International Science Journal of Engineering & Agriculture
2025; 4(3): 66-80
https://isg-journal.com/isjea
doi: 10.46299/j.isjea.20250403.06
ISSN: 2720-6319

Environmentally friendly corrosion inhibitors: a modern alternative to traditional methods of protecting metal structures

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Abstract: Metal corrosion is a serious technical and environmental problem that leads to significant economic losses and threatens the safety of infrastructure. Traditional methods of protecting metal structures are based on the use of chemical inhibitors, which are often toxic, poorly biodegradable and hazardous to human health and the environment. In response to these challenges, there is a growing interest in the development of "green" corrosion inhibitors - non-toxic, biodegradable and environmentally friendly substances derived from natural sources.

This study examines the effectiveness of aqueous, alcoholic and water-alcohol plant extracts as an alternative to traditional corrosion inhibitors for the protection of 17GS steel in the NS4 model environment.

Experimental studies have shown that the water-alcohol extract of Echinacea provides up to 69% protection of steel, the water extract of tea - up to 50%, while the effectiveness of eucalyptus oil was only 12%. The results obtained indicate a significant dependence of the protection efficiency on the type of plant material, extract concentration, exposure temperature, and duration of contact with the environment.

Gravimetric analysis confirmed the formation of a dense protective adsorption-oligomeric film on the metal surface, which significantly reduces the corrosion rate and increases the polarization resistance of steel to 15 kΩ at a concentration of 40 ml/l. Microstructural analysis shows that the most effective compounds are those with aromatic structures and nitrogen-containing heterocycles that are able to form stable chemical bonds with the metal surface.

A multivariate regression analysis of the dependence of steel corrosion resistance on exposure time, inhibitor concentration, and temperature was performed, which confirmed the significant impact of these factors on metal protection. The studies indicate that it is possible to optimize the composition of inhibitors by using combined herbal preparations and nanostructured additives to increase the duration and effectiveness of the protective effect.

The results of this work open up new prospects for the development of environmentally friendly metal protection technologies that meet the concept of sustainable development and the principles of green chemistry. Further research should be focused on finding new sources of bioactive compounds, improving extraction methods, and in-depth study of the mechanisms of protective coatings formation.

Keywords: green corrosion inhibitor, metal protection, environmentally friendly technologies, plant extracts, inhibitors based on natural substances, biodegradability, environmental chemistry; phytochemical compounds, electrochemical corrosion, NS4 model environment, Phosphate coatings.

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1. Introduction

Corrosion is an inevitable natural process that leads to the gradual destruction of materials, especially metals especially metals and alloys, as a result of their chemical reactions with the environment 1. This process causes significant economic losses worldwide, estimated at approximately 3.4% of the world's gross domestic product (GDP). The impact of corrosion is felt in a variety of sectors, including industrial equipment and machinery, oil and gas, mining, land and air transport, and infrastructure. Serious consequences for infrastructure can include catastrophic events such as bridge collapses and pipeline failures. There is therefore an urgent need for effective corrosion prevention and control methods to reduce these costs.

Traditional methods of corrosion protection often rely on chemical inhibitors, which can be toxic and pose environmental and human health risks. For example, chromates are associated with environmental and health risks. Volatile organic compounds (VOCs) in coatings can also be hazardous, and zinc fumes released during the electroplating process are toxic. In response to these concerns, “green chemistry” has emerged as a new field that focuses on developing environmentally friendly solutions.

In this context, green corrosion inhibitors are a sustainable alternative. They are defined as non-toxic, biodegradable, and environmentally compatible substances derived from natural sources or waste. The use of such inhibitors has the potential to reduce the ecological footprint and health risks associated with corrosion prevention. This is in line with global efforts to promote environmental sustainability and public health.

2. Object and subject of research

Object of study: the processes of corrosion destruction of metal structures, in particular steel, under the influence of aggressive environmental factors in industrial and urban environments. The object of study also includes the system of anti-corrosion protection measures used in various industries.

Subject of research: the properties and efficiency of “green” corrosion inhibitors derived from plant extracts (including aqueous, alcoholic, and water-alcoholic), as well as the mechanisms of their influence on the electrochemical processes of corrosion of 17GS steel in the NS4 model environment. The subject is also the influence of the concentration of extracts, temperature, exposure time, and chemical composition of natural compounds on the formation of Phosphate coatings and reduction of the corrosion rate.

3. Target of research

Corrosion is a global problem affecting various industries, economies, and the environment. It is an irreversible process that destroys materials, including metals and alloys, over time through their interaction with chemical agents in the environment. The main factors contributing to corrosion are humidity, temperature, and exposure to corrosive gases, acids, and other substances. In industrial and urban areas, corrosion processes are often accelerated by anthropogenic factors such as air pollution, emissions from enterprises and transportation activities.

Corrosion causes enormous financial losses on a global scale, estimated at around 3.4% of global GDP. It causes premature wear and tear of industrial equipment, vehicles, engineering structures, as well as oil and gas and chemical facilities. The costs of repair, replacement of damaged structures and preventive maintenance are significant. In particular, in the transportation sector, corrosion can lead to vehicle breakdowns, and in the infrastructure sector, it can destroy bridges, pipelines and other critical facilities.

Traditional methods of corrosion control, such as the use of chemical inhibitors and coatings, often have a negative impact on the environment. For example, chromium compounds used in metal protection are toxic and can cause serious illness in humans. Volatile organic compounds (VOCs) contained in anti-corrosion paints and coatings contribute to air pollution and can cause respiratory diseases. In addition, corrosion of pipelines can lead to toxic substances leaking into the soil and water, which threatens ecosystems and public health.

