

Synergistic Corrosion Inhibition of Carbon Steel in Borewell Water by Beetroot Extract and Zn^{2+} : Gravimetric, Electrochemical and Surface-Morphological Investigations

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Research Article

Keywords: carbon steel, corrosion inhibition, beetroot extract, Zn^{2+} , green inhibitor, weight-loss method, polarization, electrochemical impedance spectroscopy, SEM, synergistic inhibition

Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11255956/v1>

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Additional Declarations: The authors declare no competing interests.

Abstract

Corrosion of carbon steel in aqueous environments represents a persistent materials challenge because prolonged exposure to electrolytes can lead to surface degradation, loss of mechanical integrity and premature failure. The development of environmentally benign corrosion inhibitors based on naturally occurring plant materials has therefore attracted considerable attention as an alternative to conventional inorganic inhibitors. In the present study, the corrosion-inhibiting behaviour of an aqueous beetroot extract, both alone and in combination with Zn^{2+} , was investigated for carbon steel immersed in borewell water. The inhibitor performance was evaluated using gravimetric weight-loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and scanning electron microscopy (SEM). The weight-loss experiments revealed that beetroot extract alone exhibited limited inhibition at low concentration and could accelerate corrosion at higher concentrations. In contrast, the combined beetroot extract– Zn^{2+} system demonstrated a pronounced synergistic effect. In particular, the combination of 8 mL beetroot extract with 50 ppm Zn^{2+} produced an inhibition efficiency of 84%, whereas beetroot extract alone at the corresponding concentration showed an inhibition efficiency of –30% and 50 ppm Zn^{2+} alone exhibited approximately 14% inhibition. Electrochemical measurements further indicated an increase in linear polarization resistance and charge-transfer resistance accompanied by a decrease in corrosion current density and double-layer capacitance in the presence of the inhibitor system. The corrosion potential shifted from –756 mV to –531 mV versus SCE, suggesting a predominantly anodic contribution to corrosion inhibition. SEM observations revealed substantial surface smoothing and reduced evidence of corrosion-product formation in the inhibited system. The results demonstrate that beetroot-derived phytochemicals can act synergistically with Zn^{2+} to produce an effective and potentially environmentally preferable corrosion-inhibition system for carbon steel in aqueous environments.

1. Introduction

Corrosion is an electrochemical degradation process that progressively compromises metallic materials when they interact with their surrounding environment. Carbon and low-alloy steels are extensively employed in structural, industrial and engineering applications because of their favourable mechanical properties, availability and relatively low cost. However, their exposure to aqueous electrolytes can initiate electrochemical reactions that progressively deteriorate the metal surface. Natural waters, seawater and industrial process solutions can therefore represent aggressive environments for carbon steel.

The severity of corrosion depends strongly on the characteristics of the surrounding environment and the nature of the metal surface. In marine environments, for example, the splash, tidal, submerged and atmospheric zones can produce distinctly different corrosion conditions. Previous investigations have demonstrated that the corrosion behaviour of carbon and alloy steels varies considerably with environmental exposure and alloy composition [1–4].

In industrial applications, metallic materials may also encounter acidic or alkaline solutions that accelerate electrochemical dissolution. Corrosion inhibitors provide an established approach for mitigating such degradation. These compounds generally act by modifying the electrochemical reactions at the metal–solution interface and/or by forming an adsorbed protective layer that limits interaction between the metal surface and the corrosive medium [5–8].

Conventional corrosion inhibitors have included inorganic compounds such as chromates, phosphates, nitrites and zinc-containing formulations. Although such materials can provide effective corrosion protection, concerns regarding toxicity, persistence and environmental impact have encouraged the development of safer alternatives. This has stimulated considerable interest in naturally derived or “green” corrosion inhibitors obtained from plant leaves, roots, seeds and other renewable biological sources [9–19].

Plant extracts contain diverse organic molecules bearing functional groups and π -electron systems capable of interacting with metallic surfaces. Functional groups such as hydroxyl, amino, ether, sulfur-containing and unsaturated groups may participate in adsorption processes and thereby contribute to surface protection. A variety of plant-derived extracts have consequently been investigated as corrosion inhibitors for different metals and alloys [11–19].

Root-derived materials are particularly interesting because they contain a complex mixture of naturally occurring organic constituents. Previous investigations have examined several plant-root extracts for corrosion inhibition. The present work examines the interaction between aqueous beetroot extract and Zn^{2+} in controlling the corrosion of carbon steel in borewell water.

The objectives of the study were to: (i) evaluate the corrosion-inhibition efficiency of aqueous beetroot extract for carbon steel in borewell water using the weight-loss method; (ii) investigate the influence of Zn^{2+} on the protective performance of beetroot extract; (iii) determine the electrochemical behaviour of the metal in the absence and presence of the inhibitor system using polarization and electrochemical impedance measurements; (iv) examine changes in the morphology of the carbon-steel surface using SEM; and (v) develop a mechanistic interpretation of the observed synergistic inhibition behaviour.

2. Materials and Methods

2.1 Preparation of Beetroot Extract

Fresh beetroot was cut into slices, dried and subsequently ground into a powder. Ten grams of the powdered beetroot material were boiled with double-distilled water. The resulting suspension was filtered to remove insoluble impurities and the filtrate was made up to a final volume of 100 mL with double-distilled water. The resulting aqueous extract was used as the plant-derived corrosion inhibitor.

2.2 Carbon-Steel Specimens

Carbon-steel specimens having the composition 0.026% S, 0.06% P, 0.4% Mn, 0.1% C, with the balance being iron, were employed. The specimens had dimensions of $1.0 \times 4.0 \times 0.2$ cm. Prior to experimentation, the specimens were mechanically polished to obtain a mirror-like surface and were degreased with trichloroethylene. The prepared specimens were subsequently used for weight-loss and surface-characterization investigations.

