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White Willow Bark Extract as a Copper Corrosion Inhibitor

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Abstract

This study investigates white willow bark extract (WWBE) as a potential corrosion inhibitor for Cu-DHP in a 0.5 M NaCl solution, using a non-destructive electrochemical methods, namely electrochemical frequency modulation (EFM), and electrochemical impedance spectroscopy (EIS). Electrolytes consisted of 0.5 M NaCl solutions both with and without the addition of WWBE (0.1–0.5 g l^{-1}). The 0.5 M NaCl solution containing 0.5 g l^{-1} WWBE, both in the presence and absence of a copper plate, was analysed by ultraviolet-visible spectroscopy (UV-Vis). The experiments were conducted at room temperature. The EFM results indicated that WWBE functioned as a cathodic copper corrosion inhibitor, with the highest inhibition efficiency observed for the 0.5 M NaCl solution containing 0.5 g l^{-1} WWBE. The EIS results suggested the formation of a protective WWBE inhibitor film. The corrosion process was diffusion-controlled, both with and without the addition of WWBE. Both electrochemical methods demonstrated that WWBE adsorbed onto the copper surface in 0.5 M NaCl solution via physisorption, following the Langmuir adsorption isotherm. The Gibbs free energy values of adsorption were similar for EFM and EIS. The UV-Vis results showed that immersion of copper in an electrolyte containing 0.5 g l^{-1} WWBE for 24 h led to a change in the absorbance maximum, indicating the formation of a copper–WWBE complex. Overall, the results indicate that WWBE is an effective inhibitor of copper corrosion in chloride conditions. Further research will focus on the identification of compounds and organometallic complexes in WWBE and their individual effects on the corrosion process.

Keywords

White willow bark, NaCl, Cu-DHP, EFM, EIS, UV-Vis

1 Introduction

Corrosion is the deterioration of the desired physicochemical properties of materials due to environmental factors.[1] Chloride ions are particularly corrosive to copper, making the corrosion of copper and its alloys in chloride-containing media a widely studied topic.[2] Cu-DHP is a phosphorus- and oxygen-free copper that does not contain arsenic and is often used in pipeline production.[3] Consequently, it frequently comes into contact with chloride ions. Therefore, the aim of this study was to examine a new environmentally friendly inhibitor of copper corrosion in the presence of chloride ions. Recent research on corrosion inhibitors has focused on the discovery of herbal inhibitors, as they generally lack compounds that negatively impact the environment.[4] Plants containing tannins, especially caffeic and gallic acids, are commonly selected for testing plant-derived inhibitors on copper corrosion in chloride conditions.[5–7] Salicylic acid and its derivatives have also been shown to be effective corrosion inhibitors for copper under chloride conditions.[8,9] White willow bark extracts contain high amounts of salicylic acid, making them potential inhibitors of copper corrosion in chloride media.[10,11] The use of white willow bark extract would reduce the negative environmental impact of toxic inhibitors, given that white willow bark extracts are used for medicinal purposes.[12]

The effect of plant extracts as metal corrosion inhibitors can be investigated using electrochemical methods. Electrochemical frequency modulation (EFM) is a non-destructive technique for measuring corrosion parameters.[13] Causality factors are used to validate EFM results.[14] The EFM method has been applied to study the inhibition effect of 2-carboxymethylthio-4-(p-methoxyphenyl)-6-oxo-1,6-dihydropyrimidine-5-carbonitrile[15], blackberry leaf extract[4], and guanine derivatives[16] on copper in 3–3.5 % NaCl solutions. Another frequently applied electrochemical method is electrochemical impedance spectroscopy (EIS).[17] Corroding electrode signals with a small amplitude variable potential and variable frequency are analysed using the EIS method, enabling the determination of fundamental electrochemical kinetic parameters.[18]

Ultraviolet-visible spectroscopy (UV-Vis) is used to detect the presence of organometallic complexes formed between plant inhibitor molecules and metal ions in solution.[19] UV-Vis has been used to detect bronze and copper complexes with copper corrosion inhibitors in seawater and NaCl solutions of similar concentrations.[20,21]

This paper presents the results of the investigation into white willow bark extract as a potential copper corrosion inhibitor in 0.5 M NaCl solution, using EFM, EIS, and UV-Vis methods.

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2 Experimental

2.1 Extract preparation

White willow bark extract (WWBE) was obtained by extracting dried, crushed white willow bark (produced by "Adonis", Serbia) with distilled water. The water was heated to 95 °C before adding the plant material, using a solid-to-liquid ratio of 1 : 5. After standing for 12 h at room temperature, the aqueous extract was separated from the solid phase using a cotton cloth and then filtered using a Büchner apparatus and filter paper No. 1. To obtain a compact and stable extract mass, the solvent was removed using a Buchi R-210 rotary evaporator (BUCHI Labortechnik AG, Switzerland) at a pressure of 72 mbar and 40 °C. After evaporation, the extract and hydrolate of white willow bark were obtained. The extract was further investigated as an inhibitor of copper corrosion in chloride conditions. A schematic representation of the experimental procedure is shown in Fig. 1.

