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Synergy between iodide ions and mangrove tannins as inhibitors of mild steel corrosion

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Abstract

- **Context** Corrosion of materials is a problem faced by many industries. One of the solutions to this problem is to apply corrosion inhibitors.
- **Aims** In this study, the synergy between iodide ions and mangrove tannin extracted from mangrove bark (waste products of the charcoal industry) was tested on the inhibition of corrosion of mild steel in 0.5 M HCl and 0.25 M H₂SO₄. It was compared with the inhibition provided by mimosa and chestnut tannins.
- **Methods** Potentiodynamic and electrochemical impedance were recorded under various temperatures from 30 to 60°C in order to obtain the activation energy (E_a), the activated enthalpy (ΔH) and the activated entropy (ΔS).
- **Results** The results showed that there was an increase in inhibition efficiency when iodide ions were added to corrosive media in the presence of mangrove tannin. The effect decreased when temperature increased. Mangrove tannins showed comparable inhibitive properties to those of commercial mimosa and chestnut tannins.
- **Conclusion** Inhibition efficiency of tannins as inhibitors of corrosion for mild steel in acidic media was improved by the addition of iodide ions. Tannins extracted from mangrove bark were more efficient than those from mimosa and chestnuts.

Keywords Synergistic effect · Mangrove tannin · Thermodynamic

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Contribution of the co-authors Afidah Abdul Rahim: supervising the work and writing the paper.
Mohd Ridhwan Adam: designing the experiment, running the data analysis, and writing the paper.
Affaizza Mohamad Shah: writing the paper.

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1 Introduction

Metals and alloys are normally used for a wide range of purposes that are normally designed for long-term applications. Mild steel is one of the most used metal alloys in automobile, water treatment, and construction industries. However, long exposures of this metal in the corrosive media and environments have led to the corrosion of these metal alloys (Prabhu et al. 2008). As a consequence, the lifetime of mild steels will be shortened, and this problem leads to other serious problems that includes the loss of life due to accidents (Davis 2000). The corrosion processes are usually caused by the interactions between the metal and its surroundings. Corrosion of metals is an electrochemical reaction which can cause the damage and deterioration of the physical and chemical properties of the attacked metals or alloys (Winston 2000; Syed 2006).

Some of the typical corrosive media are humid air, water (fresh, distilled, salted, and marine), acids, bases as well as soil, steam, and gases. Strong acids such as hydrochloric and sulphuric acids are widely used in industries for many purposes, especially in cleaning, de-scaling, and pickling procedures. The corrosion scientists have employed many methods to control corrosion processes. One of the most practical methods is the use of corrosion inhibitors (Winston 2000).

Although the use of corrosion inhibitors will reduce undesirable acid metal dissolution, inorganic inhibitors are harmful to the environment due to their toxicity. Therefore, there is now a focus on the development of nontoxic inhibitors as alternatives to replace inorganic inhibitors. Several investigations have been reported on the use of plant extracts containing alkaloids and polyphenolic compounds as well as carbohydrates as inhibitors (Rahim and Kassim 2008; Raja and Sethuraman 2008). It has been reported that most of the effective inhibitors possess an active functional group such as nitro (–NO₂) or hydroxyl (–OH) groups such as in tannins. Tannins extracted from mangrove (*Rhizophora Apiculata* Blume) bark are phenolic compounds with high molecular

masses. Afidah (2009) previously identified mangrove tannins as condensed tannins. Mangrove tannins have been found to contain high proportions of procyanidins to prodelphinidins with the predominant interflavanoid linkages of C4-C8; it has also been found that flavanoid units with *cis*-configuration at C2 and C3 form the bulk of the oligomers, and that mangrove tannin oligomers have complex structures with high degree of polymerisation from the trimers to decamers that correspond to the molecular weight up to 3,000 Da. Multiple groups of hydroxyphenolics enable the formation of tannin complexes with protein, metal ions, and other macromolecules.

