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original scientific paper

## Sage Extract as a Natural Source of Corrosion Inhibitor for Tinplate in 3.0 % NaCl

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### SUMMARY

**Research background.** Due to the growing interest and attention of the world towards environmental problems and protection of environment, the worldwide demand for biodegradable and effective corrosion inhibitors for tinplate has grown. Considering the diversity of the structures of polyphenols that are present in sage extract, it represents a promising potential source of low-cost and biodegradable effective green corrosion inhibitors for tinplate in 3.0 % sodium chloride solution which is evaluated in this study.

**Experimental approach.** Tafel polarization and electrochemical impedance spectroscopy (EIS) at 25 °C has been used to evaluate the inhibition action of sage (*Salvia officinalis*, L.) extract as a green inhibitor for the corrosion protection for tinplate in 3.0 % sodium chloride solution.

**Results and conclusions.** Electrochemical impedance spectroscopy has been used to show that sage extract could serve as an effective inhibitor (90.2 %) for the corrosion of tinplate in 3.0 % NaCl at a concentration of 0.2 mg/L, and temperature of 25 °C. The results obtained from potentiodynamic polarization have revealed that the sage extract inhibitor acts as a mixed type, with inhibition efficiency up to 82.5% and the inhibition efficiencies calculated from EIS are in close

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agreement with those results. FTIR results indicated that the inhibitory effect of the sage extract is due to the presence of a passivation layer on the tinplate surface, which consists of organic compounds such as polyphenols. It has been confirmed by these results that the sage extract is more efficient at inhibiting the corrosion of tinplate at a concentration of 0.2 mg/L than in higher concentrations. Also, it exhibits good inhibitive performance for tinplate in 3 % sodium chloride solution.

*Novelty and scientific contributions.* The exceptional corrosion potential of sage extract opens a door for its use and revalorization as a green corrosion inhibitor in the food industry.

**Key words:** corrosion, green inhibitor, 3.0 % NaCl, sage, *Salvia officinalis*, tinplate

## INTRODUCTION

Tinplate cans are used for conserving various meat and fish food products, ready-made meals, pet foods, fats and oils, various fruit and vegetable products, and for packaging of confectionary products, coffee substitute drinks, other powdered food products and food supplements. Nature and addition of sodium chloride to canned food products have highly influenced the behaviour of tinplate. A 3.0 % sodium chloride solution is often used in the packaging of pet food, meat, some vegetable products and fish. Addition of some additives, such as nitrates or nitrites, as well as an increase in temperature can cause corrosion of the tinplate sheet in the sodium chloride solution (1). The corrosion occurs as oxygen penetrates via small pores and fractures on the tinplate surface. This allows rusting of steel by formation of a passive oxide layer. The technology applied for the protection of the interior of the can and lid and the type of protective lacquer coating is determined by the content to be packaged in the can because acidic or alkaline effects of some products cause corrosion. Since tinplate is quite important economically for the canning industry and due to its various industrial applications, the protection of tinplate against corrosion has attracted a lot of attention. A small number of studies on the corrosion behaviours of tinplate have been conducted, and the corrosion behaviours in neutral media are still uncertain (1-5). Therefore, a study on the corrosion behaviour of tinplate in sodium chloride solution is of great significance. Huang et al. (2) have concluded that the corrosion of tinplate was different from pure tin. Corrosion films on pure tin exposed to sodium chloride solution were composed of SnO<sub>2</sub>, SnO or Sn(OH)<sub>2</sub>. However, no corrosion products have been detected on the tinplate. The alloy layer of tinplate greatly affects the corrosion resistance of

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electrolytic tinplate. In order to improve the corrosion resistance of tinplate some studies about the alloy layer of tinplate have been conducted (1,4). There are several methods to protect tinplate against corrosion and one of them is to add natural inhibitors to the solution in contact with the surface in order to reduce the corrosion rate and inhibit the corrosion reaction. The corrosion protection is achieved by adsorption of inhibitor molecules on the tinplate surface based on two types of adsorption processes, i.e. chemical and physical adsorptions. The mechanism of adsorption on the tinplate surface reduces the corrosion rate by increasing or decreasing the cathode or anode reactions and by reducing the diffusion rate of aggressive components on the tinplate surface (6). There is a plethora of opportunities for discovering new, economical and eco-friendly corrosion inhibitors from this exceptional source of natural products, such as phytochemicals from plants. The inhibition performance of plant extracts is ascribed to the presence of complex organic species, including phenolic compounds in their composition. Functional groups with conjugated double bonds, nitrogen and oxygen atoms or aromatic rings in their molecular structures, which are the major adsorption centres (7) are the integral part of these organic compounds. This is why a new group of natural corrosion inhibitors that have a potential to replace the synthetic ones is being investigated. Several studies on the inhibition of corrosion of iron, steel, carbon steel by means of plant extracts (7-11) or purified compounds (12,13) have been recently conducted. Also, research has shown that *Ficus tikoua* leaves extract (14) is a good corrosion inhibitor for carbon steel under acidic conditions, *Rosmarinus officinalis* (7), *Ginkgo* (8), *Aloe vera* (10), *Tinospora crispa* (11), sage (15), bamboo (16), *Thymus vulgaris* (17), *Eucalyptus* (18) have been found to act as a very efficient inhibitor for iron or steel corrosion in acidic media. There is a great interest in using natural plant extracts or compounds that can act as cathodic or anodic corrosion inhibitors in neutral or acidic media. However, several studies have been conducted to investigate the corrosion inhibition by natural compounds on tinplate or pure tin used in canning industry. For example, the essential onion oil can be used as an excellent natural inhibitor of tinplate in canned tomato purée (5). Furthermore, pectin from tomato peel waste acts as a cathodic inhibitor for tin in 2 % NaCl, 1 % acetic acid and 0.5% citric acid (19). Thus, there are several studies examining the inhibitory properties of natural compounds on tinplate or pure tin. Nothing in literature has been found regarding the effect of sage as a natural inhibitor on tinplate corrosion. A research in potentiodynamic polarization has revealed that *S. officinalis* leaves extract (15) and sage essential oil (20) act as a green corrosion inhibitor of steel in acidic media. Sage (*Salvia officinalis*, Lamiaceae) contains naturally occurring phenolic dimers, flavonoids and plant oils. In this