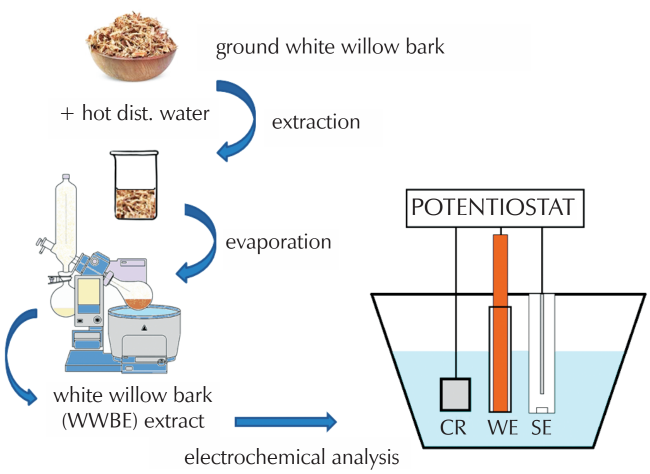

Fig. 1 – Scheme of the experimental procedure

2.2 Solution and material preparation

The electrolytes used to investigate the effect of chloride ions on the corrosion behaviour of copper were prepared using NaCl salt of p.a. purity (Zorka Pharma, Šabac, Serbia) and distilled water. Electrolytes with a concentration of 0.5 M NaCl were prepared both without and with the addition of WWBE (0.1–0.5 g l^{-1}). The working electrode for electrochemical tests was made from a Cu-DHP sheet. The chemical composition of Cu-DHP was 99.97 % Cu, 0.0198 % P, and 0.0005 % Pb. A rectangular strip of copper sheet was coated in epoxy resin using a mould, exposing a copper cross-section of 0.06 cm^2. The Cu-DHP coupon used for the UV-Vis method was prepared from the same sheet and cut to dimensions of 1 × 1 cm. Before immersion, the copper surface was cleaned with acetone and distilled water.

2.3 Electrochemical experiments

Electrochemical experiments (EFM and EIS) were performed using a Gamry Interface 1010e potentiostat/galvanostat/ZRA (Gamry Instruments, USA). As EFM is a non-destructive technique, a cycle of EFM and EIS experiments was conducted. The electrochemical data were analysed using the Gamry Echem Analyst software package (Gamry Instruments, USA). The impedance model editor within the software was used to construct the equivalent electrochemical circuit required for the EIS analysis. The experiments were carried out at room temperature using a three-electrode electrochemical cell consisting of a Cu-DHP working electrode, a platinum counter electrode, and a saturated calomel electrode as the reference electrode (+0.244 V/SHE at 25 °C). The surface of the working electrode was polished using a polishing cloth with alumina slurry (particle size 0.3 μm), followed by rinsing with distilled water and ethanol.

EFM experiments were carried out using frequencies of 2.0 and 5.0 Hz, with a base frequency of 1 Hz. The number of cycles was 16. The inhibition efficiency (IE_{EFM}, %) was calculated according to Eq. (1):[15]

$$IE_{EFM} = \left(1 - \frac{j_{corr(inh)}}{j_{corr}}\right) \cdot 100 \quad (1)$$

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

EIS experiments were carried out in the frequency range from 100 kHz to 0.1 Hz with an amplitude of 10 mV. The inhibition efficiency (IE_{EIS}, %) was calculated according to Eq. (2).[22]

$$IE_{EIS} = \frac{R_p - R_p^0}{R_p} \cdot 100 \quad (2)$$

R_p and R_p^0 are the polarisation resistance of copper in 0.5 M NaCl with and without the addition of WWBE, respectively.

2.4 UV–Vis spectroscopy

UV–Vis spectra were recorded in the wavelength range of 200–400 nm using a Lambda 25 UV–Vis spectrometer (Perkin Elmer, USA). A 0.5 M NaCl solution containing 0.5 g l^{-1} WWBE, both with and without a copper plate, was analysed. The copper coupon immersion time was 24 h.

3 Results and discussion

3.1 Electrochemical frequency modulation (EFM)

The effect of WWBE on copper corrosion in a 0.5 M NaCl solution was investigated using the electrochemical frequency modulation (EFM) method, and intermodula-