2.3 Gravimetric Weight-Loss Measurements

The corrosion behaviour of carbon steel was investigated in borewell water in the absence and presence of beetroot extract and Zn^{2+} . Different volumes of beetroot extract were evaluated, both independently and in combination with Zn^{2+} at concentrations of 25 and 50 ppm. The change in mass of the carbon-steel specimens before and after exposure was used to determine weight loss and the corresponding corrosion behaviour. The inhibition efficiency (IE) was evaluated by comparison with the uninhibited system.

The original experimental record reports the corrosion rate and inhibition efficiency for each condition; the exposure duration and the exact calculation equation were not explicitly stated in the source manuscript and should be confirmed before submission.

2.4 Effect of Zn^{2+}

The influence of Zn^{2+} on beetroot-mediated corrosion inhibition was investigated at concentrations of 25 and 50 ppm. The combined systems were compared with beetroot extract alone and Zn^{2+} -containing systems.

2.5 Surface Characterization

Scanning electron microscopy (SEM) was employed to examine the morphology of the carbon-steel surface after exposure to the test solutions. SEM was used to compare the surface condition in uninhibited and inhibited environments.

2.6 Electrochemical Measurements

Electrochemical measurements were carried out using a three-electrode cell configuration. Potentiodynamic polarization measurements were used to determine corrosion potential (E_{corr}), corrosion current density (I_{corr}), anodic and cathodic Tafel slopes and linear polarization resistance (LPR). Electrochemical impedance spectroscopy (EIS) was used to determine charge-transfer resistance (R_t), double-layer capacitance (C_{dl}), impedance and phase-angle characteristics.

The original manuscript does not specify the working-electrode area, reference/counter-electrode identities, polarization scan rate, EIS frequency range, amplitude, temperature or equivalent-circuit model. These parameters should be added from the laboratory records before final submission.

3. Results

3.1 Gravimetric Behaviour of Beetroot Extract Alone

The weight-loss data show concentration-dependent behaviour for beetroot extract in borewell water. At 2 mL extract, an inhibition efficiency of approximately 35% was reported. Increasing the extract concentration resulted in progressively lower inhibition and ultimately negative inhibition efficiencies, indicating accelerated metal dissolution under the reported conditions. At 8 mL extract, the reported inhibition efficiency was – 30%.

Table 1
Weight-loss data for carbon steel in borewell water containing beetroot extract alone.

Sl .No	Beet Root Extract (ML)	Metal Number	Weight Before Immersion (W1)	Wight After Immersion (W2)	Weight Loss	Average	Corrosion rate	I.E %
1	0	28	3.2578	3.2552	0.0026	0.00264	21.01	- %
1	0	30	3.0844	3.0812	0.00328	0.00264	21.01	- %
2	2	42	3.0666	3.0662	0.0004	0.0019	13.63	35%
2	2	45	3.2062	3.2028	0.0034	0.0019	13.63	35%
3	4	50	3.19058	3.1870	0.00358	0.00349	25.04	-18%
3	4	52	3.3926	3.3892	0.0034	0.00349	25.04	-18%
4	6	53	3.3340	3.3303	0.0037	0.0036	25.83	-22%
4	6	68	3.1482	3.1447	0.0035	0.0036	25.83	-22%
5	8	97	3.3016	3.2987	0.00029	0.00385	27.63	-30%
5	8	98	3.1907	3.1871	0.0036	0.00385	27.63	-30%

3.2 Effect of 25 ppm Zn²⁺

Addition of 25 ppm Zn²⁺ substantially modified the behaviour of beetroot extract. The reported inhibition efficiencies were 23% for the blank Zn²⁺ system, 28% at 2 mL extract, 48% at 4 mL, 31% at 6 mL and 43% at 8 mL extract.

Table 2

Weight-loss data for carbon steel in borewell water containing beetroot extract and 25 ppm Zn^{2+} .

Sl .No	Beet Root Extract (ml)	Metal Number	Weight Before Immersion (W1)	Wight After Immersion (W2)	Weight Loss	Average	Corrosion rate	I.E %
1	0	28	3.2563	3.2552	0.0011	0.000575	41.26	23%
1	0	30	3.0824	3.0812	0.0012	0.000575	41.26	23%
2	2	42	3.1888	3.1870	0.0018	0.0021	1.50	28%
2	2	45	3.3916	3.3892	0.0024	0.0021	1.50	28%
3	4	50	3.1870	3.1888	0.007	0.0015	1.07	48%
3	4	52	3.3051	3.2028	0.0023	0.0015	1.07	48%
4	6	53	3.3321	3.3303	0.0018	0.002	1.43	31%
4	6	68	3.1469	3.1447	0.0022	0.002	1.43	31%
5	8	97	3.2995	3.2987	0.0008	0.00165	1.18	43%
5	8	98	3.1893	3.1871	0.0022	0.00165	1.18	43%

3.3 Effect of 50 ppm Zn^{2+}

A stronger synergistic effect was observed at 50 ppm Zn^{2+} . The inhibition efficiency increased from 14% for Zn^{2+} alone to 57%, 67%, 60% and 84% at 2, 4, 6 and 8 mL beetroot extract, respectively. The maximum reported inhibition efficiency was therefore 84% for the 8 mL beetroot extract + 50 ppm Zn^{2+} system.

Table 3

Weight-loss data for carbon steel in borewell water containing beetroot extract and 50 ppm Zn²⁺.