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context considering the diversity of the structures of polyphenols that are present in sage, it represents a promising potential source of, so-called, green inhibitors.

The purpose of this research is to investigate the inhibition effect of the sage extract on the corrosion of tinplate in 3.0 % sodium chloride solution, by means of potentiodynamic and electrochemical impedance spectroscopy (EIS), ATR–FTIR analysis and open circuit potential (OCP). Effects of inhibitor concentration (0.05–0.5 mg/L) and immersion time (1–12 h) were investigated. The aim is to define, as accurately as possible, the anodic and cathodic processes which occur during tinplate corrosion over a specific timeframe, and to determine the type of inhibitor in question – whether sage extracts are anodic or cathodic types of inhibitors. The tinplate sample will be observed under the microscope and the results will be used to try and determine if the inhibitory layer of the plant extract on the surface of tinplate is adsorbed through a specific timeframe. Likewise, in order to determine groups of compounds that are adsorbed through time, FTIR analysis will be used. Reportedly, sage extract still has not been studied for the purpose of corrosion inhibition on tinplate in 3.0 % sodium chloride solution. This research will determine the optimal concentration of sage extract for achieving inhibitory activity of tinplate corrosion.

## MATERIALS AND METHODS

### *Reagents*

Sodium chloride purchased from Kemika (Zagreb, Croatia). Petroleum ether and ethanol were bought from Carlo Erba (Val de Reuil Cedex, France). The Millipore apparatus was used to obtain deionised water for the preparation of sodium chloride

### *Plant material*

Naturally growing Dalmatian sage (*Salvia officinalis* L.) is indigenous to the Mediterranean part of Croatia, specifically Pirovac. It was harvested in the evening and dried immediately after harvesting. After that, the dry sage was packed in polyethylene bags and kept in a dark, dry and cool place. Before being used, the plant material was crushed using a household blender (Mixy, Zepter International) and then used for extraction.

### *Tinplate samples*

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The tinplate used in this paper was a tin coated carbon steel with the thickness of the tin coating of about 2.8 g/m provided by the Lim Samoborka Company (Croatia). Round tinplate specimens, with the cross-sectional area of 1.14 cm<sup>2</sup>, were placed in a PTFE holder so that the surface area of 0.875 cm<sup>2</sup> of was exposed to the solution. Distilled water was used to wash the surface, it was degassed by ethanol in an ultrasonic bath and then dried before being exposed to 3.0 % NaCl solution.

#### *Preparation of plant extract*

Dried sage (*Salvia officinalis* L.) leaves were ground to powder. 4 g of the powder was extracted with 250 mL of petroleum ether in a Soxhlet extractor for 6 h. The extract was concentrated under vacuum at 50 °C until the solvent was completely removed. The remaining was stored in a refrigerator for future use. In order to prepare the desired concentrations by dilution with 3.0 % sodium chloride solution, stock solutions of sage extract were used. The concentration ranges of the inhibitors used were 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 mg/L in a 3.0 % sodium chloride solution.