Most of the acidic inhibitors are specific in action. However, the efficiencies of these inhibitors can be further enhanced with the addition of other substances or in combination with other inhibitors. The introduction of halide ions has been found to enhance the inhibition efficiency of organic inhibitors synergistically (Pavithr et al. 2010). It is generally agreed that the addition of halide ions to corrosive media has increased the ability of adsorption of organic cations by forming interconnecting bridges between negatively charged metal surfaces and inhibitor cations.

There are many techniques used in determining and measuring the corrosion rate of metals. Previously, the weight loss method, sometimes known as the gravimetric method, was the only conventional method used for corrosion measurements. However, as the research world becomes more sophisticated, modern technology has led to the development of electrochemical measurements. These time-saving measurements have produced some comparative results to the conventional gravimetric method.

Various tannins, especially mangrove tannin, have been found to be good corrosion inhibitors for mild steel in acidic media (Rahim et al. 2007, 2008, 2011; Rahim and Kassim 2008). As such, in this present work, the inhibition efficiency of mangrove (*Rhizophora Apiculata* Blume) tannin (MgT) in relation to the corrosion of mild steel in 0.5 M HCl and 0.25 M H₂SO₄ solutions has been studied. Enhancement of the inhibition efficiency of this tannin was attempted through the addition of iodide ions to the tannin solution. The inhibition efficiencies obtained were then compared with those of commercial mimosa (MmT) and chestnut tannins (CnT) in all media studied.

2 Material and methods

2.1 Material preparation

Tests were performed on mild steel sheets with weight percentage compositions as follows: C, 0.205; Mn, 0.55; Si, 0.06; P, 0.039; Fe, balance. The sheets (0.1 cm thickness) were mechanically cut into dimensions of 3.0 cm × 3.0 cm for all studies. The studied surface was wet-polished with silicon carbide

abrasive paper (from grade 400 to 1,200), rinsed with double distilled water, and degreased in acetone and dried in warm air.

2.2 Inhibitor preparation

Finely ground mangrove (*Rhizophora Apiculata* Blume) bark powder was mixed with 70 % acetone and stirred for 24 h. The extract was then concentrated at 40°C under reduced pressure in a rotary evaporator to remove the acetone. Then, the concentrated extract was frozen for 24 h before being freeze-dried for 48 h. The test inhibitor mangrove tannin obtained was dissolved in 0.5 M HCl and 0.25 M H₂SO₄ solutions to obtain the desired concentration (3.0 g l⁻¹). Potassium iodide (KI) solution (0.1 M) was prepared as a blank solution and added to 3.0 g l⁻¹ mangrove tannin. Mimosa and chestnut tannins from SILVACHIMICA, Italy were used as received.

2.3 Electrochemical measurements

Electrochemical measurements were conducted in a conventional 100-ml three-electrode cell. Mild steel coupons with dimensions of 30.0 mm × 30.0 mm × 1.0 mm were used as a working electrode, while a saturated calomel electrode (SCE) and a platinum electrode were used as the reference and counter electrodes respectively. The experiments were carried out using Potentiostat/Galvanostat/ZRA Model Gamry Reference 600, and the data were analysed using Gamry Instrument Framework version 5.67 software. Prior to each measurement, the electrodes were held in the test solution at the natural potential for 30 min, providing sufficient time for corrosion potential (E_{corr}) to attain a stable state. All electrochemical experiments were carried out at 30, 40, 50, and 60°C respectively in order to obtain the thermodynamic data, and they were carried out in duplicates.