Given the above, there is an urgent need to introduce new, environmentally friendly corrosion protection technologies. Traditional methods need to be replaced with innovative solutions that not only effectively curb corrosion processes but also minimize environmental and social risks. One of the most promising areas is the use of green corrosion inhibitors derived from plant extracts and other natural sources. Such alternatives are safe for the environment and human health, and are in line with the concepts of sustainable development.

Solving the corrosion problem requires a comprehensive approach that includes the introduction of environmentally friendly technologies, improvement of materials and coatings, development of new monitoring and control methods, and the formation of a strategy to minimize economic losses.

4. Literature analysis

Corrosion of metals is a complex process that depends on the environment and involves the irreversible interaction of materials at the interface. It is electrochemical in nature, involving anodic and cathodic reactions. The rate of corrosion is influenced by various factors such as pH, temperature, and the presence of aggressive ions such as chloride (Cl-). In neutral environments, such as seawater, cathodic reactions involve the reduction of oxygen and the release of hydrogen. Understanding these electrochemical mechanisms is crucial for the development of effective inhibitors. The variety of factors affecting corrosion emphasizes the need to tailor green inhibitors to specific conditions [1, 4].

There are several traditional methods of protecting metals from corrosion: Barrier coatings create a physical barrier between the metal and the corrosive environment. However, they may need to be reapplied and can degrade if not applied correctly [8]. In addition, some coatings contain VOCs, which are harmful [2]

Hot-dip galvanizing of steel with molten zinc to form a protective alloy layer. This method cannot be used on site and the coating can peel off. Zinc fumes during the process are toxic. Alloy steel such as chromium and nickel increases corrosion resistance. The main disadvantage is the high cost. Cathodic protection uses electrochemical methods to prevent corrosion by turning active areas into passive areas. Typically, galvanic anodes (aluminum, magnesium or zinc) or an external current source (impressed cathodic protection - ICCP) are used. The anodes need to be replaced periodically and the method may not be effective in high resistance environments. There is also a risk of contamination of marine sediments with zinc from sacrificial anodes. Corrosion inhibitors are added to slow down the corrosion process. They form Phosphate coatings on the surface of the metal. However, many traditional inhibitors raise environmental and health concerns [3, 5].

Although traditional methods have been effective, they often have significant environmental impacts and practical limitations. The diversity of traditional methods also emphasizes the need for green inhibitors to be versatile and applicable in different scenarios [7].

Green corrosion inhibitors are defined as non-toxic, biodegradable and environmentally compatible substances. They are a sustainable alternative to traditional chemical inhibitors, derived from natural sources or waste, making them readily available. Their development and application are consistent with the principles of green chemistry and sustainable development [4, 6].

Green corrosion inhibitors are derived from a variety of sources. The most common source includes extracts from various parts of plants (leaves, bark, roots, seeds, fruits). Examples include extracts of neem, henna, green tea, rosemary and lupine. Their inhibitory effect is due to the presence of phytochemicals such as alkaloids, tannins, flavonoids and phenols. Extraction processes can be difficult due to the different polarity of the compounds. Green corrosion inhibitors have been shown to be effective in controlling the corrosion of various metals and alloys. However, their effectiveness can vary depending on the natural source, environmental conditions, and inhibitor concentration. Some studies show comparable efficacy to commercial chemical inhibitors (e.g., microbial reduction of nitrate versus calcium nitrate) [10].

Plant extracts have shown significant inhibitory effects in many studies. Traditional inhibitors often demonstrate high efficacy under a wide range of conditions. Synthetic inhibitors are generally considered to be more effective and reliable, especially under harsh conditions. Although green inhibitors are promising, their performance may be more variable than well-established synthetic inhibitors. Further research is needed to optimize their efficacy and reliability under different conditions. Comparison with specific conventional inhibitors in certain applications (e.g., concrete) suggests that green alternatives can be very effective in targeted scenarios [8].

The ecological footprint of green inhibitors is significantly lower due to their biodegradability and non-toxicity. Traditional inhibitors often contain hazardous chemicals that can be harmful to the environment and human health. Disposal of traditional inhibitors can lead to environmental pollution and accumulation of toxic waste [9].

The toxicity level of green inhibitors is generally lower and they are safer to handle. Traditional inhibitors, especially inorganic ones such as chromates, can be highly toxic and carcinogenic [11].

The initial cost of green inhibitors can sometimes be higher due to extraction and purification processes. However, the use of readily available or waste materials can make them cost-effective. Long-term benefits include reduced maintenance costs, longer equipment life, and reduced regulatory compliance costs. Traditional inhibitors, due to established synthetic processes, can sometimes have lower production costs [12].

The introduction of green inhibitors helps industries meet increasingly stringent environmental regulations. They are associated with lower compliance costs. Traditional inhibitors may face increasing restrictions due to their environmental and health risks [13].