#### *Electrochemical measurements*

The electrochemical measurements of sage extracts on corrosion of tinplate in 3.0 % sodium chloride solution were carried out by using a Potentiostat/Galvanostat ZRA (Gamry Instruments, USA). A platinum electrode as a counter electrode and saturated calomel electrode as a reference electrode were used in electrochemical experiments carried out in an electrolytic cell. The tinplate sample embedded in the PTFE holder served as a working electrode. Before each experimental run, the working electrode (tinplate samples) had to go through the process of being washed with distilled water and degassed with ethanol in an ultrasonic bath. Then in order to attain a stable state, the electrode was immersed in a test solution at open circuit potential (OCP) for one hour. The potentiodynamic current potential curves were recorded by automatically changing the electrode potential from -0.6 to no more than -0.1 V with a scanning rate of 1 mV/s. EIS measurements were carried out within the 100 kHz–1 mHz frequency range at a steady open circuit potential (OCP) disturbed by an amplitude of 10 mV. The working electrode was immersed in the solution for 2 hours in order to allow stabilization of the stationary potential. Nyquist and polarization plots were then generated from the individual measurements. The Tafel method of extrapolation and Faraday laws were used to ascertain corrosion parameters via software, while impedance parameters were ascertained through appropriate electric circuit models. In order to ensure that reproducible results were reported, each experiment was repeated no less than three times. All electrochemical results

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were carried out at 25 °C. The kinetic parameters measured during corrosion processes have been used to calculate the surface coverage  $\theta$ , polarisation resistance  $R$ , and the corrosion current density  $i_{corr}$ .

#### *Spectroscopic analysis ATR–FTIR analysis*

ATR–FTIR analysis by Fourier transform infrared (SHIMADZU-IRAffinity-1, Japan) was used to analyse the characterisation of 3.0 % sodium chloride solution with the addition of 0.2 mg/L sage extract and the protective adsorption film modified on the tinplate after its immersion in the solution mentioned above at room temperature for 12 hours. The spectral resolution was 4 cm<sup>-1</sup> and a wave number range of 400–4000 cm<sup>-1</sup> was applied to the collection of IR spectra and identified through a comparison with the standard peak positions of the groups.

#### *Scanning microscope*

The tinplate specimens were immersed for 12 hours in two different 3.0 % sodium chloride solutions; one without and one with the addition of 0.2 mg/L of inhibitors (sage) After the experiment, the specimen was removed, rinsed quickly with distilled water and dried. The changes on tinplate surface were examined under the Microscope (Olympus BX51, USA).

## RESULTS AND DISCUSSION

#### *Electrochemical measurements*

OCP-test, the potentiodynamic polarisation method and electrochemical impedance spectroscopy (EIS) techniques have been used to investigate the corrosion behaviour of tinplate in a 3.0 % sodium chloride solution containing different concentrations (0.05–0.5 mg/L) of sage extract at 25 °C. In order to allow stabilization of the steady-state potential, electrochemical polarization was started 60 min after immersion of the working electrode in the solution in all experiments.

**Table 1** shows that, compared to 3.0 % NaCl solution, OCP values shifted to a more positive potential with time in the presence of sage extracts. From the results is evident that the steady state value of OCP for tinplate in the presence of sage extracts it shifted toward the positive direction, to -428.7 mV whereas in blank solution was -502.9 mV. The shift in the steady state value of OCP in the

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presence of sage extracts was about 73.2 mV which suggests that all sage extracts act as mixed type corrosion inhibitors.

As previously established, a differential greater than 85mV in OCP value is recognized as a classification evidence of a compound as an anodic or cathodic type of inhibitor (17,21,22). Therefore, the sage extract acts as a mixed inhibitor since the values of corrosion potential do not change significantly in the cathode or the anode direction (23). Fig. 1 shows typical 'Tafel' plots for the corrosion of tinplate in 3.0 % NaCl and in the presence of sage extracts in concentrations (0.05–0.5 mg/L), whereas their electrochemical parameters are given in Table 1. There has been a decrease of the corrosion current density ( $i_{\text{corr}}$ ) values in the presence of sage extracts in concentration of 0.2 mg/L in 3.0 % NaCl which means that the corrosion process of tinplate was suppressed in the presence of sage extracts (Table 1). However, the lowest  $i_{\text{corr}}$  values were observed in the presence of the sage extract in a concentration of 0.2 mg/L in 3.0 % NaCl, suggesting that the concentration of 0.2 mg/L has stronger inhibitive properties in comparison to other concentrations of sage extracts. It is evident from Table 1 that the highest inhibition efficiency IE was obtained for the concentration of 0.2 mg/L sage extract in 3.0 % NaCl (82.5 %).

Results clearly show that the addition of sage extract to the 3.0 % NaCl solution at a concentration of 0.2 mg/L results in a small shift in the corrosion potential to less negative values, as well a shift in both anodic and cathodic branches toward lower current densities. The decrease of  $i_{\text{corr}}$  of all sage extracts in comparison with 3.0 % NaCl may suggest mixed type corrosion inhibition behaviour with a predominant decrease at the cathodic site (17,24).

The confirmation was also supported by a substantial difference of the cathodic Tafel slope ( $\beta_c$ ) in the absence and presence of sage extract in 3.0 % NaCl. Furthermore, the displacement of  $E_{\text{corr}}$  was 73.2 mV, hence the inhibitor can be seen as a mixed type inhibitor.

