Glasnik hemičara i tehnologa Bosne i Hercegovine

Bulletin of the Chemists and Technologists of Bosnia and Herzegovina

2026

66

57-66

Print ISSN: 0367-4444
Online ISSN: 2232-7266

Original Scientific Article
DOI: 10.35666/2232-7266.2025.66.07
UDK: 547.913:541.1

Antioxidant and Antibacterial Activity of Essential Oil of *Syzygium aromaticum* (L.) Merr. & L. M. Perry and its Application as Eco-Friendly Copper Corrosion Inhibitor

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Article info
Received: 03/11/2025
Accepted: 12/03/2026

Keywords:
clove,
hydrodistillation,
GC-FID/MS analysis,
natural antioxidants,
ecoinhibitor

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Abstract: In this study, the essential oil of commercial clove (*Syzygium aromaticum* L. Merr. & L. M. Perry) was isolated. The chemical composition of the clove essential oil (CEO) was analyzed by GC-FID/MS. The reducing ability was analyzed by Ferric Reducing Antioxidant Power (FRAP) assay, while the free radical neutralization efficiency was tested by DPPH Radical Scavenging Assay. Antibacterial screening was analyzed on reference bacterial strains by diffusion test. The potential impact of CEO as a copper corrosion inhibitor was investigated by electrochemical frequency modulation (EFM), taking into account that compounds that have antibacterial and antioxidant effects also affect metal corrosion. GC-FID/MS analysis confirmed the high presence of eugenol (74.41%), (*Z*)-isoeugenol acetate (13.18%) and (*E*)-β-caryophyllene (10.60%) in CEO. The content of polyphenols is extremely high and correlates with the results of antioxidant activity. The essential oil was found to be highly effective in inhibiting the growth of the tested bacterial strains, at test concentrations of 40 and 80 mg/mL The inhibition zones of CEO were generally larger than those of the control antibiotics. The EFM results show that CEO acts as an effective inhibitor of copper corrosion in NaCl solution with a concentration of 0.5 mol/L, where it is adsorbed on the surface by physisorption according to the Langmuir adsorption isotherm.

INTRODUCTION

Aromatic plants have been an integral part of traditional medicine and culinary practices for centuries, largely due to their abundance of biologically active compounds. These plants exhibit a wide range of therapeutic properties, including antimicrobial, antioxidant, antiparasitic, antiprotozoal, antifungal, and anti-inflammatory activities (Christaki et al., 2012). Even today, a significant proportion of the global population relies on traditional herbal medicines for primary healthcare care. According to the World Health Organization, approximately 80% of people, predominantly in developing countries, use plant-derived medicines, and nearly 25% of modern pharmaceutical drugs are based on compounds originally obtained from plants or their synthetic analogs (Gurib-Fakim, 2006). The therapeutic efficacy of plants can be attributed to their ability to produce a wide variety of substances, collectively known as secondary metabolites. Historical records show that the use of medicinal plants dates back to around 2600 BC, and Mesopotamian texts document over 1000 plant-based remedies. Among the various applications of plant-derived compounds, aromatherapy has emerged as a popular complementary therapy. It uses essential oils, i.e. volatile aromatic compounds extracted by various extraction techniques from different parts of plants such as flowers, bark, stems, leaves, roots and fruits. (Ghorbanpour et al., 2017). One such plant with extensive ethnomedicinal and commercial applications is *Syzygium aromaticum* (L.) Merr. & L.M. Perry, commonly known as clove. As a member of the Myrtaceae family, clove is used in food, medicine, nutraceuticals, and agriculture (Singletary, 2014). Traditionally, clove has been valued for its pungent, astringent flavor and health benefits, including enhanced circulation, improved digestion, and relief from gastrointestinal disorders (Dey & Mukherjee, 2021). Clove essential oil is rich in bioactive components, primarily eugenol, its most abundant constituent, along with chavibetol, β-caryophyllene, eugenyl acetate, and α-humulene (Otunola, 2022). Other notable phytochemicals include flavonoids such as kaempferol and quercetin and their derivatives, as well as phenolic acids such as caffeic, ferulic, ellagic, and salicylic acids. Minor constituents such as methyl salicylate, crategolic acid, and benzaldehyde contribute to the distinct aroma and therapeutic effects of cloves (Hussain et al., 2017).

In dentistry,clove is very popular for its analgesic properties, which is why it is used in many medicinal preparations (Daniel et al., 2009; Sachan et al., 2018). Essential oils and extracts of cloves show very high antioxidant activity *in vitro*, as well as dose dependent antimicrobial activity (Otunola, 2022). Cloves also possess significant antitumor activity, as reported in *in vitro* studies where they successfully inhibited tumor incidence in rats with mammary carcinoma (Kubatka et al., 2017). Gas Chromatography-mass Spectrometry (GC-MS) is a key analytical technique for the identification and quantification of essential oil components, especially for the assessment of their medicinal quality and bioactivity (Van Asten, 2002).

