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Investigation article

Use of Organic Extracts as Effective Inhibitors of Carbonation Corrosion in Maritime Structures on the Coast of Peru

Uso de Extractos Orgánicos como Inhibidores Eficaces de la Corrosión por Carbonatación en Estructuras Marítimas en la Costa de Perú

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Abstract
Introduction: Based on the problems presented regarding corrosion, the objective of this systematic review research was to evaluate the information collected on the use of organic extracts as inhibitors of carbonation corrosion in marine structures on the coast of Peru. **Methodology:** A descriptive study was carried out, with a qualitative approach based on a review of literature articles and the analysis of different research with a total of 80 scientific articles, including Scopus, WOS and Scielo, among the most important databases. **Results:** The most relevant findings indicate that organic extracts are effective as carbonation corrosion inhibitors in marine structures; however, there are still theoretical gaps regarding the optimal percentages for their application.

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Keywords: Carbonation; Inhibitors; corrosion; organic; extracts; concrete, durability; Peru; maritime structures.

Resumen
Introducción: En función de la problemática presentada respecto a la corrosión, el objetivo de esta investigación de revisión sistemática fue evaluar la información recopilada sobre el uso de extractos orgánicos como inhibidores de la corrosión por carbonatación en estructuras marítimas en la costa del Perú. **Metodología:** Se efectuó tipo descriptivo, con un enfoque cualitativo basado en una revisión sistemática y el análisis de las diferentes investigaciones con un total de 80 artículos científicos, entre las bases de datos destacadas se encuentran Scopus, WOS y Scielo. **Resultados:** Los hallazgos más relevantes indican que los extractos orgánicos son efectivos como inhibidores de la corrosión por carbonatación en estructuras marítimas; sin embargo, aún existen vacíos teóricos respecto a los porcentajes óptimos para su aplicación.

Palabras clave: Carbonatación; Inhibidores; corrosión; extractos orgánicos; concreto, durabilidad; Perú; estructuras marítimas.

1. Introduction

Concrete is a key material in engineering, especially in developing countries, which is composed of cement, sand, aggregates, water and admixtures (Gudainiyan & Kishore, 2022). However, when exposed to marine environments, it presents aggressive conditions for the properties of concrete, due to factors such as chlorides, sulfates and biofouling (Gaylarde & Ortega, 2023).

On the other hand, the use of agricultural residues in concrete is sustainable and economical, reducing environmental damage due to their calcination or disposal, since they represent more than 50% of the global biomass (He et al., 2020). Likewise, waste reduction and sustainability in construction are key, because the industry uses concrete for its strength, which makes it urgent to look for ecological alternatives (Hakeem et al., 2023). In this context, this article examines how seawater, carbonation and inhibitors reduce pH and affect the durability of the material.

Globally, the effectiveness of concrete lies in protecting the reinforcement, which depends on the coating, quality and carbonation of the site, where the pH is reduced and favors steel corrosion (Carneiro & Roberto, 2025). Likewise, this phenomenon affects the durability of concrete, because CO_2 reacts with calcium hydroxide, weakening the protection of steel and increasing corrosion such as low temperature, humidity and permeability (Pinto et al., 2022).

However, another relevant factor is the corrosion of steel by chlorides, which can cause structural collapse, where the common method of repair is to replace the affected elements (Garcés et al., 2021). In addition, it is important to highlight this factor that depends on the environment, where the concrete paste protects the steel reinforcement, but deteriorates over time, requiring additional materials for greater durability (Flores et al., 2021).

Given this, the quality of reinforced concrete depends on factors such as chloride corrosion, carbonation, water-cement ratio, cracks, humidity, temperature, cover thickness as in marine areas (Farahani et al., 2019). In this context, to prevent corrosion in reinforced concrete, strategies such as resistant steel, cathodic protection, increased thickness, natural inhibitors and coatings are used, avoiding the use of toxic inhibitors such as nitrites and nitrates (Wang et al., 2022).

In Peru, marine constructions require concrete with high durability and low permeability, due to exposure to corrosive agents, where materials such as fibers and plant extracts are incorporated, ideal for maritime infrastructures (Quispe et al., 2021). Likewise, corrosivity affects concrete structures, especially by water quality, where LSI and RSI indexes predict scale formation, but not the amount of CaCO3 or factors such as temperature, pH cause damage (Sorlini et al., 2019).

Also, chemical attack by salts and chloride corrosion deteriorates concrete exposed to water, weakening structures and raising maintenance costs, where to reduce these effects, it is recommended to apply chemical treatments to concrete (Rocha & Ocrospoma, 2024). On the other hand, air pollution is accelerating the deterioration of concrete, causing pathologies such as carbonation and chemical attack by acids, mainly through acid rain, other contaminants such as sulfates and inorganic materials (Rucana et al., 2023). Finally, corrosion is an electrochemical process that deteriorates reinforced concrete, affecting its strength and functionality, generating high maintenance and repair costs, which has led to the development of materials and methods to control it (Jauregui et al., 2023).