In 3.0 % NaCl solution, the presence of 0.2 mg/L sage extract causes a notable drop in the corrosion rate, *i.e.* shifts both anodic and cathodic curves to lower current densities which is evident from Tafel plots. Inhibitor efficiency of sage extract in concentration of 0.2 mg/L reaches up to a maximum of 82.5 % in 3.0 % NaCl. Due to The inhibitor adsorption on the active sites of tinplate surface, the blocking of aggressive species access to the metal surface occurs. The result of coverage of adsorbed sage inhibitor molecules on the tinplate surface is the result of decreasing dissolution of the tinplate surface area and retarding the corrosion process of tinplate without any changes to the reaction mechanisms.

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**Table 1.** Kinetic parameters for corrosion of tinplate obtained from potentiodynamic polarisation curves with and without addition of sage extract in 3.0 % NaCl at 25 °C.

**Figure 1.** Potentiodynamic polarization curves (1 mV/s) for tinplate in the absence and presence of different concentrations of sage inhibitor.

Impedance measurements of tinplate at its open circuit potential after one-hour immersion in 3.0 % NaCl solution alone and in the presence of different inhibitor concentrations were performed over a frequency range of 100 kHz -1 mHz. Nyquist diagrams of tinplate in 3.0 % NaCl are shown in **Fig. 2** in order to compare the corrosion behaviour in the presence of different concentrations of the inhibitor used. The high frequencies semicircle is attributed to the time constant of charge transfer and double-layer capacitance, while the presence of a low frequency inductive-loop can be attributed to the relaxation process resulting from the adsorption process of inhibitor species on the tinplate surface.

To analyze the measured EIS data, a suitable electrical equivalent circuit has to be chosen. The fitting of the obtained experimental data was performed using the electrical equivalent circuit (EEC) shown in **Fig. 3** and the ZView software (developed by Scribner Associates).

**Figure 2.** Nyquist plots for tinplate in 3.0 % NaCl solution with and without the presence of different concentrations of sage (*Salvia officinalis* L.) extract at 25 °C.

**Figure 3.** Equivalent circuits for tinplate samples in 3.0 % NaCl with and without addition of sage (*Salvia officinalis* L.) extract.

It can be seen from the Nyquist diagrams that the depressed semicircles are present both in the cases where the electrodes are not inhibited and in the case where a protective adsorption film has been obtained on the tinplate surface. Such a phenomenon is usually observed at the practical metal electrode/solution interface, which is known to be related to the roughness of the electrode surface. Metals in the NaCl solutions usually corrode, increasing the roughness of the electrode surface and the use of a CPE element is required instead of the ideal capacitor in the EEC.

In the EEC used,  $R_s$  represents the resistance of the solution. Furthermore, the equivalent circuit consists of two RC circuit elements, where  $R_1$  is the resistance of the adsorbed film and  $CPE_1$  is the constant phase element connected to the capacitance of the adsorbed film.  $CPE_2$  is the constant phase element of the double layer connected to the double layer capacitance  $C_{dl}$  in parallel with the



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charge transfer resistance ( $R_2$ ) which is in series with the inductive element  $L$  connected in parallel. The electrochemical parameters obtained from the EIS measurements after 2.5 h of immersion, including the IE%, are shown in [Table 2](#).

**Table 2.** Equivalent circuit parameters for tinplate electrode in 3.0 % NaCl solution in the absence and presence of inhibitors after 2.5 h of immersion at 25 °C

Keddam *et al.* (25) have reported that the inductive loops in the low-frequency range are generally attributed to the existence of relaxation processes of adsorbed species (e.g. relaxation of coverage by an adsorbed intermediate). They have also been associated with the modulation of surface or salt film properties. In a paper on "exfoliation corrosion" of aluminium alloys, induction loops have been affiliated with the weakening of the protective effect of the aluminium oxide layer due to anodic dissolution of the alloy.

The presence of  $L$  in the impedance spectra in the presence of the inhibitor suggests that the tinplate could be dissolved (to a lesser extent, indicating relatively high values of polarization resistance) by a direct charge transfer at the surface with adsorbed sage extract.

As it can be seen from [Table 3](#), the polarization resistance  $R_p$  ( $R_p$  represents the sum of all resistances contained in the EEC) values increased with inhibitor concentration increment from 0.05–0.2 mg/L. The biggest semicircle diameter was obtained with the addition of 0.2 mg/L of sage inhibitor, with a value close to 298.70 k $\Omega$  cm<sup>2</sup> after 2.5 h of testing, several times bigger than the one obtained for both the uninhibited and blank solution (17).

The reason for this might be any kind of increase in the surface coverage by the inhibitor, which led to an increase in the inhibition efficiency. It can also be argued that an increase in semicircles with inhibitor concentration (as shown in [Fig. 2](#)) also means a reduction in corrosion rate, which agrees well with the results of potentiodynamic measurements.

A further increase in the concentration of an added inhibitor leads to a marked decrease in the radius of depressed semicircles in the Nyquist plots, which is also reflected in a decrease in inhibitory efficiency. In order to explain this effect, it could be speculated that an excessive concentration of inhibitor may impede the movement of inhibitor molecules (7,26), possibly even leading to the formation of larger structures or complexes with dissolved metal ions, which could make transport to the metal surface more difficult.