Previous studies investigating cloves as corrosion inhibitors have shown that clove flower extract (*Syzygium aromaticum*) acts as a corrosion inhibitor in neem biodiesel with an inhibition efficiency of 97.96% (Iyyappan et al., 2024). Aqueous extract of cloves acts as a corrosion inhibitor on carbon steel in the presence of four strains of corrosion-causing bacteria with an inhibition efficiency of about 87% (Parthipan et al., 2021). Clove essential oil also has a corrosion inhibitory effect on mild steel X70 in 1 mol/L hydrochloric acid with an inhibition efficiency of 99.33% at an inhibitor concentration of 1 g/L, for 2 hours of immersion (Adjal et al., 2023). Cu-DUP copper, which is high-purity copper (>=99.9% Cu) deoxidized with phosphorus, is often used for pipeline construction. Thus, this pipeline comes into contact with chloride ions due to the addition of chlorine to the water and due to contact with seawater, therefore its protection by applying corrosion inhibitors is very important (Zdravković et al., 2023). Based on the literature and the compounds present in clove essential oil, it can be assumed that this oil can act as an environmental inhibitor of copper corrosion under chloride conditions.

The aim of this study is to analyze the chemical composition of *Syzygium aromaticum* essential oil (CEO) by GC-MS and evaluate its antioxidant and antibacterial activities, as well as the potential use of CEO as an inhibitor of copper corrosion in chloride conditions using the electrochemical frequency modulation (EFM) method. The findings will contribute to a deeper understanding of the therapeutic potential of clove oil and support its application in the development of natural health products. Also, the results will enable the possibility of using CEO as an environmental inhibitor of copper corrosion in a 0.5 mol/L NaCl solution.

MATERIAL AND METHODS

The clove sample was purchased from a local market. Before hydrodistillation, the sample was crushed in an electric mill and immediately used for the isolation of the essential oil. Methanol, ethanol, glacial acetic acid, hydrochloric acid and sodium carbonate were purchased from Semikem (Bosnia and Herzegovina). Dimethyl sulfoxide (DMSO), 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,4,6-tris(2-pyridyl)-s-triazine (TPTZ), were purchased from Sigma Chemical Co. (St. Louis, Missouri, USA). Folin-Ciocalteu reagent, iron (III) chloride hexahydrate and ascorbic acid were purchased from Merck (Darmstadt, Germany). Sodium chloride for electrochemical testing was purchased from Zorka Pharma (Šabac, Serbia). All chemicals used were of p.a. purity and were used as received, without any further purification.

All working solutions were prepared using demineralized water. An Agilent 6890 N GC system was used to determine the chemical composition of SEAO. Spectrophotometric measurements were performed on a Perkin Elmer Lambda 25 spectrophotometer. In the case of all spectrophotometric analyses, measurements were performed in triplicate, and the results were expressed as the mean value.

CEO preparation

Clove essential oil was isolated using a Clevenger apparatus. The crushed clove material (50 grams) was mixed with 1 liter of distilled water and heated for 5 hours. The obtained essential oil was separated, dried on anhydrous sodium sulfate and stored at -20°C until analysis. Yield: 2.94%

GC-FID/MS analysis

The volatile profile was determined by gas chromatography coupled to flame ionization detection and mass spectrometric analysis (GC-FID/MS). Measurements were performed on an Agilent 6890 N GC system with a 5975 mass selective detector and an FID, employing an HP-5 MS capillary column (30 m × 0.25 mm; 0.25 μm film thickness). Samples were introduced in an injection volume of 0.002 mL, with the injector maintained at 200°C and operating in split mode (10:1). Helium served as the carrier gas at a constant flow rate of 1.0 mL/min. Separation was achieved by a programmed oven temperature starting at 60°C and increasing to 280°C at 3°C/min, followed by a 5-minute isothermal period at the final temperature. The transfer line was maintained at 250°C, while the FID detector was operated at 300°C. Electron ionization mass spectra were recorded at 70 eV within the m/z interval of 35to 550. Experimental retention indices were calculated in relation to a homologous series of n-alkanes (C8–C40) analysed under the same chromatographic conditions. Component identification was based on matching retention index values and mass spectrum data with those of reference compounds, as well as with entries from the NIST AMDIS system, Wiley spectral libraries, the Adams database, and relevant literature sources. Quantitative composition was expressed as relative percentages derived from GC peak area normalization.

Analysis of total polyphenols content (TPC)

Total polyphenolic content of the CEO was quantified spectrophotometrically using the Folin–Ciocalteu assay, following the procedure described by Singleton et al. (1999). For this purpose, an aliquot of CEO (0.2 mL) was mixed with 2.54 mL of 10% Folin–Ciocalteu reagent. After an incubation period of 5 min, 0.42 mL of 10% sodium carbonate was added. After 60 minutes incubation, 0.910 mL of distilled water was added. The absorbance of the resulting blue-colored solution was measured at 765 nm. The content of total polyphenols was expressed as gallic acid equivalent (GAE) in milligrams per gram of essential oil.

Analysis of antioxidant activity

Ferric Reducing Antioxidant Power (FRAP) Assay

The test of the reducing ability of the CEO was tested using the FRAP (ferric reducing antioxidant power) method, according to the published procedure (Benzie and Strain, 1999). The FRAP reagent (3 mL) was mixed with 0.1 mL of CEO, and the absorbance was recorded at 593 nm after incubation at 37°C for 30 min. The FRAP value was calculated from the calibration curve of iron (II) sulfate heptahydrate and expressed in µmol per gram of essential oil. Ascorbic acid was used as a comparator.