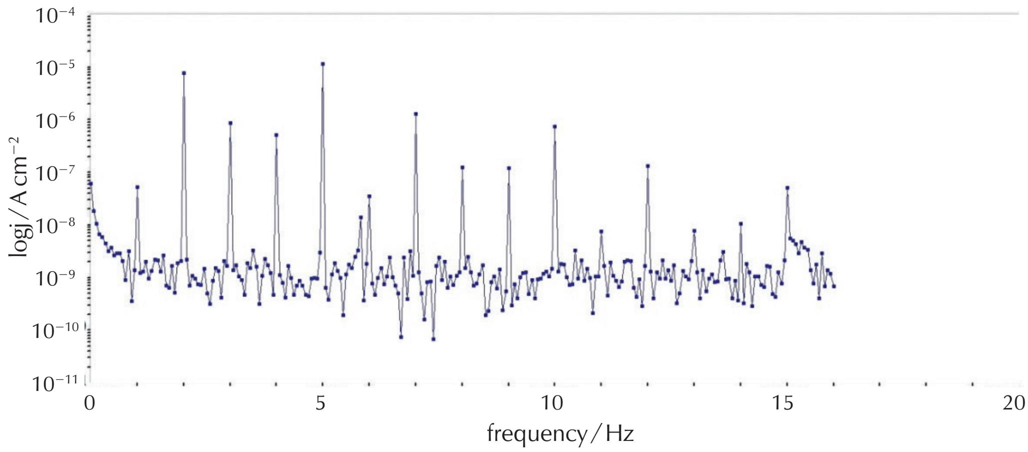

Fig. 2 – EFM intermodulation spectra for Cu-DHP in 0.5 M NaCl solution

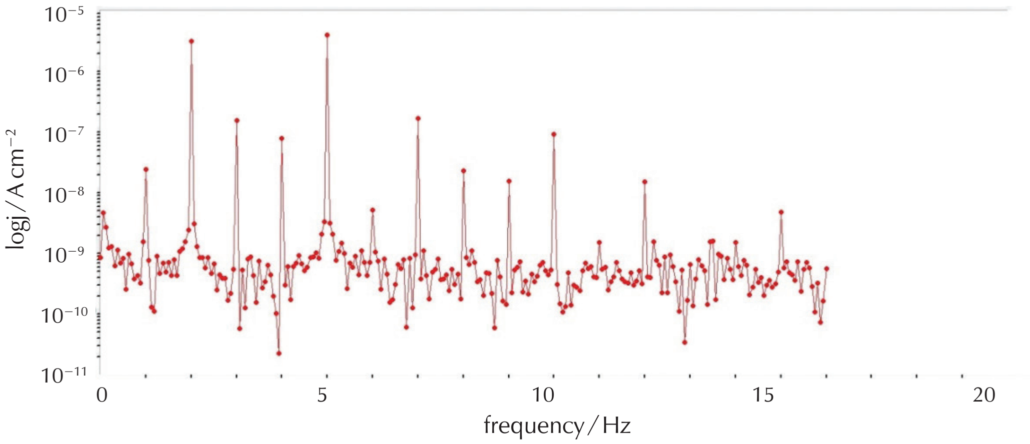

Fig. 3 – EFM intermodulation spectra for Cu-DHP in 0.5 M NaCl solution with the addition of 0.1 g l^{-1} WWBE

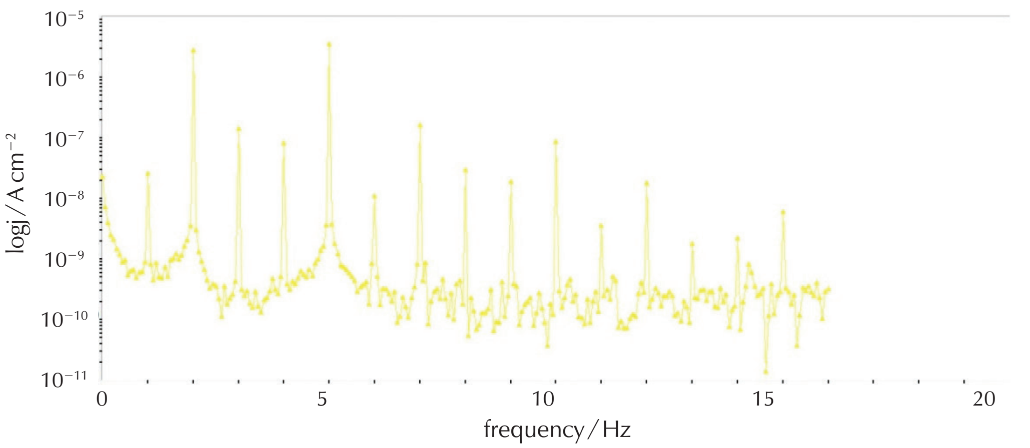

Fig. 4 – EFM intermodulation spectra for Cu-DHP in 0.5 M NaCl solution with the addition of 0.3 g l^{-1} WWBE

tion spectra were obtained. The first intermodulation spectrum, shown in Fig. 2, refers to the experiment performed in a 0.5 M NaCl solution without the addition of WWBE. The subsequent intermodulation spectra, shown in Figs. 3, 4, and 5, correspond to experiments performed in 0.5 M NaCl solutions with the addition of 0.1 g l^{-1}, 0.3 g l^{-1}, and 0.5 g l^{-1} WWBE, respectively.

Two large peaks at 2 Hz and 5 Hz correspond to excitation. The current response between these peaks is very small. All intermodulation spectra are consistent with similar examples reported in the literature, indicating that the frequencies and amplitudes of the peaks were not random.[4,15]

Based on the EFM results, electrochemical kinetic parameters were calculated using software, and the inhibition efficiency values of WWBE were determined using Eq. (1). These values are presented in Table 1, where j_{corr} is the corrosion current density, β_1 (V dec^{-1}) and β_2 (V dec^{-1}) are Tafel constants, CF-2 and CF-3 are causal factors, CR (mpy) is the corrosion rate, and IE_{EFM} (%) is the inhibition efficiency of WWBE in 0.5 M NaCl at 25 °C.

