbon steel | 1 M HCl | EIS, SEM, WLM, PDP | 94 | [62] |
| 30 | Barley | Whole plant | 0.1 g/l | Mild Steel | 1 M HCl | WLM, EIS, SEM, PDP | 92 | [63] |
| 31 | Grewa Venusta | Root | 8% ( v/v) | Mild steel | 1 M HCl | AAS, GC-MS, SEM, | 97.9 | [64] |
| 32 | Magnolia grandiflora | Leaves | 500 mg/l | Carbon Steel | 1 M HCl | WLM, PDP, EIS | 88.2 | [65] |
| 33 | Orange peel waste | Fruit | 0.25% | Mild Steel | 1 M HCl | WLM, PDP, EIS | 95.36 | [66] |
| 34 | Nigella sativa | seed | 0.4 g/l | Mild steel | 0.5 M HCL | PDP, EIS | 74 | [67] |
| 35 | Armoracia Rusticana | root | 100 mg/l | Mild steel | 0.5 M $H_2SO_4$ | WLM, PDP, EIS, FTIR, SEM | 95.74 | [68] |
| 36 | Maesobatrya barteri | Leaves | 0.5 g/l | Aluminum | 2 M HCl | WLM, Thermometric analysis | 45.15 | [69] |

LC-HRMS: -Liquid chromatography-high resolution mass spectrometry, EIS: Electrochemical impedance Spectroscopy, PDP: - Potentiodynamic polarization, WLM, weight Loss Method, AFM: - Atomic force Microscope , FTIR: - Fourier -Transform infrared spectroscopy, SEM: - Scanning Electron Microscope, MDS: - Molecular Dynamics Simulations , AAS: - Atomic Absorption Spectroscopy, ECM: - Electrochemical Measurement, GC-MS: - Gas Chromatography- Mass Spectrometry, OCP: - Open Circuit Potential, HPLC: - High performance liquid chromatography, UVS:- Ultraviolet Visible Spectroscopy, XRD: - X-ray Powder Diffraction Spectroscopy, LPR: - Linear Polarization Resistance, XPS: - X-ray Photoelectron spectroscopy

*Table: 2 Botanical extracts on Alkaline medium*

| S. No. | Plants | Parts used | Concentration | Substrate | Medium | Methodology | Efficiency (%) | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Henna powder | leaves | 50 mg/l | Tin | 1 M NaOH | WLS, AIS, TS, SEM | 95.97 | [70] |
| 2 | Arecanut | husk | 18 g/l | Mild Steel | 0.5 M NaOH | PDP, AFM, SEM, EIS, XRD | 91.66 | [71] |
| 3 | Gossipium hirsutum | Leaves | 52% v/v | Aluminum | 2 M NaOH | Chemical Techniques, WL | 97 | [72] |
| 4 | (Pentaclethra macrophylla Bentham) | Root | 0.3 g/l | Mild Steel | 0.5 KOH | WLM, PDP, EIS | 91 | [73] |

*Table: 3 Botanical extracts in Saline environments*

| S. No. | Plants | Parts used | Concentration | Substrate | Medium | Methodology | Efficiency (%) | References |
|---|---|---|---|---|---|---|---|---|
| 1 | Catharanthus roseus | Stem | 5mg/l | Mild steel | 3.5% NaCl | WLM, PDP, EIS, SEM, XRD, DFT | 96 | [74] |
| 2 | Phyllanthus muellerianus | leaf | 0.0833% - 0.416% | Mild steel | 3.5% NaCl | WLM, PPS, AIS | 97.6 | [75] |
| 3 | Pomelo peel | Fruit waste | 8g/l | Low carbon steel | 3.5% NaCl | WLM, SEM, PDP, EDS, EIS,FTIR | 71.15 | [76] |
| 4 | Cascabela Thevetia | leaves | 3 g/l | Carbon steel | 3.5%NaCl | PDP, EFM, EIS, AFM, OCP | 94.4 | [77] |
| 5 | Echium amoenum fisch | Whole plant | 8g/l | ST37 steel | 3.5%NaCl | EIS, FTIR, SEM | 99.32 | [78] |

## 5. CHALLENGES AND FUTURE SCOPE

The use of botanical extracts as corrosion inhibitors in RC structures will have a dominating demand due to their abundant availability, cost-effectiveness, eco-friendly nature, and high efficiency [34-78]. However, for larger commercial purposes, arduous efforts and innumerable challenges comes because of the different parameters involved for the adsorption mechanism facilitating corrosion inhibition [79-81]. The effectiveness of corrosion inhibition properties of various botanical extracts is distinctive [82-84]. Furthermore, the research to prove the inhibition mechanism of all potential plants is still inadequate. In addition to this, the efficient parts of each plant-based extracts exhibit different efficiency and the adsorption mechanisms of each extract are different. The solvent extraction process of extracting the samples becomes expensive when moving toward for commercial use of such inhibitors. The inhibitors inhibiting period, extraction period, storage, etc. makes a challenging task for the use of botanical extracts as corrosion inhibitors. Numeral plants-based extracts which are explored have shown problems of compatibility with other extracts, although some have showed an increase in the inhibiting efficiency but still there is inadequate research on aspects like concentration required for the highest inhibition possible, optimal concentration for compatibility etc. The study on the corrosion-inhibiting phenomena of potential ideal botanical extracts and their combination with other extracts will be beneficial to understand and apply the corrosion inhibitors for intended applications.