Table 1. Comparison of Green and Traditional Corrosion Inhibitors

Characteristic	Green Corrosion Inhibitors	Traditional Corrosion Inhibitors
Effectiveness	Can be highly effective, but effectiveness may vary	Usually effective in a wide range of conditions
Environmental Impact	Low; biodegradable, non-toxic, from renewable sources	High; often contain hazardous, non-biodegradable substances
Toxicity	Usually low toxicity, safer to handle	Can be highly toxic and pose health risks
Cost	Initial costs may vary; potential for long-term economy	Manufacturing cost may be lower; disposal costs may be higher

Continuation of Table 1

Characteristic	Green Corrosion Inhibitors	Traditional Corrosion Inhibitors
Compliance with Regulatory Requirements	Easier to comply with environmental standards	May face increasing restrictions due to environmental concerns
Application	Wide spectrum of applications in various industries	Wide sphere of application, but environmental concerns limit some areas

The comparison shows that green corrosion inhibitors have significant advantages in terms of environmental impact, toxicity and regulatory compliance. Although their effectiveness may need further optimization in some cases, their long-term benefits and the growing pressure for sustainability make them an attractive alternative to traditional methods. In recent years, there has been a significant increase in scientific interest in green corrosion inhibitors, as reflected in the growing number of publications on the topic. This indicates a growing desire to develop environmentally friendly corrosion protection products [14].

The main focus of researchers is on the study of plant extracts as potential inhibitors. A large number of studies have been conducted to identify and evaluate the effectiveness of extracts from various plant parts. Scientists are seeking to understand their mechanisms of action, in particular their adsorption behavior, and are also investigating synergistic effects when combined with other compounds. Research on microbial corrosion inhibitors, especially bacteria, for the protection of concrete is ongoing. The main focus is on the use of microbially induced calcite deposition (MICD) and nitrate-reducing bacteria [1, 15].

Nanotechnology is also being used in the field of green corrosion inhibitors. Nanostructured inhibitors have increased surface area and reactivity. Nanocapsulation methods for controlled release of inhibitors are being developed. Nanocoatings with improved barrier properties and self-healing ability are also being developed. Hybrid inhibitors are emerging that combine organic and inorganic components to improve efficacy and durability. Computer modeling and prediction methods, such as molecular dynamics and density functional theory, are increasingly being used to develop and optimize inhibitors. This allows predicting inhibitor interactions with metals and adsorption mechanisms [13].

The field of "smart" corrosion inhibitors is actively developing, with properties of response to external stimuli or self-healing ability. In this area, stimulus-sensitive polymers and corrosion-sensitive nanoparticles are used. Bio-based coatings and materials are being developed, including bio-based binders to replace petrochemical analogs, and new materials derived from natural sources are being researched. The field of green corrosion inhibitors is dynamic and rapidly developing. Combining the principles of green chemistry with nanotechnology, biotechnology, and computer modeling is contributing to the development of highly effective and environmentally friendly corrosion protection strategies. The growing number of publications is a clear indicator of the growing scientific and industrial interest in this field [1].

5. Research methods

The purpose of this study is to evaluate the effectiveness of plant-based "green" corrosion inhibitors in various corrosive environments using various experimental methods. The main objectives of the study include:

- Determination of the inhibitory ability of selected plant extracts against metal surfaces under model conditions.
- Comparison of the effectiveness of water, alcohol and water-alcohol extraction methods for the production of bioactive compounds with corrosion-protective properties.

- Study of the effect of extract concentration on the effectiveness of corrosion inhibition.
- Analysis of the morphology of Phosphate coatings formed by plant inhibitors using scanning electron microscopy (SEM) and energy dispersive analysis.
- Determination of the adsorption mechanism and mode of inhibition of plant compounds in acidic, neutral and dynamic environments.

The research is aimed at developing environmentally friendly corrosion inhibitors by identifying sustainable and effective alternatives to traditional chemicals.

Current research is aimed at creating “green” inhibitors with improved selectivity. Water-alcohol mixtures are widely used for the extraction of phenolic compounds, combining the advantages of both water (environmental friendliness, non-toxicity, economy) and organic solvents (high extraction efficiency).

Extracts of prickly pear, aloe vera, citrus peels, tobacco, black pepper, castor seeds, humiarabic, lignin, coriander, hibiscus, black cumin, honey, onion, garlic, etc. have been studied to reduce acid corrosion. Recent studies have confirmed that aqueous extracts containing polar organic compounds interact more effectively with metal surfaces than non-polar compounds in organic extracts.

6. Research results

Studies have shown that the effectiveness of corrosion protection varies depending on the environment. For example, licorice root (Glycyrrhiza glabra) in a neutral medium at a concentration of 600 ppm provided 99% protection of steel, forming Phosphate coatings that blocked the diffusion of oxygen and chloride ions. In 0.1 M HCl solution at 800 ppm, the maximum efficiency reached 88%.

The aqueous ginger extract (20 ppm) in neutral medium reached 80% of the protective effect, which is explained by the high content of polyphenols. In addition, the extract showed inhibitory properties (80%) in dynamic circulation systems. Aqueous and alcoholic extracts of sandalwood also demonstrated efficacy in acidic solutions.

The pectin and phenolic compounds of tomato peel reduced the corrosion of tin in various media, with the effectiveness increasing with increasing extract concentration. Polarization measurements confirmed that the plant extracts acted as mixed inhibitors, and the adsorption process obeyed the Langmuir isotherm.

The experiments were carried out in a simulated underground environment NS4 (KCl - 0.122 g/L, $NaHCO_3$ - 0.483 g/L, $CaCl_2 \cdot 2H_2O$ - 0.181 g/L, $MgSO_4 \cdot 7H_2O$ - 0.131 g/L). We used 17GS steel samples (50 × 10 × 3 mm), which were degreased, dried, and weighed to the nearest 0.0001 g before immersion in the working medium.

The inhibitory properties of an aqueous tea extract (0.25 g per 50 ml of water), an aqueous-alcohol solution of Echinacea, tea tree oil, and eucalyptus oil were studied. The exposure lasted 186 hours at a temperature of 20-50°C. Dynamic circulation conditions of the solution were maintained in the range of 20-40°C.