Based on the values in Table 1, the presence of WWBE in a 0.5 M NaCl solution led to a decrease in both the current density and corrosion rate compared to the solution without WWBE, with this decrease becoming more pronounced as the WWBE concentration increased. Corrosion inhibition efficiency increased with increasing WWBE concentration, with the highest inhibition efficiency obtained with the addition of 0.5 g l^{-1} WWBE.[4]

The values of the causal factors were close to the theoretical values.[23] The changes in Tafel slopes indicate that WWBE acted as a cathodic copper corrosion inhibitor under chloride conditions. These results are consistent with reports that acetylsalicylic acid, which can be derived from white willow bark, acts as a cathodic inhibitor of copper corrosion in chloride conditions.[8]

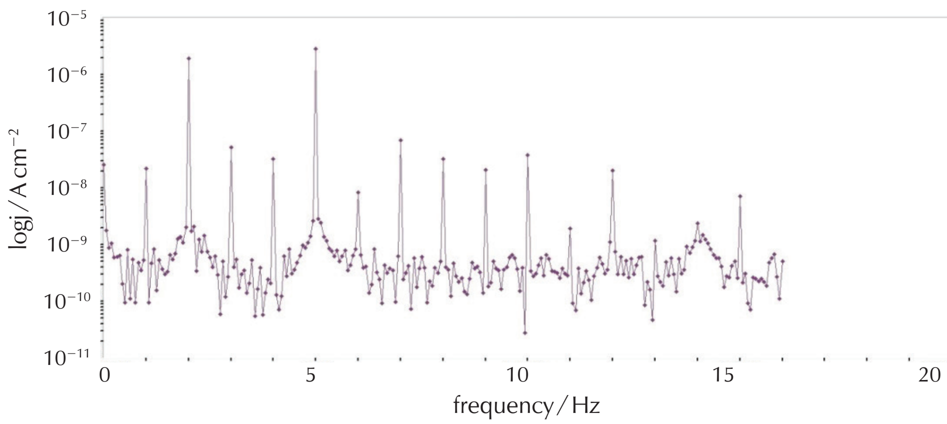

Fig. 5 – EFM intermodulation spectra for Cu-DHP in 0.5 M NaCl solution with the addition of 0.5 g l^{-1} WWBE

Table 1 – Electrochemical kinetic parameters obtained using the EFM method for Cu-DHP in 0.5 M NaCl solution with and without the addition of 0.1–0.5 g l^{-1} WWBE at 25 °C

C_{inh} / g l^{-1}	j_{corr} / μA cm^{-2}	β_1 / V dec^{-1}	β_2 / V dec^{-1}	CF-2	CF-3	CR / mpy	IE_{EFM} / %
0	20.929	0.067	0.194	1.717	2.545	160.00	–
0.1	9.271	0.096	0.155	1.923	3.834	70.79	55.70
0.3	7.177	0.083	0.128	1.717	2.540	59.80	65.71
0.5	4.294	0.075	0.090	1.710	3.103	32.79	79.48

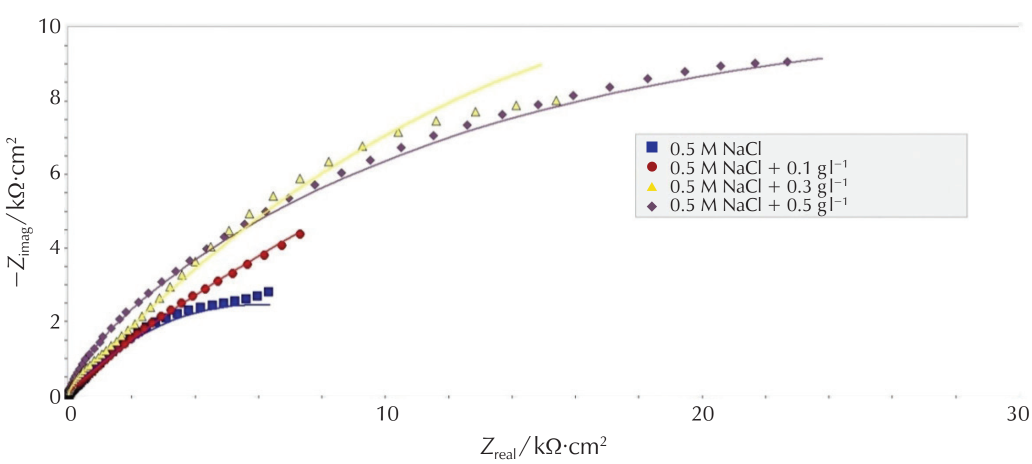

Fig. 6 – Nyquist plots for Cu-DHP in 0.5 M NaCl solution with and without the addition of WWBE