DPPH Radical Scavenging Assay

The DPPH radical neutralization assay was performed according to the published method (Horozić et al., 2019). CEO was mixed with absolute methanol and then mixed with a DPPH radical solution (0.5 mM). Absorbance measurements were performed at 517 nm, after which the DPPH radical inhibition was calculated according to the equation:

$$I = Ac - As / Ac \times 100\ [\%] \qquad (1)$$

where As is the absorbance of the solution containing the sample at 517 nm, and Ac is the absorbance of the DPPH solution. Results are expressed as IC_{50} value. Ascorbic acid was used as a reference.

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Analysis of antibacterial activity

Antimicrobial activity was tested on reference bacterial strains from the WDCM collection of Gram-positive and Gram-negative bacteria, as prescribed by the Clinical and Laboratory Standards Institute, 2009. Reference bacterial strains were cultivated overnight in brain heart infusion (BHI) broth at 37°C, aerobically. A 0.5 McFarland turbidity suspension (density of 10^7-10^8 CFU/mL) was prepared in a sterile physiological solution. The strains were then plated on the surface of Mueller-Hinton agar, which was poured into sterile 4 mm thick Petri dishes. 10 mm diameter wells were made in the agar and 0.1 mL of the essential oil was added to each well. After the dishes were left at room temperature for 15 minutes to allow the substance to diffuse into the agar, they were incubated at 37°C/24 hours. After incubation, the size of the inhibitory zone was measured. The concentration of CEO in this analysis was 40 and 80 mg/mL Amoxicillin/AMX (30 µg), Vancomycin/VAN (30 µg) and Imipenem/IMP (10 µg) antibiotic discs were used as controls.

Electrochemical Frequency Modulation (EFM)

The electrochemical frequency modulation (EFM) method was used to investigate the influence of CEO on the corrosion of copper - deoxidized high phosphorus (Cu-DHP) in a NaCl solution with a concentration of 0.5 mol/L. An electrochemical system with a three-electrode cell and a potentiostat (Gamry Interface 1010e potentiostat/galvanostat/ZRA, Gamry Instruments, USA) was used. The results obtained from the EFM modulation spectra were analyzed using Gamry Echem Analyst software package, Gamry Instruments, USA.

The experiments were performed at room temperature. The electrochemical cell consisted of three electrodes: a working electrode (Cu-DHP), a counter electrode (platinum), and a reference electrode (saturated calomel electrode, +0.244 V/SHE at 25°C). The working electrode was made of Cu-DHP sheet (99.97% Cu, 0.0198% P, and 0.0005% Pb), according to the procedure of Zdravković et al., 2023. NaCl solutions with a concentration of 0.5 mol/L without and with the addition of CEO (0.1-0.5 ppm) were used as electrolytes. The surface of the working electrode was polished using a polishing cloth with alumina slurry (particle size 0.3 µm), then washed with distilled water and ethanol.

The base frequency for the EFM experiments was 1 Hz, with frequencies of 2.0 and 5.0 Hz used. The number of cycles was 16. The inhibition efficiency (IE_{EFM}, %) was calculated according to the equation (Al-Mobarak et al., 2011):

$$IE_{EFM} = (1 - j_{corr(inh)}/j_{corr}) \cdot 100 \quad (2)$$

where j_{corr} is the corrosion current density in the blank solution and $j_{corr(inh)}$ is the corrosion current density in the presence of CEO.

RESULTS AND DISCUSSION

Chemical composition

Table 1 shows the chemical composition of clove essential oil (CEO). Figure 1. shows the GC-FID total ion chromatogram (TIC) of the tested essential oil. The main compound in the investigated oil is phenylpropanoid eugenol (74.41%). The content of eugenol is slightly lower than the Pharmacopoeia given limit (75.0-88.0%) that defines the quality of herbal drugs and preparations such as essential oils (Ph. Eur.). The oil also contained significant amounts of (*Z*)-isoeugenol acetate (13.18%) and sesquiterpene (*E*)-β-caryophyllene (10.6%). The content of (*E*)-β-caryophyllene was within the Pharmacopoeia defined limits (5.0-14.0%). The Pharmacopoeia defines the eugenol acetate (4.0-15%) in clove oil (Ph. Eur.), and the investigated oil contained its isomer (Z)-isoeugenol acetate (13.18%). Isoeugenol acetate is usually present in low concentrations in clove oil (Jirovetz et al., 2066; Amelia et al., 2017) and is probably formed by isomerization of eugenol acetate during storage (Brock et al., 2024). Sesquiterpene α-humulene was present in low amount (1.17%) while the concentrations of other compounds were below 1%.