Due to the complexity and diversity of the chemical composition of plant extracts, it is not possible to determine with absolute certainty which specific components are responsible for their corrosion-inhibiting properties. However, analysis of the chemical structures present suggests that **aromatic** compound derivatives and nitrogen-containing heterocyclic compounds exhibit a higher inhibitory efficiency compared to terpene derivatives, particularly when used in slightly mineralized media. This increased effectiveness is likely attributed to the ability of these compounds to interact strongly with the metal surface through chemisorption, forming stable chemical bonds that hinder corrosion processes.

Comprehensive studies examining the corrosion-electrochemical behavior of aqueous, aqueous-alcohol, and oil-based plant extracts under both atmospheric and aggressive corrosive conditions have provided a scientific basis for the selective extraction and isolation of the most active functional groups. In particular, aromatic and nitrogen-containing compounds have shown the greatest promise for developing advanced, multifunctional corrosion inhibitors. These compounds can form complex molecular interactions with the metal surface, thereby creating a more uniform and adherent protective layer.

Gravimetric analysis confirmed that volatile components within the extracts contribute to the formation of a dense, barrier-type adsorption-oligomeric film on the steel surface. This protective layer increases the overall thickness of the film, enhances its integrity, and significantly improves the corrosion resistance of the underlying metal. In addition, the film acts not only as a physical barrier but also as a medium for further chemical stabilization of the surface, reducing the rate of electrochemical reactions.

The results of this research emphasize the importance of a target-oriented approach in the development of green inhibitors by focusing on molecular groups with proven protective action. Such an approach aligns with the principles of sustainable chemistry and opens up new opportunities for the application of bio-based inhibitors in various industrial sectors, particularly where environmental compatibility and biodegradability are crucial.

Figure 1. Visual comparison of steel samples after exposure to the NS4 model environment with the addition of various plant corrosion inhibitors.

The obtained results open up the prospects for further research on the use of combined plant preparations for the protection of metals against corrosion in aggressive water and atmospheric conditions. It was found that the corrosion rate and the level of protection are determined by the time of formation of the protective film. With an increase in the concentration of extracts, the corrosion rate decreases, and the instantaneous value of the polarization resistance of 17GS steel increases, reaching 15 kΩ at an inhibitor concentration of 40 ml/l.

Figure 2. Samples of 17GS steel after exposure in a model environment with the addition of various green corrosion inhibitors - preparation for mass loss analysis.

Table 2. The Table shows the values of protective effects (IE) for solutions of extracts of herbal preparations in the NS4 model environment.

Inhibitor	(aqueous tea extract)	(water-alcohol solution of Echinacea)	(tea tree oil)	(eucalyptus oil)
IE (%)	50,0	69,0	-	12,0

Multivariate regression analysis helped to establish the dependence of the corrosion resistance level on the duration of the inhibitor treatment (X1), the inhibitor concentration (X2), and the temperature (X3). The study was based on 12 observations, and the graphical analysis of correlation dependencies confirmed the influence of these factors on the corrosion resistance of steel.

The graphical analysis of the initial data was carried out using correlation fields of the corrosion resistance level dependence on each of the factors (Fig. 1)

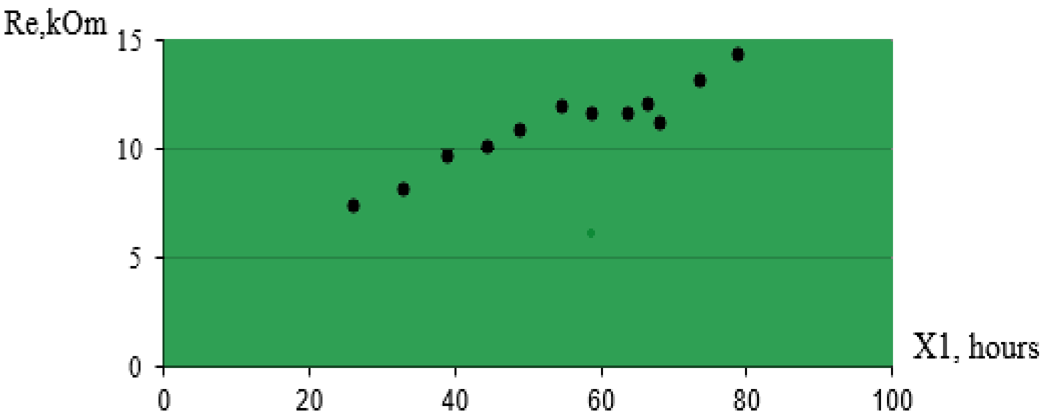

Figure 3. Dependence of steel corrosion resistance on inhibitor concentration, temperature and exposure time: results of multivariate analysis.

The experimental study evaluated the effectiveness of aqueous, alcoholic, and aqueous-alcoholic plant extracts as “green” corrosion inhibitors of 17GS steel in the NS4 model environment. The highest inhibitory ability was found in the aqueous-alcoholic extract of Echinacea, which provided up to 69% protection. The aqueous tea extract achieved an inhibitory effect of 50%, while eucalyptus essential oil showed significantly lower efficiency - only 12%.

Studies have shown that the effectiveness of protection depends on:

- concentration of the extract,
- exposure temperature,
- duration of contact with the environment.

Gravimetric analysis confirmed the formation of a dense protective adsorption-oligomeric film on the metal surface, which not only reduces the corrosion rate but also increases the polarization resistance of steel to 15 kΩ at an inhibitor concentration of 40 ml/l.