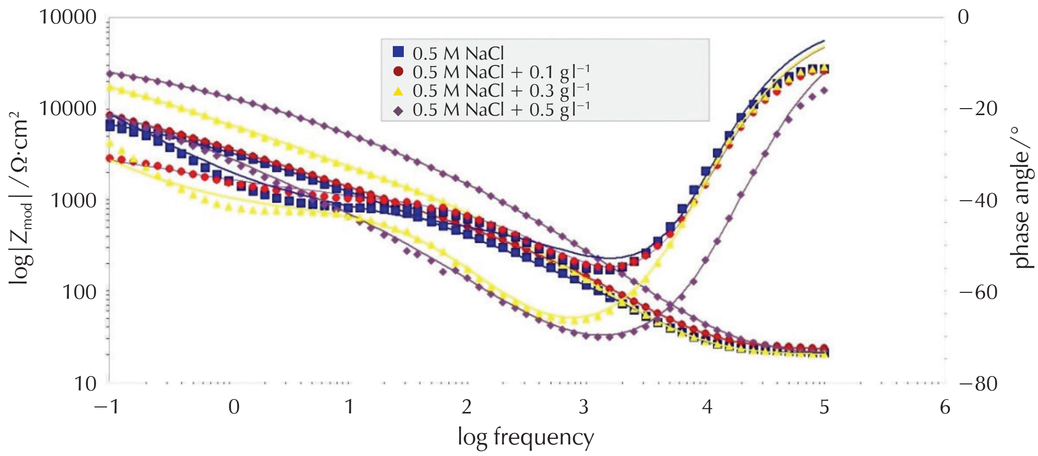

Fig. 7 – Bode plots for Cu-DHP in 0.5 M NaCl solution with and without the addition of WWBE

3.2 Electrochemical impedance spectroscopy (EIS)

The EIS results are presented as Nyquist (Fig. 6) and Bode (Fig. 7) plots. The imperfect semicircles in the Nyquist plots for Cu-DHP in 0.5 M NaCl solution, with and without the addition of WWBE, can be attributed to frequency dispersion. The diameter of the semicircle increased in the presence of WWBE, indicating the inhibitory effect of WWBE on Cu-DHP corrosion in 0.5 M NaCl solution.[4] A line indicating the presence of Warburg impedance is visible in the Nyquist diagram, suggesting that diffusion influenced the corrosion process.[24]

A small phase angle in the Bode diagram indicates the corrosive effect of chloride ions, while an increase in the phase angle in the presence of WWBE suggests the formation of a protective film on the metal surface.[25,26] Additionally, the log|Zmod| values increased with higher WWBE concentration, indicating increased resistivity in the presence of the extract.[25]

EIS fitting was performed using the electrochemical equivalent circuit shown in Fig. 8, where R_s (Ω·cm²) is the solution resistance, R_f (Ω·cm²) is the resistance associated with the corrosion products film formed on the copper surface, R_{ct} (Ω·cm²) is the charge transfer resistance corresponding to electron transfer at the Cu/electrolyte interface, CPE1 (10^{-5}·Ω^{-1}·cm^{-2}·sm) is the constant phase element of the corrosion products film, CPE2 (10^{-5}·Ω^{-1}·cm^{-2}·sn) is the constant phase element of the double layer, and W (10^{-3}·Ω^{-1}·cm^{-2}·s$^{1/2}$) is the Warburg impedance related to diffusion processes in the low-frequency region. The values of m and n measure the heterogeneity and roughness of the surface.[15]

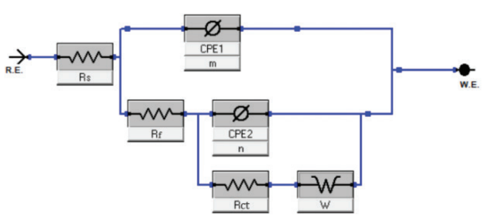

Fig. 8 – Electrochemical equivalent circuit

Using the fitting procedure, the results presented in Table 2 were obtained. The polarisation resistance (R_f + R_{ct}) was used to calculate IE_{EIS} (%) according to Eq. (2), where represents the sum of R_f and R_{ct}.

Table 2 – EIS parameters for Cu-DHP corrosion in 0.5 M NaCl solution with and without the addition of WWBE at 25 °C

C_{inh} / g l^{-1}	0	0.1	0.3	0.5
R_s / Ω·cm²	19.44	20.96	19.29	19.78
R_f / Ω·cm²	11200	21650	27900	39320
R_{ct} / Ω·cm²	0.485	552.400	1354.000	6284.000
R_f+R_{ct} / Ω·cm²	11200.5	22202.4	29254.0	45604.0
CPE1 / 10^{-5}·Ω^{-1}·cm^{-2}·s^m	0.45	0.64	0.38	0.13
m	0.86	0.80	0.87	0.90
CPE2 / 10^{-5}·Ω^{-1}·cm^{-2}·s^n	7.99	4.55	4.40	1.97
n	0.56	0.66	0.58	0.49
W / 10^{-3}·Ω^{-1}·cm^{-2}·s$^{1/2}$	76.9	17.1	20.4	13.7
GofF / 10^{-3}	0.370	0.102	0.501	0.336
θ	–	0.4955	0.6171	0.7544
IE_{EIS} / %	–	49.55	61.71	75.44