On the other hand, 36% of the land surface, representing about 5 billion hectares, is used for agriculture, which generates approximately 998 million tons of waste annually and causes considerable environmental damage (Khalife et al., 2024). In this context, it is alarming that, in the last 50 years, greenhouse gas emissions in Latin America have increased by more than 130%, with agriculture being responsible for between 10% and 17% of these emissions (Albíter et al., 2021).

Although agroindustrial residues are of natural origin, they generate problems such as CO2 emissions and pests (Romero, 2022). Despite these challenges, the agroindustrial sector plays a crucial role in the fight against climate change, because it produces emissions, but also has the capacity to sequester carbon (Li & Zhang, 2024). In addition, these wastes can be used in construction, since they offer a performance equal to or higher than that of traditional materials (Soares et al., 2025).

Based on the problems presented, it was proposed as a research objective to evaluate the information gathered on the use of organic extracts as effective inhibitors of carbonation corrosion in maritime structures on the coast of Peru.

1.1. Corrosion mechanism

Metallic corrosion occurs when metals come into contact with corrosive agents, initiating an electrochemical reaction (Assad & Kumar, 2021), which occurs when a metal loses electrons and forms oxidized ions at the anodic sites, while at the cathodic sites electrons are consumed and reduced products are formed, depending on the acidity or basicity of the system (Zomorodian & Behnood, 2023). Corrosion also occurs when two dissimilar metals come into contact with an electrolyte, accelerating the wear of the more active metal, where it can be localized as cracks, gradually weakening the materials and compromising their strength (Fuhaid & Niaz, 2022).

On the other hand, moisture, salts and aggressive gases accelerate corrosion, affecting key structures, where to prevent this damage, resistant materials and protective coatings are used to protect exposed surfaces, ensuring their long-term durability and functionality (Mirsayapov et al., 2020).

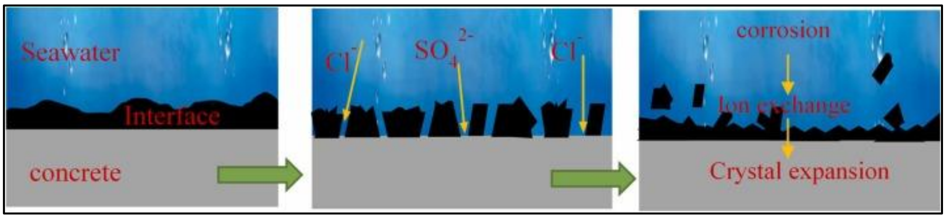
$$Y_0 \rightarrow Y_0\, e^2 + 2e \text{ .... (1)}$$

1.2. Corrosion in marine areas

Marine corrosion is a complex process affected by physical, chemical and biological factors, which occurs in different zones: atmospheric, tidal, immersion, mud and splashing being the most intense zone (Liu et al., 2025). It is also noted that in coastal areas, where reinforced concrete is vulnerable to corrosion due to humidity and dryness, techniques such as electrochemical rehabilitation, concrete modifications and bioremediation are used to prevent chloride erosion (Pan et al., 2020). In view of this, seawater, with 3.5% salinity, contains compounds such as NaCl, MgCl2 and CaSO4, where Cl-, Mg2+ and SO42- ions are responsible for the corrosion of concrete by interacting, intensifying or reducing its effects (Zhu & Liu, 2023). Likewise, the corrosion rate and products vary according to the marine zone, where in total immersion, α-FeOOH, γ-FeOOH and Fe3O4 predominate; in wet-dry cycles, γ-FeOOH, Fe3O4 and β-FeOOH, with no pitting after 60 cycles (Tian et al., 2022).

Figure 1.

Corrosion process in structures near marine environments



Source: Tian et al., (2022).

Corrosion starts with the adhesion of contaminating organisms, where carbonation and acid ions reduce the pH of concrete from 13 to 8 in 6 months, favoring the growth of alkalophilic microbes at pH close to 9 (Chen et al., 2024). On the other hand, microbial corrosion in eutrophic marine environments mainly affects metallic materials near low tide, causing losses between 33% and 66% in ports and harbors, due to environmental and microbial factors (Guo et al., 2024).

In this context, microbial corrosion (MIC) occurs when bacteria such as sulfate reducing bacteria (SRB) accelerate the deterioration of material especially in structures exposed to the sea, reducing their useful life and generating significant economic losses (Dalmora et al., 2025). In response to this phenomenon, anti-corrosion strategies include corrosion resistant materials, treatments, coatings, cathodic protection, inhibitors and monitoring, where research on aluminum alloys such as 7075 is key to mitigate these effects (Sheng et al., 2022).