Table 1: The composition (%) of CEO

Component	RI	Composition (%)
3-octanol	967	0.05
6-methyl-heptan-2-ol	977	0.05
Methyl salicilate	1243	0.03
Chavicol	1306	0.12
Eugenol	1437	74.41
α-Copaene	1453	0.13
(*E*)-β-Caryophyllene	1506	10.60
α-Humulene	1544	1.17
(*E*,*E*)-α-Farnesene	1595	0.11
(*Z*)-Isoeugenol acetate	1613	13.18
Elemol acetate	1690	0.20

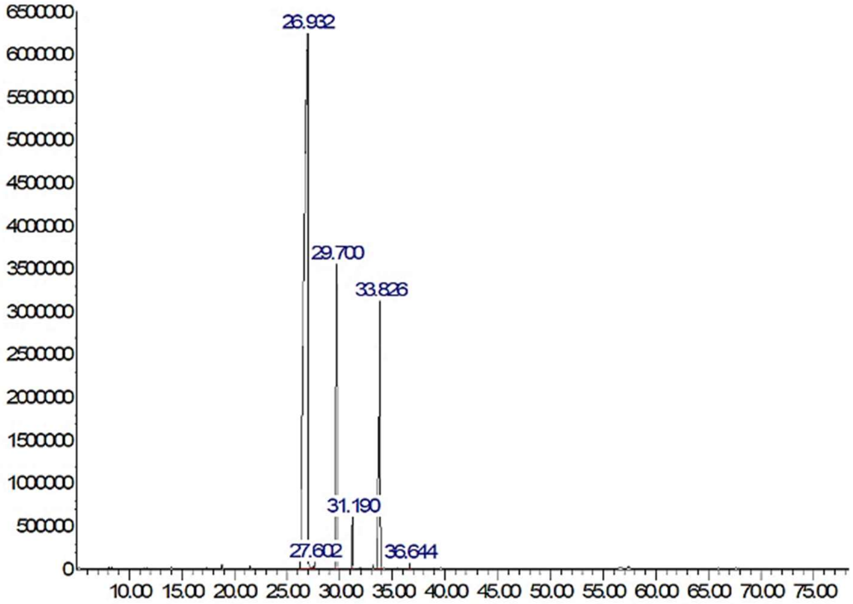

Figure 1: The GC- FID total ion chromatogram (TIC) of clove essential oil (CEO)

Total polyphenols content and antioxidant activity

The results of the total polyphenols content and antioxidant activity of the CEO are shown in Table 2. The total polyphenols content is extremely high (441.04 mg GAE/g of CEO). A review of previously published results of similar studies confirmed the high content of polyphenolic compounds in CEO (Sarrami et al., 2023; Das et al., 2024). The high reducing capacity and DPPH radical neutralization efficiency correlate with the high content of polyphenolic compounds in isolated CEO. Compared to ascorbic acid, which was used as a control, CEO showed a higher antioxidant capacity.

Table 2: Results of polyphenol content and antioxidant activity of CEO

Sample	TPC [mg GAE//g]	FRAP value [µmol/g]	DPPH IC_{50} value [mg/mL]
CEO	441.04	16220	0.005
Ascorbic acid	-	14250	0.030

Antibacterial activity

A total of six bacterial strains were tested in this study, including three Gram-positive strains (*Staphylococcus aureus*, *Listeria monocytogenes*, *Bacillus subtilis*) and three Gram-negative strains (*Salmonella enterica*, *Pseudomonas aeruginosa*, *Escherichia coli*). This classification allowed for a comparative evaluation of the antibacterial efficacy of *Syzygium aromaticum* essential oil against bacteria with distinct cell wall structures. The results showed significant growth inhibition in both groups, with certain strains showing larger inhibition zones compared to the tested control antibiotics (amoxicillin, vancomycin, and imipenem), which were used for comparison purposes. The antibacterial activity results of *S. aromaticum* essential oil are summarized in Table 3

Table 3: Results of antibacterial activity of CEO and control antibiotics

Reference strains	WDCM number	Inhibition zone [mm]				
		EO [80 mg/mL]	EO [40 mg/mL]	AMX [30 µg]	VAN [30 µg]	IPM [10 µg]
S. enterica	00030	30	26	21	n.t.	n.t.
P. aeruginosa	00025	20	18	n.t.	n.t.	20
E. coli	00012	35	31	20	n.t.	33
S. aureus	00034	27	22	33	20	n.t.
L. monocitogenes	00109	30	25	32	18	n.t.
B. subtilis	00003	30	26	14	n.t.	n.t.

*EO - essential oil; AMX - Amoxicillin; VAN - Vancomycin; IPM - Imipenem; n.t. - not tested

Both tested concentrations of the essential oil (40 mg/mL and 80 mg/mL) showed antibacterial activity against all isolates (*S. enterica, P. aeruginosa, E. coli, S. aureus, L. monocytogenes, B. subtilis*), showing moderate to high efficacy. Larger inhibition zones were observed at a higher concentration (80 mg/mL), with the largest zone recorded for the *E. coli* 00012 strain, consistent with the general principle that higher concentrations of bioactive substances usually result in enhanced effects.

As shown in Table 3, both concentrations of the essential oil demonstrated higher antibacterial activity against *S. enterica* 00030, *E. coli* 00012, and *B. subtilis* 00003 compared to amoxicillin. Imipenem, tested on *E. coli* 00012, showed a smaller inhibition zone compared to both essential oil concentrations. Moderate to high antibacterial activity was also observed against *P. aeruginosa, S. aureus,* and *L. monocytogenes*, with inhibition zones comparable to or slightly lower than those of the tested control antibiotics. *S. aureus* and *L. monocytogenes* showed larger inhibition zones in response to the essential oil compared to the control antibiotic vancomycin. According to standard criteria for evaluating the antibacterial potential of plant extracts, including essential oils, an inhibition zone of less than 10 mm indicates bacterial resistance, 10–15 mm indicates weak activity, 16–20 mm indicates moderate activity, and a zone of ≥20 mm indicates high antibacterial activity.