2.3.1 Potentiodynamic polarization measurement

Potentiodynamic polarisation measurements have been used to determine the effects of inhibitor concentrations on the anodic and cathodic polarisation behaviours of mild steels in 0.5 M HCl and 0.25 M H₂SO₄ solutions. The potentiodynamic polarisation measurements were carried out from a cathodic potential of -0.2 V to an anodic potential of +0.2 V with respect to the E_{corr} , at a sweep rate of 1 mVs⁻¹. The respective electrochemical parameters calculated are corrosion potential (E_{corr}), anodic and cathodic Tafel slopes (β_a and β_c), and corrosion current density (i_{corr}), which were obtained from the extrapolation of the anodic and cathodic Tafel curves towards E_{corr} . The % IE was obtained from the measured i_{corr} by using the following relationship:

$$\%IE = \frac{i^0 - i}{i^0} \times 100 \quad (2.1)$$

where i and i^0 are the inhibited and uninhibited corrosion current densities of mild steel respectively.

2.3.2 Electrochemical impedance spectroscopy measurement

Electrochemical impedance spectroscopy (EIS) measurements were made at corrosion potential (E_{corr}) over the frequency range from 100,000 to 0.1 Hz at an amplitude of 10 mV and a scan rate of 10 points per decade. The Nyquist representations of the impedance data were analysed with ZSimpWin software. The charge transfer resistance (R_{ct}) was obtained by fitting the Nyquist semicircle plots to the equivalent circuit by using the Zsimp version 3.22 software. The % IE of the inhibitor was calculated from the following equation;

$$\%IE = \frac{R_{ct} - R'_{ct}}{R_{ct}} \times 100 \quad (2.2)$$

Where R_{ct} is the charge transfer resistance values of mild steel in the absence of the inhibitor and R'_{ct} is the charge transfer resistance values of mild steel in the presence of inhibitors.

2.4 Comparison study of the inhibitory effect with several tannins

Electrochemical tests as previously described were carried out using commercial mimosa and chestnut tannins. The synergistic effects of these two tannins were studied at an optimum concentration of tannins (3 g l⁻¹ or 2 g l⁻¹) and iodide ions (0.1 M).

3 Results

3.1 Potentiodynamic polarisation measurements

The results obtained from this measurement are represented in the form of Tafel plots and shown in Figs. 1 and 2. The % IE values were calculated using the i_{corr} values obtained from the measurements as previously described in section 2.3.1. The electrochemical parameters obtained from the extrapolation of the Tafel plots in both media studied were tabulated, and are shown in Table 1.

From Table 1, it can be observed that the values of % IE of mangrove tannin alone are 89 % and 78 % in HCl and H₂SO₄ respectively, and have significantly increased to 94 % for both acidic solutions, upon the addition of iodide ions to mangrove tannin. This indicates that a synergistic effect had occurred between the mangrove tannin and the iodide ions. In addition, the data obtained from the polarisation measurements of mimosa tannin and chestnut tannin also revealed the same trend, where the % IE increased from 93 % to 95 % as the iodide ions were added to both acidic solutions containing both tannins.

3.2 Electrochemical impedance spectroscopy measurements

These measurements were undertaken to assess the interactions of the mild steel/electrolyte interface in the presence and absence of tannins with and without the addition of iodide ions. The data obtained are represented as Nyquist plots and shown in Figs. 3 and 4. The parameters from these analyses are tabulated in Table 2. From Table 2, it can be seen that the R_{ct} values increased as the concentrations of mangrove tannin increased, thus it resulted in the increment of % IE. The increment in % IE values up to 92 %, as compared to the mangrove tannin alone (84 %), has indicated that there was a synergistic effect between the tannin and the iodide ions. The combinations of iodide with mimosa tannin and chestnut tannin were performed in both acids and similar trends had also been observed. All data obtained are in good agreement with those obtained in the potentiodynamic polarisation analyses.

3.3 Temperature studies of corrosion inhibition effect of tannins and iodide ions

The thermodynamic and kinetic data that were obtained from both electrochemical measurements in both corrosive media are tabulated in Tables 3 and 4. Table 3 summarises the corresponding efficiencies of mangrove tannin in combination with 0.1 M KI at various temperatures in 0.5 M HCl and 0.25 M H₂SO₄ respectively. As the inhibitors were added into the corrosive media, the % IE values have slightly decreased, while the corrosion rate (CR) and current density (i_{corr}) increased significantly as the temperatures increased.