1.3. Corrosion of Reinforcing Steel in Concrete

Corrosion of steel in concrete has led to the development of protection techniques, especially in the renewal of the protective layer, where in alkaline environments, a passive layer is formed that degrades upon contact with chloride ions (Teymouri et al., 2021). This process of rebar corrosion in concrete occurs when chloride reaches a critical threshold on the steel surface, which represents a constant challenge for experts and researchers (Wang et al., 2024).

In addition, the impact of environmental conditions and metallic materials on microorganism-induced corrosion (MIC) varies. For example, BioMnOx, formed by manganese-reducing bacteria, affects carbon steel and stainless steel differently (Dong et al., 2024).

It is also important to note that the corrosion of steel in concrete is a complex electrochemical process and the most common methods for measuring its rate are electrochemical (Shevtsov et al., 2022). In terms of materials, weather-resistant steels, reinforced with anticorrosion elements, are perfect for marine environments with high chloride concentration, because they maintain their mechanical properties and prevent corrosion without additional coatings (Niu et al., 2024).

Figure 2.

Corrosion process in structures close to marine environments

Source: Own elaboration (2025).

1.4. Environmentally friendly corrosion inhibitors

Reinforcing bars in reinforced concrete are corroded by chloride ions, where methods such as epoxy coating, cathodic protection, sensors, increased coverage and injection of inhibitors are used to prevent it (Yong et al., 2021). Likewise, organic corrosion inhibitors were used in the oil industry since the 1950s and in concrete since the 1990s, where their toxicity led to the use of natural plant extracts (Marzorati et al., 2019). Organic inhibitors such as amines and carboxylates were also developed, where organic inhibitors are an efficient, economical and low toxicity alternative, where benzoate and derivatives are used on steel rods in concrete (Shehnazdeep & Pradhan, 2022).

On the other hand, plant-derived corrosion inhibitors are natural, non-toxic and biodegradable compounds that contain oxygen, nitrogen and aromatic rings, and protect metals by forming a protective film against corrosion (Dai & An, 2023). Likewise, plant extracts are inexpensive and non-toxic, where they protect against corrosion by adhering to metals, which contain tannins, terpenes and polyphenols, present in plant biowaste, which promotes their ecological use (Mwakalesi & Nyangi, 2020). In addition, these are extracted from various plant species, investigating leaves, barks, seeds and roots, where compounds with nitrogen, sulfur and oxygen are effective, because they bind to metal ions and prevent corrosion (Al Otaibi & Hammud, 2021).

1.5. Mechanism of action of organic inhibitors

Organic inhibitors, such as alcohol amine and imidazole, adsorb on the surface of the reinforcement, forming a protective layer that blocks the diffusion of aggressive substances and prevents corrosion (Xu et al., 2023). In addition, organic inhibitors adsorb on the surface of the metal, forming a layer that slows down anodic or cathodic processes, where they are common in reinforced concrete, including amines, alkanolamines, carboxylic acids, salts, ester mixtures, alcohols and amines (Tian et al., 2023).

Likewise, plant extractions, such as amino acids and alkaloids, are investigated as biodegradable and inexpensive corrosion inhibitors, acting by adsorption according to the chemical structure and charge of the metal, while anodization improves corrosion in aluminum and alloys (Hossain et al., 2023). Also corrosion inhibition forms a protective film on the metal by adsorption, which can be either physisorption (ionic interactions) or chemisorption (electron exchange), mixed adsorption occurs at anodic and cathodic sites of the metal (Holla et al., 2024).

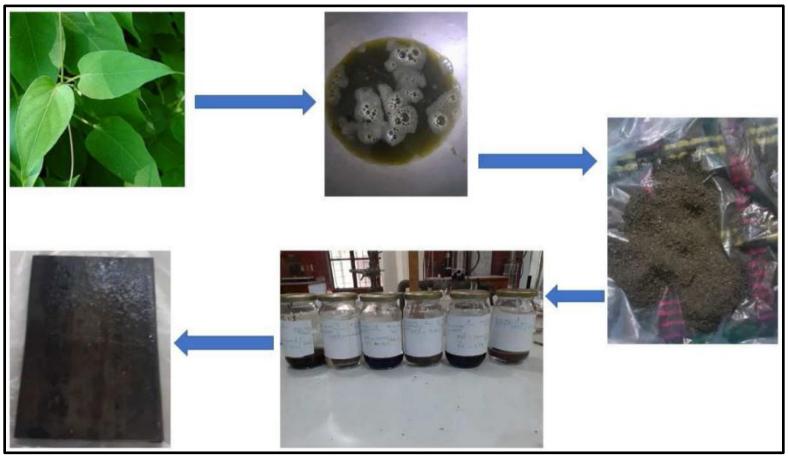
1.6. Corrosion Inhibitors: Sustainable Natural Alternatives

The study of natural products as corrosion inhibitors has increased due to their low cost and ecological properties, highlighting plant extracts such as molasses and Aloe vera, which replace synthetic inhibitors in acidic media (Hossain et al., 2021). Likewise, these ecological inhibitors are biodegradable and act by slowing down reactions in metal, where some compounds such as resveratrol, carob gum and tea are effective, but their limited stability hinders their use (Liao et al., 2023).