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Another possible explanation would be that after specific inhibitor quantities increment in the solution no active site existed for adsorption. Therefore, the inhibitors molecules could not adsorb on the metal substrate. However, corrosion is still occurring (which means the inhibitory layer did not change but corrosion activity increased against immersion time). This is why the efficiency decreased to lower values.

It has been previously reported that capacitance values corresponding to the adsorption (or desorption) process are of around 100–1000-times higher than  $C_{dl}$  (27).

A significant increase in capacitance was observed at a concentration of added inhibitor between 0.05–0.3 mg/L, ranging from 68.28 to 117.63  $\mu\text{F}/\text{cm}$ . In this concentration range the radius of the depressed semicircles also increases sharply compared to the uninhibited surface. Thus, we confirm the presence of an adsorbed protective film, which is also accompanied by a significant increase in the polarization resistance and, consequently, a rise in inhibition efficiency.

However, at the concentration of the added inhibitor  $c > 0.03$  mg/L, the capacitance of the adsorbed film again decreases sharply, indicating a problem with adsorption and thus lower IE values. It should be noted that this study has once again demonstrated the importance of optimizing the concentration of the added inhibitor to avoid activation rather than inhibition.

**Table 3** also shows that as the exposure time of the tinplate samples to the corrosive medium increases with and without the presence of the inhibitor, the inhibition effect starts to decrease. Obviously, the dynamics of the anodic process could have a destructive effect on the self-assembling adsorption layer, reducing the possibility of a more successful adsorption of inhibitor molecules.

**Table 3.** Polarization resistance (EIS measurements) and inhibition efficiency for tinplate in 3.0 % NaCl with and without inhibitor addition after 2.5 h, 5 h, 8 h, 10 h, and 12 h of immersion.

It is evident from the results that after the addition of sage extract in 3.0 % NaCl the impedance response of tinplate has changed.

The surface coverage of sage inhibitor on the tinplate surface after immersion of tinplate in 3.0 % NaCl with sage inhibitor was shown in **Fig. 4a** and **4b**. It has been confirmed by these results that the sage extract exhibits good inhibitive performance for tinplate in a 3.0 % NaCl solution at a concentration of 0.2 mg/L. ATR–FTIR spectra was utilised to confirm the protective adsorption film modified on the tinplate surface after exposure to a 3.0 % sodium chloride solution with additions of 0.2 mg/L sage extracts (**Fig. 5**).

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### *Optical microscopic studies*

Optical images of tinplate morphology before immersion and after the corrosion test in 3.0 % sodium chloride solution, with addition of the sage extract in a concentration of 0.2 mg/L, are shown in Fig. 4a and 4b. A layer of inhibitors (3.0 % NaCl with the sage extract at 0.2 mg/L concentration) is clearly visible on the tinplate surface due to the inhibiting action of the sage extract. The morphology of tinplate surface in Fig. 4b is due to the electrochemical action of sage extract inhibition on tinplate surface. The sage extract formed a protective adsorption film on the tinplate surface, inhibiting the diffusion of corrosive anions in the sodium chloride solution.

**Figure 4.** Micrographs of tinplate surface: a) before immersion; b) after 12 h of immersion at 25 °C in 3.0 % NaCl at a concentration of 0.2 mg/L sage inhibitor.

### *Characterization of sage extract*

ATR–FTIR analysis was utilised to confirm the presence of some functional group present in the prepared protective adsorption film on the tinplate surface which act as active corrosion inhibitors. Fig. 5 shows the ATR–FTIR spectra of the protective adsorption film modified on the tinplate surface after exposure to the 3.0 % sodium chloride solution with additions of 0.2 mg/L sage extracts. The peak at  $3728.40\text{ cm}^{-1}$  is attributed to N–H or O–H stretching. The band at  $2926.01\text{ cm}^{-1}$  and  $2854.65\text{ cm}^{-1}$  are related to C–H stretching vibration. The peak at  $1732.08\text{ cm}^{-1}$  is assigned to C=C or C=O stretching vibration bands, which correspond to stretching modes of carbonyl groups; and one more vibration on  $1026.13\text{ cm}^{-1}$  due to a single bond (C–O). The C–H bending bands in  $-\text{CH}_2$  and  $\text{CH}_3$  are found to be  $1454.33\text{ cm}^{-1}$  and  $1365.60\text{ cm}^{-1}$ , respectively. Besides these, there are adsorption bands at  $1261.45\text{ cm}^{-1}$ ,  $1174.64\text{ cm}^{-1}$ ,  $1109.07\text{ cm}^{-1}$ ,  $1087.75\text{ cm}^{-1}$  and  $1026.13\text{ cm}^{-1}$  are attributed to stretching modes of C–O stretching vibrations. The absorption bands below  $1000\text{ cm}^{-1}$  can be assigned to stretching mode of aliphatic or aromatic C–H groups respectively. The presence of O–H, C–H and C=O bonds is evident, which suggests the presence of carboxylic acids. The phenolic components possess heteroatoms, such as N and O that can act as adsorption centres. All these characteristics correspond to compounds such as phenolic and fatty acids, mono and diterpens and flavonoids. These results indicate that the sage extract adsorbed on tinplate surface contains O and N atoms in functional groups and aromatic ring which is in accordance with other authors (3,7,16,17). Fang *et al.* (12) conducted a research in which the aromatic structure of phenolic compounds was attributed to corrosion inhibition properties. This FTIR spectrum shows that the sage extract contains