The main bioactive component of *S. aromaticum* essential oil is eugenol, responsible for most of its therapeutic properties, including its antibacterial effect. Numerous studies consistently confirm the antibacterial potential of this essential oil (Selles et al., 2020; Wadi et al., 2025; Valarezo et al., 2025; Maggini et al., 2024).

In a paper published by Teles et al. (2024), the antibacterial activity of clove essential oil was demonstrated against both Gram-positive and Gram-negative bacteria. It was observed that the antibacterial activity was stronger against gram-positive bacteria and that clove essential oil also had a stronger effect than eugenol alone, indicating that the biocomplex was responsible for the stronger inhibitory activity.

The authors of a review article (Maggini et al., 2024) suggested that the antimicrobial activity of EOs can be influenced by various factors: characteristics of the target microorganisms, temperature, pH, concentration of antimicrobial substances and the presence of organic matter. It was observed that the antimicrobial activity of *S. aromaticum* EO was twenty times higher at a temperature of 37°C. Since temperature affects the fluidity of the lipid layer of membrane, higher temperatures compromise membrane function and increase permeability, resulting in greater cell sensitivity to antimicrobial agents. Regarding the presence of organic material, the bactericidal activity of clove EO is preserved but reduced, which highlights its potential as an antimicrobial agent for external use, for example, in dentistry or for the treatment of skin problems.

The antibacterial mechanism of essential oils involves disruption of the cell membrane, resulting in loss of membrane stability, leakage of cell contents, and ultimately cell death. *S. aromaticum* essential oil has been shown to inhibit the growth of Gram-negative bacteria such as *Salmonella spp., Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa,* and *Agrobacterium spp*., as well as Gram-positive bacteria, including *Streptococcus spp.* and *Staphylococcus aureus* (Haro-González et al., 2021), which confirms our findings.

Previous research by Hernández-Ochoa et al. (2014), Guran et al. (2015), Khaleque et al. (2016), and Teles et al. (2024) have shown that essential oils, including *S. aromaticum*, generally exhibit stronger inhibitory effects on Gram-positive bacteria compared to Gram-negative bacteria. This is explained by the structural differences in the bacterial cell wall: Gram-positive bacteria possess a thick peptidoglycan layer that is directly accessible to essential oils, while the outer membrane of Gram-negative bacteria, rich in lipopolysaccharides, restricts the passage of hydrophobic molecules, reducing their susceptibility. Our results are consistent with these observations, showing strong antibacterial activity against Gram-positive strains, as well as significant activity against Gram-negative strains.

According to a study published in 2025 (El-Wehedy et al., 2025), the essential oil of *S. aromaticum* showed significant antibacterial activity against multidrug-resistant bacterial strains, such as *P. aeruginosa*, indicating its potential as one of the possible candidates for the development of new plant-based antibacterial drugs. In our study, *S. aromaticum* essential oil showed moderate antibacterial activity against *P. aeruginosa*. Beta-lactamase-producing strains, including *P. aeruginosa* and *E. coli*, showed high inhibition zones when tested with this essential oil (Mejía-Argueta et al., 2020).

Gram-positive bacteria such as *L. monocytogenes, S. aureus,* and *B. subtilis* are common causes of food spoilage. The use of *S. aromaticum* essential oil as a natural preservative is supported by its potent antimicrobial and antifungal activity. The primary bacteria investigated in this context included *Listeria monocytogenes, Escherichia coli, Staphylococcus aureus, and Bacillus cereus* (Valarezo et al., 2025), where high inhibition zones were observed, which is consistent with the findings of our study.

Electrochemical Frequency Modulation (EFM)

The EFM method was used to determine corrosion parameters in an electrochemical system where a basic solution of 0.5 mol/L NaCl and solutions with CEO added (50 ppm - 300 ppm) , were used as electrolytes. All experiments were carried out in a Faraday cage at room temperature. The results are presented as intermodulation spectra for the electrolyte without the CEO (Figure 3), for electrolytes with the addition of 50 ppm CEO (Figure 4), 100 ppm CEO (Figure 5), 150 ppm CEO (Figure 6) and 300 ppm CEO (Figure 7).