Sl .No	Beet Root Extract (MI)	Metal Number	Weight Before Immersion (W1)	Wight After Immersion (W2)	Weight Loss	Average	Corrosion rate	I.E %
1	0	28	3.2563	3.2558	0.0005	0.00045	32.29	14%
1	0	30	3.0824	3.0820	0.0004	0.00045	32.29	14%
2	2	42	3.0669	3.0660	0.0009	0.00095	0.68	57%
2	2	45	3.2051	3.2035	0.00016	0.00095	0.68	57%
3	4	50	3.1888	3.1875	0.0004	0.00125	0.89	67%
3	4	52	3.3916	3.3910	0.0013	0.00125	0.89	67%
4	6	53	3.3321	3.3309	0.0012	0.00165	1.18	60%
4	6	68	3.1469	3.1448	0.0021	0.00165	1.18	60%
5	8	97	3.2995	3.2985	0.0001	0.00115	0.82	84%
5	8	98	3.1893	3.1880	0.0013	0.00115	0.82	84%

3.4 Polarization Measurements

The electrochemical polarization results indicate increased corrosion resistance in the presence of beetroot extract. The corrosion potential shifted from – 756 mV/SCE for borewell water to – 531 mV/SCE in the presence of beetroot extract. The corrosion current density decreased from 1.121×10^{-5} to 1.007×10^{-5} A cm⁻², while LPR increased from 3385 to 3980 Ω cm².

Table 4

Electrochemical polarization parameters for carbon steel.

System	E _{corr} mV/SCE	b _c mV/decade	b _a mV/decade	LPR Ohmcm2	I _{corr} A/cm2
Borewell water	-756	153	204	3385	1.121×10^{-5}
Borewell water + Beetroot extract	-531	239	150	3980	1.007×10^{-5}

3.5 Electrochemical Impedance Spectroscopy

The EIS data show a marked increase in charge-transfer resistance from 312 to 2189 Ω cm² in the presence of beetroot extract. The double-layer capacitance decreased from 16.36×10^{-9} to 2.329×10^{-9} F cm⁻². The reported impedance and phase angle also increased from 2.59 to 3.376 and from 38° to 41°, respectively.

Table 5
Electrochemical impedance parameters for carbon steel.

System	R _t Ohmcm ²	C _{dl} F/cm ²	Impedance Log(Z/Ohm)	PhaseAngle°
Borewell water	312	16.36x10 ⁻⁹	2.59	38
Borewell water + Beetroot extract	2189	2.329 x10 ⁻⁹	3.376	41

4. Discussion

The gravimetric results demonstrate that the corrosion-inhibition behaviour of beetroot extract is not simply proportional to extract concentration. Beetroot extract alone produced moderate inhibition at 2 mL but became increasingly ineffective at higher concentrations, with negative inhibition at 4–8 mL. This observation suggests that the net interfacial effect of the mixture depends on concentration and on the balance between adsorbing organic constituents and species that may promote metal dissolution.

The introduction of Zn²⁺ changes this behaviour substantially. At 25 ppm Zn²⁺, the reported inhibition efficiencies were higher than those of beetroot extract alone over much of the investigated concentration range. At 50 ppm Zn²⁺, the effect was still more pronounced, culminating in 84% inhibition at 8 mL beetroot extract. Because 8 mL beetroot extract alone produced – 30% inhibition and 50 ppm Zn²⁺ alone produced 14% inhibition, the combined response is consistent with a synergistic interaction rather than a simple additive effect.

The electrochemical data support the formation of a protective interfacial layer. The increase in LPR and decrease in corrosion current density indicate suppression of the overall electrochemical corrosion process. The shift in E_{corr} toward the anodic direction, together with the reported Tafel parameters, suggests that anodic dissolution is particularly affected under the investigated conditions.

The EIS response provides complementary evidence. The large increase in R_t indicates greater resistance to charge transfer across the metal–solution interface. The pronounced decrease in C_{dl} is compatible with replacement or modification of water molecules at the interface by adsorbed inhibitor species and/or development of a protective layer. The increase in phase angle is also consistent with a more capacitive and protected interface.

The SEM observations are consistent with the electrochemical measurements. The untreated surface exposed to borewell water is described as rough and covered with corrosion products, whereas the surfaces in the presence of Zn²⁺ exhibit substantially greater smoothness. These morphological changes support the interpretation that adsorption and film formation reduce the accessibility of corrosive species to active sites on the steel surface.

Taken together, the gravimetric, electrochemical and morphological observations support a synergistic inhibition mechanism in which beetroot-derived organic constituents interact with Zn²⁺ and the carbon-

steel surface to produce a protective interfacial film. However, the precise molecular composition of the beetroot extract was not determined in the supplied study. Consequently, the mechanistic interpretation should be regarded as a chemically plausible working model rather than a definitive molecular mechanism.

5. Conclusion

- Aqueous beetroot extract exhibits concentration-dependent corrosion behaviour toward carbon steel in borewell water.
- Zn^{2+} markedly enhances the protective performance of the beetroot extract.
- The maximum reported inhibition efficiency was 84% for 8 mL beetroot extract in combination with 50 ppm Zn^{2+} .
- The combination shows a clear synergistic effect because the individual components produced substantially lower protection under the reported conditions.
- Polarization measurements indicate increased polarization resistance and reduced corrosion current density in the inhibited system.
- EIS measurements show increased charge-transfer resistance and decreased double-layer capacitance, supporting the development of a protective interfacial film.
- SEM observations demonstrate improved surface morphology in the presence of the inhibitor system.
- The beetroot extract– Zn^{2+} combination therefore represents a promising plant-derived/inorganic synergistic approach to corrosion control in aqueous environments. Further work should quantify the phytochemical composition, establish adsorption behaviour, evaluate temperature dependence and determine long-term stability before practical deployment.

Declarations

6.1 Ethics Approval and Consent to Participate

Not applicable. The reported work involved carbon-steel specimens and laboratory corrosion measurements and did not involve human participants, human biological material or experimental animals.