Based on the values in Table 2, the solution resistance values in the presence of WWBE are similar to those without WWBE. The R_f and R_{ct} values in the presence of WWBE are higher than those without the additive, indicating that the extract creates a barrier on the copper surface, preventing contact between the metal and the electrolyte and thereby inhibiting copper corrosion in chloride conditions.[27] The values of both constant phase elements decrease significantly in the presence of WWBE, which can be attributed to the replacement of water molecules by corrosion inhibitor molecules at the copper-electrolyte interface, as well as the formation of a smaller amount of corrosion products on the copper surface.[28,29] The values of parameter m in the presence of the inhibitor are similar to those in 0.5 M NaCl solution without WWBE, indicating a rough and porous copper surface due to the formation of corrosion products.[15] The value of parameter n showed a significant change in the presence of the inhibitor, suggesting that the reduction in dissolved O_2 was a minor cathodic process.[24] The Warburg impedance was lower in the presence of WWBE compared to the solution without the additive, indicating that the corrosion process was significantly less activation/diffusion-controlled in the presence of the inhibitor.[4] The degree of surface coverage and inhibition efficiency using WWBE as a corrosion inhibitor for Cu-DHP in 0.5 M NaCl solution increased with increasing WWBE concentration. Overall, the EIS results indicate that WWBE acts as an inhibitor of copper corrosion in chloride conditions, significantly affecting both the resistances and constant phase elements of the investigated electrochemical system.

3.3 Adsorption isotherms

Results from electrochemical frequency modulation (EFM) and electrochemical impedance spectroscopy (EIS) were used to determine the adsorption isotherm of WWBE on the surface of Cu-DHP in a 0.5 M NaCl solution. Analysis of the adsorption isotherms showed that the Langmuir adsorption model provided the best fit, as shown in Fig. 9. The Equation (3) was used to determine the Langmuir isotherm[4].

$$\frac{C_{inh}}{\theta} = C + \left(\frac{1}{K_{ads}}\right) \quad (3)$$

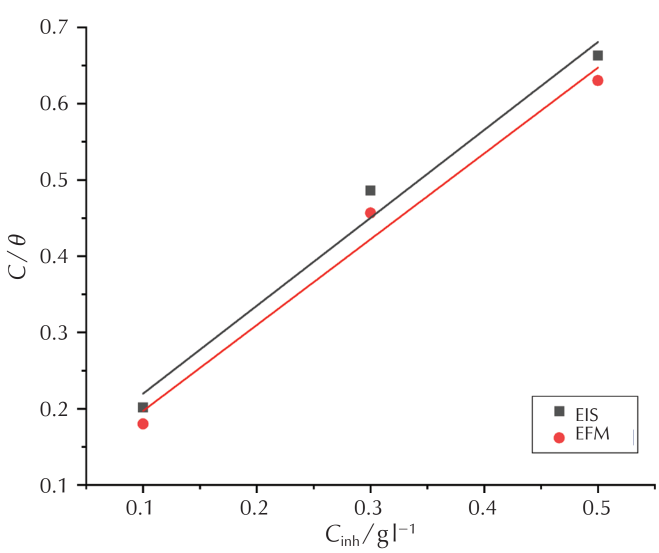

Fig. 9 – Langmuir adsorption isotherm of Cu-DHP in 0.5 M NaCl solution with the addition of WWBE, obtained by electrochemical frequency modulation (EFM) and electrochemical impedance spectroscopy (EIS)

C_{inh} (g l^{-1}) is inhibitor concentration, θ is the degree of surface coverage, and K_{ads} (l mol^{-1}) is the equilibrium constant of the adsorption–desorption process. Relation $\theta = IE/100$ was used to calculate the degree of surface coverage, where *IE* is the inhibition efficiency.[30]

A regression equation was obtained for each function:

$$y = 1.1525 \cdot x + 0.104483,\ R^2_{EIS} = 0.98217 \quad (4)$$

$$y = 1.125 \cdot x + 0.084667,\ R^2_{EFM} = 0.98284 \quad (5)$$

Since the adsorption of WWBE molecules followed the Langmuir adsorption isotherm, the molecules were adsorbed at single active sites without interaction between adsorbed molecules.[4,30] Based on the equilibrium constant obtained from the regression equations, the Gibbs free energy of adsorption (ΔG°_{ads}) was calculated using the Eq. (6).[31]

$$\Delta G^\circ_{ads} = -RT \ln(55.5\ K_{ads}) \quad (6)$$

R is the universal gas constant (J mol^{-1} K^{-1}), *T* is the absolute temperature (K), and 55.5 is the molar concentration of water. The ΔG°_{ads} values obtained were −15.39 kJ mol^{-1} (EIS) and −15.89 kJ mol^{-1} (EFM). Very close values were obtained for both methods and both values, indicating that spontaneous physisorption of WWBE molecules occurred on the copper surface in 0.5 M NaCl solution.[4,29]

3.4 UV–Vis spectroscopy

The results obtained by UV–Vis spectroscopy are presented as spectra in Fig. 10. UV–Vis spectra were recorded for 0.5 mol l^{-1} NaCl solution containing 0.5 g l^{-1} WWBE, both before and after immersion of the copper coupon.