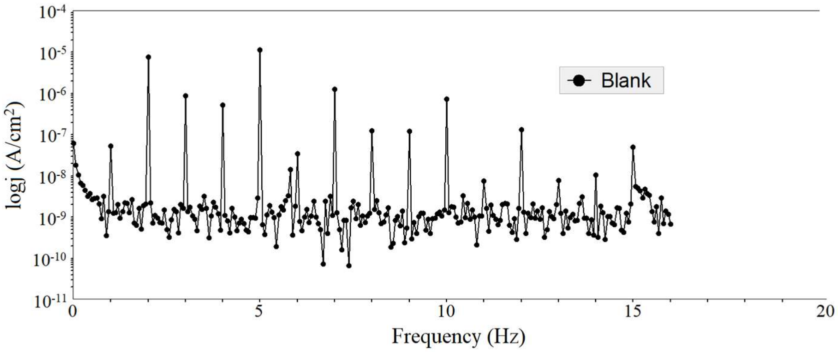

Figure 3: Intermodulation spectrum for Cu-DHP in 0.5 mol/L NaCl electrolyte (blank solution)

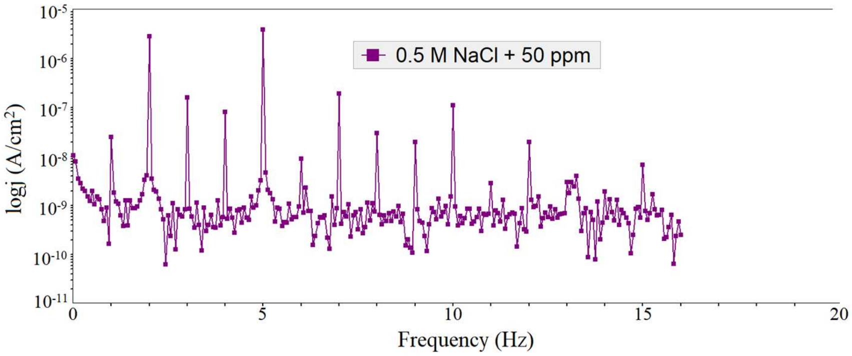

Figure 4: Intermodulation spectrum for Cu-DHP in 0.5 mol/L NaCl electrolyte with added 50 ppm CEO

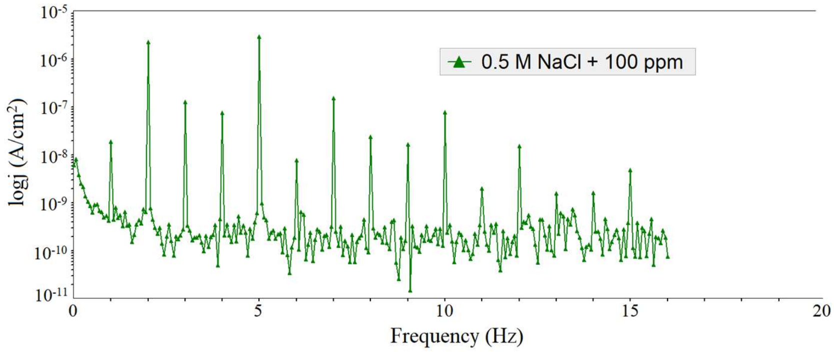

Figure 5: Intermodulation spectrum for Cu-DHP in 0.5 mol/L NaCl electrolyte with added 100 ppm CEO

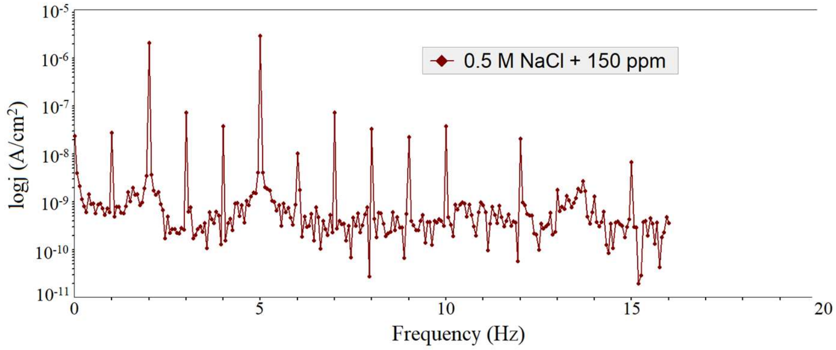

Figure 6: Intermodulation spectrum for Cu-DHP in 0.5 mol/L NaCl electrolyte with added 150 ppm CEO

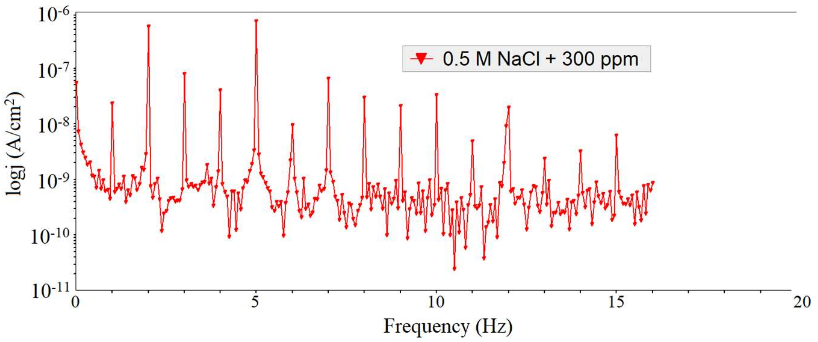

Figure 7: Intermodulation spectrum for Cu-DHP in 0.5 mol/L NaCl electro lyte with added 300 ppm CEO