6.2 Consent for Publication

Not applicable.

6.3 Funding

No funding was provided.

6.4 Competing Interests

“The authors declare that they have no competing interests.”

6.5 Data Availability

The numerical results reported in the manuscript are presented in Tables 1–5. The authors confirm the underlying raw weight-loss and electrochemical datasets are available from the corresponding author.

6.6 Author Contributions

C.S.A. Raj conceived and conducted the experimental work, including preparation of the beetroot extract, preparation and treatment of carbon-steel specimens, corrosion measurements, electrochemical studies, and surface characterization. S. Rajendran contributed to the interpretation and scientific analysis of the experimental results. Both authors contributed to the preparation and revision of the manuscript and approved the final version.

6.7 Acknowledgements

The author, Dr. C.S.A. Raj, sincerely thanks Dr. S. Rajendran for his valuable encouragement, scientific support, and constructive guidance throughout the study.

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Figures

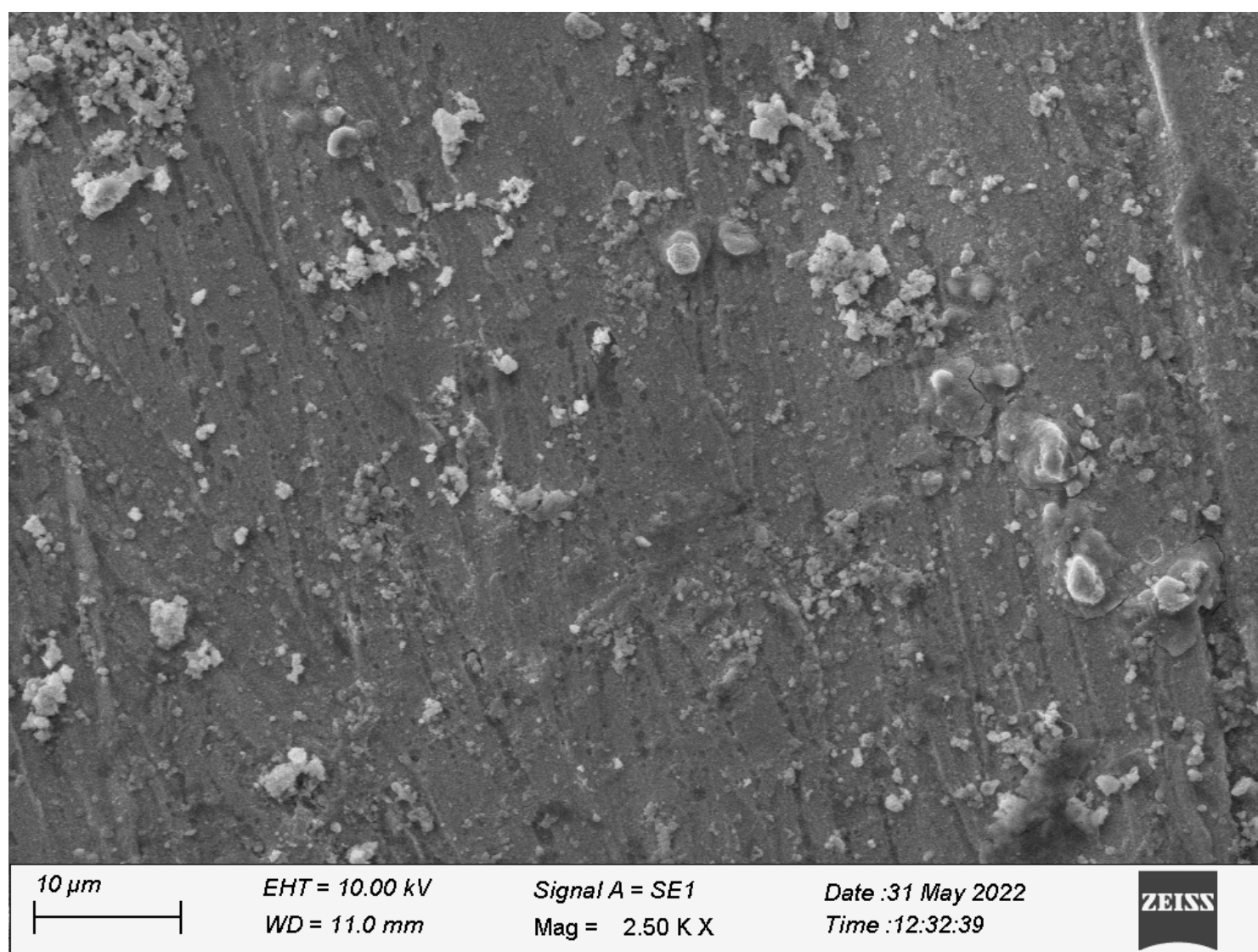


Figure 1

SEM morphology of carbon steel after immersion in borewell water.