Comparison of these two spectra shows no change in shape when copper was added to the solution. The adsorption maximum and the slight slope appeared at the same wavelengths on both curves, corresponding to a solution of 0.5 M NaCl containing the plant inhibitor, both with and without copper.[19] The change in the absorption maximum in the presence of copper indicates the formation of an organometallic complex between WWBE molecules and copper ions from the solution.[19,32] Moreover, such a change in the wavelength of the adsorption maximum suggests that the electron transfer can be attributed to π–π* and n–π* transitions.[19]

3.5 Comparison with previous results

To assess the significance of WWBE in protecting copper from corrosion in chlorine conditions, a comparison with previous studies is provided in Table 3. These include the corrosion-inhibiting performance of acetylsalicylic acid – a compound obtained from white willow bark – as well as other copper corrosion inhibitors in chloride conditions derived from various tree bark.

Based on the values shown in Table 3, WWBE exhibited higher maximum corrosion inhibition efficiency than acetylsalicylic acid, although it should be noted that the

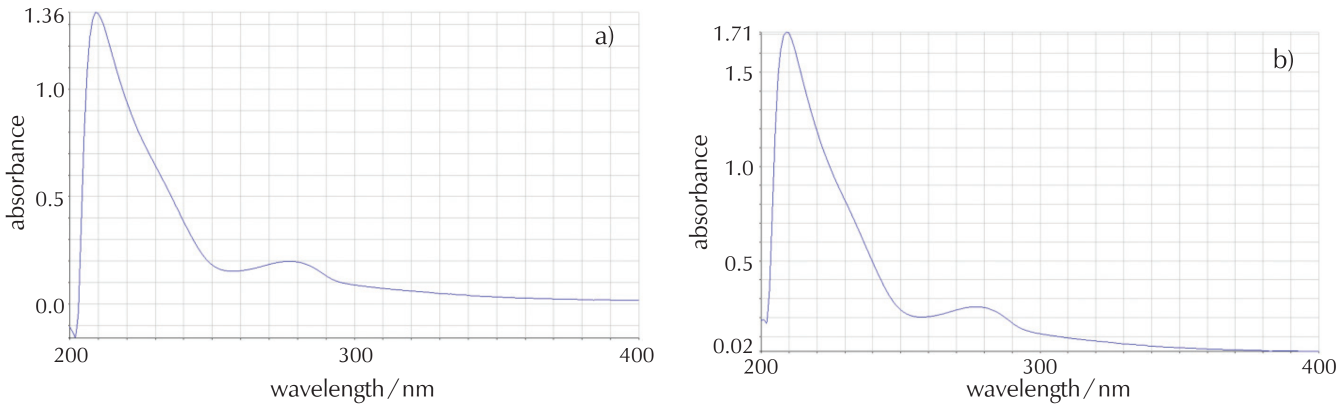

Fig. 10 – UV–Vis spectra of 0.5 mol l^{-1} NaCl containing 0.5 g l^{-1} WWBE (a) before, and (b) after 24 h of copper immersion

Table 3 – Comparison of WWBE with similar copper corrosion inhibitors under chloride conditions

Corrosion inhibitor	Electrolyte	Inhibitor concentration	Max IE / %	Inhibitor type	Adsorption isotherm	Literature
WWBE	0.5 M NaCl	0.5 g l^{-1}	79	Cathodic	Langmuir	–
Acetylsalicylic acid	0.5 M HCl	120 ppm	67	Cathodic	Langmuir	8
Cassia siamea-gonrai	0.005 M NaCl	*4 %	58	–	Langmuir	33
Cassia auriculata	0.005 M NaCl	*4 %	72	–	Langmuir	33
Crataeva religiosa	0.005 M NaCl	*4 %	77	–	Langmuir	33
Strychnos nux-vomica	0.005 M NaCl	*4 %	80	–	Langmuir	33

* vapour phase

WWBE concentration used was higher. When compared to other bark-derived inhibitors, WWBE performed better than most. An additional advantage of WWBE is that its maximum inhibition efficiency was achieved in a NaCl solution of higher concentration, where the influence of chloride ions on corrosion is greater. A similar corrosion protection mechanism was observed for WWBE and acetylsalicylic acid, whereas the other bark-derived inhibitors listed showed no significant effect on either the anodic or the cathodic mechanism. All copper corrosion inhibitors examined in chloride conditions adsorbed onto the copper surface according to the Langmuir adsorption isotherm.