Using electrochemical software, the adjusted results were used to obtain EFM electrochemical parameters (Table 4). The values of corrosion current (j_{corr}), anodic Tafel slope (β_1), cathodic Tafel slope (β_2), causal factors (CF2 and CF3), corrosion rate (CR) were obtained, while the percentage values of inhibitor efficiency (IE_{EFM}) were calculated using the equation (2). The value of the corrosion current density decreases significantly when CEO is added to the electrolyte, and this decrease is greater with increasing CEO concentration (Zdravković et. al, 2023; Fouda and Wahed, 2016). At the highest concentration, CEO acts as a mixed type of copper corrosion inhibitor in the tested electrolyte, while at lower concentrations it acts as a dominant cathodic corrosion inhibitor (El-Haddad, 2013). The values of the parameters CF2 and CF3 correspond to the theoretical values and the reviewed literature (El-Haddad, 2013; Fouda and Wahed, 2016). The corrosion rate and percent inhibition efficiency increase with increasing CEO concentration (Khaled, 2008). The highest effectiveness (97.06%) of the tested oil as an inhibitor of copper corrosion is achieved with the addition of 300 ppm CEO. Based on the comparison with the results of experiments where copper corrosion inhibitors were tested using the same method, it can be concluded that the tested clove oil has a significant effect on reducing copper corrosion in chloride conditions (El-Haddad, 2013). The effect of CEO can be explained by the compounds present in the oil. The high content of eugenol in CEO may indicate the effect of this oil as an inhibitor of copper corrosion, considering that eugenol has been shown to be an inhibitor of copper corrosion in chloride solution (Samontha and Lugsanangarm, 2019). CEO also contains (*Z*)-isoeugenol acetate, (*E*)-β-caryophyllene and α-humulene, where isoeugenol acetate was found in the *Cupressus sempervirens* L. extract, which acts as an inhibitor of copper corrosion (Dahmani et al., 2023), and α-humulene was found in the essential oil extracted from *Moroccan Salvia officinalis L.*, which acts as an aluminum corrosion inhibitor in a 3% NaCl solution (Belcadi et al., 2023). Also, it is common for substances that have an antibacterial effect to also act as metal corrosion inhibitors (Feng et al., 2020). Pipelines are often exposed to corrosion caused by the presence of bacteria, so as Cu-DHP is used for the construction of pipelines, it is important to test the antibacterial effect of the corrosion inhibitors (Javed et al., 2016). In addition, research shows that the positive effect of plants as corrosion inhibitors has an antioxidant effect, with moringa leaf extract and bitter leaf lxtract being shown to be ecological inhibitors of oil and gas pipelines, which have a high antioxidant effect (Ogboro et al., 2025). In this case, the antibacterial and antioxidant effect of CEO gives positive indications for the protection of copper pipes themselves, in addition to the aforementioned protection against chloride ions, which means that is possible to apply CEO in industries where pipelines made of copper come into contact with chloride ions, especially with seawater solutions.

Table 4: Electrochemical parameters obtained by EFM measurements for copper in sodium chloride electrolyte in the presence and absence of CEO

C_{inh} [ppm]	j_{corr} [µA/cm^2]	β_1 [mV/dec]	β_2 [mV/dec]	CF-2	CF-3	CR [mpy]	IE_{EFM} [%]
0	20.93	66.71	193.6	1.72	2.85	159.8	-
50	7.720	84.33	137.1	1.83	2.95	58.95	63.12
100	5.949	83.42	163.8	1.82	2.95	45.43	71.56
150	4.391	72.66	89.19	1.91	3.10	33.53	79.02
300	0.61	36.74	58.15	1.96	2.98	12.54	97.06

Adsorption of CEO on copper surface

When determining the adsorption method of CEO molecules on the copper surface in chloride conditions, it was determined that the electrochemical results correspond best to the Langmuir adsorption isotherm (Zdravković et al., 2024). The IE_{EFM} data from Table 4 were used to form the adsorption isotherm, whereby the value of the degree of surface coverage (θ) was obtained as the ratio of $IE_{EFM}/100$ (Miralrio and V´azquez, 2020). This parameter, in combination with the inhibitor concentration, was used to plot the Langmuir adsorption isotherm graph (Figure 8) and in the formula (Zdravković et al., 2023):

$$\frac{C_{inh}}{\theta} = C + \left(\frac{1}{K_{ads}}\right)$$

where C_{inh} is inhibitor concentration and K_{ads} is the equilibrium constant.

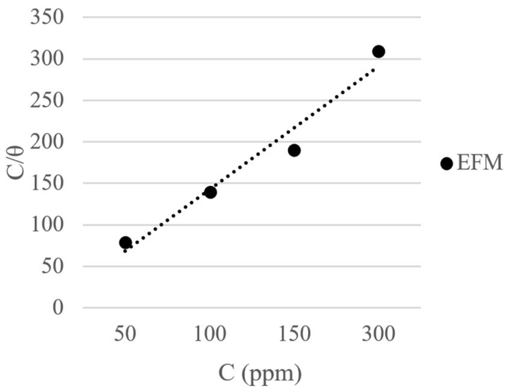

Figure 8: Langmuir adsorption isotherm for an electrochemical system with copper and electrolyte 0.5 mol/L NaCl with added CEO