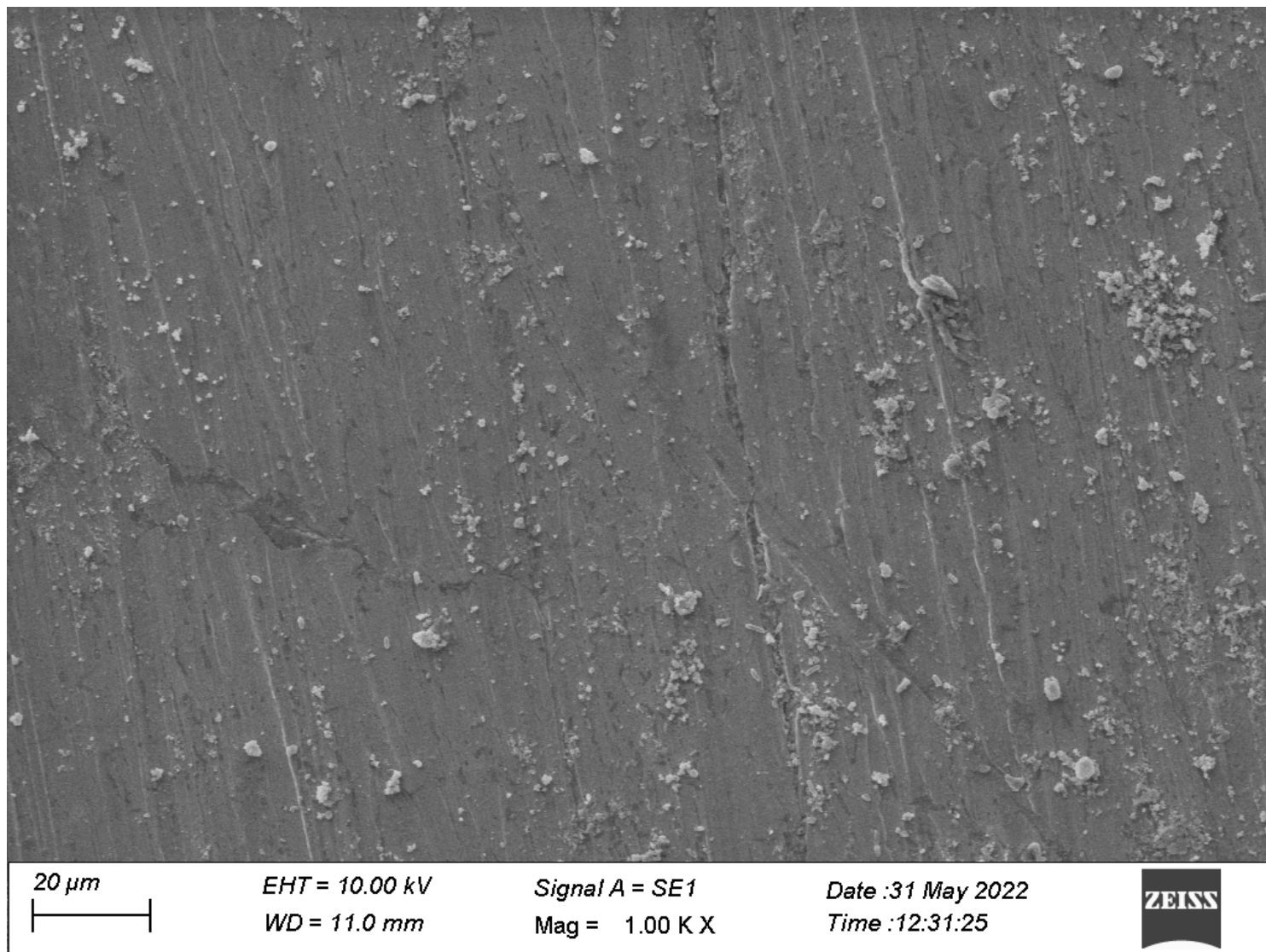


Figure 2

SEM morphology of carbon steel in borewell water containing 25 ppm Zn^{2+} .