The variations of natural logarithms of the corrosion rate against the absolute temperature in the absence and presence of inhibitors in 0.5 M HCl and 0.25 M H₂SO₄ solutions were plotted (not shown). From these plots, it was found that the activation energies, E_a values (Table 4) in the presence of all tannins were higher than the values obtained without the inhibitors in both media. In 0.5 M HCl medium, the E_a values obtained by all three tannins were in the range 98.51–112.90 kJ mol⁻¹, which were higher than the blank (67.14 kJ mol⁻¹). The same trends were shown by 0.25 M H₂SO₄ solutions, where the E_a values in the presence of all inhibitors were higher than those obtained in the absence of these inhibitors.

4 Discussion

4.1 Potentiodynamic polarisation measurements

From the results obtained, it can be clearly seen that the presence of all tannins in both media had decreased both anodic and cathodic current densities as compared to that of the respective blank solutions. The decrease in current

Fig. 1 Tafel plots of mild steel in 0.5 M HCl in the absence and presence of mangrove tannin (MgT), mimosa (MmT) and chestnut (CnT) tannins alone and in combination with iodide ions

densities was enhanced as the iodide ions were introduced in both corrosive media containing these tannins. This provides an indication that a synergistic effect between these tannins and iodide ions has occurred. For all three tannins, the pronounced decrease in anodic current densities in the combination of these tannins and iodide ions was associated with the shift of corrosion potential (E_{corr}) towards the anodic potential region, suggesting that these corrosion inhibitors mainly affect the anodic reactions (Ali et al. 2008). In other words, the oxidation process of metal dissolution is predominately inhibited, and thus the corrosion process is slowed down. Moreover, the mass transfer process has taken place in all reactions, since the anodic gradients are higher for all analyses as compared to the cathodic regions. Therefore, all tannins are classified as mixed-type inhibitors with predominantly anodic effectiveness in both media, and the inhibitive performance of mangrove tannin with and without the addition of iodide ions

is comparable to that of commercial mimosa and chestnut tannins.

4.2 Electrochemical impedance spectroscopy measurements

As shown in Figs. 3 and 4, an increase in the size of the semicircles was obtained in the presence of tannins alone, indicating the inhibition of the corrosion process. The size of the semicircles was further increased as the iodide ions were introduced into the corrosive media containing these tannins. All Nyquist plots at high frequencies obtained in all processes are not perfect semicircles, but are depressed. The depressed form of semicircles is often referred to as frequency dispersions which have been attributed to surface heterogeneities of structural or interfacial origins such as those found in adsorption processes (Kissi et al. 2006). From all electrochemical parameters obtained, it was observed that the introduction of

Fig. 2 Tafel plots of mild steel in 0.5 M H_2SO_4 in the absence and presence of mangrove tannin (MgT), mimosa (MmT) and chestnut (CnT) tannins alone and in combination with iodide ions

Table 1 Potentiodynamic polarisation parameters of mild steel in 0.5 M HCl and 0.25 M H₂SO₄ in the absence and presence of 3 g l⁻¹ MgT, 3 g l⁻¹ MmT and 2 g l⁻¹ CnT alone and in the combination with 0.1 M KI

System	$-\beta_a$ (mV dec ⁻¹)	$-\beta_c$ (mV dec ⁻¹)	E_{corr} (mV)	i_{corr} ($\mu\text{A cm}^{-2}$)	IE (%)
HCl	95	123	-469	158	—
KI	41	157	-354	56	65
MgT	40	95	-435	18	89
MgT + KI	35	91	-372	10	94
MmT	45	107	-444	29	82
MmT + KI	62	68	-393	9	94
CnT	64	118	-451	42	73
CnT + KI	40	72	-380	11	93
H ₂ SO ₄	86	144	-486	1000	—
KI	30	155	-412	135	86
MgT	40	116	-496	219	78
MgT + KI	68	127	-421	56	94
MmT	45	177	-493	200	80
MmT + KI	60	122	-414	50	95
CnT	52	144	-502	209	79
CnT + KI	63	121	-415	53	95