In addition, other materials used are organic corrosion inhibitors (OCI) such as alkanolamine, fatty acid esters and amines protect reinforced concrete by adsorbing on the surface of the reinforcement and delaying corrosion reactions (Hu et al., 2021). On the other hand, they are also used in pipes, tanks and ports where they act as chelating agents, forming rings with groups such as -NH2, -OH, -SH, -COOH and -SO3H, which bind to metals and protect steel from corrosion (Tian et al., 2023). Migrating inhibitors (MCI) also exist but these can evaporate, which affects their performance and determining the appropriate amounts is difficult due to the variability of concrete (Kobbekaduwa et al., 2024).

Figure 3.

Natural plant alternatives as corrosion inhibitors



Source: Hossain et al., (2021).

2. Methodology

The research was carried out under a descriptive methodology, with a qualitative approach based on a review of literature articles and the analysis of different researches, based on high impact scientific articles which share similar characteristics in the use of organic extracts as effective inhibitors of carbonation corrosion in maritime structures.

On the other hand, the selected sources and journals were from high impact databases such as Scopus, Scielo and WOS, which present valuable information to corroborate the analysis, as well as a total of 80 indexed scientific articles.

The search strategy applied was systematic, which began with the selection of the most relevant databases such as Scopus, Scielo and WOS, where, in order to obtain a broader view, combinations of keywords such as "organic extracts", "corrosion inhibitors", "maritime structure", "carbonation" and "concrete" were used. Subsequently, we filtered by years of publication (7 years), language (English, Spanish and others), type of article (scientific article).

The inclusion criteria applied for the selection of the scientific articles were 4:

1) The scientific articles must share a relationship with the study variables,

2) The bases from which they come must be of high impact and indexed,

3) The research must be within 7 years old,

4) The languages most considered are English, Spanish and others.

Likewise, the review resulted in a total of 150 scientific articles of which the filters mentioned above were applied and reduced to 80 researches.

Table 1.

Summary of the databases according to study collection

Database	Year of publication period							
	2019	2020	2021	2022	2023	2024	2025	Subtotal
Scopus	6	6	9	15	13	12	4	65
Web of Science			1	3	4	1	1	10
Scielo	1		3					4
Latindex						1		1
			TOTAL					80

Source: Own elaboration (2025).

3. Results and Discussion

3.1. Polarization curves

The study analyzes how the concentration of Eucommia cortex inhibitor affects the electrochemical impedance of Q235 steel in a solution of the simulated concrete with NaCl, showing a unique charge transfer mechanism in Nyquist plots (Liu, 2022). Tafel polarization curves were also used on mild steel in 0.5 M H2SO4 solutions with lychee peel extract, showing that it reduces the corrosion current (i_corr), acting as an inhibitor without affecting the corrosion potential (E_corr) (Ramananda Singh et al., 2019).

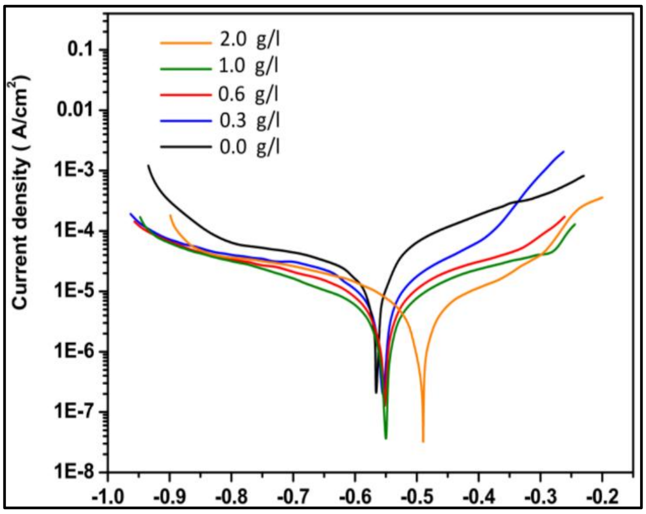
Likewise, upon addition of the three compounds, E_corr remained constant, acting as mixed inhibitors, while i_corr decreased with the organic compounds, reaching its minimum at 200 ppm by adsorption and formation of protective products (Rodriguez et al., 2024). In another experiment, mild steel samples were polarized in acid with inhibitor (200-1000 ppm) in which they showed the decrease in current density suggests that the inhibitor covers the surface, reducing the active sites for corrosion (Karki et al., 2022).