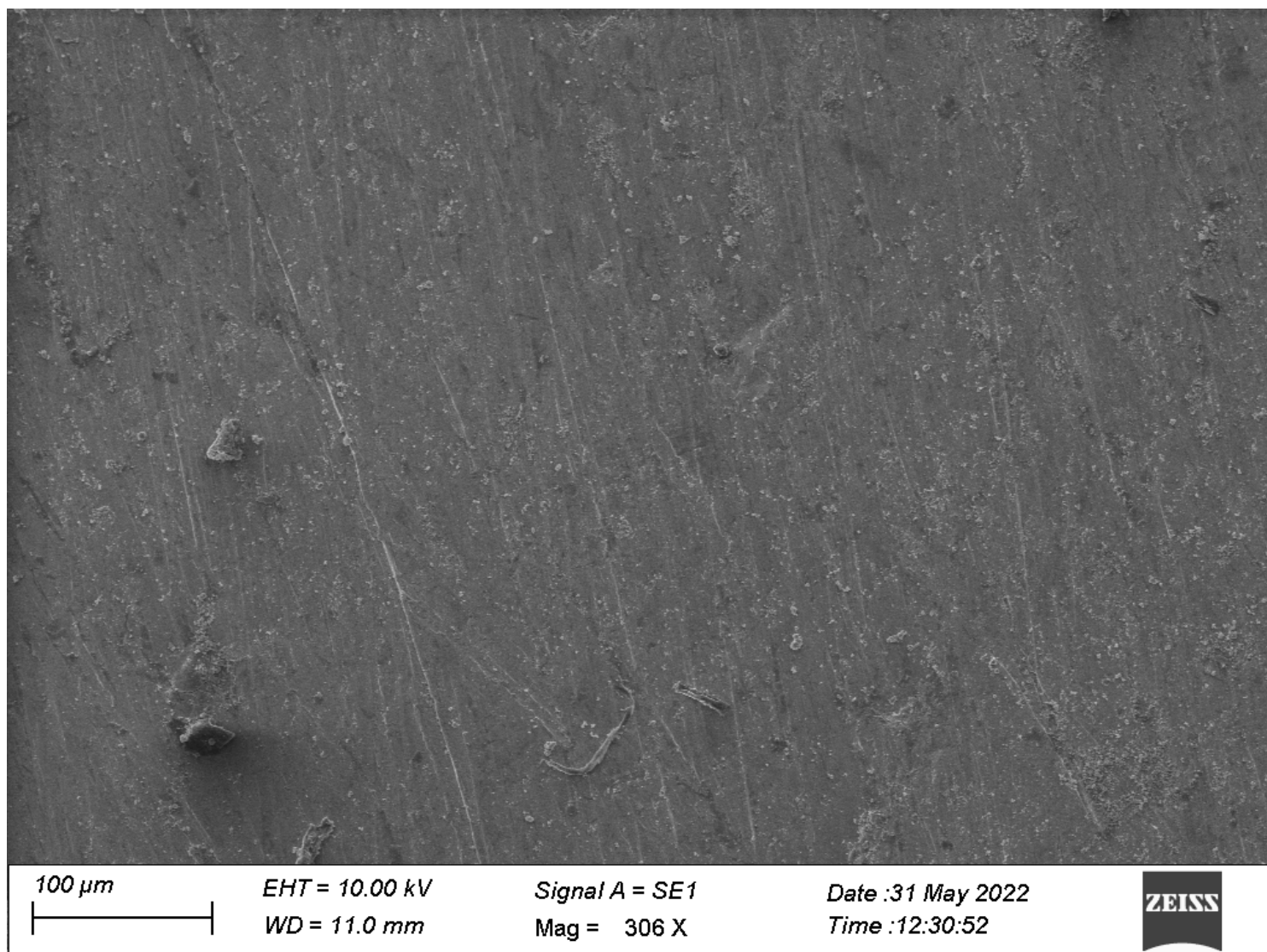


Figure 3

SEM morphology of carbon steel in borewell water containing 50 ppm Zn^{2+} .

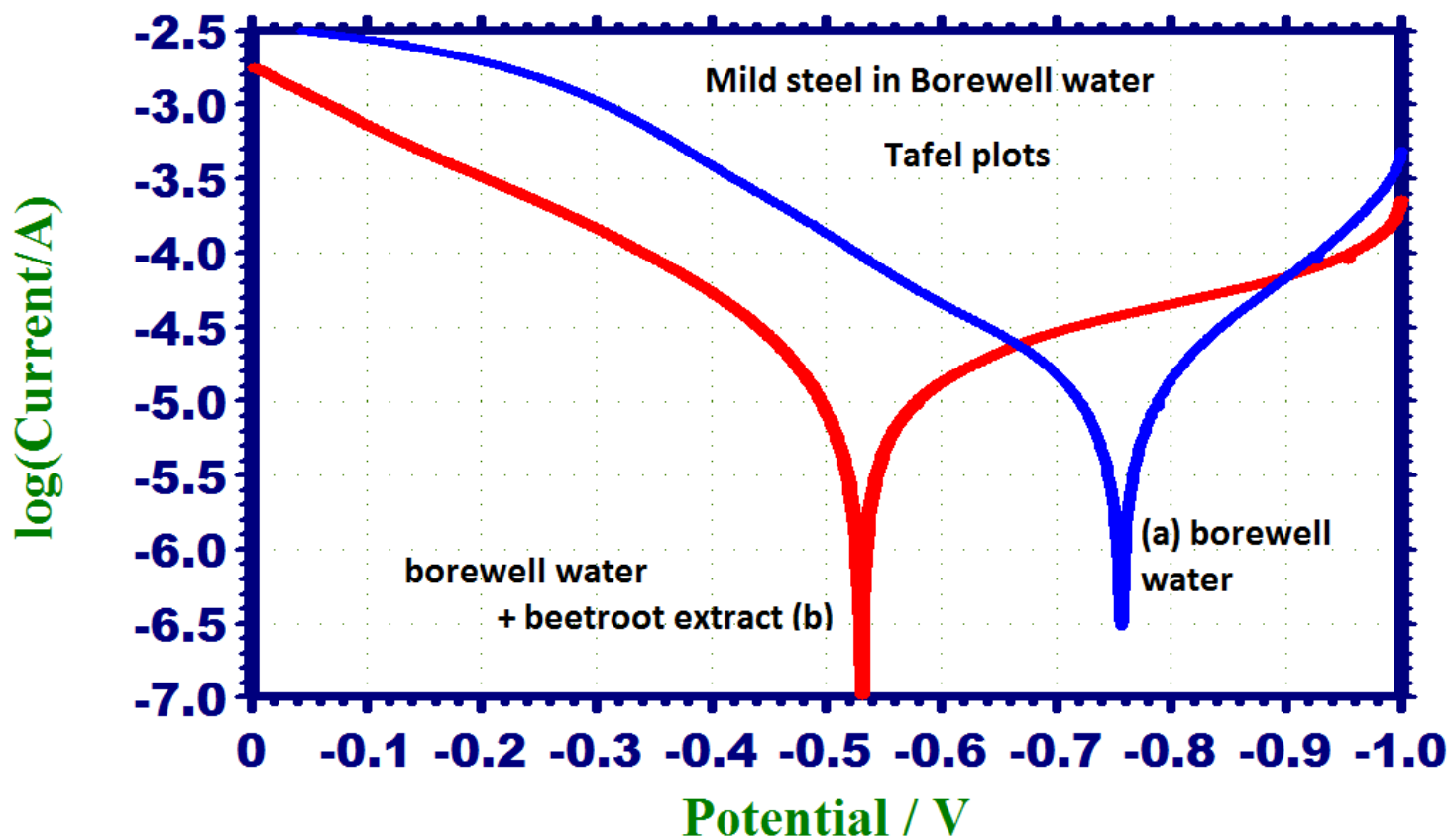


Figure 4

Polarization response of carbon steel in the investigated media.