4 Conclusion

White willow bark extract (WWBE) acts as an environmentally friendly copper corrosion inhibitor in 0.5 M NaCl solution. WWBE acted as a cathodic-type copper corrosion inhibitor under chloride conditions, attributable to the presence of acetylsalicylic acid in the white willow bark. The corrosion inhibition efficiency increased with higher WWBE concentrations. Spontaneous physisorption of the inhibitor occurred on the copper surface according to the Langmuir adsorption isotherm, forming a barrier that prevents contact between the metal and the electrolyte, thereby inhibiting copper corrosion. The copper corrosion process in 0.5 M NaCl solution without WWBE was activation/diffusion-controlled. In the presence of WWBE, the corrosion process was less activation/diffusion-controlled, and the inhibitor significantly affected the constant phase elements of the corrosion film and the electrochemical double layer. The copper ions transferred to the electrolyte through corrosion interacted with WWBE molecules to form organometallic complexes. Future research into WWBE will focus on more precise identification of the compounds and organometallic complexes that affect copper corrosion in chloride electrolyte. Considering the small number of publications related to the analysis of plant bark as a potential inhibitor of copper corrosion in chloride conditions, the results obtained with WWBE demonstrate a strong potential for discovering new environmentally acceptable copper corrosion inhibitors derived from plant bark.

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List of abbreviations and symbols

WWBE	– white willow bark extract
Cu-DHP	– deoxidised, oxygen-free copper
EFM	– electrochemical frequency modulation
EIS	– electrochemical impedance spectroscopy
UV-Vis	– ultraviolet-visible spectroscopy
SHE	– standard hydrogen electrode
j_{corr}	– corrosion current density in blank solution
$j_{corr(inh)}$	– corrosion current density in the presence of WWBE
R_p	– polarisation resistance of copper in 0.5 M NaCl with the addition of WWBE
R_p^0	– polarisation resistance of copper in 0.5 M NaCl without the addition of WWBE
β_1	– anodic Tafel constant
β_2	– cathodic Tafel constant
CF-2, CF-3	– causal factors for EFM method
CR	– corrosion rate
IE_{EFM}	– inhibition efficiency of WWBE for EFM method
IE_{EIS}	– inhibition efficiency of WWBE for EIS method
Z_{mod}	– impedance modulus
Z_{imag}	– imaginary impedance
Z_{real}	– real impedance
R_s	– solution resistance
R_f	– resistance associated with the corrosion products film
R_{ct}	– charge transfer resistance
CPE1	– constant phase element of the corrosion products film
CPE2	– constant phase element of the double layer
W	– Warburg impedance
m	– measure of surface heterogeneity
n	– measure surface roughness
C_{inh}	– inhibitor concentration
θ	– degree of surface coverage
K_{ads}	– equilibrium constant of the adsorption–desorption process
ΔG°_{ads}	– Gibbs free energy of adsorption
R	– universal gas constant
T	– absolute temperature

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SAŽETAK

Ekstrakt kore bijele vrbe kao inhibitor korozije bakra

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Ovo istraživanje ispituje ekstrakt kore bijele vrbe (WWBE) kao potencijalni inhibitor korozije Cu-DHP u otopini 0,5 M NaCl, primjenom nedestruktivnih elektrokemijskih metoda, i to elektrokemijske frekvencijske modulacije (EFM) i elektrokemijske impedancijske spektroskopije (EIS). Elektroliti su se sastojali od otopina 0,5 M NaCl, s i bez dodatka WWBE (0,1–0,5 g l^{-1}). Otopina 0,5 M NaCl s dodatkom 0,5 g l^{-1} WWBE, u prisutnosti i bez bakrene ploče, analizirana je ultraljubičasto-vidljivom spektroskopijom (UV-Vis). Eksperimenti su provedeni pri sobnoj temperaturi. Rezultati EFM metode pokazali su da WWBE djeluje kao katodni inhibitor korozije bakra, s najvećom učinkovitošću inhibicije u otopini 0,5 M NaCl koja sadrži 0,5 g l^{-1} WWBE. Rezultati EIS metode upućuju na stvaranje zaštitnog filma inhibitora WWBE. Proces korozije bio je kontroliran difuzijom, kako u prisutnosti tako i bez dodatka WWBE. Obje elektrokemijske metode pokazale su da se WWBE adsorbira na površinu bakra u otopini 0,5 M NaCl fizisorpcijom, slijedeći Langmuirovu adsorpcijsku izotermu. Vrijednosti Gibbsove slobodne energije adsorpcije bile su slične za EFM i EIS metode. UV-VIS rezultati pokazali su da uranjanje bakra u elektrolit koji sadrži 0,5 g l^{-1} WWBE tijekom 24 h dovodi do promjene maksimuma apsorbancije, što ukazuje na stvaranje kompleksa bakar–WWBE. Sveukupno, rezultati pokazuju da je WWBE učinkovit inhibitor korozije bakra u kloridnim uvjetima. Daljnja istraživanja bit će usmjerena na identifikaciju spojeva i organometalnih kompleksa u WWBE te njihov pojedinačni utjecaj na proces korozije.

Ključne riječi
Kora bijele vrbe, NaCl, Cu-DHP, EFM, EIS, UV-VIS

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