In another study, the cathodic curves did not change with acetate (AcO), but the anodic curves shifted to more negative values with its concentration, indicating that AcO acts as an inhibitor, mainly cathodic and improves protection at 0.5 M H2SO4 (Altunbaş, 2022). Likewise, polarization curves of steel with and without 0.75 g/L Rhus coriaria and quercetin show that both inhibitors reduce corrosion, decreasing anodic and cathodic currents, where the plant extract inhibits 84% of corrosion in 0.5 M H2SO4 (Hijazi et al., 2021).

As for berberine reduces corrosion, being an effective inhibitor in the cathodic branch, it is also mixed, with potential change less than 85 mV, and reaches 98.19% efficiency at 1000 ppm in H_2SO_4 1.0 M (N. Karki et al., 2021). Finally, polarizing mild steel (MS) samples in acidic media with green inhibitors at ±350 mV and 18 °C showed that the inhibitor covers the MS surface and reduces the active sites for corrosion (Oli et al., 2022). Based on the studies reviewed, they confirm the effectiveness of organic extracts against corrosion, but the lack of standardization, environmental variability, and limited evidence of durability still limit their practical application in maritime structures.

Figure 4.

Natural plant alternatives as corrosion inhibitors



Source: Hossain et al., (2021).

3.2. Electrochemical parameters

The analysis shows that the organic extracts presented inhibition efficiencies (IE_j %) in the following order: methanol (91.9%), hexane (81.7%), dichloromethane (73.2%) and ethyl acetate (85.2%) (Ben et al., 2020). In addition, a decrease in corrosion current density (j_corr) was observed at 0.23 µA cm-2. The changes in corrosion potential (E_corr) were less than 85 mV, indicating that the extracts act as mixed inhibitors (Deyab & Mohsen, 2023).

On the other hand, an organic inhibitor proved to be effective on the corrosion of C38 steel, reaching an IE% of 90.9% at 60°C and 2 g/L (Al-Sharabi et al., 2022). Although the extract reduced i_corr more than 55-fold, proving to be an effective mixed inhibitor with a change in potential less than 85 mV, the IE increased reaching 98.19% at 1000 ppm in 1.0 M H_2SO_4 (Karki et al., 2021). Similarly, in a study with leaf extract, E_corr was observed to shift towards more negative values, and at a concentration of 1000 ppm, protection reached 91.8%, although it decreased at higher concentrations (Kaya et al., 2023).

In this context, organic extracts demonstrate high efficacy as corrosion inhibitors, even exceeding 98%. However, variability across conditions and the lack of studies in real-world environments still limit their practical application.

Table 2.

Comparison of natural inhibitor concentrations in corrosion

Corrosion inhibitor	Concentration (η)	Time (η)
Chamaerops humilis L.	0,75 g/L (60%)	–
Eucommia bark	2,0 g/l (85,48 %)	–
Liquorice plant	1% v/v% (74,06%)	24 hours (80,88%)
Pinus resinosa	1000 mg/L (37,17%)	720 hours (54,75%)
Henna leaves	0,2 g/L (93%)	–
gluten flour	2,0 g/L (88,10%)	–
damask rose	12 % by weight (80,2 %)	–
Platanus acerifolia	3% UEE (99,56%)	72 hours (96,66%)
Fatsia japonica	1000 mg/L (89,6%)	168 hours (91,2%)

Source: Wang et al., (2022).

Regarding the polarization parameters of Q235 steel in 0.5 M H_2SO_4 with organic inhibitor at 298 K, changes were observed in E_corr, i_corr and the anodic, cathodic slopes (β_a, β_c), also in η, with inhibition efficiencies of 86.2% (Wang et al., 2022). In another experiment, when measuring the polarization of J55 steel in CO_2 chloride-carbonate at 35 °C with inhibitor at 300 mg/L, the E_corr shifted towards more positive values, achieving an inhibition efficiency of 95.78% (Pustaj, 2019).

Moreover, in another study, at a concentration of 0.05 mM, compounds such as dithiodianiline, diphenyl and methylphenyl exhibited Cu corrosion inhibition efficiencies in sulfuric acid increased to 93.4%, 96.9% and 98.9%, respectively (Zhao et al., 2025). In this context, variability reflects the lack of standardized protocols and limits direct comparison between studies. Furthermore, most trials have been conducted under controlled laboratory conditions, leaving open the question of their durability and effectiveness in real marine environments.

$$EI_j(\%) = \left(1 - \frac{j_{corr}}{j^0_{corr}}\right) X100 \ldots\ldots\ldots\ldots\ldots (2)$$

Table 3.