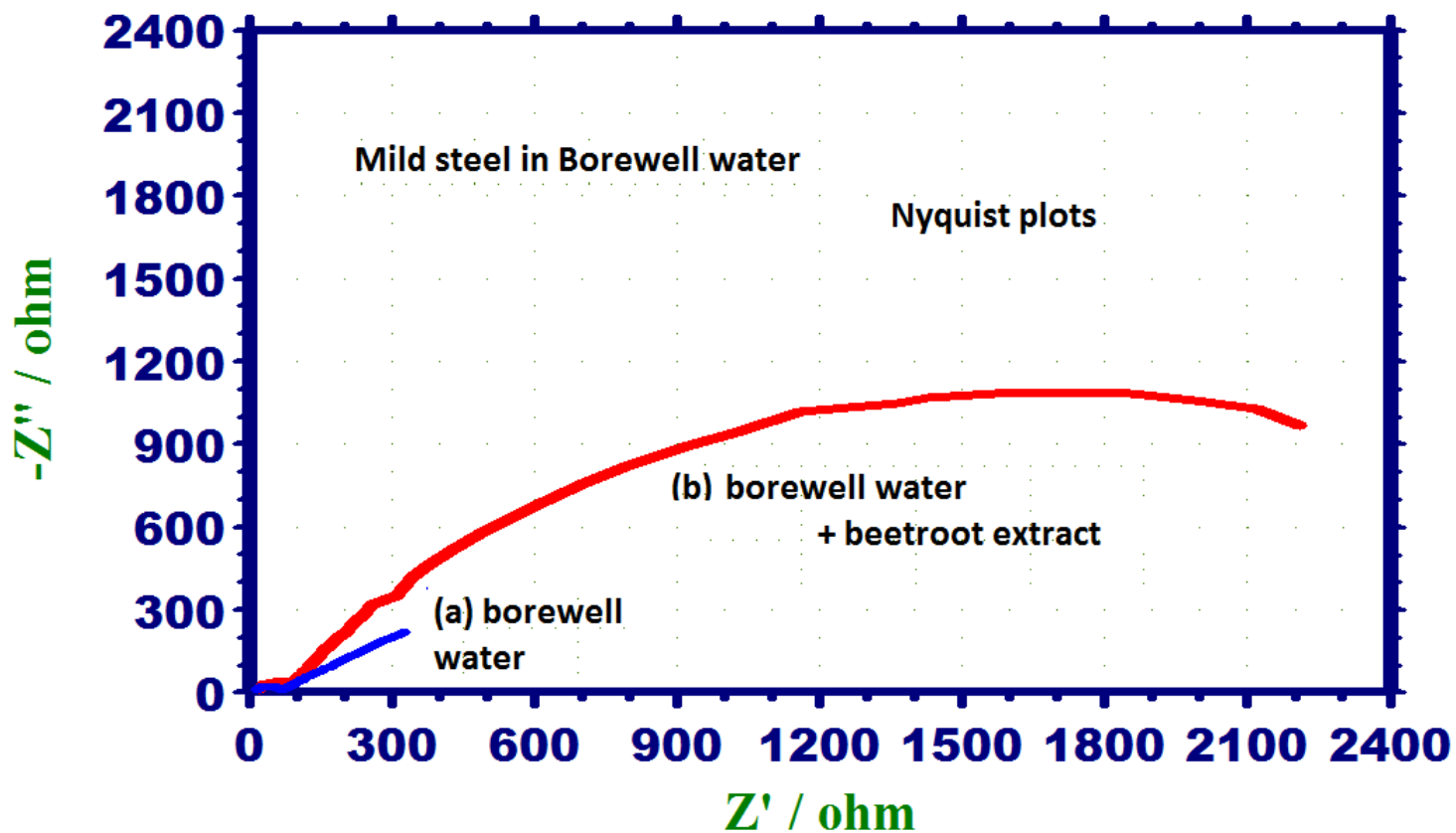


Figure 5

Potential–current response of carbon steel in borewell water and in the presence of beetroot extract.