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a mixture of compounds *i.e.* flavonoids, fatty acids and mono and diterpens. It can be seen from the results from FTIR characterization that the reason for anti-corrosion property of sage extract is the presence of O atoms and aromatic rings flavonoids which exist in the extract; the band shifting confirms that the sage extract inhibits corrosion by adsorption on the tinplate surface. Sage extract has not yet been used as a corrosion inhibitor for tinplate, but this research has shown evidence of good inhibition properties of sage regarding tinplate corrosion, due to its chemical composition and high share of phenolic compounds. The efficiency of sage extract in inhibiting the corrosion of tinplate is attributed to the synergistic effect of several organic molecules present in the extract.

**Figure 5.** FTIR spectra of tinplate surface after 12 h of immersion at 25 °C in 3.0 % NaCl at a concentration of 0.2 mg/L sage inhibitor.

## CONCLUSIONS

Sage extract has not yet been used as a corrosion inhibitor for tinplate, but this research has shown compelling evidence of good inhibition properties of sage regarding tinplate corrosion, due to its chemical composition. The sage extract inhibits the tinplate in a 3.0 % sodium chloride solution corrosion medium and the corrosion rate decreases with the increase in sage concentration to 0.2 mg/L. EIS analysis revealed that by increasing the concentration of sage extract in 3.0 % NaCl to 0.2 mg/L the inhibition efficiency increased to 94.1% after 2.5 h. The Tafel polarization and inhibition efficiency of 82.5 % were in reasonably good agreement while the sage extract showed a mixed type inhibition effect. The inhibitive action of the sage extract was attributed to the adsorption of organic compounds, such as polyphenolic compounds, to the tinplate surface, thereby blocking the active corrosion sites. Our results show that sage extract in sodium chloride solution can be exploited as an effective mixed type of inhibitor for tinplate which would replace the use of synthetic ones and can find their application in food packaging industry.

## AUTHORS' CONTRIBUTIONS

Conceptualization, M.D. and R.F.G.; methodology, M.D. and R.F.G.; formal analysis, M.D. and R.F.G.; investigation, M.D. and R.F.G.; writing – original draft preparation, M.D.; supervision, R.F.G.; project administration, R.F.G.; funding acquisition R.F.G. All authors have read and agreed to the published version of the manuscript.

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## CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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**Table 1.** Kinetic parameters for corrosion of tinplate obtained from potentiodynamic polarisation curves with and without addition of sage extract in 3.0 % NaCl at 25 °C

$\gamma$ /(mg/L)	$E_{\text{corr}}$ /mV	$i_{\text{corr}}$ /( $\mu\text{A}/\text{cm}^2$ )	$v_{\text{corr}}$ /(mm/year)	$\beta_c$ /mV	$\beta_a$ /mV	$\theta$	IE/%
Blank	-502.9	2.880	0.0338	438.8	55.24	-	-
0.05	-518.6	2.261	0.0265	197.1	54.40	0.215	21.5
0.1	-521.6	1.521	0.0183	255.0	44.99	0.472	47.2
0.2	-428.7	0.503	0.0059	251.8	18.53	0.825	82.5
0.3	-561.7	0.599	0.0070	309.4	-	0.792	79.2
0.4	-454.4	0.869	0.0102	333.1	28.85	0.698	69.8
0.5	-493.6	0.962	0.0113	370.3	51.47	0.666	66.6

**Table 2.** Equivalent circuit parameters for tinplate electrode in 3.0 % NaCl solution in the absence and presence of inhibitors after 2.5 h of immersion at 25 °C

Corrosive media 3.0 % NaCl +x mg/L sage extract	$R_1$ /(k $\Omega$ cm <sup>2</sup> )	$n_1$	$C_1$ /( $\mu\text{F}/$ cm <sup>2</sup> )	$R_2$ /(k $\Omega$ cm <sup>2</sup> )	$n_2$	$C_2$ /( $\mu\text{F}/$ cm <sup>2</sup> )	$R_p'$ (k $\Omega$ cm <sup>2</sup> )	% $\eta_{Rp}$
Blank	8.17	0.815	4.44	19.91	0.646	2.29	19.91	
0.05	19.02	0.825	68.26	98.24	0.503	2.82	117.26	83.02
0.1	45.76	0.830	88.50	101.50	0.538	3.61	147.26	86.48
0.2	40.76	0.752	101.83	298.70	0.559	2.84	339.46	94.13
0.3	31.47	0.753	117.63	80.39	0.524	6.56	111.85	82.20
0.4	9.18	0.789	6.84	87.82	0.776	5.02	90.00	77.88
0.5	9.05	0.825	6.90	49.97	0.651	3.12	59.02	66.27