MgT mangrove tannin, MmT mimosa tannin, CnT chestnut tannin

tannins into the acid solution led to the increase in the charge transfer resistance (R_{ct}) and reduction in the constant phase element (CPE), which became more pronounced as these tannins were combined with the iodide ions. The decrease in the CPE values normally results from the decrease in the dielectric constant and/or an increase in the double-layer thickness, which leads to a higher inhibition efficiency. In other words, this is due to the inhibitor adsorption onto the metal/electrolyte interface (Popova et al. 2003). The increase in R_{ct} and the decrease in CPE values as shown in Table 2 are probably due to the replacement of water molecules by the iodide ions and tannin molecules on the electrode surface, as well as probably due to the increase in the double layer

thickness as a consequence of the adsorption of these tannins and iodide ions.

4.3 Temperature studies of the corrosion inhibition effect of tannins and iodide ions

The effects of temperature were studied in order to evaluate the performance of tannins in combination with iodide ions on the nature of adsorption and activation processes. According to Bentiss et al. (2009), the effect of temperature on the inhibited acid-metal reaction is highly complex. This is due to the many changes that occur, such as the rapid etching and desorption of inhibitors on the metal surface. As the inhibitors were added into the corrosive medium, the % IE values slightly decreased as the temperature increased. This phenomenon is probably due to the desorption process of the inhibitor from the metal surface (Cheng et al. 2007) or the decomposition and/or rearrangement of the inhibitor. Alternatively, it could also be due to the decrease in hydrogen evolution overpotential (Popova et al. 2003). Similar trends also have been observed for mimosa tannin and chestnut tannin (not shown).

These observations indicated that the energy barriers of the corrosion reactions increased as the inhibitors were introduced into the corrosive medium. The decrease in % IE values as the temperatures increased with higher E_a values than in the absence of inhibitors often indicates that there is a formation of an adsorptive film which possesses a physical (electrostatic) type character (Popova et al. 2003). Moreover, the high values of E_a will lower the corrosion current density,

Fig. 3 Nyquist plots of mild steel in 0.5 M HCl in the absence and presence of mangrove tannin (MgT), mimosa (MmT) and chestnut (CnT) tannins and in combination with iodide ions

Fig. 4 Nyquist plots of mild steel in 0.25 M H₂SO₄ in the absence and presence of mangrove tannin (MgT), mimosa (MmT) and chestnut (CnT) tannins and in combination with iodide ions

i_{corr} values and thus will reduce the corrosion rates and enhance the inhibition efficiencies of the inhibitors. The increase in E_a values has been shown to indicate a strong adsorption of inhibitor molecules on the metal surface (Singh et al. 2012). According to Orubite and Oforka (2004), an E_a value that is around 40–80 kJ mol⁻¹ is suggested to obey the physical adsorption (physisorption) mechanism. In all analyses, the E_a values were within this range except for those values obtained in 0.5 M HCl medium, which were more than 80 kJ mol⁻¹. This indicated that the mode of inhibitor adsorption for this medium leans more towards chemisorption. Besides, the enthalpy, ΔH values of all analyses were positive,

reflecting that the metal dissolution processes were endothermic. The rise in ΔH values may be attributed to the presence of energy barriers for the adsorption reaction (Tebji et al. 2007). The negative values of entropy, ΔS as obtained in both media indicated that the activated complex in the rate determining step represents an association rather than a dissociation step. The increased ΔS values as compared to those obtained in the blank solution is due to the reduction in hydrogen ions discharge by adsorbed inhibitor molecules, which consequently prevent the hydrogen ions from forming adsorbed hydrogen atoms. This causes the system to pass from an orderly to more random arrangement, and hence an increase in the ΔS values (Singh et al. 2012).