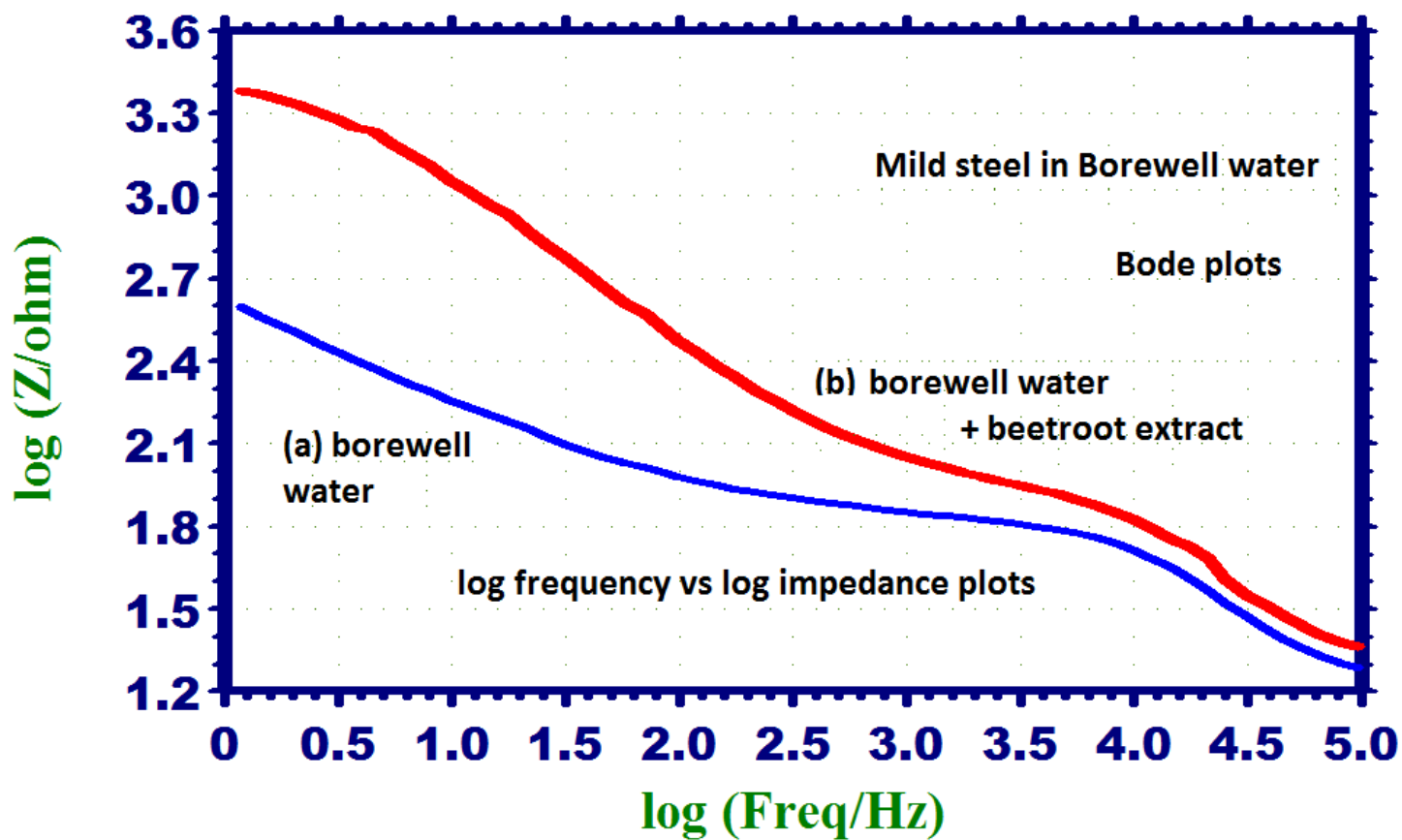


Figure 6

Nyquist representation for carbon steel in the investigated media.

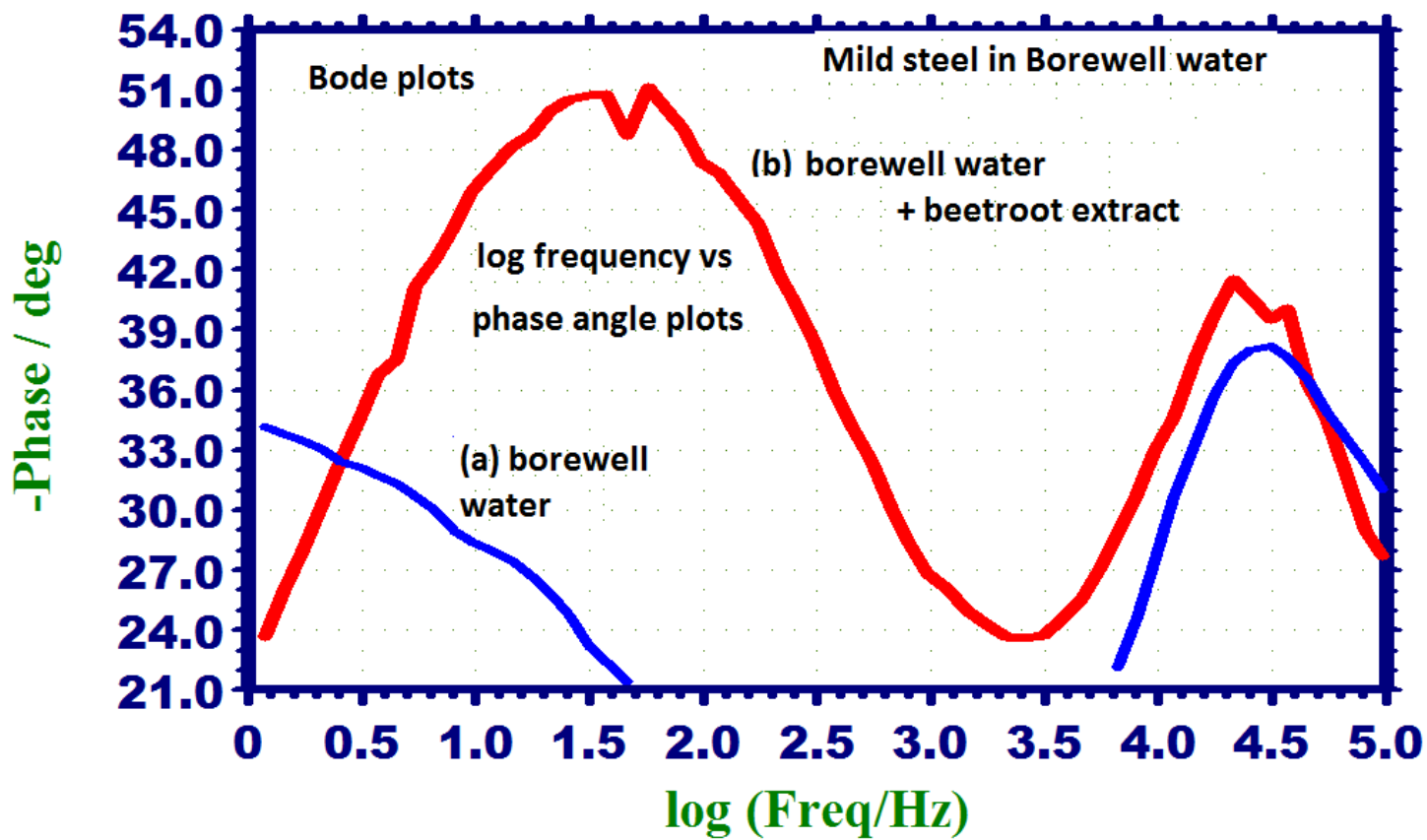


Figure 7

Bode/phase response for carbon steel in the investigated media.