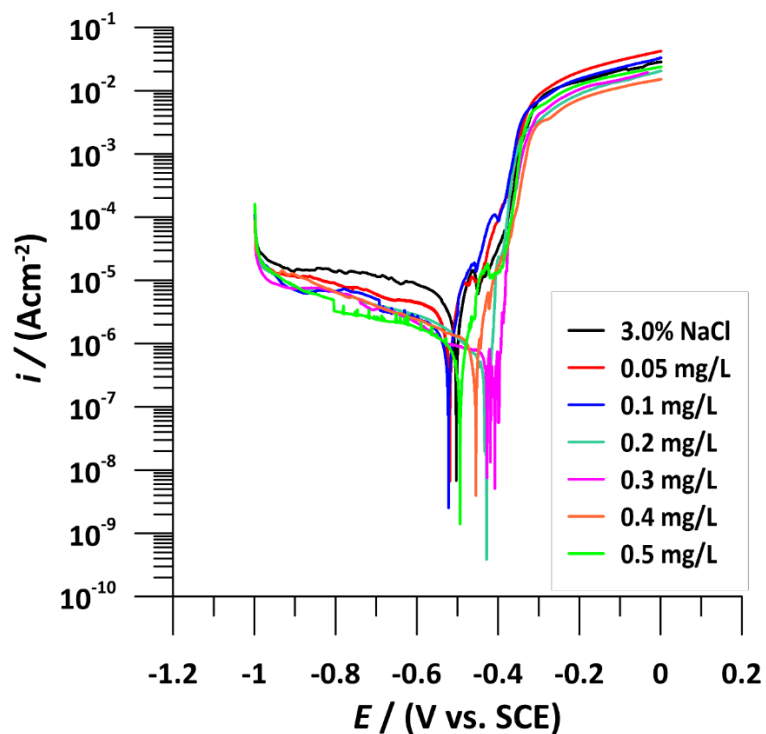
$$R_p = R_1 + R_2$$

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**Table 3.** Polarization resistance (EIS measurements) and inhibition efficiency for tinplate in 3.0 % NaCl with and without inhibitor addition after 2.5 h, 5 h, 8 h, 10 h, and 12 h of immersion

$\gamma$ /(mg/L)	t/h	$R_p$ /(k $\Omega$ cm <sup>2</sup> )	IE/%
Blank	2.5	19.91	-
	5	11.60	-
	8	7.40	-
	10	5.94	-
	12	4.76	-
0.05	2.5	98.24	83.0
	5	24.30	52.3
	8	11.52	35.8
	10	9.01	34.0
	12	9.01	47.1
0.1	2.5	101.50	86.5
	5	60.49	80.8
	8	25.76	71.6
	10	13.61	56.4
	12	8.46	43.7
0.2	2.5	298.70	94.1
	5	133.20	91.3
	8	67.07	89.0
	10	41.70	85.8
	12	25.82	81.6
0.3	2.5	80.39	82.2
	5	27.45	57.7
	8	16.78	55.9
	10	13.81	57.0
	12	13.71	65.3
0.4	2.5	87.82	77.9
	5	25.87	55.2
	8	16.49	55.1
	10	13.57	56.2
	12	12.13	60.7
0.5	2.5	49.97	78.0
	5	72.61	84.0
	8	46.73	84.2
	10	33.15	82.1
	12	28.67	66.3

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**Fig. 1.** Potentiodynamic polarization curves (1 mV/s) for tinplate in the absence and presence of different concentrations of sage inhibitor

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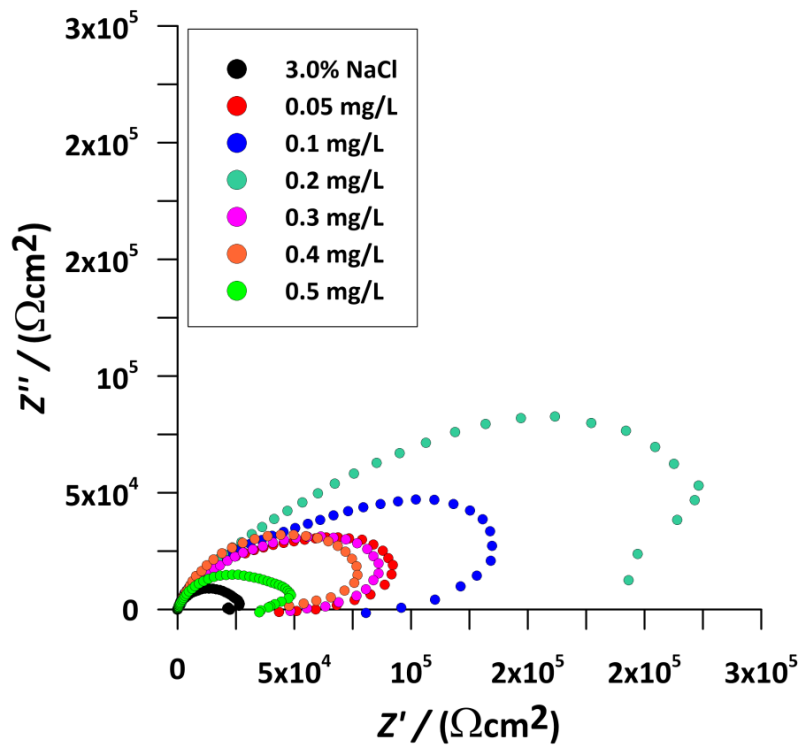