The regression equation was obtained by fitting the results to the graph:

$$y = 0.8789 \cdot x + 44.66225,\ R^2 = 0.99057$$

The regression equation obtained by fitting with Langmuir model has a slope of 0.8789, and this deviation from 1 is the result of interactions between adsorbates or the average number of sites occupied by one adsorbed inhibitor molecule or the number of adsorbed water molecules displaced from the surface by one adsorbed inhibitor molecule (Kokalj et al., 2023).The high value of the correlation coefficient (R^2) clearly confirms that the adsorption takes place according to the Langmuir adsorption isotherm, which means that each adsorbed molecule occupies one free place on the copper surface and does not interact with other adsorbed compounds (Vaszilcsin et al., 2023). Another significant parameter that describes the CEO adsorption process on the copper surface in detail is the Gibbs free energy of adsorption (ΔG°_{ads}), which was calculated using the equation (Walczak et al., 2019; Mas'ud et al., 2020):

$$\Delta G^{\circ}_{ads} = -RTln(55.5K_{ads})$$

where R is the universal gas constant (J/mol·K), T is absolute temperature (K) and 55.5 is molar concentration of water. Based on the intercept from the regression equation, the value of K_{ads} was obtained. The obtained value for K_{ads} was 0.0224 dm^3/mol and ΔG°_{ads} was -533 J/mol. The obtained negative value of ΔG°_{ads} has a smaller value of -20 kJ/mol which indicates the spontaneous physisorption of CEO molecules on the copper surface in a NaCl solution of 0.5 mol/L, whereby a protective film is formed that protects the copper surface from the negative influence of chloride ions (Othman et al., 2025; Vaszilcsin et al., 2023; Zdravković et al., 2023; Khaled, 2008). Earlier research shows that under chloride conditions, eugenol is adsorbed by physisorption according to the Fremkin adsorption isotherm (Samontha and Lugsanangarm, 2019). Based on the large presence of eugenol in CEO and adsorption according to the Langmuir adsorption isotherm, it can be concluded that the influence of copper inhibition by the application of CEO is influenced by other substances present in the oil besides to eugenol.

CONCLUSION

Commercial clove essential oil of isolated by hydrodistillation shows high efficiency in neutralizing DPPH radicals and high reducing capacity. The results of the content of polyphenolic compounds correlate with antioxidative capacity. SEAO was also confirmed to have extremely high efficiency in inhibiting the growth of reference bacterial strains from the WDCM collection. The obtained results indicate that essential oil of cloves is a good candidate for further studies in terms of its broad biological activities. Using Electrochemical Frequency Modulation (EFM), CEO was found to act as a highly effective copper corrosion inhibitor in a solution containing 0.5 mol/L NaCl, with a maximum efficiency of 97.06% at 300 ppm CEO. Its action as a corrosion inhibitor is reflected in physical adsorption on the copper surface, where the adsorption takes place spontaneously according to the Langmuir adsorption isotherm. In this way, a barrier is created that prevents the corrosive action of chloride ions and reduces the copper corrosion process. Considering the identified composition of CEO and the reviewed literature, it is assumed that eugenol has the most dominant influence on the inhibition of copper corrosion, but that the other compounds present also have an influence. In addition to the fact that a high inhibitor efficiency value is achieved at a low inhibitor concentration, the novelty of this work is that this oil is tested for the first time as an inhibitor of Cu-DHP corrosion under chloride conditions, with the results corresponding to the antibacterial and antioxidant effects of CEO, which confirms that the higher the antioxidant and antibacterial effect, the better it acts as a corrosion inhibitor.

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Summary/Sažetak

U ovoj studiji, izolovano je eterično ulje komercijalnog karanfilića (*Syzygium aromaticum* (L.) Merr. & L. M. Perry). Hemijski sastav eteričnog ulja klinčića (CEO) analiziran je GC-FID/MS metodom. Sposobnost redukcije analizirana je pomoću FRAP (Ferric Reducing Antioxidant Power) testa, dok je efikasnost neutralizacije slobodnih radikala testirana pomoću DPPH testa za uklanjanje slobodnih radikala. Antibakterijski skrining je ispitan na referentnim bakterijskim sojevima, korištenjem difuzijskog testa. Ispitivanje potencijalnog uticaja CEO kao inhibitora korozije bakra izvršeno je korištenjem elektrohemijske frekventne modulacije (EFM), uzimajući u obzir da jedinjenja koja imaju antibakterijski i antioksidativni učinak također imaju uticaj na koroziju metala. GC-FID/MS analiza potvrdila je visoku prisutnost eugenola (74,41%), (*Z*)-izoeugenol acetata (13,18%) i (*E*)-β-kariofilena (10,60%) u eteričnom ulju karanfilića. Sadržaj polifenola je izuzetno visok i korelira s rezultatima antioksidativne aktivnosti. Utvrđeno je da je eterično ulje veoma efikasno u inhibiranju rasta testiranih bakterijskih sojeva, pri testnim koncentracijama od 40 i 80 mg/mL. Zone inhibicije CEO bile su uglavnom veće od onih kod kontrolnih antibiotika. Rezultati EFM-a pokazuju da CEO djeluje kao efikasan inhibitor korozije bakra u 0,5 M rastvoru NaCl, gdje se adsorbira na površini fizisorpcijom prema Langmuirovom adsorpcionom izotermi.