Comparison of electrochemical parameters of organic inhibitors from 50 - 500 ppm

Dose (ppm)	Solvent/Extract	Dilution	E_corr (mV/SCE)	I_corr (μA/cm²)	IE (%)	Author
50	Olea europaea (Methanol)	NaOH (0,1 M) + NaCl (0,5 M)	-0.52	2.3	91.9	(Ben Harb et al., 2020).
	Olea europaea (Hexane)		-0.55	5.2	81.7	
	Olea europaea (Dichloromethane)		-0.53	7.6	73.2	
	Olea europaea (Ethyl acetate)		-0.52	4.2	85.2	
	Fatsia japonica leaves (FJLE)	0,05 mol/L KH_2PO_4	−395	0.9	78.6	(Wang et al., 2022).
100	Sweet yellow pepper (SYCE)	30,0 kJ mol –1	332	2.52	70,5	(Deyab & Mohsen, 2023).
	Rheum ribes leaf	HCl 1,0 M	-0,519	-	69.6	(Kaya et al., 2023).
	Fatsia japonica leaves (FJLE)	0,05 mol/L KH_2PO_4	−395	0.9	78.6	(Wang et al., 2022).
	Olive leaf	30 g L-1 de NaCl,	-689	22.86	78.77	(Pustaj, 2019).
120	Methylphenyl	0,5 mol/LH 2 SO 4	27	0.11	98.9	(Zhao et al., 2025).
150	Sweet yellow pepper (SYCE)	30,0 kJ mol –1	313	0,83	90.3	(Deyab & Mohsen, 2023).
	Diphenyl	0,5 mol/LH 2 SO 4	−14	0.34	96.9	(Zhao et al., 2025).
	Olive leaf	30 g L-1 de NaCl,	-687	20.27	81.18	(Pustaj, 2019).
200	Sweet yellow pepper (SYCE)	30,0 kJ mol –1	305	0,44	94.8	(Deyab & Mohsen, 2023).
	Berberine	1,0 M H_2SO_4	0.434	1.46×10^{-4}	92.46	(Karki et al., 2021).
	Fatsia japonica leaves (FJLE)	0,05 mol/L KH_2PO_4	−371	0.7	83.3	(Wang et al., 2022).
	Olive leaf	30 g L-1 de NaCl,	-669	10.45	90.30	(Pustaj, 2019).
250	Olive leaf	30 g L-1 de NaCl,	-659	6.49	93.97	(Pustaj, 2019).
	Dithiodianiline	0,5 mol/LH 2 SO 4	−36	0.64	93.4	(Zhao et al., 2025).
	Rheum ribes leaf	HCl 1,0 M	-0,518	-	81.8	(Kaya et al., 2023).
300	Sweet yellow pepper (SYCE)	30,0 kJ mol –1	281	0,23	97.3	(Deyab & Mohsen, 2023).
	Olive leaf	30 g L-1 de NaCl,	-658	4.56	95.78	(Pustaj, 2019).
400	Berberine	1,0 M H_2SO_4	0.436	7.80×10^{-5}	95.97	(Karki et al., 2021).
500	Rumex ethanolic extract	1 M HCl	498.7	454.9	77.6	(Al-Sharabi et al., 2022).
	Fatsia japonica leaves (FJLE)	0,05 mol/L KH_2PO_4	−361	0.6	85.7	(Wang et al., 2022).
	Rheum ribes leaf	HCl 1,0 M	-0,514	-	85.6	(Kaya et al., 2023).

Source: Own elaboration (2025).

Table 4.

Comparison of electrochemical parameters of organic inhibitors of 600 – 2000 ppm

Dose (ppm)	Solvent/Extract	Dilution	E_corr (mV/SCE)	I_corr (μA/cm²)	IE (%)	Author
600	Berberine	1,0 M H_2SO_4	0.440	7.24×10^{-5}	96.26	(Karki et al., 2021).
750	Rheum ribes leaf	HCl 1,0 M	-0,513	-	89.0	(Kaya et al., 2023).
800	Berberine	1,0 M H_2SO_4	0.442	4.49×10^{-5}	97.68	(Karki et al., 2021).
1000	Rheum ribes leaf	HCl 1,0 M	-0,484	-	91.8	(Kaya et al., 2023).
	Rumex ethanolic extract	1 M HCl	474.5	353.7	82.6	(Al-Sharabi et al., 2022).
	Fatsia japonica leaves (FJLE)	0,05 mol/L KH_2PO_4	−414	0.5	88.1	(Wang et al., 2022).
	Berberine	1,0 M H_2SO_4	0.428	3.5×10^{-5}	98.19	(Karki et al., 2021).
1500	Rumex ethanolic extract	1 M HCl	485.9	280.3	86.2	(Al-Sharabi et al., 2022).
2000	Rheum ribes leaf	HCl 1,0 M	-0,516	-	89.2	(Kaya et al., 2023).
2000	Rumex ethanolic extract	1 M HCl	470.8	205.2	89.9	(Al-Sharabi et al., 2022).

Source: Own elaboration (2025).