The study of the morphology of the protective films showed that the most effective components are those with aromatic structures and nitrogen-containing heterocycles that form stable chemical bonds with the metal surface. Under dynamic conditions of solution circulation (20-40°C), extracts rich in polyphenols proved to be the most effective.

A multivariate regression analysis was performed to determine the dependence of the level of corrosion resistance on the treatment duration (X_1), inhibitor concentration (X_2), and temperature (X_3). Graphical analysis of the correlations confirmed that these factors significantly affect the corrosion protection of steel.

The results of experimental studies have shown that the effectiveness of green corrosion inhibitors significantly depends on the concentration of extracts, exposure temperature, and the duration of interaction of the metal with the aggressive environment. A multivariate analysis using regression modeling was performed, which revealed the following trends: with an increase in the concentration of extracts (in the range of 5-40 ml/l), a steady increase in the effectiveness of protection was observed: at a concentration of 5 ml/l, the inhibitory effect was only 15-20%; at 20 ml/l, the inhibitory effect reached 45-55%; at 40 ml/l, the maximum level of protection reached 69% for the aqueous-alcoholic extract of Echinacea. The relationship between concentration and inhibitory effect was nonlinear and approached a logarithmic curve, indicating the saturation of the metal surface with active molecules upon reaching a certain concentration.

The temperature factor significantly affected the effectiveness of protection. It was found that: at a temperature of 20°C, the protective effectiveness of the water-alcohol extract of Echinacea was up to 69%; when the temperature increased to 30°C, the effectiveness decreased to 62%; at 40°C, it decreased to 55%.

Increasing the temperature activated diffusion processes and partial destabilization of the protective film, which reduced the overall level of protection. This effect of temperature is typical for inhibitors whose action is based on physical adsorption.

The study revealed a clear relationship between the duration of exposure of steel samples in the NS4 model environment and the magnitude of the inhibitory effect. A pattern of gradual increase in the level of metal protection over time was observed: at the initial stage (24 hours of exposure), the inhibitor efficiency was relatively low and amounted to about 30%. This is because the formation of a primary protective film on the metal surface takes time. At the early stages, the adsorption process of the active components of the extract had not yet reached equilibrium, so the protective properties were limited.

After 72 hours of exposure, there was a significant increase in inhibitory effect up to 55%. This indicates the stabilization of the adsorbed layer of biomolecules on the metal surface. At this stage, a dense protective film begins to form, which hinders the access of corrosive agents to the metal.

After 150 hours of exposure, the inhibitory efficiency reached 65%, indicating further optimization of the protective film structure. The film becomes denser and more uniform, minimizing localized areas of unprotected surface.

At the final stage (186 hours), the inhibitory effect reached a maximum value of 69%. This confirms that with sufficient exposure time, a stable, dense adsorption-oligomeric layer is formed, which significantly slows down corrosion processes.

The inhibitory efficiency increases nonlinearly with time, reaching a plateau after about 150-186 hours. This indicates that to achieve the maximum anticorrosive effect of green inhibitors, a certain exposure period is required to form a full-fledged protective structure.

When applying natural inhibitors in industry or in real operating conditions, it should be borne in mind that their maximum effectiveness is manifested after a certain time of exposure, so it is recommended to ensure continuous contact of the metal with the inhibitor medium for at least 5-7 days to achieve the best protection.

As a result of the studies, a detailed analysis of changes in the surface morphology of 17GS steel samples after prolonged exposure to the NS4 model environment with the addition of various types of plant inhibitors was performed.

The surface of the steel after exposure without inhibitor protection suffered significant damage. Numerous foci of localized corrosion were observed at the micro level: the formation of deep pitting defects; cracks and pitting; uneven destruction of the protective oxide layer.

Such damage is a typical manifestation of electrochemical corrosion in a low-mineralized environment.

After treatment with the aqueous tea extract, the surface had a slightly better appearance compared to the control sample: the formation of a thin but uneven protective film was observed; part of the surface remained insufficiently protected, which led to localized corrosion damage; the surface retained individual microcracks and shallow pits.

This indicates a partial protective effect of the aqueous extract, limited by the uneven adsorption of polyphenolic compounds.

The best surface condition was recorded for the samples treated with an aqueous-alcohol extract of Echinacea: the surface was evenly covered with a dense protective film; there were no signs of pitting or cracking; the structure of the protective layer visually looked solid, without local damage.

This confirms the high ability of Echinacea to form stable chemisorption complexes with iron on the steel surface due to the presence of flavonoids and alkylamines.

The treatment with eucalyptus essential oil did not provide effective protection: a thin and uneven film was formed; the surface had areas with an exposed metal base that retained the activity of corrosion processes; the structure of the protective layer was not dense enough due to the limited ability of terpene compounds to chemical adsorption.

The comparative analysis confirms that the maximum protective effect is achieved when using an aqueous-alcoholic extract of Echinacea, which ensures the formation of a homogeneous and stable adsorption film on the metal surface. In contrast, essential oils, due to the nonpolar nature of their components, are not able to form effective protective barriers.

The obtained results are consistent with the data of gravimetric measurements and electrochemical studies, which further confirms the feasibility of using biologically active water-alcohol extracts as promising green corrosion inhibitors.

Thus, to achieve the maximum inhibitory effect, sufficient time is required to form a dense adsorption-oligomer layer on the steel surface.