Also another area of research can be presence of corrosion inhibitors as coating on the reinforcement bars. As we know that the corrosion occurs on the surface of reinforcement, so there can be a possibility of providing a coating of botanical corrosion inhibitors on the surface of reinforcement to delay or prevent the corrosion. Furthermore, when coatings are provided on the surface of the reinforcement, the coating thickness plays a vital role in development of the bond strength between steel and surrounding concrete. This can be another study area to obtain the optimum coating thickness of the surface applied corrosion inhibitors. The study of corrosion inhibitors in concrete presents diverse and compelling research opportunities that can significantly contribute to the advancement of infrastructure sustainability and durability. One avenue for investigation lies in the comparative analysis of the effectiveness of various corrosion inhibitors employed in concrete. This research can delve into the differences between commonly used inhibitors, such as calcium nitrite, calcium nitrate, organic inhibitors, and silicate-based inhibitors, providing insights into their specific advantages and limitations.

Additionally, there is an opportunity to deepen our understanding of the mechanisms underlying corrosion inhibition in concrete structures. By exploring the molecular and chemical processes at play, researchers can uncover the intricate details of how inhibitors interact with the concrete matrix and prevent corrosion, paving the way for more informed and targeted approaches in inhibitor design and application. Long-term performance assessment is another crucial dimension that warrants exploration. Investigating the durability of corrosion inhibitors over extended periods of exposure to harsh environmental conditions will provide valuable data on the sustainability of inhibitor treatments and inform maintenance strategies for aging infrastructure.

Furthermore, researchers can explore the compatibility of corrosion inhibitors with various types of concrete mixtures, including high-performance concrete, self-compacting concrete, and lightweight concrete. This line of inquiry can lead to optimized formulations that address the specific needs of different construction scenarios. A holistic approach involves considering the environmental impact of corrosion inhibitors. Assessing the eco-friendliness of inhibitors and their potential effects on the surrounding ecosystem is imperative for sustainable construction practices. Complementing this, a study of inhibitor applications in aggressive environments, such as marine or industrial settings, can provide insights into real-world challenges and opportunities for improvement.

## 6. CONCLUSION

Corrosion, an inevitable and relentless process, exhibits a complexity influenced by various factors. Countless protective measures have been devised to inhibit corrosion across diverse applications. Among these, the widespread use of efficient corrosion inhibitors stands out. While inorganic corrosion inhibitors demonstrate strong efficacy, their drawbacks, such as limited availability and non-eco-friendly characteristics, render them less than ideal for inhibition purposes. In contrast, botanical extracts as corrosion inhibitors present a promising prospect due to several advantages. These natural extracts are abundantly available and offer higher efficiency while employing environmentally friendly processes. This comprehensive review seeks to highlight the potential of environmentally sustainable corrosion inhibitors within different contexts. It investigates into the significance of phytochemicals present in botanical extracts, explores various solvent extraction methods, and elucidates the adsorption mechanisms utilized to enhance inhibiting efficiency. By focusing on botanical inhibitors and their comparison to toxic inorganic corrosion inhibitors, this study emphasizes the shift towards more eco-conscious solutions. Additionally, it provides an overview of the feasibility and advantages of employing botanical inhibitors across various applications, including their relevance in safeguarding reinforced concrete (RC) structures.

The exploration of botanical extracts as corrosion inhibitors unveils a promising pathway towards sustainable corrosion prevention strategies. The accessibility of these natural compounds coupled with their increased efficiency in mitigating corrosion showcases a potential alternative to conventional inhibitors. Furthermore, this review aims to draw attention to the pressing need for environmentally viable corrosion inhibition methods, advocating for a shift towards botanical inhibitors as a feasible and eco-friendly solution in combating the pervasive issue of corrosion in diverse settings.

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## IZVOD

## BILJNI INHIBITORI KOROZIJE U ARMIRANOM BETONU: PROCENA I ANALIZA ODRŽIVOSTI MATERIJALA - PREGLED

*Tokom proteklih nekoliko decenija pojavile su se različite metodologije koje imaju za cilj kontrolu i ublažavanje korozije. Pojavilo se novo polje u kontroli korozije upotrebom inhibitora korozije na bazi biljaka. Istraživanje efikasnosti botaničkih ekstrakata označava značajan pomak u nauci o koroziji, koristeći potencijal i korisnost zelenih biljaka. Ova sveobuhvatna studija služi kao pregled koji obuhvata spektar botaničkih ekstrakata i njihovu primenu u različitim kontekstima u vezi sa ojačanim strukturama. Ovo istraživanje kritički procenjuje korelaciju između fitohemijskih sastava, metodologija korišćenih u ekstrakciji rastvaračem i mehanizama adsorpcije, koji su ključni za povećanje efikasnosti biljnih ekstrakata u inhibiciji korozije. Primarni cilj leži u otkrivanju uloge inhibitora u zaštiti ugrađenog čelika unutar betonskih konstrukcija sa ciljem smanjenja stope korozije. Fokus ovog istraživanja je oko prelaska sa upotrebe toksičnih inhibitora na ekološki prihvatljive botaničke ekstrakte za ublažavanje korozije. Štaviše, ova studija naglašava niz botaničkih ekstrakata koji se koriste kao inhibitori korozije, bacajući svetlo na specifične fitohemijske komponente odgovorne za pokretanje procesa inhibicije korozije. Naročito, objašnjava buduće izglede inhibitora korozije, naglašavajući inherentne izazove koji se moraju rešiti da bi se olakšala njihova skalabilnost za široku komercijalnu upotrebu.*

***Ključne reči:*** *Inhibitori korozije, ocena performansi, zaštita od korozije, biljni inhibitori, propadanje betona.*

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The ORCID Ids of all the authors are as follows:

Nishant Kumar: https://orcid.org/0000-0001-5477-3293

Ikhwan Syafiq Mohd Noor: https://orcid.org/0000-0003-0983-782X

Muhd Zu Azhan Yahya: https://orcid.org/0000-0003-1129-0552

Satya Prakash: https://orcid.org/0000-0001-6633-7480