3.3. Electrochemical impedance spectroscopy measurements (EIS)

Electrochemical Impedance Spectroscopy (EIS) studies corrosion. On steel exposed to HCl (1 M) with prickly pear cactus pulp (PPUN), Nyquist plots showed a depressed semicircle, indicating that corrosion is controlled by charge transfer (Madaci et al., 2023). Likewise, tests were performed with an XC18 electrode (0.14 cm²) in a three-electrode cell (platinum, XC18 and SCE), using a Corrtest potentiostat and a thermostat at 298±0.5 K, including impedance spectroscopy and polarization tests (Ahchouch et al., 2024).

In another study, Nyquist plots for MS in H_2SO_4 showed a capacitive loop at high frequencies, related to charge transfer and an inductive loop at low frequencies, associated with the relaxation of adsorbed species and inhibitors (Lima et al., 2020). In addition, a 26 % NH_4Cl solution with hydroxyethylcellulose (HEC) was analyzed by EIS, where the spectra showed a depressed capacitive loop, indicating charge transfer, which increased with HEC concentration and inhibitor adsorption (Deyab, 2019). In a recent study, EIS results for steel electrodes in various solutions showed Nyquist and Bode plots, where a capacitive loop and a time constant were observed, indicating that corrosion is controlled by charge transfer (Meng et al., 2024).

Also, electrochemical tests were performed with a CS310H station in a three-electrode cell: Q235 (work), platinum (counter electrode), SCE (reference), stabilizing the OCP, using EIS (10^4 at 10^{-2} Hz) and polarization (Zhou et al., 2023). Likewise, the addition of cucumber leaf extract (ECSL) shifted the anodic and cathodic branches, reducing the corrosion current. At higher concentration, the metal-corrosive medium contact decreased, with small changes in Tafel and fluctuations less than 85 mV (Feng et al., 2022). In this context, the standard enthalpy of adsorption (ΔH⁰_ads) indicates the type of adsorption: chemical (endothermic) if greater than zero, and physical if less. ΔH⁰_ads less than 40 kJ/mol suggests physisorption, greater than 100 kJ/mol, chemisorption (Zakeri et al., 2022). Thus, EIS studies show that organic extracts enhance charge transfer resistance and act as effective inhibitors. However, the lack of standardization and limited evidence on the mechanisms under real-world conditions limit their practical application.

$$\Delta G^{0}_{ads} = -RT\ln(55.5K_{ads}$$

$$lnK_{ads} = \left(\frac{-\Delta H^{0}_{ads}}{RT}\right) + \text{constant}$$

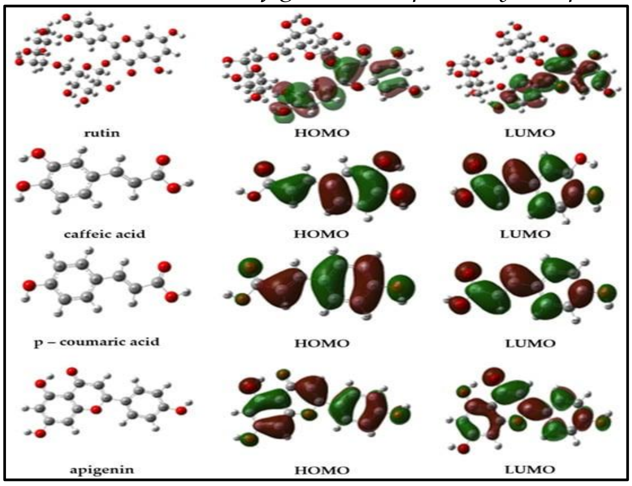
$$\Delta G^{0}_{ads} = \Delta H^{0}_{ads} - T\Delta S^{0}_{ads} \ldots\ldots\ldots\ldots (3)$$

3.4. Quantum chemical analysis

Quantum calculations with DFT (B3LYP/6-31+G(d,p)) are used to study corrosion inhibition, optimizing molecular geometry and calculating parameters like HOMO, LUMO, ΔE (El Ibrahimi et al., 2019), where the molecular geometry reached the energy minimum, with high correlation (0.94) in the parameters and without imaginary frequencies, confirming global minima, also the images show the optimized structure and HOMO/LUMO maps, indicating efficient adsorption (Hernández-Sánchez et al., 2024). It was also determined that several organic corrosion inhibitors, such as heterocycles, contain unshared electrons in N, O, S and P, polar groups (OH, Cl, NO2, CN, CH3) and double/triple bonds allow to donate electrons and protect the metal (Assad & Kumar, 2021). Therefore, DFT studies confirm that the molecular structure and HOMO-LUMO distribution explain the extracts' ability to adsorb and protect the metal. However, their practical applicability remains limited without further experimental validation.

Figure 5.