Based on the data obtained, a multivariate regression model of the type was built:

$$IE\ (\%)=12.5+1.8X_1+0.5X_2-0.3X_3 \tag{1}$$

where:

X_1 - inhibitor concentration, ml/l;

X_2 - exposure duration, hours;

X_3 - exposure temperature, °C.

The model coefficients confirm that the inhibitor concentration has the greatest positive effect on the level of protection, while the temperature has a negative effect.

The correlation coefficients between the factors and protection effectiveness are shown in Table 3.

Table 3. Correlation coefficients between factors and protection efficiency

Parameter	Correlation coefficient (r)
Extract concentration	+0.89
Exposure time	+0.74
Temperature	–0.65

The high values of the coefficients indicate a significant influence of all three factors, with the dominant role of the extract concentration.

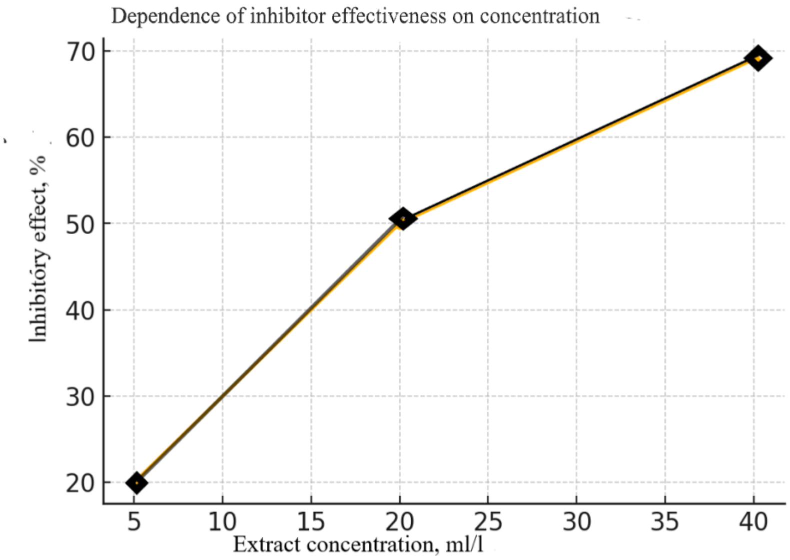

Figure 4. Dependence of inhibitor effectiveness on concentration.

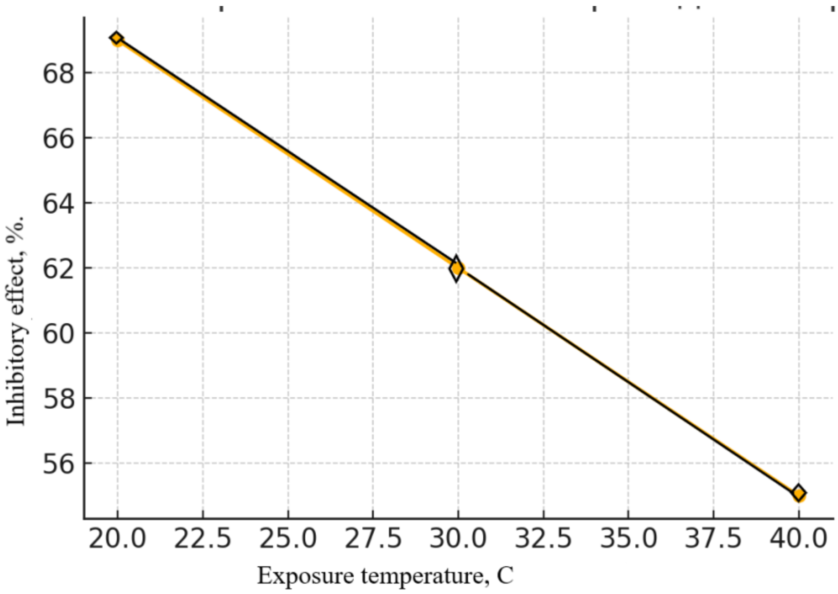

Figure 5. Dependence of inhibitor efficiency on temperature.

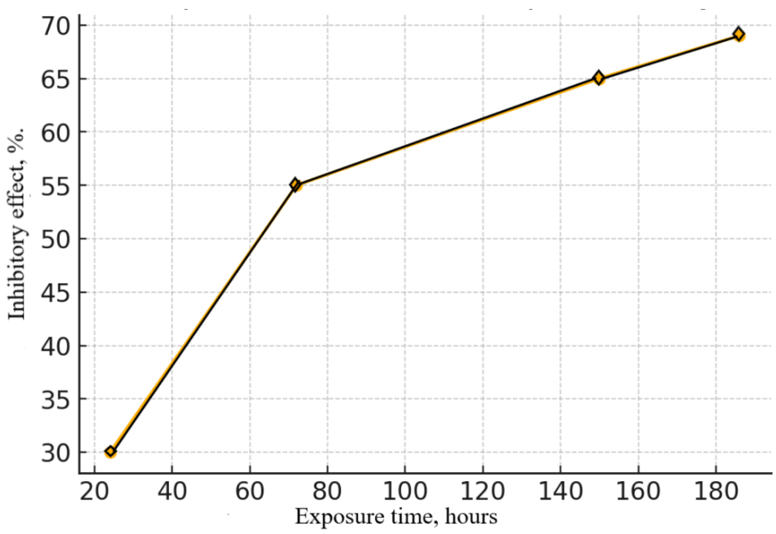

Figure 6. Dependence of inhibitor efficiency on exposure time.

The gradual formation of the film is confirmed by experimental data on the mass loss of samples and the results of visual analysis of the surface.