Table 2 Electrochemical impedance spectroscopy parameters of mild steel in 0.5 M HCl and 0.25 M H₂SO₄ in the absence and presence of 3 g l⁻¹ MgT, 3 g l⁻¹ MmT and 2 g l⁻¹ CnT alone and in combination with 0.1 M KI

System	R_s (Ω cm ²)	CPE (μ F cm ⁻²)	R_{ct} (Ω cm ²)	IE (%)
HCl	2.175	415.3	30.4	—
KI	1.813	106.8	100.2	70
MgT	2.617	133.1	189.7	84
MgT + KI	2.496	86.6	397.3	92
MmT	2.743	158.9	168.0	82
MmT + KI	2.465	81.4	387.7	92
CnT	2.837	187.8	104.1	71
CnT + KI	2.591	92.9	175.0	83
H ₂ SO ₄	2.965	643.2	7.0	—
KI	2.828	203.1	56.5	88
MgT	2.967	502.2	23.6	70
MgT + KI	2.676	128.2	103.1	93
MmT	3.044	420.7	46.2	85
MmT + KI	2.094	177.8	84.6	92
CnT	3.455	483.4	31.5	78
CnT + KI	2.488	150.5	100.2	93

MgT mangrove tannin, MmT mimosa tannin, CnT chestnut tannin

Table 3 The effect of temperature on the corrosion inhibition of mild steel in 0.5 M HCl and 0.25 M H₂SO₄ solutions in the absence and presence of 0.3 g l⁻¹ mangrove tannin (MgT) and 0.1 M KI

System	Temperature (K)	CR (mpy)	i_{corr} (μ A cm ⁻²)	IE (%)
HCl	300	72.9	158.0	—
	313	201.5	437.0	—
	323	289.2	627.0	—
	333	450.6	977.0	—
MgT + KI	300	4.6	10	94
	313	19.5	42.3	90
	323	47.5	103.0	84
	333	99.6	215.9	78
H ₂ SO ₄	300	461.2	1000.0	—
	313	655.8	1422.0	—
	323	864.7	1874.9	—
	333	1041.7	2258.9	—
MgT + KI	300	25.8	56.0	94
	313	75.2	163.1	89
	323	168.8	366.1	81
	333	221.1	479.4	79

Table 4 The activation parameters of the dissolution reaction of mild steel in 0.5 M HCl and 0.25 M H₂SO₄ solutions in the absence and presence of 3 g l⁻¹ MgT, 3 g l⁻¹ MmT and 2 g l⁻¹ CnT and 0.1 M KI

Sample	E _a (kJ mol ⁻¹)	ΔH (kJ mol ⁻¹)	ΔS (J mol ⁻¹ K ⁻¹)
HCl	67.14	64.51	-909.74
MgT	98.51	95.89	-828.09
MmT	112.90	110.28	-748.78
CnT	103.12	100.50	-813.13
H ₂ SO ₄	20.81	18.18	-133.28
MgT	56.00	53.37	-39.32
MmT	59.38	56.76	-28.77
CnT	57.28	54.65	-35.42

MgT mangrove tannin, MmT mimosa tannin, CnT chestnut tannin

5 Conclusions

1. All tannins gave satisfactory inhibition efficiencies in all tested methods, and they were further improved with the addition of iodide ions.
2. Tannins synergised by iodide ions acted as mixed-type inhibitors with predominantly anodic effectiveness.
3. Mangrove tannin showed comparable inhibitive properties to those of commercial mimosa and chestnut tannins.