Fig. 2. Nyquist plots for tinplate in 3.0 % NaCl solution with and without the presence of different concentrations of sage (*Salvia officinalis* L.) extract at 25 °C

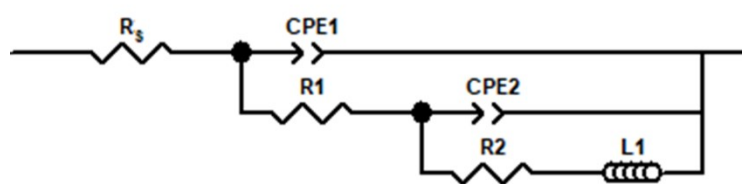
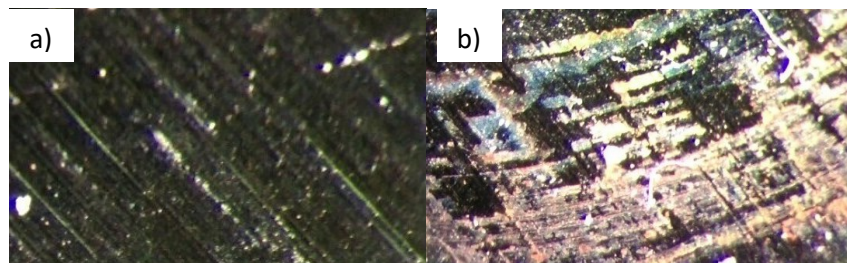


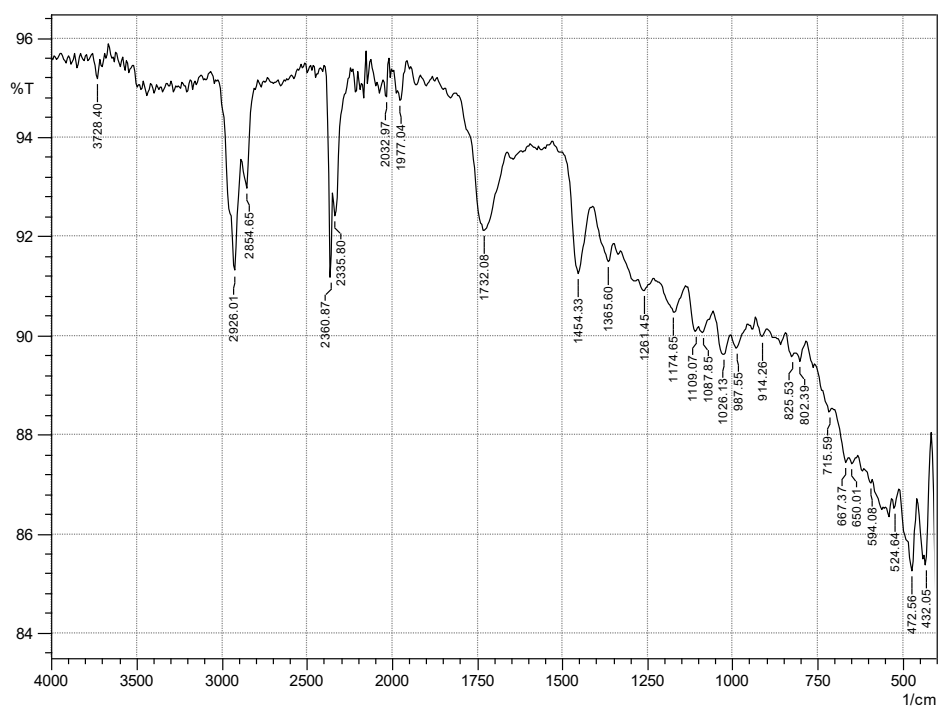
Fig. 3. Equivalent circuits for tinplate samples in 3.0 % NaCl with and without addition of sage (*Salvia officinalis* L.) extract

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**Fig. 4.** Micrographs of tinplate surface: a) before immersion; b) after 12 h of immersion at 25 °C in 3.0 % NaCl at a concentration of 0.2 mg/L sage inhibitor

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**Fig. 5.** FTIR spectra of tinplate surface after 12 h of immersion at 25 °C in 3.0 % NaCl at a concentration of 0.2 mg/L sage inhibitor