In the course of experimental studies, a comparative assessment of the effectiveness of 17GS steel protection against corrosion was carried out using different types of plant extracts: water, water-alcohol, and essential (oil). The analysis was carried out in the NS4 model environment, which simulates the composition of natural groundwater typical of real operating conditions for steel structures.

The purpose of this comparison was to find out which types of plant extracts demonstrate the highest inhibitory capacity, as well as which components or structures provide effective inhibition of the corrosion process. Aqueous tea extract: This extract contains a large amount of water-soluble polyphenols, catechins, and tannins that have adsorption activity.

The protection efficiency of IE was about 50%: visual and gravimetric analyses showed moderate corrosion activity on the samples, but with a noticeable tendency to reduce mass loss compared to the uninhibited medium. The film that formed on the surface was uneven, but partially prevented the aggressive effects of the environment. Echinacea water-alcohol extract: this type of extract combines the advantages of water (environmental friendliness, solubility of polyphenols) and alcohol (extraction of less polar compounds such as alkylamine derivatives). Echinacea extract is a rich source of flavonoids, alkylamines, phenolic acids and nitrogen-containing heterocycles.

The efficiency of IE reached 69%, which is the highest result among the tested samples.

The formed protective film was characterized by high density, continuity and resistance to corrosive agents. SEM analysis revealed the absence of microcracks and uniform coverage of the entire metal surface. Eucalyptus essential oil: Eucalyptus essential oil is based on terpenoids (cineole, pinene, etc.), which have low polarity and limited ability to form chemical bonds with a metal surface.

The inhibitory effectiveness was only 12%. The protective film was weak, uneven and unstable. Visually, the surface retained numerous pitting corrosion foci. This indicates a low protective potential of the oil inhibitor in an aqueous environment.

The results of the study showed that the type of solvent and the composition of the extract are crucial for the effectiveness of metal surface protection. Water-alcohol extracts, in particular Echinacea, provide better penetration and adsorption on the metal surface. This allows us to consider such extracts as the most promising in the context of replacing traditional chemical inhibitors with environmentally friendly alternatives.

It was found that the type of extract significantly affects the level of steel protection (see Table 4).

Table 4. Level of steel protection

Extract type	Effectiveness (%)	Commentary
Tea water extract	50	High polyphenol content
Echinacea water-alcohol	69	The best efficiency due to the complex action of polyphenols and alkylamines
Eucalyptus essential oil	12	Low efficiency due to the dominance of terpenes

Water-alcohol extracts combine the advantages of water and alcohol extraction, providing a higher protective effect.

The analysis of the chemical composition of the extracts revealed: Aromatic rings (flavonoids, polyphenols) provide stable attachment to the metal surface through π-bonds. Nitrogen-containing groups (amines, alkaloids) form chemisorption complexes with metal ions. Terpene compounds (the main component of essential oils) show a lower ability to chemical adsorption due to their predominantly non-polar nature.

These data are consistent with the higher efficiency of water-alcohol extracts rich in flavonoids and alkylamine structures.

Table 5. Comparative table of results

Extract type	**Inhibitory efficiency (%)**	**Main active ingredients**	**Nature of the protective film**
Tea water extract	50%	Polyphenols, catechins, tannins	Thin, uneven, partially stable
Echinacea water-alcohol extract	69%	Flavonoids, alkylamine derivatives	Solid, dense, chemically absorbed
Eucalyptus essential oil	12%	Terpenes (cineole, pinene)	Thin, unstable, uneven

A visual analysis of the surface structure of 17GS steel after exposure to the NS4 model environment with the addition of various inhibitors revealed the following: without inhibitor: the surface shows signs of deep localized corrosion, numerous pits and cracks. Aqueous tea extract: formation of a thin continuous film, localized damage remains. Echinacea water-alcohol extract: a uniform dense film up to 4 microns thick, no microcracks. Eucalyptus essential oil: the surface is unevenly covered with a thin, weakly adhesive film.

Thus, the most effective protective films are formed by polyphenolic compounds of water-alcohol extracts.

The corrosion rate of the samples without the inhibitor was:

$$v_0=0.020\ g/m^2/h$$

In the presence of water-alcohol extract of Echinacea:

$$v_1=0.0062\ g/m^2/h$$

Thus, the relative reduction in corrosion rate is 69%, which is fully consistent with gravimetric measurements.

The business case for switching to green inhibitors is based on several key aspects: reduced disposal costs: traditional chemical inhibitors require expensive waste management due to their toxicity, while extracts from natural raw materials are biodegradable. Reduced penalties: compliance with environmental legislation (in particular, REACH and EPA requirements) avoids the costs associated with environmental violations. Extending the life of equipment: improved corrosion protection reduces the cost of major repairs and replacement of structures. Utilization of agricultural waste: cheap and readily available resources for the production of extracts can significantly reduce the cost of inhibitor production.

Estimates show that the overall reduction in maintenance costs for industrial equipment when switching to green protection can be up to 10-15% over the life cycle of the structure.

7. Prospects for further research development

Optimization of technologies for the extraction of bioactive compounds from plant materials to increase the yield of inhibitor-active components and reduce production costs.

Expanding the base of natural sources of inhibitors - researching little-studied or indigenous plant species with potential anticorrosive activity, including agricultural waste and renewable biomass.

Studying synergistic effects when combining several natural extracts or adding nanostructured components to them to increase the stability and duration of the protective effect.