Optimization and HOMO/LUMO distributions of graveolens pathway components



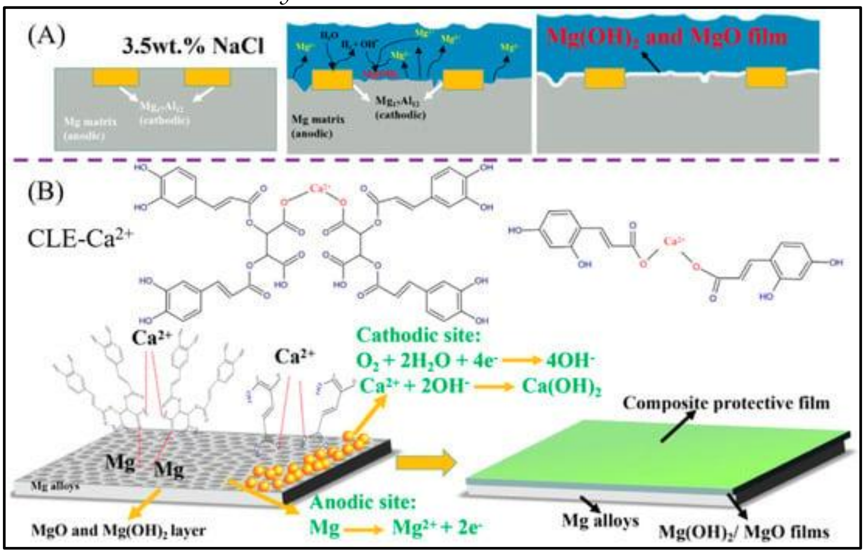
Source: Hernández-Sánchez et al., (2024).

B3LYP, DFT and Hartree-Fock were used to optimize the inhibitor of Phyllanthus amarus (PAE), analyzing parameters such as Fukui index and electronegativity, inhibitors were developed from grapefruit peel, Calotropis procera and Glycyrrhiza glabra with inhibition up to 87% (Shang & Zhu, 2021). Likewise, GC-MS analysis of Olea europaea extract showed N- and O-containing molecules with functional groups such as OH and NH2, where the phytochemicals adsorb on the metal surface, confirming that N-heterocyclics effectively inhibit corrosion (Ben Harb et al., 2020).

On the other hand, chicory extract and zinc ions formed a protective layer with chicoric and caffeic acid, achieving 96% inhibition, where when combined with inorganic cations (Ca^{2+}, Fe^{3+}, Fe^{2+}, Ni^{2+}), 92% was reached with CLE-Ca^{2+} (Zhao et al., 2023). In this context, the presence of heteroatoms and polar groups explains the high inhibitory efficacy of the organic extracts, which in some cases exceeds 95%. However, methodological variability limits the possibility of extrapolating these results to real-life conditions.

Figure 6.

Corrosion inhibition mechanism in alloy materials



Source: Zhao et al., (2023).

4. Conclusions

The use of organic extracts as carbonation corrosion inhibitors in maritime structures along the coast of Peru represents a promising and sustainable alternative to improve the durability of concrete exposed to aggressive environments. Likewise, throughout this study, it has been demonstrated that organic extracts are not only effective in reducing corrosion of reinforcing steel, but also offer ecological benefits, being biodegradable and low cost.

The results indicate that the inhibitors act by forming complexes with metal ions, such as iron (Fe^{2+} and Fe^{3+}), common corrosion products, where phenolic compounds in plant extracts react with these ions to form stable complexes as Fe^{2+} reacts with phenol (C_6H_5OH) and converts to phenolate ion (C_6H_5O-), which binds to iron to form the Fe($C_6H_5O_2$) complex, where this reduces the availability of iron for corrosion and stabilizes the metal surface.

Several studies have confirmed that organic extracts of Eucommia, Rhus coriaria and Fatsia japonica are effective as corrosion inhibitors in marine structures, where these extracts protect steel against carbonation in aggressive environments, with inhibition efficiencies between 70% and 98%, depending on the extract and its concentration, these act as mixed inhibitors, affecting both cathodic and anodic reactions, as Rhus coriaria extract has an efficiency of up to 84% in an environment of H_2SO_4 0. 5 M, while berberine extract reaches up to 98.19% in H_2SO_4 1.0 M at 1000 ppm. Furthermore, electrochemical impedance spectroscopy shows that these extracts form a protective film on the metal, reducing corrosion, while quantum calculations indicate that phytochemical compounds favor adsorption on the metal, enhancing their inhibitory action as the Olea europaea extract in methanol, which showed an efficiency of 91.9% at 50 ppm.

Further study of the interaction between different types of organic extracts and their synergy with other protection methods, such as coatings and chemical treatments, is recommended. Long-term research evaluating the effectiveness of these inhibitors under real exposure conditions, as well as their impact on the mechanical strength of concrete, would also be valuable. The use of organic extracts as corrosion inhibitors in marine structures is not only feasible, but also represents a step towards more sustainable and responsible construction practices aligned with current environmental and economic needs.

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