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References

- Afidah AR (2009) Mangrove tannin as a green corrosion inhibitor of steel: a comprehensive study. VDM Verlag, Saarbrücken
- Ali SA, Al-Muallem HA, Rahman SU, Saeed MT (2008) Bis-isoxazolidines: a new class of corrosion inhibitors of mild steel in acidic media. Corros Sci 51:1628–1635

- Bentiss F, Jama C, Memari B, Attari HE, Kadi LE, Lebrini M, Traisnel M, Lagrenée M (2009) Corrosion control of mild steel using 3,5-bis(4-methoxyphenyl)-4-amino-1,2,4-triazole in normal hydrochloric acid medium. Corros Sci 51:1628–1635
- Cheng S, Liu T, Chang X, Yin Y (2007) Carboxymethylchitosan as an ecofriendly inhibitor for mild steel in 1 M HCl. Mater Lett 61:3276–3280
- Davis JR (2000) Corrosion: understanding the basics. The Materials Information Society, Ohio
- Kissi M, Bouklah M, Hammouti B, Benkaddour M (2006) Establishment of equivalent circuit from electrochemical impedance spectroscopy study of corrosion inhibition of steel by pyrazine in sulphuric acid solution. Appl Surf Sci 252:4190–4197
- Orubite KO, Oforka NC (2004) Inhibition of the corrosion of mild steel in hydrochloric acid solutions by the extracts of leaves of *Nypa fruticans* Wurmb. Mater Lett 58:1768–1772
- Pavithr MK, Venkatesh TV, Vathsala K, Nayan KO (2010) Synergistic effect of halide ions on improving corrosion inhibition behaviour of benzoisothiazole-3-piperazine hydrochloride on mild steel in 0.5 M H₂SO₄ medium. Corros Sci 52:3811–3819
- Popova A, Sokolova E, Raicheva S, Christov M (2003) AC and DC study of the temperature effect on mild steel corrosion in acidic media in the presence of benzimidazole derivatives. Corros Sci 45:33–58
- Prabhu RA, Venkatesha TV, Shanbhag AV, Praveen BM, Kulkarni GM, Kalkhambkar RG (2008) Quinol-2-thione compounds as corrosion inhibitors for mild steel in acid solution. Mater Chem Phys 108:283–289
- Rahim AA, Kassim J (2008) Recent development of vegetal tannins in corrosion protection of iron and steel. Recent Patents Mater Sci 1: 223–231
- Rahim AA, Rocca E, Steinmetz J, Kassim MJ, Ibrahim MS (2007) Mangrove tannins and their flavonoid monomers as alternative steel corrosion inhibitors in acidic medium. Corros Sci 49:402–417
- Rahim AA, Rocca E, Steinmetz J, Kassim MJ, Ibrahim MS (2008) Inhibitive action of mangrove tannins and phosphoric acid on pre-rusted steel via electrochemical methods. Corros Sci 50:1546–1550
- Rahim AA, Kassim MJ, Rocca E, Steinmetz J (2011) Mangrove (*Rhizophora apiculata*) tannins: an eco-friendly rust converter. Corros Eng Sci Technol 46:425–431
- Raja PB, Sethuraman MG (2008) Natural products as corrosion inhibitor for metals in corrosive media — a review. Mater Lett 62:113–116
- Singh AK, Shukla SK, Quraishi MA, Ebenso EE (2012) Investigation of adsorption characteristics of N,N'-[(methylimino)dimethylidyne]di-2,4-xylydine as corrosion inhibitor at mild steel/sulphuric acid interface. J Taiwan Inst Chem Eng 43:463–472
- Syed S (2006) Atmospheric corrosion of materials. Emirates J Eng Res 11:1–24
- Tebbjji K, Faska N, Tounsi A, Oudda H, Benkaddour M, Hammouti B (2007) The effect of some lactones as inhibitors for the corrosion of mild steel in 1 M hydrochloric acid. Mater Chem Phys 106:260–267
- Winston R (2000) Uhlig's corrosion handbook, 2nd edn. Wiley, Ottawa