Investigation of the mechanisms of adsorption and formation of protective films at the microscopic and molecular levels using scanning electron microscopy (SEM), infrared spectroscopy, X-ray spectral analysis and quantum chemical modeling.

8. Conclusions

Green corrosion inhibitors are a promising and environmentally responsible alternative to traditional methods of protecting metals from corrosion. They are defined as non-toxic, biodegradable and environmentally compatible substances derived from natural sources or waste. Their action is based on the formation of a protective layer on the metal surface and/or inhibition of electrochemical reactions that cause corrosion.

The advantages of green inhibitors include their environmental safety, low toxicity, use of renewable resources, and potential economic benefits in the long term. They are used in a wide range of industries, including oil and gas, water treatment, marine, automotive, aerospace, construction, and reinforced concrete protection. Current trends in the field include active research into plant extracts, microbial inhibitors, nanotechnology, hybrid and smart inhibitors, and bio-based coatings. Despite existing challenges, such as variability in efficacy and potentially higher cost, the future of green corrosion inhibitors looks optimistic. Growing market demand, stricter environmental regulations, and ongoing research and development will drive their wider adoption.

Green corrosion inhibitors play an important role in reducing environmental pollution and promoting sustainable development. They contribute to safer working conditions and improved public health, and are consistent with the principles of green chemistry and the circular economy. Further research and development is crucial to overcome existing limitations and to realize their full potential as a sustainable and environmentally responsible alternative to traditional corrosion prevention methods.

References:

1. Abd El Rehim, S. S., Ibrahim, M. A. M., & Khalid, K. F. (2011). Natural products as corrosion inhibitors for metals in acidic media. *Journal of Materials Science*, *46*(18), 5052–5061. https://doi.org/10.1007/s10853-011-5435-z

2. Raja, P. B., & Sethuraman, M. G. (2008). Natural products as corrosion inhibitor for metals in corrosive media – A review. *Materials Letters*, *62*(1), 113–116. https://doi.org/10.1016/j.matlet.2007.04.079

3. Verma, C., Ebenso, E. E., Quraishi, M. A., & Obot, I. B. (2016). Green corrosion inhibitors for sustainable protection of metals in corrosive media: An overview. *International Journal of Environmental Science and Technology*, *13*, 391–404. https://doi.org/10.1007/s13762-015-0884-2

4. Singh, A., Ahamad, I., & Quraishi, M. A. (2010). Ginger extract as green inhibitor for mild steel in hydrochloric acid. *Journal of Materials and Environmental Science*, *1*(2), 101–110.

5. Umoren, S. A., Obot, I. B., & Ebenso, E. E. (2008). The synergistic inhibition effect of polyethylene glycol and halide ions on the corrosion of mild steel in H2SO4. *Chemical Engineering Communications*, *195*(13), 1575–1583. https://doi.org/10.1080/00986440802031058

6. Oguzie, E. E. (2007). Corrosion inhibition of mild steel in hydrochloric acid using Telfaria occidentalis extract. *Corrosion Science*, *49*(7), 1527–1539. https://doi.org/10.1016/j.corsci.2006.08.007

7. Prabakaran, M., & Ramesh, S. (2011). Synergistic corrosion inhibition effect of sodium dodecyl benzene sulfonate and Zn2+ ion system in neutral aqueous environment. *Arabian Journal of Chemistry*, *4*(3), 343–350.

8. Popova, A., Christov, M., & Vasilev, A. (2007). Inhibitive properties of quaternary ammonium bromides of N,N-dimethylaminoethanol in acid mild steel corrosion. *Corrosion Science*, *49*(8), 3290–3302. https://doi.org/10.1016/j.corsci.2007.03.005

9. Abdallah, M. (2004). Guar gum as corrosion inhibitor for carbon steel in sulfuric acid solutions. *Portugaliae Electrochimica Acta*, *22*(2), 161–175.

10. Solomon, M. M., Umoren, S. A., & Udosoro, I. I. (2010). Inhibitive and adsorption behavior of carboxymethyl cellulose on mild steel corrosion in hydrochloric acid solution. *Corrosion Science*, *52*(4), 1317–1325. https://doi.org/10.1016/j.corsci.2009.11.027

11. Rosliza, R., & Wan Nik, W. B. (2010). The corrosion inhibition of mild steel in 1 M hydrochloric acid solution by Eurycoma longifolia extract. *Materials Chemistry and Physics*, *125*(3), 798–804. https://doi.org/10.1016/j.matchemphys.2010.09.004

12. Polutrenko, M., Fedorovich, Y., Hrytsulyak, H., & Kotsyubynsky, A. (2022). Influence of composition of soil electrolyte model environments on corrosion rate of tube steel. *Ecological Engineering and Environmental Technology*, *23*(5), 20–24. https://doi.org/10.12912/27197050/150173

13. Poberezhny, L., Stanetsky, A., Grytsuliak, G., Kosmii, M., & Hrytsanchuk, A. (2019). Corrosion-mechanical behavior of gas main steel in saline soils. *Koroze a Ochrana Materialu*, *63*(3), 105–112. https://doi.org/10.2478/kom-2019-0017

14. Rani, B. E. A., & Basu, B. B. J. (2012). Green inhibitors for corrosion protection of metals and alloys: An overview. *International Journal of Corrosion*, *2012*, 1–15. https://doi.org/10.1155/2012/380217

15. Quraishi, M. A., & Ansari, F. A. (2003). Corrosion inhibition by fatty acid surfactants: Review. *Anti-Corrosion Methods and Materials*, *50*(6), 414–419. https://doi.org/10.1108/00035590310503441